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Potential benefits of genotype-based adaptation strategies for grain sorghum production in the Texas High Plains under climate change

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ABSTRACT

Adaptation measures are required to enhance climate change resilience of agricultural systems and reduce risks associated with climate change at both regional and global scales. The Texas High Plains is a semi-arid region that faces major challenges from climate change risks and dwindling groundwater supply from the exhaustible Ogallala Aquifer for sustaining irrigated agriculture. The overall goal of this study was to assess the impacts of climate change on yield and water use of grain sorghum and identify optimum climate change adaptation strategies for three study sites in the Texas High Plains. Future climate data projected by nine Global Circulation Models (GCMs) under two Representative Concentration Pathways (RCPs) of greenhouse gas emissions (RCPs 4.5 and 8.5) were used as input for the DSSAT CSM-CERES-Sorghum model. The climate change adaptation strategies were designed by modifying crop genotype parameters to incorporate drought tolerance, heat tolerance, high yield potential, and long maturity traits. Irrigated and dryland grain sorghum yield and irrigation water use were projected to decrease at varying percentages at the study sites in the future. On an average (of 9 GCMs), irrigated grain sorghum yield is expected to decrease by 5–13 % and 16–27 % by mid-century (2036–2065) and late-century (2066–2095), respectively under RCP 8.5 compared to the baseline (1976–2005). The irrigation water use is expected to decrease by 7–9% and 14–16 % by the mid-century and late-century, respectively. Among the adaptation strategies, an ideotype with high yield potential trait (10 % higher partitioning to the panicle, radiation use efficiency, and relative leaf size than the reference cultivar) resulted in maximum grain sorghum yield gains in the future under both irrigated (6.9 %–17.1 %) and dryland (7.5 %–17.1 %) conditions, when compared to the reference cultivar. Enhancing drought tolerance by increasing root density at different soil depths also resulted in a significantly higher irrigated grain sorghum yield than the reference cultivar. A longer maturity cultivar will likely increase irrigation water use and, therefore, is not recommended for water limited conditions.

1. Introduction

Climate change is a major threat to global food security (Challinor et al., 2014; Rosenzweig and Parry, 1994). Rise in anthropogenic greenhouse gas emissions, especially carbon dioxide (CO_2), since the industrial revolution is a key driver of climate change and has led to an overall increase in energy uptake of the climate system. The global mean surface temperature increased by about 0.6 °C over the 20th century, and is projected to increase between 1 °C–3.7 °C by the end of 21st century relative to 1986–2005 (IPCC, 2014). It is likely that the frequency and intensity of temperature and precipitation extremes will increase in the future as a result of climate change (IPCC, 2014). Atmospheric greenhouse gas emissions continue to rise and stringent mitigation efforts are required to reduce climate change risks (IPCC, 2014). The interactive effect of different climate variables (e.g., temperature, precipitation, and atmospheric CO_2 concentration [CO_2]) on agricultural systems and their response to adaptation strategies varies with the type of crop and the agroclimatic region (Lobell and Burke,

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2008). It is therefore important to develop crop-specific adaptation strategies at regional scale to sustain crop production and maintain profitable crop yield under climate change (Howden et al., 2007). This study focused on the Texas High Plains, which is one of the most intensive agricultural regions in the USA and on grain sorghum due to its economic importance to this region. Sorghum has a higher drought and heat tolerance than other cereal crops like corn (Rooney et al., 2007) and its production requires less irrigation water than other major crops in the Texas High Plains region such as winter wheat (Amosson et al., 2005).

Grain sorghum [*Sorghum bicolor* L. Moench] is the fifth major cereal crop in the world, the majority of which is grown in the USA, Nigeria, Mexico, India, Argentina, Sudan, and Ethiopia (Dicko et al., 2006). The USA is the largest producer and exporter of grain sorghum (Awika and Rooney, 2004), which is primarily used for livestock feed (Schober et al., 2005). In recent years, there has been a growing interest in this crop due to current and emerging domestic and international markets such as a gluten-free whole grain diet substitute (Schober et al., 2005) and ethanol production (Rooney et al., 2007). The states of Kansas and Texas make up the largest sorghum acres in the US, with about 43 % and 32 % of total USA acres planted annually during 2010–2019, respectively (USDA-NASS, 2019). More specifically, the Texas High Plains region produces sorghum in about 9% (0.2 million ha) of the total and 32 % of the irrigated grain sorghum crop area in the USA (NASS, 2012), and the average annual grain sorghum production during 2010–2019 in this region was 1 million metric ton (USDA, 2019). This semi-arid region faces many challenges for sustaining irrigated agriculture such as rapidly declining groundwater resources in the Ogallala Aquifer and projected warmer and drier future climatic conditions (Chaudhuri and Ale, 2014; Modala et al., 2017; Scanlon et al., 2012). Agricultural industry in this region plays a vital role in Texas economy contributing over $6.6 billion annually (Guerrero and Amosson, 2013) and climate change could thus severely affect farm income. Expansion of area under grain sorghum could be one of the strategies to maintain economic yields under limited irrigation water availability in the Texas High Plains under climate change.

Grain sorghum is a C_4 plant and photosynthetic rate of C_4 plants is typically saturated at current [CO_2]. A further increase in [CO_2] should theoretically have little to no effect on photosynthesis (Leakey et al., 2006; Vu and Allen, 2009). However, free air CO_2 enrichment (FACE) (Ottman et al., 2001; Wall et al., 2001) experiments at Maricopa, AZ and open top field chamber (Prior et al., 2003) experiments at Auburn, AL, have shown mixed trends in grain sorghum yields at twice the ambient [CO_2]. The effects of CO_2 enrichment on grain sorghum yields were positive under water-limited conditions, whereas the effects were both positive and negative under ample water conditions. Prasad et al. (2006) used outdoor soil-plant-atmospheric-research chambers to study grain sorghum growth at different combinations of [CO_2] and day/night temperature regimes. They reported that doubling of [CO_2] increased grain sorghum yields by 26 % under lower daytime maximum/nighttime minimum temperature regimes (32/22 °C), while under higher temperatures (36/26 °C) grain sorghum yield decreased by 10 %.

Process-based crop simulation models have been used extensively to elucidate the impacts of different climate variables on crop production under climate change. A simulation study at different locations in India using the InfoCrop-SORGHUM model estimated a 6–37 % decline in dryland grain sorghum yields with a 5 °C increase in air temperature without considering CO_2 fertilization effect (Srivastava et al., 2010). However, when [CO_2] was increased from 369 ppm to 550 ppm, grain sorghum yield increased by about 8%. Another study using the SARRA-H model predicted up to 41 % reduction in grain sorghum yield for 6 °C temperature rise and 20 % rainfall reduction in Sub-Saharan West Africa (Sultan et al., 2013). Both studies suggested that any amount of rainfall increment would not be enough to recover grain sorghum yield loss beyond +2 °C temperature increase. Several other simulation studies (Carbone et al., 2003; Chipanshi et al., 2003; Tubiello et al., 2000) have also shown similar negative impacts of climate change on grain sorghum yield. In contrast, fewer simulation studies have also reported a positive effect of climate change on grain sorghum. For example, grain sorghum yields simulated by DSSAT and APSIM models increased between 5% and 23 % in Tanzania in the mid-century, for four out of eight GCMs under the RCP 4.5 scenario (Msongaleli et al., 2014). Overall, these studies indicate that the changes in grain sorghum yield under climate change were different for different geographic locations, and in a majority of the cases, positive effects of CO_2 fertilization on grain sorghum production are far less when compared to the negative impacts of rising temperatures and resultant grain sorghum yield will most likely decrease under climate change without adaptation.

The climate change adaptation measures tested in the previous studies include genetic alterations (Singh et al., 2014b) and changes in crop management decisions such as planting date (Srivastava et al., 2010). Singh et al. (2014b) used the CSM-CERES-Sorghum model to quantify the potential benefits of altering crop genetic characteristics that would enable better adaptation to climate change at two sites each in India and Mali. They found that a longer duration grain sorghum cultivar with 10 % increase in maturity period resulted in a 7 − 33 % increase in grain yield. Under future climate, grain yield increased by 0–8 %, 0–12 % and 4–17 %, respectively when drought tolerance, heat tolerance, and both drought and heat tolerance traits were incorporated. Drought tolerance was incorporated by increasing root growth and soil water holding capacity in each soil layer. Heat tolerance was incorporated by shifting optimum and failure temperature limits by 2 °C during the reproductive stage. Singh et al. (2014b) considered only dryland grain sorghum production and the future projections were for the mid-century period (2040–2069).

The majority of the research on sorghum has been done for locations in Africa and Asia (Amouzou et al., 2019; Elramlawi et al., 2018; Srivastava et al., 2010), and only a handful of studies were conducted in the USA. Tack et al. (2017) reported that current sorghum cultivars in the USA offer a narrow range for heat resilience, and they suggested introducing genetic diversity to enhance resilience of sorghum production to a warmer climate. We tested potential cultivars with different genetic traits using the DSSAT model. We utilized some ideotypes that have been tested outside the USA (Singh et al., 2014b), and created some new ideotypes. In addition, we accounted for the effects of adaptation on irrigation water use as well as grain yield, as opposed to solely assessing cultivars based on grain yield as was done in previous studies. Testing new cultivars along with existing genetically diverse cultivars could assist breeders in screening for climate change resilience. Crop models allow testing of genotype and environment interactions speedily, which would be beneficial in identifying and prioritizing cultivars that perform better under the simulated future climate. Therefore, the specific goals of this study were to: (a) assess the impacts of climate change on irrigated and dryland grain sorghum yield, and irrigation water use at three locations, Halfway, Bushland and Lamesa in the Texas High Plains region by considering projected annual increases in [CO_2] in the future, and (b) identify optimum climate change adaptation strategies for irrigated and dryland grain sorghum production.

2. Materials and methods

2.1. Study area/sites

The Texas High Plains region, located in the northwest Texas, comprises of 39 counties and borders the states of New Mexico and Oklahoma (Fig. 1). This study focused on three locations in the Texas High Plains region; namely, 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 sites represent northern, central, and southern regions within the Texas High Plains. These sites were selected due to the availability of data required for

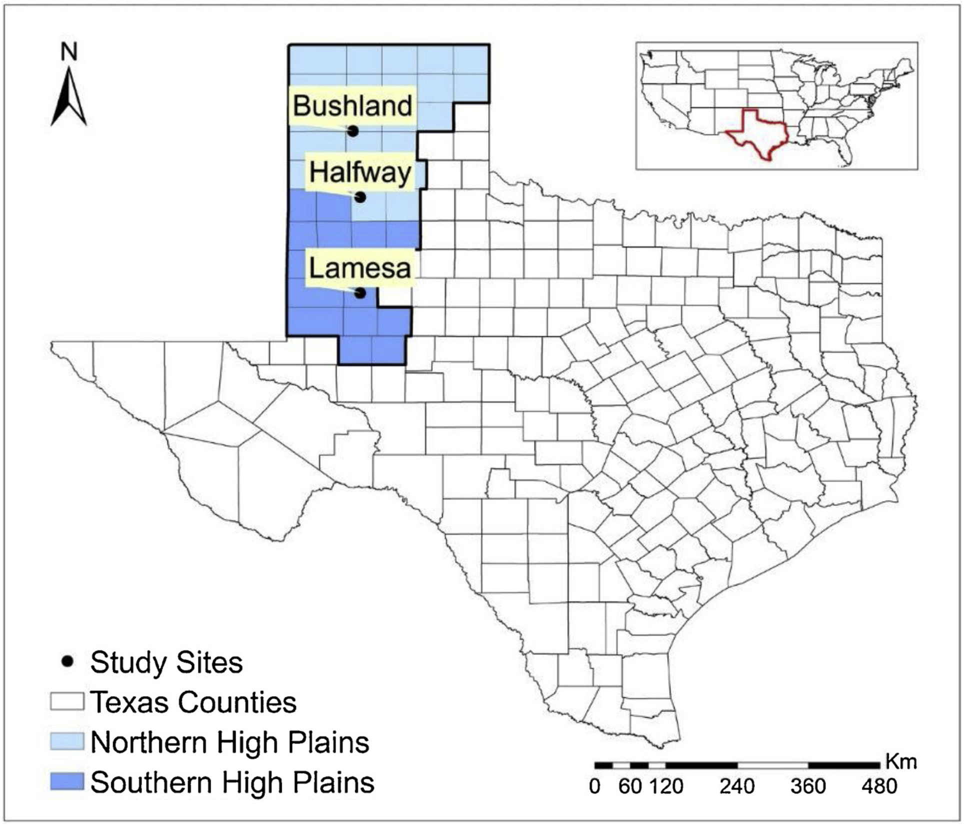

Fig. 1. Location of the study sites in the northern and southern High Plains Agricultural Statistical Districts, collectively known as the Texas High Plains.

parameterization of the DSSAT model and the differences in soil types and climate among the sites. The average annual precipitation for the 1980–2010 period at Bushland, Halfway, and Lamesa were 494 mm, 515 mm, and 478 mm, respectively (NOAA, 2017). The average annual temperatures at these sites during the same period, were 14.2 °C (Bushland), 15.1 °C (Halfway), and 16.1 °C (Lamesa).

2.2. The DSSAT model

The Decision Support System for Agrotechnology Transfer (Jones et al., 2003) Cropping System Model (DSSAT-CSM) version 4.6 (Hoogenboom et al., 2015, 2019) was used in this study. The CSM-CERES-Sorghum module (Alagarswamy and Ritchie, 1991; White et al., 2015) within the DSSAT was used to simulate grain sorghum growth and development. In the CSM-CERES-Sorghum module, duration of different growth stages is simulated based on daily thermal time accumulation which is calculated from minimum and maximum temperatures with a base temperature of 8 °C (Alagarswamy and Ritchie, 1991). Daily potential biomass production is a function of radiation use efficiency and photosynthetically active radiation, with adjustment factors for [CO_2], plant population, and leaf area index (White et al., 2015). Calculation for actual biomass incorporates stress factors related to temperature, soil water and nitrogen deficits. Changes in [CO_2]are reflected in daily biomass accumulation and transpiration rates (Singh et al., 2014b). Further details of sorghum growth, phenology and root dynamics as simulated with the CSM-CERES-Sorghum model in DSSAT can be found in Alagarswamy and Ritchie (1991); White et al. (2015), Ritchie et al. (1998) and Adam et al. (2018).

The typical inputs required to simulate crop growth and development in DSSAT include: crop management, daily weather data, soil characteristics, and crop specific genotype (cultivar, ecotype and species) parameters (Hoogenboom et al., 2012; Hunt et al., 2001). Out of the four types of analysis available in DSSAT (Thornton and Hoogenboom, 1994; Thornton et al., 1995), "seasonal" analysis was used in this study, in which soil water and nutrient balance were not carried over to the next season and these conditions were re-initialized at the beginning of each year. The same initial conditions and crop management practices were repeated each year from 1950 to 2099 with different weather inputs. This was done to ensure that changes in crop yield and irrigation water use are indeed due to climatic and genotype changes rather than changes in soil initial conditions. In this study, we have used the CERES-Sorghum module that we have recently evaluated for Halfway site using measured data from a cotton-sorghum rotation experiment over a nine year period in a separate study (Kothari et al., 2019).

2.3. Model input data

2.3.1. Crop management inputs

Crop management related inputs for sorghum production such as planting date and fertilizer amount and application date were obtained from the High Plains Production Handbook (McClure et al., 2010) and used in this study. These crop management practices, commonly adopted in the Texas High Plains region, were kept the same for all three sites to facilitate comparison of climate change impacts across the sites due to the changes in climate variables alone. Sorghum was planted on June 1st at a rate of 18 seeds m^{-2} for irrigated and 6 seeds m^{-2} for dryland conditions. For irrigated and dryland sorghum production, 150 kg N ha^{-1} and 60 kg N ha^{-1} nitrogen fertilizer was applied, respectively. Half of the fertilizer dose was applied at 20 days after planting (DAP) and the other half at 40 days (DAP). Tillage operation was done one month prior to planting, with a V-ripper at 13 cm depth (Bean et al., 2003).

Seeds were planted at 3.8 cm depth at a row spacing of 1.02 m. The initial soil water was assumed to be 100 % of plant available water content under irrigated conditions. For dryland, initial soil water was

Table 1
Physical and hydraulic properties of soils at the selected locations in the Texas High Plains.

Site	Depth (cm)	Clay (%)	Sand (%)	Lower limit (cm^3 cm^{-3})	Drained upper limit (cm^3 cm^{-3})	Saturated hydraulic conductivity (m s^{-1})	Bulk density (g cm^{-3})
Bushland	0–15	33	21	0.12	0.34	1.7×10^{-6}	1.26
	15–30	39	21	0.13	0.33	1.1×10^{-6}	1.48
	30–45	35	19	0.12	0.33	1.0×10^{-6}	1.56
	45–60	37	21	0.13	0.33	1.1×10^{-6}	1.62
	60–90	37	23	0.13	0.33	1.0×10^{-6}	1.62
Halfway	0–15	17	64	0.13	0.23	7.2×10^{-6}	1.48
	15–30	25	48	0.17	0.29	1.2×10^{-6}	1.44
	30–45	31	42	0.20	0.31	6.4×10^{-7}	1.44
	45–60	36	40	0.22	0.34	6.4×10^{-7}	1.44
	60–90	34	42	0.21	0.32	6.4×10^{-7}	1.45
Lamesa	0–15	7	75	0.06	0.14	7.2×10^{-6}	1.53
	15–30	9	77	0.07	0.14	7.2×10^{-6}	1.58
	30–45	11	75	0.09	0.15	7.2×10^{-6}	1.59
	45–60	11	75	0.09	0.16	7.2×10^{-6}	1.58
	60–90	11	75	0.08	0.15	7.2×10^{-6}	1.59

set at 75 % of plant available water content, which is close to the average soil water at planting measured at Bushland (Unger, 1978; Unger and Baumhardt, 1999). Initial soil nitrogen content in the top 210 cm soil profile were set at 100 kg N ha–^{1} and 45 kg N ha–^{1}, respectively for irrigated and dryland sorghum. These values were within the range of measured values for sorghum fields in the Texas High Plains under irrigated (Hao et al., 2014) and dryland (Eck and Jones, 1992) conditions. These initial conditions were reinitialized each year on the simulation start date, i.e., January 1. For irrigation simulations, irrigation was applied to replenish plant available water content in the top 30 cm profile to 100 % whenever it dropped to 50 % using the "auto-irrigation" feature of DSSAT.

2.3.2. Soil data input

Soil parameters for selected sites were either directly obtained from field measurements as documented in Adhikari et al. (2016), or generated using the SBuild tool within DSSAT (Uryasev et al., 2004) (Table 1). The parameters taken from field measurements were percentages of clay, silt, total nitrogen, organic carbon, pH, and cation exchange capacity (cmol kg^{-1}). The parameters estimated from the SBuild were hydraulic conductivity (cm h^{-1}), soil bulk density (g cm^{-3}), soil water at saturation (cm cm^{-1}), drained upper limit (cm cm^{-1}), soil water lower limit (cm cm^{-1}), and soil root growth factor. The soil type at the Bushland and Halfway experimental sites is a Pullman clay loam (*Fine, mixed, superactive, thermic Torrertic Paleustolls*), whereas the soil at the Lamesa site is Amarillo fine sandy loam (*Fine-loamy, mixed, superactive, thermic Aridic Paleustalfs*).

2.3.3. Climate data

Weather data inputs for the model include daily solar radiation, maximum and minimum temperature, rainfall, wind speed, and relative humidity. Daily climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) were obtained from the Multivariate Adaptive Constructed Analogs (MACA) dataset (retrieved from https://climate.northwestknowledge.net/MACA/index.php). This dataset was bias corrected and statistically downscaled at $4-6$ km using the MACA technique (Abatzoglou and Brown, 2012). The MACAv2-METADATA dataset contains maximum and minimum temperature, precipitation, relative humidity, solar radiation, and wind speed for the period from 1950 to 2099. The MACA dataset was used for both historic and future periods due to non-availability of good long-term historic weather data at the selected locations. Although the length of available rainfall and temperature data at these sites was fairly reasonable, daily values of other climate variables (solar radiation, wind speed, and relative humidity) were not available for the entire duration and for all locations. In addition, a comparison between observed weather data and the bias corrected and statistically downscaled GCM projected MACA dataset (Abatzoglou, 2013) at the study sites showed a close match between the two datasets (Fig. S1, S2 and S3). Temperature datasets matched more closely than the precipitation datasets, and high monthly rainfall values were slightly overestimated by some GCMs in case of Bushland and Halfway. MACA dataset was also directly used in several other published climate change impact studies on crop production in the Southwestern US (Elias et al., 2018), Southeast US (Cammarano and Tian, 2018), and US Pacific Northwest (Antle et al., 2018; Karimi et al., 2018; Kerr et al., 2018; Stöckle et al.,

Table 2
Summary of nine CMIP5 GCMs used to project daily weather data under climate change.

GCM Name	Institution	Main reference	Atmosphere Resolution (Lon × Lat)
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	(Wu, 2012)	2.8° × 2.8°
CCSM4	National Center for Atmospheric Research, USA	(Gent et al., 2011)	1.25° × 0.94°
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization and Queensland Climate Change Centre of Excellence, Australia	(Rotstayn et al., 2012)	1.8° × 1.8°
GGFDL-ESM2M	NOAA Geophysical Fluid Dynamic Laboratory, USA	(Dunne et al., 2012)	2.5° × 2.0°
CNRM-CM5.1	National Centre of Meteorological Research, France	(Voldoire et al., 2013)	1.4° × 1.4°
IPSL-CM5A-LR	Institute Pierre Simon Laplace, France	(Dufresne et al., 2013)	3.75° × 1.8°
MIROC5	University of Tokyo, Japanese National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	(Watanabe et al., 2010)	1.4° × 1.4°
MRI-CGCM3	Meteorological Research Institute, Japan	(Yukimoto et al., 2012)	1.1° × 1.1°
NorESM1-M	Norwegian Climate Centre, Norway	(Kirkevag et al., 2008)	2.5° × 1.9°

Climate forcings from Multivariate Adaptive Constructed Analogs Dataset (Abatzoglou, 2013) were retrieved from https://climate.northwestknowledge.net/MACA/index.php.

2018; Zhang et al., 2017).

In view of high variability in the future climate projections, a total of 18 climate change scenarios, generated from 9 GCMs (Table 2) and two representative concentration pathways (RCPs), i.e., 4.5 and 8.5, were used. The RCP 8.5 scenario is the extreme future scenario with the highest greenhouse gas emissions resulting from high population growth, increased energy consumption, land use changes, and slow income and technology growth (Riahi et al., 2011). In contrast, RCP 4.5 is an intermediate scenario with an assumption of practicing adaptive policies such as low emission technologies and afforestation, which stabilize radiative forcing at 4.5 W m^{-2} in the year 2100 (Thomson et al., 2011). The [CO_2] is projected to reach 544 ppm and 912 ppm in 2099 under RCPs 4.5 and 8.5, respectively (IPCC, 2014). In this study, [CO_2] was varied annually using the "environmental modification" setting in DSSAT. A similar approach, of varying [CO_2] annually, was adopted in previous modeling studies (Adhikari et al., 2016; Balkovič et al., 2014; Xiong et al., 2014). Future projections of [CO_2] were taken from (IPCC, 2014); and historic [CO_2] were obtained from the NOAA/ESRL portal (Keeling et al., 1976; Thoning et al., 1989).

2.3.4. Genotype parameters

The cultivar, ecotype, and species parameters are collectively known as genotype parameters in DSSAT. Cultivar parameters are specific to a crop variety, ecotype parameters apply to a group of cultivars, and species traits are common to all cultivars in a particular crop species (Pathak et al., 2007). In this study, grain sorghum cultivar and ecotype parameters estimated in a recent study (Kothari et al., 2019), based on field experiments at Halfway, TX (TALR, 2016), were used. The field experiments comprised of three irrigation treatments in two adjacent wedges of a center pivot irrigation system, in which sorghum was rotated after two years of cotton from 2006–2014. The genotype parameters evaluated for Halfway in our previous study (Kothari et al., 2019), were used for all three sites further calibration. These genotype parameters were referred to as reference parameters and the evaluated grain sorghum cultivar was referred to as the reference cultivar in this study.

2.4. Adaptaion strategies/ ideotypes

A total of eight climate change adaptation strategies that are aimed at maintaining crop yield and achieving sustainable use of irrigation water were evaluated in this study (Table 3). These adaptation strategies were developed by creating ideotypes by modifying genotype parameters and root characteristics in the soil file from the reference cultivar. This methodology was based on and extends the work done by Singh et al. (2014b). The following climate change adaptation strategies were evaluated in this study.

2.4.1. Drought tolerance ideotypes I to IV

Differences in physical and hydraulic properties of roots could play an important role in selecting drought tolerant cultivars (Assefa et al., 2010), but it has not received sufficient attention in the screening of drought resistance in grain sorghum (Krupa et al., 2017). In this study, the first drought tolerant grain sorghum ideotype was created by increasing the root density in different soil layers to improve the capability of crops to extract water from the soil. This was achieved by increasing root density in the soil (*.SOL) input file by modifying the formula used for soil root growth factor (SRGF) estimation from $e^{-0.02\times Z}$ to $(1–Z/500)^6$; where Z is the soil depth in cm. This strategy was similar to Singh et al. (2014b), however, in this study only SRGF was changed and the soil lower limit (LL) was kept the same for drought tolerant and non-drought-tolerant ideotypes.

The second drought tolerant ideotype was created by altering other root parameter in the species file. The species parameter RLWR (root length to weight ratio, cm/g) was increased by 20 % from 0.98 (default) to 1.18. RLWR was increased in accordance with a field study (Tsuji et al., 2005), in which drought tolerant hybrid had a higher root length to weight ratio under dry conditions than drought susceptible hybrid; indicating an increase in fine roots in drought tolerant hybrid under water stress. This is corroborated by another field study (Magalhães et al., 2016), in which an increase in fine root length was associated with drought tolerance in sorghum. In previous CSM-CERES-Sorghum studies, researchers have used the default value of RLWR parameter, and, therefore, a range of values for this parameter was not available in the literature.

While root physical characteristics have been a focus of many breeding programs for drought tolerance, a few researchers (Vadez, 2014) have also highlighted the importance of root hydraulics. Variation in potential water extraction from soil profile has been found among different sorghum genotypes (Tardieu et al., 2017; Vadez et al., 2011), and it could be used to test for drought tolerance. Extracting more water from soil under water stress can lead to drought tolerance (Hao et al., 2015). However, faster depletion of soil water in case of limited water supplies can be detrimental to plant growth in later stages (Lilley and Kirkegaard, 2016). Therefore, both higher and lower potential water uptake per unit length than the default value were considered for drought tolerance. The third drought tolerant ideotype tested for drought tolerance was created by increasing maximum water uptake per unit length (RWMX cm^3 water cm^{-1} root) from 0.03 (default) to 0.04, which is close to the maximum value (0.0375) used by Lopez et al. (2017).

The fourth drought tolerant ideotype tested for drought tolerance was created by decreasing maximum water uptake per unit length (RWMX cm^3 water cm^{-1} root) from 0.03 (default) to 0.02 which is close to the minimum value (0.0225) used by Lopez et al. (2017).

Table 3
A summary of the differences between the reference cultivar and ideotypes.

Ideotype	Parameter	Units	Reference cultivar	Adaptive cultivar
Drought tolerant I[a]	Soil root growth factor (SRGF)	fraction	$e^{-0.02\times \text{soil depth, cm}}$	$\left(1-\frac{\text{soil depth, cm}}{500}\right)^6$
Drought tolerant II	Root length to weight ratio (RLWR)	cm g^{-1}	0.98	1.18
Drought tolerant III	Maximum water uptake per unit root length (RWMX)	cm^3 cm^{-1}	0.03	0.04
Drought tolerant IV	RWMX	cm^3 cm^{-1}	0.03	0.02
Heat tolerant I[a]	Upper optimum temperature (TOP2)	ºC	27	29
	Failure temperature (TMAX)	ºC	35	37
Heat tolerant II	TOP2	ºC	27	30
	TMAX	ºC	35	38
High yielding[a]	Relative leaf size (G1)	–	3.4	3.85
	Partitioning of assimilates to panicle (G2)	–	7	7.7
	Radiation use efficiency (RUE)	g MJ^{-1}	3.2	3.52
Long maturity[a]	Thermal time from emergence to the end of juvenile phase (P1)	degree days	334	390
	Thermal time from beginning of grain filling to physiological maturity (P5)	degree days	575	640
	Critical photoperiod (P2O)	hours	15.2	14.2

[a] Adapted from Singh et al. (2014b).

2.4.2. Heat tolerance ideotypes I and II

The first heat tolerance ideotype was created by increasing upper optimum (TOP2) and failure (TMAX) temperatures in the species (*.SPE) file by 2 °C. The TOP2 was changed from 27 °C to 29 °C and TMAX was changed from 35 °C to 37 °C for the relative grain filling rate process, similar to Singh et al. (2014b). The default values of TOP2 (27 °C) and TMAX (35 °C) in DSSAT v4.6 were decided based on response of a sorghum genotype to different temperature regimes grown in growth chambers (Prasad et al., 2006). In a recent study (Singh et al., 2015), researchers reported that threshold temperature for seed set and tolerance varied within the twenty genotypes grown in a controlled environment. Some genotypes had significantly lower seed-set at a maximum temperature regime of 38 °C compared to that at 36 °C, while for a few genotypes seed-set at the two temperature regimes were only marginally different. These differences in temperature threshold and tolerance level among genotypes could be explored to screen grain sorghum genotypes for heat tolerance. Therefore, the second heat tolerant ideotype was created by increasing TOP2 and TMAX by 3 °C each from their default values. The TOP2 was changed from 27 °C to 30 °C and TMAX was changed from 35 °C to 38 °C for the relative grain filling rate process.

2.4.3. High yield potential ideotype

A high yielding crop ideotype was developed by increasing leaf size, partitioning factor, and/or radiation use efficiency in the cultivar (*.CUL) and ecotype (*.ECO) files. For grain sorghum, original values of scaler for relative leaf size (G1 = 3.4), scaler for partitioning of assimilates to the panicle (G2 = 7), and radiation use efficiency in g dry matter/MJ PAR (RUE = 3.2), were increased by 10 %, similar to Singh et al. (2014b). The RUE in the ideotype (3.52 g MJ^{-1}) was within the range of RUE (2.13–3.83 g MJ^{-1}) estimated from field experiments at Kansas, USA (Narayanan et al., 2013). The values of parameters G1 and G2 of reference and modified cultivars were also within the range of values reported in previous CERES-Sorghum studies (MacCarthy et al., 2010; Pachta, 2007).

2.4.4. Long maturity ideotype

A long maturity ideotype was created by increasing total length of the growing season by 10 % (Singh et al., 2014b).The thermal time from seed emergence to the end of juvenile phase (P1, degree days above 8 °C) was changed from 334 to 390; P2O (critical photoperiod at which development occurs at the maximum rate, hours) was changed from 15.2 to 14.2; and P5 (thermal time from beginning of grain filling to physiological maturity, degree days above 8 °C) parameter was changed from 575 to 640.

2.5. DSSAT CSM CERES-Sorghum model evaluation

As mentioned earlier, evaluation of the CERES-Sorghum model for one of the selected sites, Halfway, was carried out as a part of our previous study(Kothari et al., 2019). The experimental data for model evaluation were obtained from cotton-sorghum experiments conducted at the AgriLife Research Farm at Halfway, TX, over nine years (2006–2014), which included four sorghum growing seasons (2007, 2010, 2012 and 2013). The model was calibrated and evaluated against the onset of growth stages, sorghum grain yields, and irrigation water use efficiency (IWUE). After a systematic evaluation, CERES-Sorghum model adequately simulated grain sorghum yield during the calibration (average percent error (PE) of 1.3 % and root mean square error (RMSE) of 7.6 %) and evaluation (average PE of −2.2 % and RMSE of 16.3 %) periods. An average PE of 7.4 % was obtained during the evaluation of model for IWUE prediction. A satisfactory simulation of sorghum grain yield and IWUE over four growing seasons and twelve irrigation treatments suggested that the model could be used for evaluating climate change adaptation strategies for Halfway and the other two Texas High Plains sites with reasonable confidence.

2.6. Evaluation of climate change adaptation strategies

Climate data projected by nine GCMs considered in this study were initially grouped into three time periods including historic or baseline (1976–2005), 2050s or mid-century (2036–2065), and 2080s or late-century (2066–2095) periods for three selected sites. The ensemble of nine GCM projections under RCP 4.5 and 8.5 were then averaged over the above mentioned three time periods and projected future changes in rainfall and average temperature in the mid- and late-century were assessed. DSSAT simulations were then run for both irrigated and dryland conditions using the climate data projected by each GCM under RCP 4.5 and 8.5 scenarios. The simulated average irrigated/dryland grain sorghum yield and irrigation water use were estimated for the historic, mid-century and late-century periods for each GCM and RCP scenario, and the variability in simulated grain sorghum yield and irrigation water use under different RCPs and time periods was studied.

Additionally, average grain sorghum yield and irrigation water use for nine GCMs under each RCP scenario were estimated for each year, and 30-year average grain sorghum yield and irrigation water use under each RCP scenario over the historic, mid-century and late-century periods were finally estimated and used for assessing the impacts of climate change on grain sorghum production and evaluation of climate change adaptation strategies. The percent differences between the 30-year average historic and future yields/irrigation water use, and the coefficient of variability (CV, standard deviation divided by the 30-year average) were estimated and used for climate change impact assessment. The statistical significance of the difference in the 30-year average historic and future yield/irrigation was tested using the two-sample *t*-test for unpaired data (Welch, 1938) at 95 % confidence interval. For the evaluation of adaptation strategies, simulated grain sorghum yield and irrigation water use under a “specific adaptation” and “no adaptation” scenario were compared. Apart from irrigated and dryland crop yields and irrigation water use, other model outputs such as the length of growing season, maximum leaf area, growing season rainfall, temperature, nitrogen uptake, canopy weight at maturity were also analyzed to elucidate the effects of climate change on different crop growth processes.

3. Results and discussion

3.1. Future climate projections

Projected future changes in average temperature and rainfall in the mid-century (2036–2065) and the late-century (2066–2095) compared to the historic period (1976–2005), under two RCPs are presented in Fig. 2a–c. Mean monthly temperatures are expected to rise under all future scenarios compared to the historic period. The increase in mean monthly temperature compared to the historic period was greater under RCP 8.5 scenario than under RCP 4.5, and greater for the late-century than for the mid-century period. The increase in mean monthly temperature varied from 1.5 °C (November, RCP 4.5 at Lamesa) to 2.9 °C (June, RCP 8.5 at Bushland) for the mid-century; and from 1.9 °C (December, RCP 4.5 at Halfway) to 5.0 °C (June, RCP 8.5 at Bushland) for the late-century. Average temperature in summer months increased by a greater magnitude than winter months under climate change when compared to historic period. This is consistent with the temperature projections for Texas reported in a previous study (Jiang and Yang, 2012). The month of June (when sorghum was planted in this study) had the highest temperature rise among all the months. The differences in temperature rise in different months indicate that shifting planting dates to avoid hottest months could be a strategy to adapt to climate change. However, in a recent simulation study with the APSIM model (Singh et al., 2017), researchers found that changing planting date did not reduce the risk of heat stress during anthesis, whereas genetic manipulations could mitigate sorghum yield losses. In this study, adaptation strategies were, therefore, restricted to altering crop

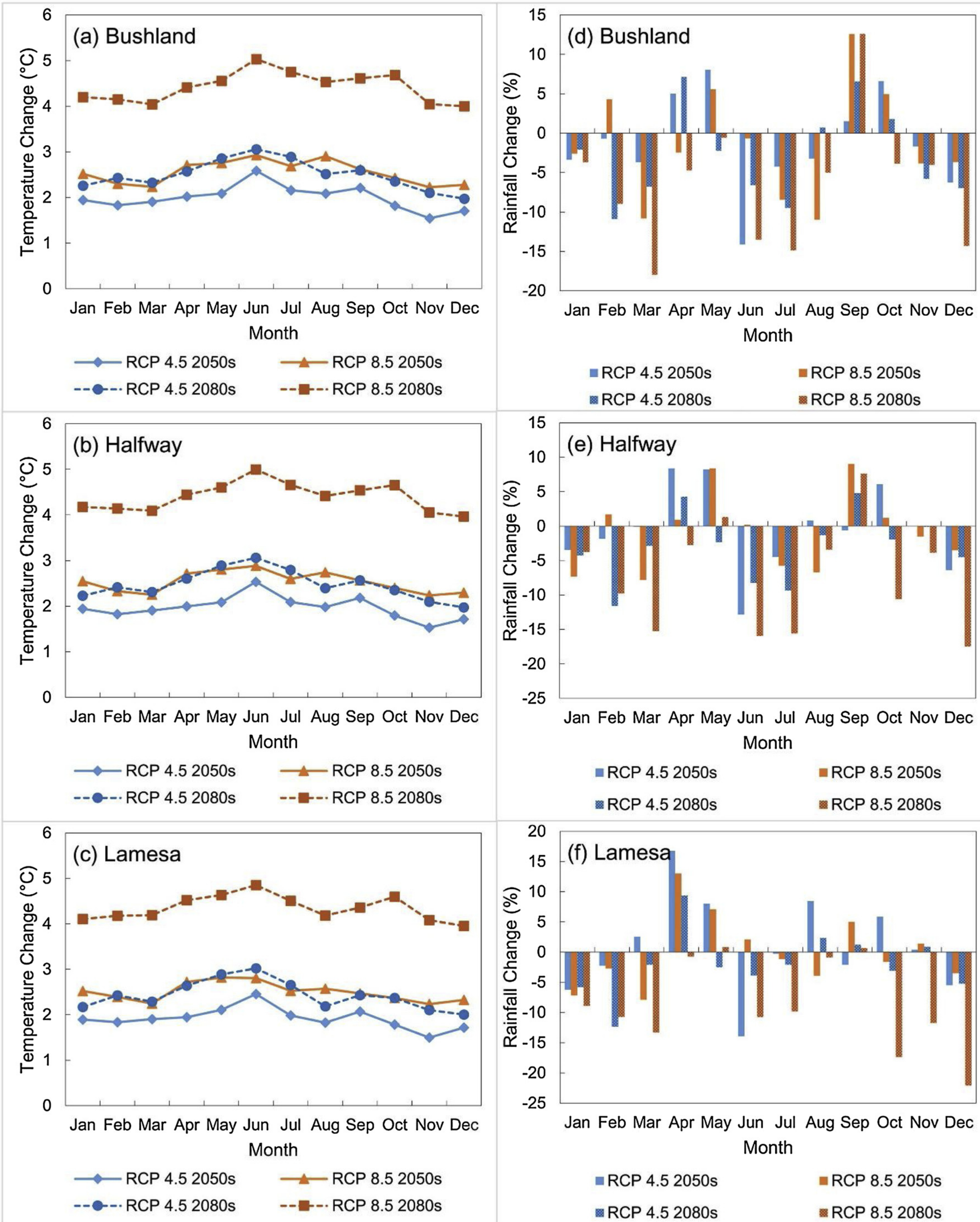

Fig. 2. Projected changes in monthly average (ensemble average of nine GCMs) temperature (a–c) and rainfall (d–f) in 2050s (2036–2065) and 2080s (2066–2095), compared to the historic period (1976–2005), under RCPs 4.5 and 8.5.

genetics rather than changing management decisions. The pattern of temperature increase under different RCPs and different months was similar across the three sites studied.

The differences between the projected future and historic monthly rainfall showed a mixed, but predominantly decreasing trend (Fig. 2d–f). The future monthly rainfall during the growing season was projected to vary between a 6 mm increase (about 12 % increase, September 2050s Bushland, RCP 8.5) and a 13 mm decrease (about 15 % reduction, June 2080s Halfway, RCP 8.5), compared to the historic period. Monthly rainfall for the late-century period (2080s) was lower than that in the historic period for all the months, except September under RCP 8.5, and September and April under RCP 4.5. Likewise, for the mid-century (2050s), April, May, and September months were wetter in the future compared to the historic period. The first two months from grain sorghum planting (June and July) were projected to be drier in the future compared to the historic period, and hence could potentially affect sorghum yields negatively. The pattern of future rainfall deviation from the historic period for different months and RCPs was not consistent among the three sites.

Table 4
Projected irrigated and dryland grain sorghum yield, irrigation water use, and temporal/inter-annual coefficient of variation (CV).

	Historic (1976–2005)		2050s (2036–2065)				2080s (2066–2095)			
			RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
	Y (kg ha^{-1}) or I (mm)	CV[a] (%)	ΔY[b] (%)	CV (%)	ΔY (%)	CV (%)	ΔY (%)	CV (%)	ΔY (%)	CV (%)
Irrigated grain sorghum yield (Y)										
Bushland	6511	1.4	−2.1[c]	2.1	−4.8[c]	4.0	−3.7[c]	3.1	−15.8[c]	8.3
Halfway	6990	1.9	−3.9[c]	3.0	−6.7[c]	4.4	−6.5[c]	3.6	−19.8[c]	9.6
Lamesa	4977	3.9	−9.3[c]	4.3	−13.1[c]	6.9	−12.4[c]	4.6	−26.9[c]	11.3
Dryland grain sorghum yield (Y)										
Bushland	2638	10.1	−2.5	10.5	−5.0	13.2	−4.7	13.1	−11.2[c]	13.5
Halfway	2262	17.5	−12.6[c]	21.7	−13.6[c]	23.4	−15.8[c]	23.5	−27.2[c]	25.5
Lamesa	1289	16.8	−8.3	20.8	−11.4[c]	24.6	−9.5[c]	21.1	−19.3[c]	22.2
Sorghum irrigation water use (I)										
Bushland	273	11.6	−2.5	11.9	−7.5[c]	9.6	−4.4	12.2	−13.7*	9.7
Halfway	334	8.6	−4.9[c]	8.4	−6.9[c]	8.9	−5.6[c]	8.8	−13.6[c]	8.2
Lamesa	323	6.3	−6.0[c]	6.3	−8.8[c]	8.1	−8.1[c]	7.5	−16.4[c]	7.2

[a] CV is coefficient of variation: CV = (standard deviation) ÷ (30-year average yield).
[b] ΔY is the percent change in yield/irrigation from the baseline: $\Delta Y = (Y_i - Y_{Historic}) \div Y_{Historic} \times 100$.
[c] Indicates that the change is significant at 0.05 significance level.

3.2. Climate change impact on grain sorghum production

The impact of climate change on irrigated and dryland grain sorghum production and irrigation water use are presented in the following sections.

3.2.1. Irrigated grain sorghum yield

The future irrigated grain sorghum yield is expected to decrease significantly when compared to the historic yield under all RCPs at all the three sites (Table 4). Irrigated grain sorghum yield declined according to climate change projections by most GCMs, with a few exceptions (Fig. 3). The difference between future and historic irrigated grain sorghum yield varied between −51 % (RCP 8.5 2080s at Lamesa under IPSL-CM5A-LR GCM) and 2% (RCP 4.5 2050s at Halfway under GFDL-ESM2M GCM) among climate change projections by nine GCMs. As expected, the yield decline was larger under RCP 8.5 than under RCP 4.5, and larger in the late-century than in the mid-century. For example, the decrease in yield at Halfway under RCP 4.5 in the mid-century was much smaller (4%) than that under RCP 8.5 in the late-century (20 %). The extents of differences in irrigated grain sorghum yield reduction among different RCPs and future time periods could be attributed to the differences in temperature rise under these scenarios (Fig. 2). The rise in growing season temperature significantly shortened the growing season length (data not shown), which has been associated with grain sorghum yield loss (Singh et al., 2014b; Srivastava et al., 2010). Warming leads to hasty crop development and less time for grain filling, thus reducing grain yield crops (Amthor, 2001). For example, the simulated length of growing season at Bushland was shorter by 15 days and 22 days under RCP 8.5 in mid-century and late-century, respectively when compared to the historic period.

Interannual variability in the simulated irrigated grain sorghum yield, as indicated by CV, increased under climate change for all the three sites (Table 4). For example, CV in simulated irrigated grain sorghum yield increased from 4% (historic period) to 11 % (under RCP 8.5 in the late-century) at Lamesa. The increase in CV suggests that climate in the Texas High Plains will shift from optimal to marginal growing conditions under climate change (Doherty et al., 2003).

Among the three locations studied, irrigated grain sorghum yield was the lowest at Lamesa (Table 4). The CV in irrigated grain sorghum yield was also slightly higher at Lamesa than that at Halfway or Bushland. The soil at Lamesa has a much greater sand percentage and lower water holding capacity than Halfway and Bushland soils (Table 1), which led to drought stress in spite of replenishing the soil profile to 100 % plant available water content. Differences in grain sorghum yield between sandy loam and clay loam soils have also been reported in field experiments at Bushland, TX (Tolk and Howell, 2003; Tolk et al., 1997). The percent reduction in irrigated grain sorghum yield in the future compared to historic yield was higher at Lamesa than at the other two sites (Table 4). Under RCP 4.5 in the late-century, irrigated grain sorghum yield was 4%, 7%, and 12 % lower than historic yield at Bushland, Halfway, and Lamesa, respectively. The difference in grain sorghum response to climate change at the three sites could be attributed to the differences in the current and future climatic conditions and soil type. The historic June–Sept average temperature at Bushland, Halfway, and Lamesa was 23.5 °C, 24.0 °C and 25.5 °C, respectively. The mean June–Sept temperature (ensemble average of nine GCMs) in the late-century under RCP 8.5 was 28.3 °C, 28.6 °C, and 30.0 °C at Bushland, Halfway and Lamesa, respectively. The projected increase in temperature likely resulted in a larger departure of growing season temperature from the optimum temperature for sorghum growth at Lamesa, resulting in a larger yield loss compared to the other two sites. The optimum mean temperature for vegetative growth in grain sorghum ranges between 26 °C–34 °C, and that for reproductive stages ranges between 25 °C–28 °C (Maiti, 1996; Prasad et al., 2006).

3.2.2. Dryland grain sorghum yield

The simulated future dryland grain sorghum yield is also expected to decrease in the future when compared to the historic period (Table 4), owing to the decline in June–Aug rainfall and increase in temperature (Fig. 2). The changes in future dryland grain sorghum yield compared to the historic yield, varied between −53 % (RCP 8.5 2080s at Halfway under IPSL-CM5A-LR GCM) and 28 % (RCP 8.5 2050s at Bushland under GFDL-ESM2M GCM) among climate change projections by nine GCMs (Fig. 3). The greatest reduction in dryland grain sorghum yield of 53 % under RCP 8.5 at Halfway in late-century was the result of 53 % lower growing season (planting–harvest) rainfall, 7.2 °C warmer growing season, and 28 days shorter crop cycle than the historic period under projected climate by the IPSL-CM5A-LR GCM. On the other hand, the maximum increase in dryland grain sorghum yield (28 %) was simulated under RCP 8.5 at Bushland in the mid-century due to 16 % higher growing season rainfall, 1.8 °C warmer growing season, and 10 days shorter crop cycle than the historic period as projected by the GFDL-ESM2M GCM.

The effects of elevated [CO_2] are simulated in DSSAT in terms of

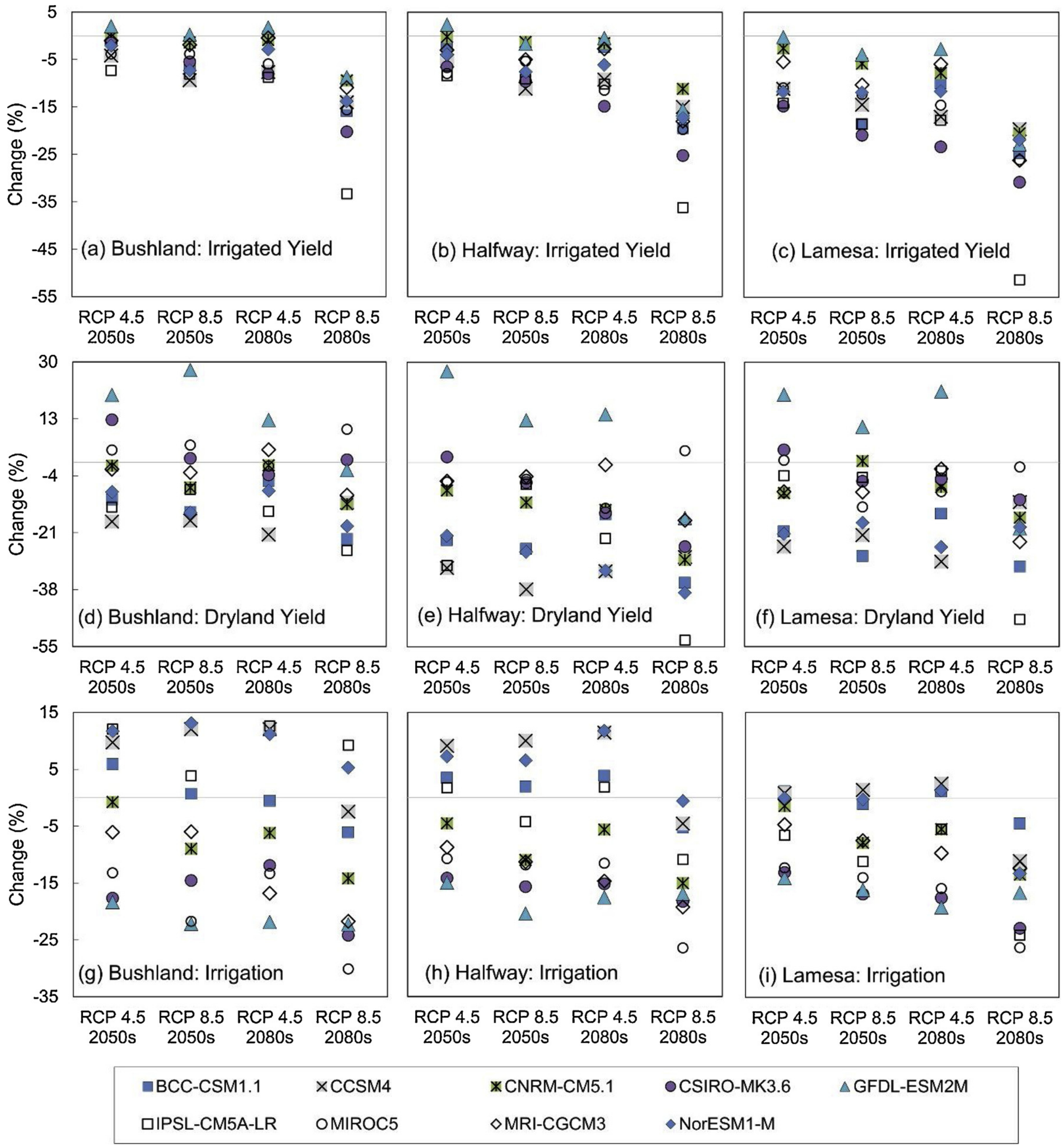

Fig. 3. Percent change in irrigated and dryland grain sorghum yield and irrigation water use in 2050s and 2080s compared to historic period under nine GCMs.

increased radiation use efficiency and reduced transpiration (Singh et al., 2014a; White et al., 2015). Upon doubling [CO_2], a 4% increase in grain yield is simulated in DSSAT v4.6, which is in accordance with a FACE study at Maricopa, AZ (Ottman et al., 2001) and a growth chamber study at Gainesville, FL (Prasad et al., 2006). In addition, the evapotranspiration of non-water-stressed sorghum is reduced by 13 % when [CO_2] is doubled, which is consistent with another FACE study conducted at Maricopa, AZ (Triggs et al., 2004). In our study, dryland grain sorghum was benefitted from an increase in rainfall and CO_2 fertilization when the temperature increase was moderate (< 3 °C). However, out of 108 total scenarios (9 GCMs × 3 sites × 2 RCPs × 2 future periods), dryland grain sorghum yield decreased in 87 scenarios when compared to the historic period. Similar to irrigated yield trends, the percent decline in dryland grain sorghum yield under RCP 4.5 in the late-century was comparable to that under RCP 8.5 in the mid-century (e.g. 5% reduction at Bushland). The highest reduction in grain sorghum yield was found for RCP 8.5 in the late-century at all three sites.

Interannual variability in dryland grain sorghum yield generally increased in the future compared to the historic period (Table 4). The CV in dryland grain sorghum yield under historic conditions was lowest at Bushland among the three sites and it increased marginally in the future, which could be due to higher water holding capacity and milder current temperatures at Bushland as discussed previously. The CV in dryland grain sorghum at Halfway and Lamesa was comparable under historic and mid-century time periods, and slightly higher at Halfway for the late-century (Table 4).

Among the three locations, the historic dryland grain sorghum yield was lowest at Lamesa (Table 4). Overall, average dryland grain sorghum yield (ensemble average based on nine GCM projections) reduced in the future compared to the historic period. This reduction was the highest at Halfway and the lowest at Bushland. This reduction in grain sorghum yield in the future was statistically significant—at Bushland under RCP 8.5 in the late-century; at Halfway for all RCPs and future periods; at Lamesa for all RCPs and time periods, except RCP 4.5 in the mid-century (Table 4). The reasons behind higher and more significant reduction in dryland grain sorghum yield at Halfway than at Lamesa

Table 5
Simulated changes (%) in irrigated and dryland grain sorghum yield (ΔY), and irrigation water use (ΔI) under different adaptation scenarios with respect to the no adaptation scenario for Bushland, TX.

	Irrigated Yield (ΔY)[+]				Dryland Yield (ΔY)				Irrigation Water Use (ΔI)[‡]			
	2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)	
Adaptation	RCP											
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Drought tolerant I	6.8[†]	6.5[†]	6.4[†]	5.0[†]	9.5[†]	11.7[†]	10.6[†]	14.2[†]	−6.1	−6.1[†]	−5.6	−6.4[†]
Drought tolerant II	−0.3	−0.2	−0.2	−0.1	−0.2	0.1	−0.2	0.6	−1.0	−1.1	−1.4	−1.2
Drought tolerant III	0.3	0.3	0.3	0.2	−0.8	−0.5	−0.7	−0.3	1.0	1.1	0.5	0.6
Drought tolerant IV	−0.4	−0.4	−0.4	−0.3	1.4	0.8	1.5	1.0	−0.9	−1.1	−1.2	−1.2
Heat tolerant I	1.2[†]	2.5[†]	1.8[†]	5.4[†]	1.2	1.7	1.7	3.7	0.6	1.3	0.8	2.3
Heat tolerant II	1.4[†]	2.9[†]	2.1[†]	7.2[†]	1.3	2.0	2.1	4.6	0.6	1.6	1.0	3.8
High yielding	6.9[†]	8.2[†]	7.7[†]	12.4[†]	7.5[†]	8.1[†]	7.6[†]	10.3[†]	−1.2	−0.9	−2.0	−1.8
Long maturity	2.3[†]	3.7[†]	3.1[†]	8.1[†]	−2.9	−3.2	−1.7	0.3	12.6[†]	11.8[†]	10.4[†]	8.7[†]

[†] Indicates that the change is significant at 0.05 significance level.
[+] $\Delta Y = [(\text{Yield}(\text{Adaptation}, i) - \text{Yield}(\text{No Adaptation})) \div \text{Yield}(\text{No Adaptation})] \times 100$.
[‡] $\Delta I = [(\text{Irrigation}(\text{Adaptation}, i) - \text{Irrigation}(\text{No Adaptation})) \div \text{Irrigation}(\text{No Adaptation})] \times 100$.

was most likely due to the greater reduction in June–August rainfall at Halfway than at Lamesa (Fig. 2). The lowest reduction in dryland grain sorghum yield at Bushland when compared to other two sites could be attributed to its higher water holding capacity and lower current temperatures as discussed in the previous section.

3.2.3. Grain sorghum irrigation water use

The average irrigation water use is simulated to decrease in the future when compared to the historic values under all RCP scenarios and at all three sites (Table 4). This reduction in irrigation water use was significant under all cases, except under RCP 4.5 at Bushland. The difference between future and historic irrigation water use of grain sorghum, as simulated under individual GCM projections (Fig. 3g–i), varied between –30 % (RCP 8.5 2080s at Bushland under MIROC5 GCM) and 13 % (RCP 8.5 2050s at Bushland under NorESM1-M GCM). The greatest reduction in irrigation water use of 30 % at Bushland in the late-century was the result of 2% higher June–August rainfall, 5.2 °C warmer growing season, and 22 days shorter crop cycle than the historic period. On the other hand, the maximum increase in irrigation water use (13 %) was simulated at Bushland in the mid-century, mainly due to 23 % lower rainfall received during June–August when compared to the historic period. Out of 108 total scenarios (9 GCMs × 3 sites × 2 RCPs × 2 future periods), simulated seasonal irrigation water use of grain sorghum decreased in 78 scenarios, when compared to the historic period. The primary reason behind reduced seasonal irrigation was reduced growing season length. Other possible reasons behind the reduction in irrigation water use in the future compared to the historic period could be the reduced transpiration per unit leaf area under elevated [CO_2] (Conley et al., 2001; Singh et al., 2014b), reduction in maximum leaf area and canopy weight at maturity, and increased growing season rainfall in case of a few GCMs In our study, the effects of temperature rise were more prominent than the effects of [CO_2]. The growing season length strongly correlated with temperature (correlation coefficient, r = −0.94). The temperature was also highly correlated with biomass at maturity and maximum LAI (r = 071). The seasonal transpiration was more correlated with temperature (−0.65) than [CO_2] (−0.48). Across the GCMs, the maximum reduction in irrigation water use was simulated under GFDL-ESM2M GCM (Fig. 3g-i). This was due to mild increase in temperature and wetter growing season projected under this GCM. Although seasonal irrigation water use decreased in most of the future scenarios, it increased in 30 out of 108 scenarios due to substantial reduction in seasonal rainfall, and subsequent reduction in water availability.

Average daily irrigation water use, a ratio of seasonal irrigation and growing season length, was calculated to elucidate climate change impacts on irrigation water use further (data not shown). Out of 108 scenarios, average daily irrigation water use increased in the future in 67 scenarios compared to the baseline. This was likely because of increased soil evaporation and reduced rainfall. While average daily irrigation water use increased in 67 scenarios, total seasonal irrigation water use increased only in 30 scenarios. This suggests that shortening of growing season was one of the main reasons behind the reduced seasonal irrigation water use in the future.

Across GCMs, the maximum reduction in irrigation water use and maximum increase in dryland yield was typically under GFDL-ESM2M GCM (Fig. 3). This was due to a lower temperature rise and wetter growing season projected under this GCM. When compared to the baseline, wetter conditions resulted in yield and irrigation benefits due to greater water availability in the future. When compared to the other GCMs, milder temperature rise resulted in lower yield loss due to temperature stress under GFDL-ESM2M GCM.

The CV in grain sorghum irrigation water use was comparable between the historic and future periods, although the CV in irrigated grain sorghum yield was higher in the future than in the historic period (Table 4). The CV in irrigation water use was the lowest for Lamesa and the highest for Bushland among all scenarios. Simulated irrigation water use under different GCM projections showed mixed trends in the future at Bushland and Halfway, and predominately decreasing trend at Lamesa (Fig. 3g–i). The primary reason behind these differences between the three sites could be the difference in current growing season temperature regimes. The beneficial effects of CO_2 fertilization tend to lessen at higher temperatures. Using controlled environment in growth chambers, Prasad et al. (2006) showed that at elevated [CO_2], the percent reduction in transpiration was larger for the higher temperature regimes. Historic growing season temperatures at Lamesa were higher than those at Bushland and Halfway, and a further increase in temperature in the future would decrease irrigated grain sorghum yield as well as irrigation water use rapidly at Lamesa.

3.3. Climate change adaptation strategies

3.3.1. Bushland

All adaptation strategies, except drought tolerant II and IV resulted in a yield gain for irrigated grain sorghum at Bushland (Table 5). Yield gain refers to the percent increase in grain sorghum yield under an ideotype compared to the reference cultivar for the corresponding time period and RCP. These yield gains were significant for drought tolerant I, heat tolerant I and II, high yield potential, and long maturity ideotypes. Among the drought tolerant strategies, increasing root density at different soil depths (drought tolerance I) was found to increase irrigated grain sorghum yield by an order of 7% for the mid-century and 5–6% for the late-century. Reducing root length to weight ratio or making roots finer (drought tolerance II) and reducing maximum water uptake per unit root length (drought tolerance IV) had a slightly negative effect on irrigated grain sorghum yield (< 0.4 % yield loss). Irrigated grain sorghum yield gains under heat tolerance II strategy were slightly higher than those under heat tolerance I strategy, especially under RCP 8.5 in the late-century. This is expected since the projected temperature rise under RCP 8.5 was higher than that under RCP 4.5. The ideotype with higher yield potential resulted in the highest irrigated grain sorghum yield gains among all of the eight ideotypes tested under both RCPs and time periods. The yield gain by incorporating high yield potential was 6.9 % and 8.2 % under RCP 4.5 and RCP 8.5 in the mid-century, respectively; and of the order of 7.7 % and 12.4 % under RCP 4.5 and RCP 8.5 in the late-century, respectively. The long maturity ideotype resulted in the third highest irrigated grain sorghum yield gain among the adaptation strategies tested under both RCPs in mid-century and under RCP 4.5 in the late-century. The ranking of yield gains under different adaptation strategies was slightly different under RCP 8.5 in the late-century; where the first, second and third highest yield gains were simulated under high yield potential, long maturity, and heat tolerant II ideotypes, respectively.

Irrigation water use of grain sorghum, which was simulated using the auto-irrigation tool in DSSAT, was lower under drought tolerant I cultivar than the reference cultivar (Table 5). This difference was significant under RCP 8.5 for both mid-century (−6.1 %) and late-century (−6.4 %) periods. This is primarily due to improved capability of roots to extract water from deeper soil layers. Irrigation water use was found to decrease slightly (up to −2.0 %) under drought tolerant II and IV, and high yield ideotypes compared to the reference cultivar. Irrigation water use marginally increased (up to 3.8 %) under drought tolerant III and heat tolerant I and II ideotypes compared to the reference cultivar. The irrigation water use was significantly higher under long maturity ideotype than the reference cultivar for both RCPs and future time periods. The increase in irrigation water use in case of longer maturity cultivar compared to the reference cultivar was 12.6 % and 11.8 % under RCP 4.5 and RCP 8.5 for the mid-century, respectively, and of the order 10.4 % and 8.7 % under RCP 4.5 and RCP 8.5 for the late-century, respectively.

A simultaneous examination of irrigated grain sorghum yield and irrigation water use across different adaptation strategies was performed to identify ideal strategies for irrigated grain sorghum production at Bushland under climate change. While drought tolerant I trait minimized irrigation water use, high yield potential trait maximized irrigated grain sorghum yield under all RCPs and time periods (Table 5). The yield gains were comparable under both ideotypes expect under RCP 8.5 in the late-century. When heat stress was dominant, greater yield gains were simulated with heat tolerant, high yield potential, and longer maturity traits than drought tolerant I trait. This shows that, increasing root density at different soil depths (drought tolerant I cultivar) could result in irrigation water savings while enhancing irrigated grain sorghum yield, given the temperature remains close to the optimum level for grain sorghum production. However, under extreme heat stress conditions, enhancing yield potential traits (RUE, G1, and G2) and heat tolerance during grain filling could be a potential adaptation strategy. Although the longer maturity trait resulted in irrigated grain sorghum yield gains, the associated increase in irrigation water use makes this adaptation less favorable in places such as Texas High Plains where irrigation water conservation is of prime importance.

With regards to the dryland grain sorghum production, drought tolerant I cultivar resulted in the maximum yield gains followed by high yield potential cultivar under both RCPs and future time periods (Table 5). Yield gains were also simulated under drought tolerant IV, heat tolerant I and II ideotypes in the order of 1%, 3.7 %, and 4.6 %, respectively under RCP 8.5 in the late-century. Surprisingly, incorporating the longer maturity trait resulted in dryland grain sorghum yield loss at Bushland. This outcome is contrary to that of Singh et al. (2014b), who simulated yield gains for longer maturity grain sorghum cultivar under dryland conditions for both historic and future periods at all four sites in India and Mali. A possible reason for this might be the temporal distribution of rainfall at Bushland; lengthening growing season has likely led to reduced availability of rainfall during critical stages of grain sorghum production. Simulated water stress during the period between panicle initiation and end of leaf growth was higher for the long-maturity cultivar than the reference cultivar for all GCMs and RCPs at Bushland. The average length of growing season in the mid-century for the reference and long maturity cultivars was 99 and 110 days, respectively. The months of June (when sorghum was planted) and August were typically wetter than July and September at Bushland. The longer maturity cultivar was designed by increasing the duration of both vegetative (time between emergence to end of juvenile phase) and reproductive phases (time between beginning of grain filling to maturity). Increased vegetative growth due to the cultivar design as well as CO_2 enrichment could be another reason for reduced availability of water during reproductive growth stage (grain filling). Further work is required to elucidate the relationship between rainfall distribution and performance of longer maturity sorghum cultivar under rainfed conditions at Bushland. These results suggest that increasing soil root density and enhancing yield potential traits could significantly increase dryland grain sorghum yields under climate change. Performance of longer maturity cultivars under dryland conditions will likely depend upon the rainfall distribution over the growing season. Adopting a longer maturity grain sorghum cultivar as an adaptation strategy under dryland conditions will require additional caution due to the higher uncertainty associated with rainfall projections than the temperature projections under climate change.

3.3.2. Halfway

At Halfway, all adaptation strategies except drought tolerant IV resulted in an increase in yield for irrigated grain sorghum (Table 6). These yield gains were significant for drought tolerant I, heat tolerant II, high yield potential, and long maturity ideotypes under both RCPs and future time periods. Similar to the trends at Bushland, the largest increase in yield was simulated for the cultivar with high yield potential traits among all the ideotypes that were evaluated. The increase in yield by incorporating high yield potential were 7.4 % and 8.4 % under RCP 4.5 and RCP 8.5 in the mid-century, respectively; and of the order 8.3 % and 13.6 % under RCP 4.5 and RCP 8.5 in the late-century, respectively. The second largest increase in yield gains was simulated under drought tolerant I cultivar for the mid-century, and for the long maturity cultivar for the late-century period. The increase in yield by incorporating drought tolerance I was comparable across RCPs and future time periods, whereas, the increase in yield progressively increased with heat tolerance, long maturity, and high yield potential traits as the temperature rise increased from RCP 4.5 to RCP 8.5 and from mid- to late-century.

The drought tolerant I ideotype consumed less irrigation water than the reference cultivar (e.g. 2.5 % lower irrigation water use under RCP 8.5 in the late-century; Table 6). Irrigation water use for the longer maturity cultivar was significantly higher than the reference cultivar under both RCPs and time periods. The difference between the irrigation water use of longer maturity cultivar and reference cultivar was 10.7 % and 9.6 % under RCP 4.5 and RCP 8.5 for the mid-century, respectively; and of the order of 9.7 % and 11.4 % under RCP 4.5 and RCP 8.5 for the late-century, respectively. Irrigation water use of other ideotypes was comparable with that of the reference cultivar. Unlike at Bushland, the differences in irrigation water use under drought tolerant I and high yield potential cultivars were comparable at Halfway. These results suggest that improving yield potential traits could be an optimal climate change adaptation strategy for irrigated grain sorghum production at Halfway.

For dryland grain sorghum production, the highest increase in yield gains was simulated for the high yield potential ideotype (up to 17.1 %)

Table 6
Simulated changes (%) in irrigated and dryland grain sorghum yield (ΔY), and irrigation water use (ΔI) under different adaptation scenarios compared to no adaptation scenario for Halfway, TX.

	Irrigated Yield (ΔY)⁺				Dryland Yield (ΔY)				Irrigation Water Use (ΔI)‡			
	2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)	
Adaptation	RCP											
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Drought tolerant I	4.6†	4.8†	4.5†	3.8†	7.0	7.9	6.9	7.7	−1.8	−2.0	−2.1	−2.5
Drought tolerant II	−0.05	0.2	0.1	0.3	2.3	2.1	2.3	3.2	−0.2	−0.4	−0.4	−0.4
Drought tolerant III	0.04	0.3	0.01	0.2	0.2	−0.1	−0.2	0.05	0.7	0.7	0.5	1.1
Drought tolerant IV	−0.5	−0.3	−0.5	−0.4	0.3	−0.04	0.3	0.1	−1.1	−1.2	−1.7	−1.4
Heat tolerant I	1.4	2.4†	1.9†	5.9†	1.2	2.5	1.5	4.5	0.3	0.5	0.3	1.3
Heat tolerant II	1.6†	2.7†	2.2†	7.8†	1.4	3.0	1.9	5.7	0.3	0.8	0.3	1.7
High yielding	7.4†	8.4†	8.3†	13.6†	14.3†	13.8†	14.4†	17.1†	−0.7	−1.2	−0.4	0.0
Long maturity	3.1†	4.7†	4.9†	10.9†	7.2	5.8	6.7	9.1	10.7†	9.6†	9.7†	11.4†

† Indicates that the change is significant at 0.05 significance level.
⁺ $\Delta Y = [(\text{Yield (Adaptation, i)} - \text{Yield (No Adaptation)}) \div \text{Yield (No Adaptation)}]\times 100$.
‡ $\Delta I = [(\text{Irrigation (Adaptation, i)} - \text{Irrigation (No Adaptation)}) \div \text{Irrigation (No Adaptation)}]\times 100$.

followed by the long maturity (up to 9.1 %) and drought tolerant I (up to 7.9 %) cultivars (Table 6). The heat tolerant II (up to 5.7 %) cultivar produced a relatively higher yield than the heat tolerant I (up to 4.5 %) cultivar. These results corroborate with the findings of Singh et al. (2014b). Interestingly, unlike at Bushland, the drought tolerant II cultivar (20 % higher root length-to-weight ratio than the reference cultivar) resulted in an increase in yield of 2.1 % and 3.2 % for the mid- and late-century under RCP 8.5, mainly because of an increase in the nitrogen (N) uptake rate. While the simulated N uptake of drought tolerant II cultivar at Halfway was on an average about 3% greater than that of the reference cultivar under dryland conditions, the N uptake rate at Bushland was about the same for both cultivars under dryland conditions (data not shown). Based on field and greenhouse studies of common bean, Polania et al. (2017) also reported a higher N uptake from a soil with a fine root system under drought stress. Fine roots can facilitate greater water and nutrient acquisition under low soil water conditions, due to their greater surface area per unit mass (Huang and Fry, 1998). Similar effect of increase in peanut pod yield with increasing root length-to-weight ratio was simulated in a previous DSSAT study (Naab et al., 2015), due to increased rooting volume for phosphorus (P) extraction. The effect was more prominent under low P fertility conditions. Overall, the increase in yield by increasing root length-to-weight ratio were not statistically significant and they were lower than those simulated with a higher root density (drought tolerant I cultivar). In summary, the results indicate that dryland grain sorghum production at Halfway in the future could benefit from improving yield potential traits, increasing soil root density, and using longer maturity cultivar.

3.3.3. Lamesa

Majority of the adaptation strategies resulted in an increase in grain sorghum yield under irrigated conditions at Lamesa (Table 7). These increases were significant for all strategies, except drought tolerant II, III and IV cultivars. The largest and second largest increase in yield was simulated with high yield potential and long maturity traits, respectively for all RCPs and future time periods. The third largest increase in yield was simulated with drought tolerant I trait under both RCPs in the mid-century, and RCP 4.5 in late-century. Under RCP 8.5 for the late-century, the third largest increase in yield was simulated with the heat tolerant II trait. The increase in yield by incorporating high yield potential was 12.5 % and 13.6 % under RCP 4.5 and RCP 8.5 in the mid-century, respectively; and about 13.9 % and 17.1 % under RCP 4.5 and RCP 8.5 for the late-century, respectively. The increase in yield under high yield potential was the largest compared to other climate change adaptation strategies for all the three sites. However, the magnitude of the increase in yield at Lamesa was almost double compared to the yield increase for both Bushland and Halfway. One of the possible reasons for this trend is the differences in the crop cycle among the three sites. According to Singh et al. (2014b), who compared sorghum yield with different genetic traits, increasing yield potential traits resulted in larger increase in yield for the shorter cycle cultivar than for longer cycle cultivars. For the historic period, the average growing season duration for grain sorghum at Bushland, Halfway, and Lamesa were 114, 110, and 100 days, respectively.

The simulated irrigation water use of the adaptive cultivars was comparable with that for the reference cultivar, except for the long maturity cultivar (Table 7). For the long maturity cultivar, irrigation water use was significantly higher than for the reference cultivar. The difference between irrigation water use for the long maturity cultivar and reference cultivar was 12.5 % and 13.0 % under RCP 4.5 and RCP 8.5 for the mid-century, respectively, and about 13.4 % and 14.9 % under RCP 4.5 and RCP 8.5 for the late-century, respectively. These results further support the use of high yield potential as an optimum climate change adaptation strategy for irrigated grain sorghum production in the Texas High Plains in the future, and indicate that the long maturity cultivars would increase irrigation water use significantly.

The first, second and third largest increase in dryland grain sorghum yield were simulated with the high yield potential, drought tolerant I, and long maturity cultivars, respectively, for all RCPs and future time periods (Table 7). However, the increase in yield was significant for only the high yield potential cultivar. Marginal yield loss was simulated with drought tolerant III cultivar. The recommendations for optimum ideotypes for Lamesa are similar to those for Halfway with high yield potential being the most effective strategy among the climate change adaptation strategies tested. However, the magnitude of the yield increase was different for different locations, suggesting that same adaptation strategy may not be equally effective at all sites in the Texas High Plains.

4. Conclusions

The climate change impacts on irrigated and dryland grain sorghum yield and irrigation water use were studied at three sites in the Texas High Plains region. Under irrigated conditions, average (of nine GCMs) sorghum yield reduced between 2% and 13 % for the mid-century and between 4% and 27 % for the late-century compared to the historic period, primarily due to heat stress and resultant shortening of growing season length. For dryland conditions, a severe increase in growing season temperature (> °3C) coupled with large rainfall reductions (> 20 %) resulted in a 23 % average reduction in dryland grain sorghum yield. The interannual variability in irrigated and dryland grain sorghum yield was found to increase under climate change in the future

Table 7
Simulated changes (%) in irrigated and dryland grain sorghum yield (ΔY), and irrigation water use (ΔI) under different adaptation scenarios with respect to the no adaptation scenario for Lamesa, TX.

	Irrigated Yield (ΔY)[+]				Dryland Yield (ΔY)				Irrigation Water Use (ΔI)[‡]			
	2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)		2050s (2036–2065)		2080s (2066–2095)	
	RCP											
Adaptation	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
Drought tolerant I	8.9[†]	9.3[†]	9.0[†]	7.7[†]	9.5	11.3	9.7	10.7	−1.9	−1.7	−1.7	−2.1
Drought tolerant II	2.6[†]	3.1	3.0[†]	3.3	2.2	2.6	2.4	2.8	0.7	0.9	0.7	1.0
Drought tolerant III	1.7	2.3	2.1	2.2	−0.3	−0.2	−0.2	−0.2	−0.4	−0.4	−0.2	−0.4
Drought tolerant IV	0.7	0.9	1.0	0.9	0.4	0.3	0.5	0.5	−1.4	−1.6	−1.3	−1.5
Heat tolerant I	5.5[†]	7.4[†]	6.3[†]	9.0[†]	3.2	3.8	3.3	5.4	−0.7	−0.5	−0.4	−0.5
Heat tolerant II	6.5[†]	9.1[†]	7.4[†]	11.7[†]	3.7	5.0	4.1	7.5	−0.7	−0.5	−0.5	−0.5
High yielding	14.1[†]	15.7[†]	15.7[†]	19.3[†]	14.6[†]	15.7[†]	15.2[†]	16.7[†]	0.6	0.5	1.0	1.6
Long maturity	11.0[†]	12.1[†]	13.0[†]	16.7[†]	8.6	7.2	8.3	8.2	11.8[†]	12.5[†]	12.8[†]	14.3[†]

[†] Indicates that the change is significant at 0.05 significance level.
[+] $\Delta Y = [(\text{Yield (Adaptation, i)} - \text{Yield (No Adaptation)}) \div \text{Yield (No Adaptation)}]\times 100$.
[‡] $\Delta I = [(\text{Irrigation (Adaptation, i)} - \text{Irrigation (No Adaptation)}) \div \text{Irrigation (No Adaptation)}]\times 100$.

compared to the baseline, indicating that climate will shift from optimal to marginal growing conditions. Irrigation water use for grain sorghum is expected to decrease under climate change, primarily due to shortening of growing season. Grain sorghum yield and irrigation water use predictions for the three sites varied due to the differences in soil properties and climatic conditions. While the selected sites in this study represent typical growing conditions in the Texas High Plains, similar efforts in other major sorghum growing regions would be necessary for adapting sorghum cultivation to climate change on global scale.

Among the ideotypes tested, a maximum and significant increase in yield for both irrigated and dryland conditions was simulated with the high yield potential trait under both RCPs and future time periods compared to the reference cultivar. The drought tolerant I strategy was also found to significantly increase irrigated grain sorghum yield at all the three locations. The efficacy of different ideotypes was not consistent at the three locations, suggesting that a single adaptation method for sustaining grain sorghum production may not be applicable for all the locations in the Texas High Plains. Enhancing yield potential trait was found to be an optimum strategy as it maximized grain sorghum yield without substantially altering irrigation water demand. The longer maturity cultivar had a significantly higher irrigation water demand and hence it was found to be not suitable for the Texas High Plains.

CRediT authorship contribution statement

Kritika Kothari: Conceptualization, Methodology, Validation, Writing - original draft. **Srinivasulu Ale:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition. **James P. Bordovsky:** Data curation, Writing - review & editing. **Dana O. Porter:** Writing - review & editing. **Clyde L. Munster:** Supervision, Writing - review & editing, Funding acquisition. **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.

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Appendix A. Supplementary data

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