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Vulnerabilities of irrigated and rainfed corn to climate change in a humid climate in the Lower Mississippi Delta

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Abstract

The use of fossil fuels for energy needs increases atmospheric greenhouse gas (GHG) concentrations to levels that can significantly exacerbate the climate on earth. Assessing the vulnerability of regional crop production systems to such an altered climate in the future is essential for implementing appropriate adaptation and mitigation strategies for sustainable agriculture. We investigated the possible impacts of climate change (CC) projected by multiple global climate models (GCMs) on rainfed and irrigated corn (*Zea mays L.*, a C4 plant) in the Lower Mississippi Delta region (LMD), USA. The CSM-CROPGRO-Maize v4.6 module in the RZWQM2 model (hereafter referred to as the "corn model") was previously calibrated and validated for modeling corn at Stoneville, Mississippi, a representative location in the LMD was used. The CC scenarios considered in this study were ensembles of climate projections of multiple GCMs (97 ensemble members) that participated in the Climate Model Inter-comparison and Improvement Program 5. These CC scenarios were bias-corrected and spatially downscaled (BCSD) at the location for the years 2050 and 2080. Four representative GHG concentration pathways (RCP) 2.6, 4.5, 6.0, and 8.5 drove these CC scenarios. Under both irrigated and rainfed conditions, corn yield responses to enhanced CO_2 were weak; thus, yield declined significantly in response to the enhanced air temperatures under all the RCP scenarios in both 2050 and 2080. The yield declines across RCPs ranged between 10 and 62% under irrigated conditions, and between 9 and 60% under rainfed conditions, mainly due to increased frequency of extreme temperatures and reduced crop durations. Water use efficiency declined between 22 and 150% under irrigated, and 8 and 54% under rainfed management. As an adaptation measure, planting corn up to 9 weeks earlier in the season, in general, failed to boost yields from increased crop duration and reduction in upper extreme air temperatures, as incidences of lower extreme temperatures also increased alarmingly. Development of cultivars that are more heat tolerant and produce higher yields under extreme temperatures would be required to combat corn yield decline in the region from climate change.

Keywords Climate change · Corn · Rainfed systems · Irrigated systems · Water use efficiency · Cropping system model · Climate impacts in agriculture · Climate adaptations

1 Introduction

Greenhouse gas (GHG) discharges into the atmosphere from human activities continue to increase unabatedly since the Industrial Revolution. The rise in CO_2 concentration, the most abundant of all the GHG, per decade since 2000, is about 20 ppm (Bereiter et al., 2015). Human activities were assessed to have already warmed the surface temperature of Earth by about 1.0 °C above that of preindustrial levels, and if the current level of warming continues, this warming can exceed 1.5 °C by 2052 (IPCC, 2018; Field et al., 2014; Tans and Keeling, 2016). Along with the temperature, increasing trends in frequency and intensity of weather extremes that can devastate human establishments have also been detected (IPCC, 2018).

Cropping production systems are among the key human enterprises most vulnerable to climate warming, as crop growth, development, and yield production mostly depend on realized weather. The observed frequency and intensity of extreme rain events and dry spells, and extreme hot and cold days disturb crop production across the globe (Liebig et al., 2012; Bita and Gerats, 2013). The soil, water, and other natural resources, across many locations, have shown signs of deterioration (e.g., Aeschbach-Hertig and Gleeson, 2012). Rising temperatures above the maximum thresholds in which crop growth processes get adversely affected are, in general, detrimental for crop production (Hussain et al., 2019; Priya et al., 2019). However, the plant's response to increasing CO_2 levels depends on their photosynthetic pathway for carbon assimilation, i.e., C_3, C_4, or CAM (crassulacean acid metabolism). The photosynthetic responses of a C_3 species to increased CO_2 concentrations in the air can be considerably more positive than that of a C_4 or CAM due to the photosynthetic fertilization effect—enhancing carbon fixation by lowering photorespiration (oxygenation) by the enzyme Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) occurring in the first step of the photosynthetic Benson-Calvin Cycle in the chlorophyll of plant cells. Photosynthesis of a C_3 species has been reported to increase by about 58% from a doubled concentration of CO_2 in the ambient air (Drake et al. 1997). But, in C_4 species, photosynthesis, in general, is virtually saturated under the current ambient CO_2 concentration because of the special function of the phosphoenolpyruvate, a carboxylase enzyme, located in the epidermal cells, in enhancing CO_2 concentration at the photosynthetic site of the Benson-Calvin cycle located in the bundle sheath cells of leaves (von Caemmerer et al. 1997, Ghannoum et al., 2000). However, reduced stomatal conductance seen in C_3 plants from enhanced CO_2 in the ambient air can reduce leaf transpiration rates in the C_4 species also. The reduced transpiration water loss from plants can stimulate leaf CO_2 assimilation by saving soil water for improving the shoot-water relations (Ghannoum et al., 2000). As such, the combined effects of CO_2 concentrations, and altering precipitation and air temperature, across C_3 and C_4 crop species depends on the magnitudes of those changes and their complex interactions affecting crop growth and development. Combining artificial air heating with Free Air CO_2 Enrichment (FACE) experiments provides a direct indication of these processes on crop production in the short term. Data from such short-term experiments can be used to develop and improve cropping system simulation models that can predict the impact in the long term and assist in developing adaptations across spatial and temporal dimensions (Dijkstra et al., 2010; White et al., 2011). In this study, we investigate the likely impacts of a GCM-projected climate change on corn crop production in the LMD of the USA using a cropping system simulation model.

Cropping system models were developed to integrate, synthesize, and extend location-specific research across climates and soils (Ma et al., 2006; Saseendran et al., 2015). These models are proven time-tested tools in investigating the impacts of GCM-projected climate on crop production and exploring alternative management under CC scenarios (Anapalli et al., 2016; Durand et al., 2018). Numerous research in the past has testified on the usage of DSSAT (Decision Support Systems for Agrotechnology Transfer) cropping system models for investigating the impacts of climate change across the world (for example, Rosenzweig and Tubiello 1996; Boote et al., 1997; Saseendran et al., 2000; Jones et al., 2003). The DSSAT suite of crop models have been linked to the detailed soil and water simulation modules of RZWQM2 (Root Zone Water Quality Model, USDA, ARS; Ahuja et al., 2000) and used in simulating the impacts of FACE- and GCM-projected climate on cropping systems and crop rotations in the Great Plains of the USA (Ko et al., 2010, 2012; Islam et al., 2012a, 2012b). The CSM-CERES-Maize v4.6 is available within the RZWQM2 for simulation of corn (http://arsagsoftware.ars.usda.gov/). Anapalli et al. (2018) simulated corn in a conventional tillage vs. no-tillage comparison study in the LMD region.

GCMs are tools used for predicting the response of the global climate system to changing GHGs and other land-ocean surface boundary conditions in the future (Christensen and Lettenmaier, 2007). Many competing GCMs developed in different parts of the world participate in the global efforts of providing projections of climate change in the future (IPCC, 2014). Since these GCMs often differed from each other in predicting the future climate, the IPCC-AR4 suggested creating an ensemble average of all available predictions (IPCC, 2007). In this study, we used the total ensemble of all the models that participated in the CMIP5 study reported in the IPCC AR5 (IPCC, 2014).

Corn is a significant row crop grown in the LMD, with a net return of about 455 million USD in 2019 (https://www.mdac.ms.gov/agency-info/mississippi-agriculture-snapshot/). In this pioneering study, we investigated the likely vulnerabilities of rainfed and irrigated corn production systems in the LMD to climate change projected by an ensemble (97 members) of GCMs in the CMIP5 driven by the RCP emission scenarios and explored alternative crop management strategies to reduce possible adverse climate change impacts on the system.

2 Materials and methods

2.1 Climate projections

The bias-corrected and spatially disaggregated (BCSD) climate projections from the Coupled Model Intercomparison and Improvement Project Phase 5 (CMIP5) and World Climate Research Program's (WCRP) climate projections archive downscaled to the nearest grid point for Stoneville, Mississippi (33.45° N, 90.87° W, 32 amsl) were used for developing the CC scenarios for this investigation (Anapalli et al., 2016). The study was limited only to one location in the LMD as continuous climate data with reliable quality was available only for this location; however, the results and conclusions of the investigation represent the possible climate change impacts on corn, a typical C4 plant, in humid climates across the world in general and the LMD region in particular. The detailed procedure involved in the climate scenario development is available in Anapalli et al. (2016). In brief, the GCM projections from 97 ensemble members available in the CMIP5 for precipitation and air temperature maximum and minimum were averaged and used for climate change impact analysis. Separate sets of CC scenarios represent four possible RCPs adopted by IPCC AR5, representing GHG emission pathways predicted to induce radiative forcing up to 2.6, 4.5, 6.0, and 8.5 W m^{-2} in the atmosphere by the end of the twenty-first century were used in the analysis. The atmospheric concentrations of CO_2 in 2050 and 2080 under RCP 2.5, 4.5, 6.0, and 8.5 were 443, 487, 478, and 541 ppm, respectively, in 2050, and 431, 532, 594, and 757, respectively, in 2080 (Anapalli et al., 2016). The RCP 2.6 represents a mitigation scenario resulting in a very low radiative forcing level (2.6 Wm^{-2}). The RCP 4.5 and 6.0 represent two medium GHG stabilization scenarios, and RCP 8.5 represents a very high emission scenario (Table 1 in Supplementary Material 1).

Following Anapalli et al. (2016), the delta change method was adopted for developing climate change scenarios for the location of interest. In this method, changes (a delta value) in monthly averaged daily air temperature and rainfall between current and future climates, both projected by a GCM or an ensemble of GCMs, were used to modify the daily climate data recorded during 1960–2019 at the location (baseline climate, BL). In this study, the GCM-projected monthly averaged daily temperature and monthly total precipitation between 1985 and 2015 were averaged to represent the current climate in 2000 projected by GCM. Averages of similar projected data from 2035 and 2065 and 2065 and 2095 were averaged to obtain projected climate for 2050 and 2080, respectively. Applying the delta change method, two separate climate series representing the measured climate variability from 1960 to 2019 (61 years) were developed for future years 2050 and 2080 and used to investigate the impacts of climate variability and climate change on corn production in those years (2050 and 2080) by integrating them with a cropping system simulation model, RZWQM2 (Anapalli et al., 2016). In the Delta change method, the measured weather during 1960–2019 modified with the projected changes in climate provides 61 all equally probable, corn season weather sequences in 2050 and 2080. The accuracies in the GCM-projected intra-seasonal variabilities in the climates across the world remain uncertain, as such, not addressed in this study (IPCC, 2018).

2.2 RZWQM2 model

The RZWQM2 simulates the impacts of soil-residue cover, tillage, water, fertilizers, pesticides, and crop management on crop production and the soil environment in a cropping system (Ahuja et al., 2000). Crop simulations in RZWQM2 are the CSM (Cropping System Model) crop modules of DSSAT v4.6 for simulating specific crops (Saseendran et al., 2015; Ma et al., 2006, 2009; Hoogenboom et al., 1991; http://arsagsoftware.ars.usda.gov/). The minimum inputs required for simulating cropping systems in RZWQM2 are solar radiation, minimum and maximum air temperatures, air relative humidity, wind speed, and rainfall at the location. Soil physical and hydraulic properties required to simulate an agricultural system using RZWQM2 were described in Anapalli et al. (2016). The corn model uses a radiation use efficiency (RUE) approach for simulating biomass production from the photosynthetically active radiation intercepted by the corn canopy. The effects of atmospheric CO_2 concentration on biomass production were modeled by modifying RUE following data provided by Allen et al. (1987) and Peart et al. (1989). The CO_2 concentration also modifies the stomatal conductance value used in the Shuttleworth and Wallace (1985) equation for computing potential transpiration. For simulating a corn hybrid, the CERES-Maize 4.6 model requires six cultivar parameters (Jones et al., 2003). Agronomic data required for the calibration include tillage dates and methods; irrigation and fertilizer amounts and dates of applications; planting density, depth, and row spacing; grain yield; crop biomass; leaf area index; and phenology. All these data were collected from the "corn experiments" described below. A detailed account of the model calibration procedure was described in Anapalli et al. (2018).

2.3 Climate change impacts on corn

All the crop season simulations were independent, with the same initial conditions starting on Jan. 1 of every year. Both irrigated and rainfed corn under both the BL climate and CC scenarios representing 2050 and 2080 with atmospheric CO_2 concentrations for RCPs 2.6, 4.5, 6.0, and 8.5 were simulated. In the simulations, irrigations were applied for replenishing 90% of the cumulative evapotranspiration (ET) demand at the end of every week from planting until physiological maturity. Fertilizer application amount was 224 Kg N ha^{-1} at planting every year.

To investigate individual contributions of CO_2 concentration, temperature, and rainfall on simulated crop production under the CC scenarios, the crop was also simulated, changing only one of those variables at a time, keeping the other variables constant. Outputs of the 61-year crop simulations (BL or CC) were averaged for comparing grain yield, irrigation mount, crop duration, and ET. Significant differences between results ($p < 0.01$) were analyzed using a single-factor ANOVA (analysis of variance) procedure (Microsoft Office Suite Professional Plus 2016).

2.4 Corn experiments

Field experiments for collecting crop growth data (10 years from 2008 to 2018) for testing and validation of the corn model were conducted at Stoneville, Mississippi (33.45° N, 90.87° W, 32 aml) in the LMD region of the state of Mississippi, USA (Anapalli et al., 2018). The soil was a Dubbs silt loam soil (fine-silty, mixed, thermic Typic Hapludalfs). Climate was classified as warm temperate, humid, with hot summer seasons (Köppen-Geiger climate classification; Kottek et al., 2006). The climate is characterized by precipitation more or less evenly distributed throughout the year and average monthly air temperatures between − 3 °C and + 18 °C. The location of this experiment receives an annual rainfall of around 129 cm. In the LMD, corn is planted in the latter half of March or the first half of April and harvest in August, to avoid hot July and August with less rainfall chances. For that reason, the first week of April can be considered the normal time for planting. The experiments were set up for investigating conservation tillage impacts on crop production, as described in Anapalli et al. (2018). Corn was planted on 102 cm spaced ridges at about 70,000 seeds ha^{-1} (Table 1 in Anapalli et al., 2018). The crop was furrow irrigated. Farm scale, 1.5 ha, with dimensions of 185 m in the north-south and 49 m in the east-west direction was used. At planting, fertilizer N as Urea Ammonium Nitrate was injected into the ridge-base at about 224 Kg ha^{-1}. The leaf area index (LAI) and biomass were measured biweekly and grain yield at harvest. Details of soil water, texture, bulk density, and total C and N measurements are available in Anapalli et al. (2018). Phenology observations were visual, recorded every week from 2015 to 2018.

The daily climate data used in the study (air temperature and humidity, solar radiation, rainfall, and wind speed) were collected from a climate station maintained at the Delta Research and Extension Center, Mississippi State University (http://www.Deltaweather.MSstate.edu). The detailed hydraulic properties of the soil required for simulation were estimated using the RZWQM2 model database for a silt loam (Table 2 in Anapalli et al., 2018). Anapalli et al. (2018) calibrated and validated the corn model (CSM-CERES-maize model v4.6 in RZWQM2) for applications, using the above data collected in this experiment.

Salient results of the model's performance reported by Anapalli et al. (2018) are briefly described below.

Simulations of LAI across CT and NT in 2016 and 2018 were with root mean squared deviations (RMSD $= \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi-Oi)^{2}}$, where P_i is the ith simulated value, O_i is the ith observed value, and n is the number of data pairs) between 0.49 and 0.70 (Fig. 4a-d in Anapalli et al., 2018). The RMSD of simulations of biomass were between 6 and 12% across seasons of available measurement. Simulated silking and physiological maturity stages deviated from the measured data between − 3 and + 4 days. Grain yields were simulated with an RMSD of 9% under conventional tillage and 12% under no-tillage treatments (Fig. 1 in Supplementary Material 1). In 2017, the RMSD of biomass simulations were 5 and 6%, respectively, under CT and NT. The biomass simulations in 2016 under CT were with RMSD = 12%, and under NT were with RMSD = 16% (Fig. 5a-d in Anapalli et al., 2018).

3 Results and discussion

3.1 Climate scenarios

In the LMD, on average, farmers start planting corn in the last week of April and harvest in August. Climate (monthly averaged air temperatures and average monthly rainfall) as reflected in the GCM-projected climate (average of 97 ensemble members) in response to the four RCP scenarios (2.6, 4.5, 6.0, and 8.5) in 2050 and 2080 were significantly different from the current climate (centered at 2000) (Table 2 in Supplementary Material 1). This signals the likelihood of a substantial climate change at the location due to the predicted RCP scenarios of GHG emissions. Excepting the RCP 2.6, monthly average rainfall projected in response to all the RCPs pooled together varied only between − 7 and + 6% (Table 2 in Supplementary Material 1).

On a monthly basis, across the corn season, in response to RCP 2.6 in 2050, the daily minimum air temperature increases were between 0.5 and 1.1 °C. Daily maximum air temperature increases were between 1.0 and 1.8 °C. In 2080, the daily minimum temperature increases were between 0.6 and 1.1 °C, and the maximum temperature was between 0.9 and 1.8 °C (Table 2 in Supplementary Material 1). Under the RCP 4.5 scenario, the maximum temperature increased between 1.6 and 2.0 °C in 2050, and between 2.2 and 2.6 °C in 2080; and the minimum temperature increased between 1.5 and 1.8 °C in 2050 and between 2.0 and 2.4 °C in 2080 across the four months of the season (Table 2 in Supplementary Material 1). In 2050, in response to the RCP 6.0 scenario, the maximum temperature increased between 1.4 and 2.2 °C; in 2080, the increases in maximum temperatures were between 2.5 and 3.3 °C, while the minimum temperature increased was between 1.0 and 1.7 °C in 2050 and 2.2 and 2.8 °C in 2080 (Table 2 in Supplementary Material 1). The monthly average maximum temperature increases in response to RCP 8.5 were between 2.1 and 2.8 °C in 2050 and between 3.8 and 4.8 °C in 2080. In response to RCP 8.5, the minimum temperature increased between 1.9 and 2.6 °C in 2050, between 3.5 and 4.6 °C in 2080.

3.2 Effects of air CO_2 concentration increase alone on rainfed and irrigated corn yields

While the CO_2 fertilization effect stimulates significant carbon gain in C_3 plants, the effect is less pronounced in C_4 plants, mainly due to the phosphoenolpyruvate carboxylase (PEPc) located in the plant epidermal cells, that receives CO_2 input from the ambient air, eventually concentrating it around Rubisco at the photosynthetic site located in the bundle sheath cells (Benson-Calvin cycle), up to six times its concentration in the ambient air. Under irrigated conditions, corn yield simulated in response to CO_2 emissions alone represented by the RC 2.6, 4.5, 6.0, and 8.5 scenarios in both 2050 and 2080 did not change significantly from the BL climate (Fig. 1; Table 3 in Supplementary Material 1). The cumulative probability curves of grain yields simulated with the 60-year climate with enhanced CO_2, representing the four RCP scenarios in 2050 and 2080, coincided (Fig. 1). As the crop simulations from 1960 to 2019 (61 seasons) were under identical agronomic management, the observed yield variations resulted from the climate variations across seasons (Fig. 1). These simulation results represent sixty possible corn production outcomes from climates that can be experienced, as it occurred between 1960 and 2019, at the location in 2050 and 2080.

The average grain yield in the BL climate was 12.5 Mg ha^{-1} (Table 3 in Supplementary Material 1). Grain yields in 2050 and 2080, in response to CO_2 concentrations representing the four RCPs, ranged between 12.6 and 12.7 Mg ha^{-1}. While the grain yields forecast for the future did not vary significantly from the BL value, the average seasonal crop evapotranspiration (ET) was slightly reduced from 45 cm in the BL to 41 cm in the climate of RCP 8.5 in 2080. In the corn model, based on a combination of algorithms developed by Allen et al. (1987), increased CO_2 in the air modulated leaf stomatal conductance in the Shuttleworth and Wallace (1985) equation

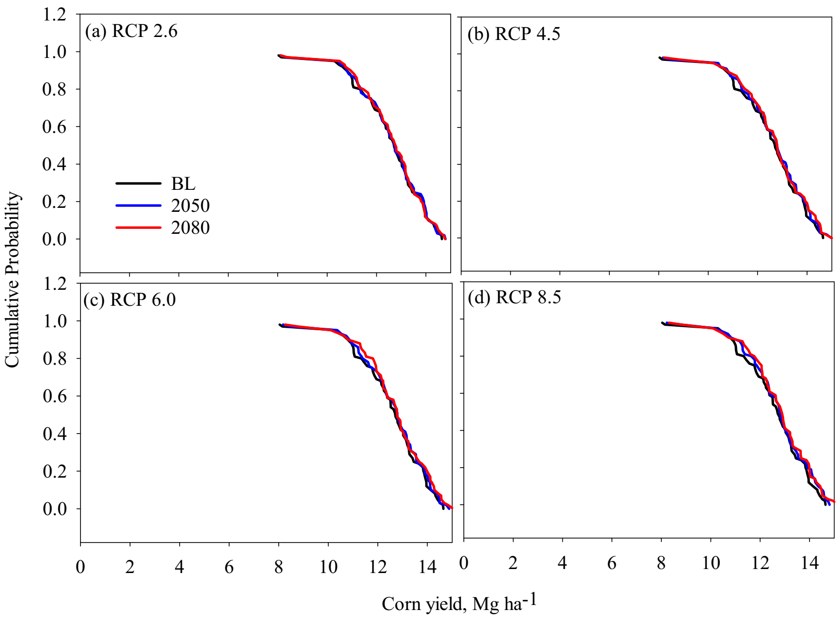

Fig. 1 Simulated impacts of atmospheric CO_2 concentration alone (temperature and CO2 concentration unchanged from BL climate) under representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 greenhouse gas (GHG) emission scenarios on irrigated corn yield in 2050 and 2080. The GCM-projected temperature and rainfall changes were not considered

used for computing the potential crop ET. The reduced stomatal conductance in this equation cuts down the computed crop transpiration loss, which in turn reduced ET (combined plant water loss to the air due to transpiration and soil evaporation) from the plants. Bernacchi et al. (2003) reported a reduction in poplar's (*Poplus* L.) stomatal conductance in elevated CO_2 experiments in the EURO FACE study. Seasonal total irrigation water applied went down from 12 cm under the BL climate to 9 cm under the RCP 8.5 in 2080. In response, the water use efficiency (WUE, the ratio of grain yield to ET) was enhanced by 12% (Table 3 in Supplementary Material 1).

The C_4 photosynthetic pathway, which fails to exhibit a significant CO_2 fertilization effect, can mimic this to some extent by reducing transpiration water loss from the crop to the air by modulating leaf stomatal conductance: in water-limited environments, such as rainfed or dryland cropping systems, lessening of transpiration water loss can reduce drought stress otherwise impacting the crop growth, resulting in a net crop yield gain (von Caemmerer and Furbank, 2003; Attavanich and McCarl, 2014). Consistent with these findings, the simulated rainfed corn yields increased significantly with increasing CO_2 concentrations represented by the four RCPs. From the 10.2 Mg ha^{-1} under the BL climate, grain yield increased to 11.7 Mg ha^{-1} under RCP 8.5 in 2080 (Fig. 2; Table 3 in Supplementary Material 1). Corresponding WUE enhancement was 18%, with 12% in the irrigated system. Under both rainfed and irrigated scenarios, there were no grain yield changes in response to CO_2 concentrations under RCP 2.6 in 2080. Of the four RCPs, 2.6 represents a GHG mitigation scenario leading to a low radiative forcing level of 2.6 Wm^{-2}

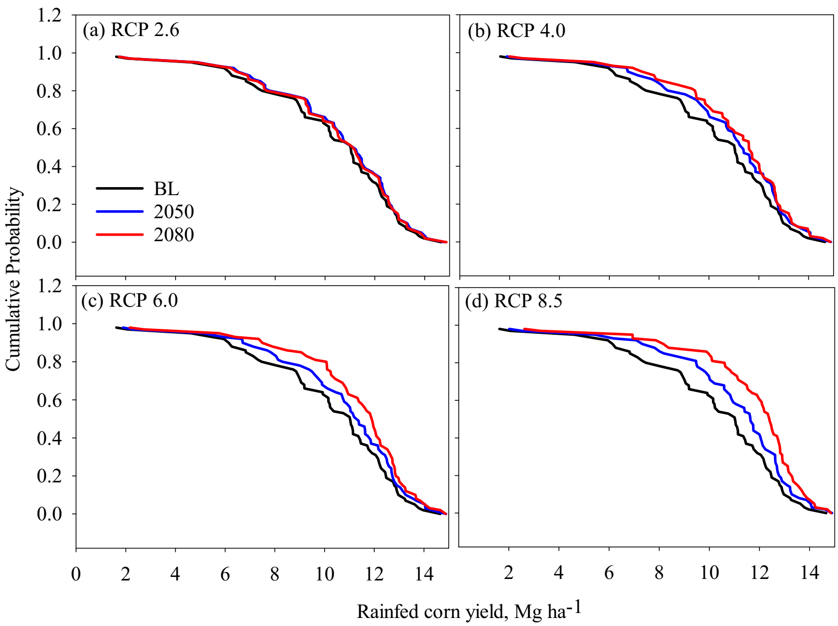

Fig. 2 Simulated impacts of atmospheric CO_2 concentration alone (temperature and CO2 concentration unchanged from BL climate) under representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 based greenhouse gas (GHG) emission scenarios on rainfed corn yield in 2050 and 2080. The GCM-projected temperature and rainfall changes were not considered

in the atmosphere by 2080 (van Vuuren et al., 2011). As the crop performance across the 60 years (1960–2019) was simulated with initial conditions and soil-crop-water management, the yield variation obtained was due only to the climate variations across the crop seasons (Fig. 2).

3.3 Effects of air temperature increase alone on crop performance (CO_2 concentration in the air and rainfall were kept unchanged from the measured BL climate)

To isolate the possible contribution of the GCM-projected temperature changes alone on corn growth performance at the location, the crop was simulated by changing only this variable in the historical climate data from 1960 to 2019, keeping the air CO_2 concentration and rainfall the same as measured. The crop was simulated under rainfed and irrigated conditions (Figs. 3 and 4; Table 4 in Supplementary Material 1). In response to the projected temperatures based on RCP 2.6, 4.5, 6.0, and 8.5 emission scenarios, averaged over 60 years (1960 to 2019), irrigated corn yields decreased by 12, 39, 29, and 48% in 2050, and by 31, 29, 38, and 64% in 2080, respectively (Fig. 3; Table 4 in Supplementary Material 1). Corn yields under rainfed conditions also declined at similar rates: the decline in yield in 2050 varied between 15 and 37% and between 13 and 67% in 2080 (Fig. 4; Table 4 in Supplementary Material 1). Sixty-year average irrigated corn yield under BL climate was 12.5 Mg ha^{-1}, and rainfed yield was 10.2 Mg ha^{-1} (Table 5 in Supplementary Material 1). The temperature changes in response to RCP 2.6, 4.5, 6.0, and 8.5 reduced corn yields significantly: irrigated corn yields were 11.2, 8.7, 8.0, and 6.5 Mg ha^{-1} in 2050 and 9.6, 8.1, 7.8, and 4.6 Mg ha^{-1} in 2080, and rainfed corn yields were 8.7, 7.6, 7.8, and 6.4 in 2050 and 8.8, 6.7, 6.8, 3.4 in 2080, respectively, in response to the four RCPs. Corn growth, development, and grain yield of corn are controlled by the surrounding air and soil (Hatfield and Preuger, 2015). A lower threshold below defines the temperature range in which the plant can grow and an upper threshold above which the plant ceases to grow, known as cardinal temperatures. In between these two thresholds, there is another sub-range of temperatures within which the plant can grow at its optimum level. Jones and Kiniry (1986), Kiniry and Bonhomme (1991), and Hatfield and Preuger (2015) reported the base temperature below which corn growth ceases as 8 °C, and the upper temperature for optimum growth as 34 °C, and at about 38 °C, growth stops. These cardinal temperatures were adopted in the corn model (CSM-CERES-maize) for simulating corn. The yield declines in both rainfed and irrigated corn simulations in response to the projected temperature increases under the four RCPs in both 2050 and 2080 were from lessened photosynthesis encountered at super-optimum temperatures and associated reduction in the duration of growth (crop filling duration). The time (in days) the crop takes to reach physiological maturity under both irrigated and rainfed conditions (the phenology module in the corn model does not respond to water stress) decreased from 123 under the BL climate to 103 days in 2080 under the RCP 8.5 scenario. The average number of days with daily maximum temperatures above the upper optimum for photosynthetic growth (34 °C) went up from 23 to 60 days across temperature projections in 2050 and 2080 across the four RCPs (Table 4 in Supplementary Material 1). However, with the projected increase in daily minimum air temperatures, the number of days with the minimum temperatures falling below the base temperature for growth (8 °C) only was reduced from an average of 4 days in the BL climate to 1 day in the climate in response to RCP 8.5 in 2080. The corn yield enhancement from the reduction in daily minimum air temperature going below the base temperature could not compensate for the yield loss from increases in daily maximum temperatures above 34 °C.

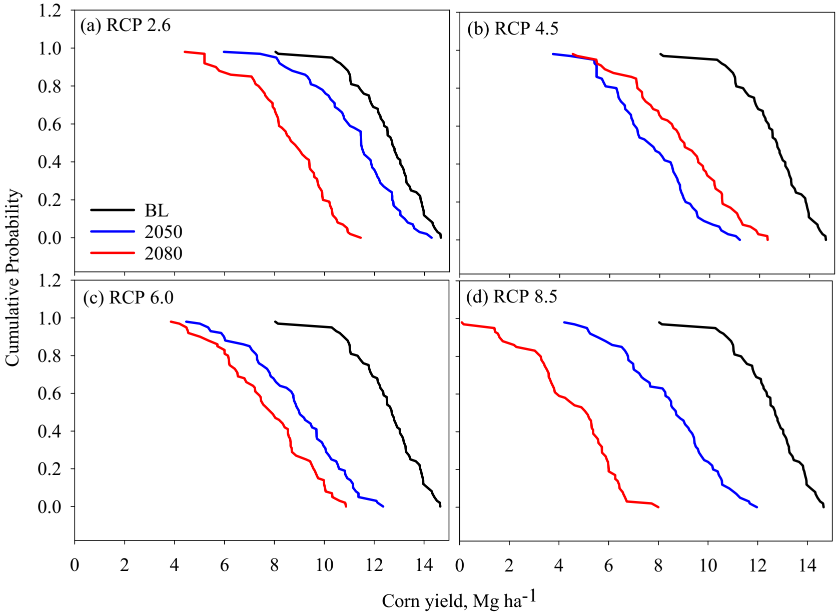

Fig. 3 Simulated impacts of atmospheric temperature alone (CO_2 concentration in the air and rainfall unchanged from BL climate) projected by an ensemble of GCMs in response to representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 greenhouse gas (GHG) emission scenarios on irrigated corn yield in 2050 and 2080

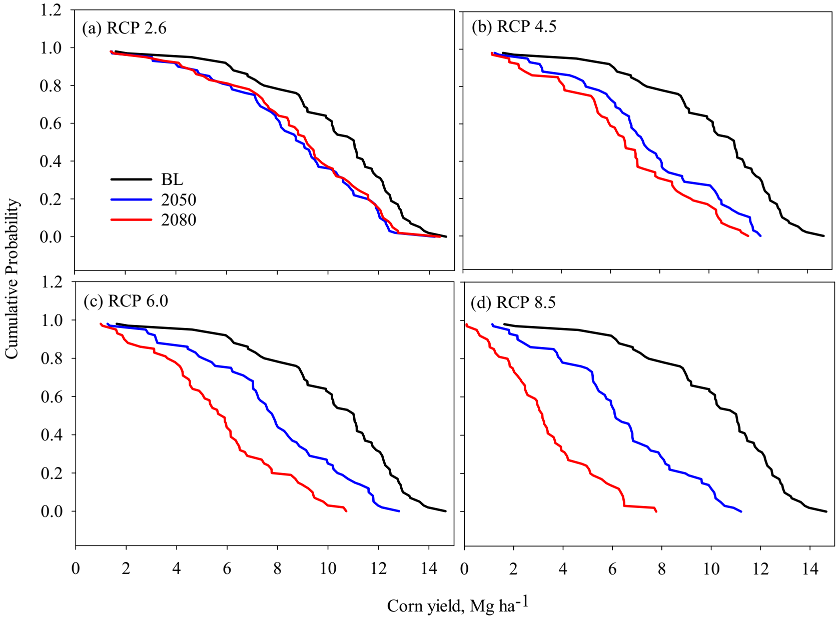

Fig. 4 Simulated impacts of atmospheric temperature alone (rainfall and CO_2 concentration unchanged from BL climate) projected by an ensemble of GCMs in response to representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 greenhouse gas (GHG) emission scenarios on rainfed corn yield in 2050 and 2080

3.4 Effects of projected rainfall changes alone (keeping air temperature and CO_2 concentration as in the BL climate) on rainfed and irrigated corn production

Under the irrigated corn scenario, the crop was irrigated weekly to replenish the soil with profile water at 90% of corn ET loss, accounting for rainfall inputs, during the preceding week. As such, irrigated corn yield simulated in response to projected rainfall did not vary significantly across the four RCPs in 2050 and 2080 (data not shown). In the case of rainfed corn, some differences, but not significant, in simulated yield were found only in response to RCP projected weather across 2050 and 2080 (Fig. 2 in Supplementary Material 1). The average crop season (simulated) during the 61-year BL climate lasted 123 days, and the rainfall received (measured data) during this period was 43 cm (Table 5 in Supplementary Material 1). When the GCM-projected rainfall during the crop season was incorporated into the measured rainfall during the BL climate, the modified rainfall amounts were 46, 44, 42, and 43 cm in 2050 and 49, 44, 43, and 42 cm in 2080, respectively, for the four RCPs. As stated above, GCM-projected rainfall was significantly different from the BL only in the climate in response to RCP 2.6 (both 2050 and 2080): deviation of the projected rainfall from the BL was between − 17 and 37% in 2050, and between − 26 and 34% in 2080 (Table 2 in Supplementary Material 1). Deviations of the projected rainfall from the BL in response to RCPs 4.5, 6.0, and 8.5 were between − 7 and 6%, respectively, in 2050 and 2080.

3.5 Effects of climate change (combined effects of air temperature, CO_2, and rainfall) on rainfed and irrigated corn production

In response to the GCM-projected climate change, the combined effects of air temperature, CO_2, and rainfall, the corn model simulated irrigated grain yields declined significantly across the RCP scenarios in both 2050 and 2080 (Fig. 5 Table 6 in Supplementary Material 1). Similar significant yield reductions across the four RCPs in both 2050 and 2080 were observed in the case of the rainfed corn production scenarios as well (Fig. 6; Table 7 in Supplementary Material 1). However, in response to RCP 2.6, under both irrigated and rainfed conditions, corn yield reduction in 2080 was slightly less than the yield reduction in 2050 (Figs. 5 and 8; Table 6 and 7 in Supplementary Material 1). Under irrigated conditions, average yield reductions in 2080 were 0%, and under rainfed conditions, yields were 6% less than those obtained under the BL climate (Tables 6 and 7 in Supplementary Material 1). The yield reductions were 10 and 9% less than those under BL in 2050. This anomaly in yield projection with time was due to the RCP 2.6 scenario actually comprised of one mitigation scenario, which potentially leads to a shallow radiative forcing level of 2.6 Wm^{-2} by 2080. The CO_2 concentration level represented by this RCP for 2080 (431 ppm) was lower than that of 2050 (443 ppm).

Consequently, the GCM-projected minimum and maximum air temperatures also dropped in 2080 relative to 2050. Maximum air temperatures projected in 2050 for April, May, June, and July were higher than those in 2080; however, in August, the trend reversed. In the case of minimum air temperatures, the temperatures in 2080 were higher than those in 2050 in April.

While the 60-year averaged irrigated corn yield simulated in the BL climate was 12.5 Mg ha^{-1}, the average maximum grain yield simulated was 11.6 Mg ha^{-1} in 2080 under RCP 2.6 and 4.8 Mg ha^{-1} under RCP 8.5 in 2080, a 62% yield reduction (Table 6 in Supplementary Material 1). Under rainfed conditions, the 60-year average corn yield under the BL climate was 10.2 Mg ha^{-1}. In response to the four RCPs, the maximum average yield

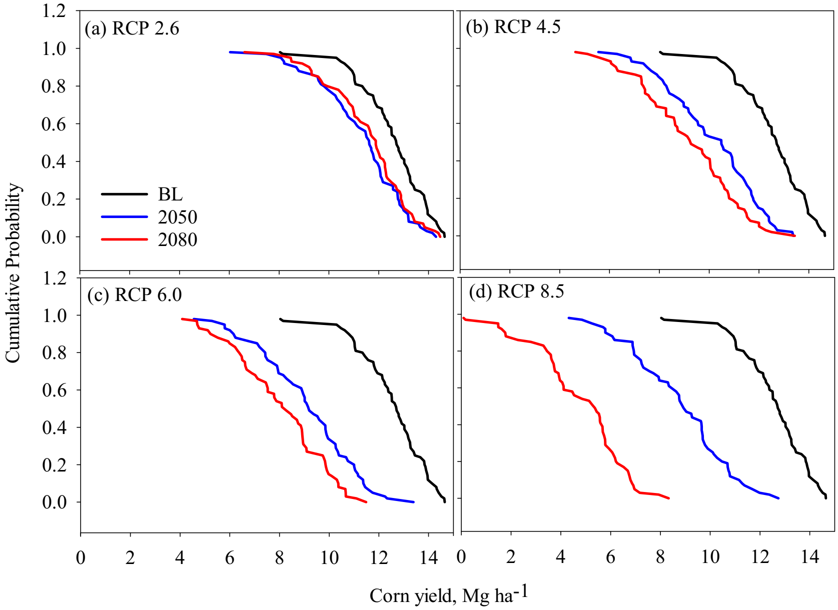

Fig. 5 Simulated impacts of climate change (atmospheric temperature, rainfall, and CO_2 concentration) projected by an ensemble of GCMs in response to representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 based greenhouse gas (GHG) emission scenarios on irrigated corn yield in 2050 and 2080

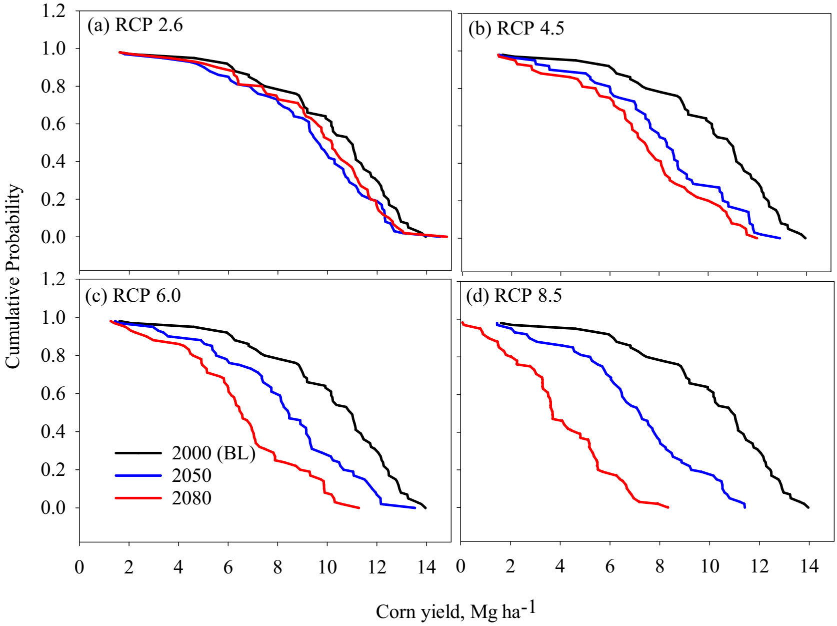

Fig. 6 Simulated impacts of climate change (atmospheric temperature, rainfall, and CO_2 concentration) projected by an ensemble of GCMs in response to representative concentration pathway (RCP) 2.6, 4.5, 6.0, and 8.5 based greenhouse gas (GHG) emission scenarios on rainfed corn yield in 2050 and 2080

simulated was 9.6 Mg ha^{-1} in 2080 under RCP 2.6, and the minimum was 4.1 Mg ha^{-1} under RCP 8.5 in 2080, a 62% reduction in yield compared to the BL (Table 7 in Supplementary Material 1). In the Central Great Plains region of Colorado, USA, Ko et al. (2012) and Islam et al. (2012a) reported similar significant corn yield reductions under GCM-projected climate scenarios.

As discussed above, the GCM-projected temperature changes alone decreased irrigated corn yields by 12, 39, 29, and 48% in 2050 and by 31, 29, 38, and 64% in 2080, respectively, under the RCP 2.6, 4.5, 6.0, and 8.5 scenarios (Fig. 3). Similar yield reductions in rainfed corn yield in 2050 were between 15 and 37% and between 13 and 67% in 2080 across the four RCPs (Fig. 4; Table 4 in Supplementary Material 1). It was also clear from the corn simulations considering only the CO_2 effects on corn growth in 2050 and 2080 in response to the four RCPs. Being a C_4 plant, there can hardly be a CO_2 fertilization effect that can enhance corn yield significantly (Table 3 in Supplementary Material 1). Similarly, the impact of GCM-projected rainfall changes alone on corn yields in the future was also insignificant (Table 5 in Supplementary Material 1). As such, it is clear that in the event of a GHG induced climate change, the CO_2 fertilization effect on corn yield production may not be able to compensate the negative impacts of air temperature on yield reduction substantially. The temperature effect on yield reduction dominates these negative impacts due to more incidences of extreme above optimum temperatures. To a lesser extent, the reduction in crop durations also is a factor (Table 6 and 7 in Supplementary Material 1). Extreme temperatures above 34 °C increased from 23 days under BL climate to 60 days under the climate in response to RCP 8.5 in 2080. On average, 43 cm of rainfall was received during the crop season, and 12 cm of irrigations was applied to grow the crop under fully irrigated conditions without significant water stress. Corn ET under the BL climate was 45 cm, which went down to 38 cm under the RCP 8.5 climate in 2080.

Under the irrigated corn production scenario, as the reductions in yield in response to the climate across the four RCPs were sharper than the crop ET reduction, the WUE in grain production reduced from 0.37 Mg ha^{-1} cm^{-1} under the BL climate to 0.13 Mg ha^{-1} cm^{-1} under the RCP 8.5 climate in 2080 (Table 6 in Supplementary Material 1). Under the rainfed corn production scenario, the WUE in the BL climate was 0.28 Mg ha^{-1} and 0.13 Mg ha^{-1} under the RCP 8.5 climate in 2080 (Table 7 in Supplementary Material 1). It is also clear from the results presented above that the yield reductions under both irrigated and rainfed conditions, in response to all but RCP 2.6 (both in 2050 and 2080), are severe. The consequent decline in economic returns can potentially lead to farmers moving away from growing corn in the LMD under irrigated and rainfed conditions.

3.6 Adapting irrigated and rainfed corn production systems to climate change

In the past, several studies representing different climates across the world recommended adapting longer duration corn cultivars as one of the possible strategies for combating the negative impacts of climate change on corn yield (Islam et al., 2012a; Tubiello et al., 2000; Ko et al., 2012; Deryng et al., 2014). This adaptation strategy was based on the positive correlations they observed between reducing corn yield and reduction in crop duration in the climate at their locations. As discussed above in this study, compared to the effects of decreasing crop duration, increasing occurrences of extreme temperatures above 34 °C contributed more to the simulated grain yield declines due to warming: increasing crop duration by advancing planting dates did not enhance crop yields due to higher incidences of the number of days with extreme above optimum (above 34 °C) temperatures (data not shown). At the location of this study, Anapalli et al. (2016) were able to counterbalance a climate warming–induced yield decline in cotton yield, a C_3 crop, by advancing planting dates and, by doing so, encountering lower air temperatures, evading extreme temperatures in the early spring season. In this study, we explored a similar strategy by advancing planting dates by about 2 months into the cooler weather in February, from the average planting time for corn in the LMD around April 5 (Figs. 7 and 8).

The advantage of advancing planting dates under both irrigated and rainfed scenarios was significant only up to about 9 weeks ahead of the normal planting date, that is, the first week of February (Figs. 7 and 8). The advanced planting enhanced grain yields enough to compensate for part of the yield loss under different RCP induced climate extremes in both 2050 and 2080. When the irrigated corn yield in the BL climate under normal planting date was 12.5 Mg ha^{-1}, yields achieved by this advanced plantings were 11.4, 11.1, 10.5, and 10.7 Mg ha^{-1} under climates in response to RCP 2.6, 4.5, 6.0, and 8.5, respectively, in 2050 and 11.6, 10.8, 10.3, and 8.6 Mg ha^{-1}, respectively, in 2080. Yield declines from BL between 10 and 62% across four RCPs, in 2050 and 2080, normal planting dates came down to between 10 and 47% by advancing planting by 9 weeks on Feb 5 (Fig. 7; Table 8 in Supplementary Material 1).

In the case of the rainfed system, from the current average corn yield of 10.2 Mg ha^{-1}, in the BL climate, yield declines were between 10 and 60% across climates in response to the four RCPs in 2050 and 2080 (Fig. 8; Table 9 in Supplementary Material 1). With the advanced planting in the first week of February, these yield declines compared to the yield under the BL climate were between 6 and −25% in climates in response to the four RCPs in 2050 and 2080. Under the irrigated and rainfed scenarios, crop durations increased from 123 days (normal

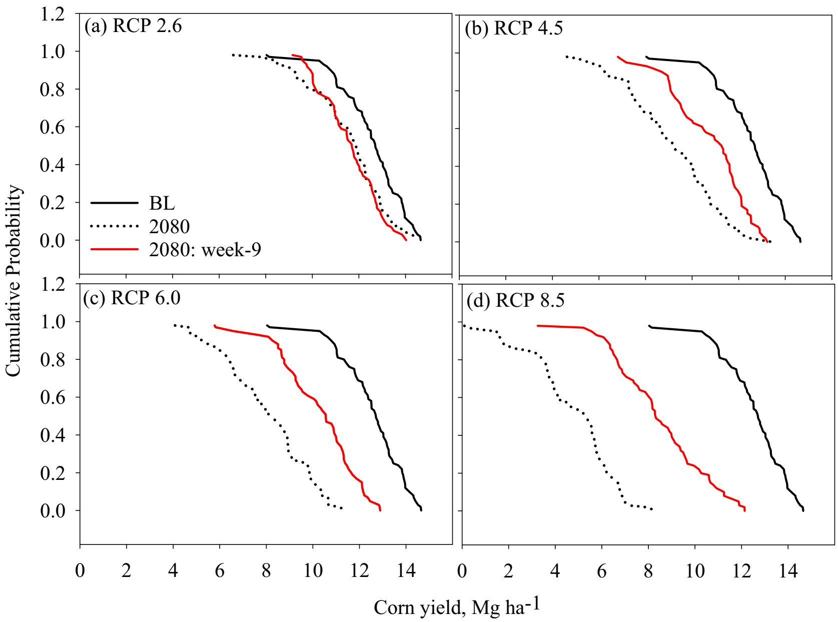

Fig. 7 Comparison between simulated yield impacts of irrigated corn planted on a normal day-of-planting under climate change projected by an ensemble of GCMs in response to representative concentration pathways (RCP) 2.6, 4.5, 6.0, and 8.5 based greenhouse gas (GHG) emission scenarios in 2050 and 2080, with grain yields obtained in a 9-week earlier planting in the same climate (week 9)

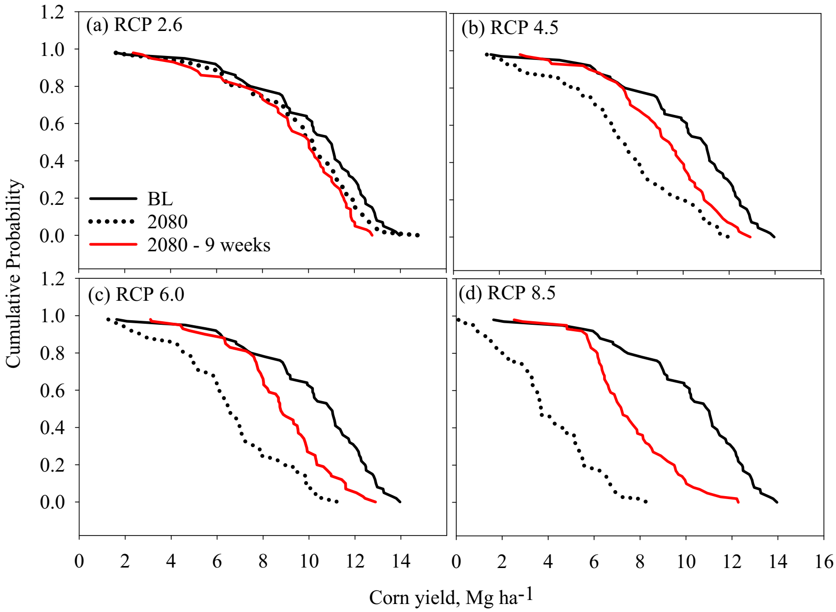

Fig. 8 Comparison between simulated yield impacts of rainfed corn planted on a normal day-of-planting (April 5) under climate projected by an ensemble (97 members) of GCMs in response to representative concentration pathways (RCP) 2.6, 4.5, 6.0, and 8.5 based greenhouse gas (GHG) emission scenarios in 2050 and 2080, with grain yields obtained in a 9-week advance planting in the same climate (week 9)

planting date) under the BL climate to a maximum of 162 days under the climate in response to RCP 2.6 in 2050. With the advanced planting, averaged across the climates in response to the four RCPs in 2050 and 2080, the number of days with the maximum air temperature above 34 °C, the upper threshold extreme temperature for corn growth, was reduced by about 16 days compared to the corn planted on the normal date of plantings in corresponding climate scenarios. However, these enhanced crop durations and the reductions in the number of days with extreme super-optimum temperatures only partially compensated for the decline in yield due to enhanced temperatures under the CC scenarios. This was mainly because, with the enhanced crop duration, the number of days with minimum air temperatures going below the base temperature for growth (8 °C) increased drastically, negating the positive effects. Under the BL climate, the number of days with suboptimum temperatures was 4 days, and under the CC scenarios in response to the normal planting, it ranged between 1 and 3 days. In the 9-week advance planting under climates in response to the four RCPs in 2050 and 2080, the number of days with suboptimum temperatures varied between 31 and 42 days (Table 9 in Supplementary Material 1).

4 Conclusions

Based on the study, we conclude that the GCM-projected climate change scenarios in response to four RCPs (2.6, 4.5, 6.0, and 8.5), in both 2050 and 2080, can reduce both irrigated and rainfed corn yields in the LMD region substantially. As a crop with a C_4 photosynthetic pathway, the photosynthetic fertilization effect of CO_2 concentration increases in the atmosphere associated with the RCP scenarios, which fails to enhance grain yield. The adverse effects of air temperature rise on crop production dominate corn cropping system performance in the region. The identified adverse impacts of increased air temperature on corn production were reduced growth duration (mainly grain filling) and photosynthesis rates on days with ambient air temperatures rising above the optimum required process. The GCM-projected rainfall changes at the location did not affect corn yields significantly under either the irrigated or rainfed scenarios. Planting corn up to 9 weeks in advance (first week of February) of the normal planting time (around the first week of April) as an adaptation measure compensates for the reduction in crop duration due to enhanced temperature under CC, compensated for only about 50% of the yield losses. This strategy could not achieve further yield gain because, as planting time advanced into colder air temperatures, along with the decrease in the fewer number of days with super-optimum extreme temperatures, the number of days with suboptimum extreme temperatures also increased at a faster rate negating its positive effect on yield.

Caveats: 1. The present-day GCMs with their coarse resolution are widely accepted for global climate change projections at a global mean level; however, uncertainties still exist in their applicability at the regional level for agricultural applications. 2. In the crop model simulations, pests, weeds, and diseases, different toxicities and micronutrients in the soil, soil salinity, and soil erosion problems are assumed to be fully controlled.

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