SIMULATING THE IMPACTS OF FUTURE CLIMATE VARIABILITY AND CHANGE ON COTTON PRODUCTION IN THE TEXAS ROLLING PLAINS

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Abstract

The Texas Rolling Plains region in the north central Texas accounts for approximately 13% of the total cotton production in the state. Cotton production in this region in recent years has been experiencing challenges due to reduced rainfall amounts and frequent occurrence of severe droughts. Projected changes in climate are expected to further add to the uncertainty of cotton production in this region. The overall goal of this research is to study the impacts of climate change on cotton yields using the CSM-CROPGRO-Cotton model within the Decision Support System for Agrotechnology Transfer (DSSAT). The future climate data generated by three Regional Climate Models (RCMs), namely RCM3-GFDL, RCM3-CGCM3 and CRCM-CCSM, was obtained from the North American Regional Climate Change Assessment Program (NARCCAP), bias-corrected and used in this study. The CROPGRO-Cotton model, which was previously evaluated for Chillicothe in the Texas Rolling Plains, was used to study the impacts of projected climate change on seed cotton yield at Chillicothe over the period from 2041 to 2070. Results indicated a decrease in seed cotton yield under future climate scenarios within a range of 2% (RCM3-CGCM3) to 14.9% (RCM3-GFDL) when the projected increase in CO_2 concentration was not considered, and an increase in seed cotton yield within a range of 30% (RCM3-GFDL) to 53% (RCM3-CGCM3) with the consideration of the projected increase in CO_2 concentration.

Introduction

In the agriculture industry across the globe, crop models are being extensively used by researchers and policy makers as important decision making tools for studying the impacts of climate change, management practices and irrigation strategies on crop yields (Thorp et al., 2014). Field experiments in these research areas are resource-intensive and challenging to implement. Under these circumstances, calibrated and validated crop models offer alternative solutions with comparable outcomes. The Cropping System Model (CSM), CROPGRO-Cotton distributed with the Decision Support System for Agrotechnology Transfer (DSSAT) can be used to study the impacts of climate change and management practices on crop growth, crop yields, and crop water use. Cotton production in the Texas Rolling Plains (TRP) region has experienced a noticeable decline in recent years due to reduced rainfall amounts and frequent occurrence of severe droughts. Since this region receives inadequate rainfall to meet crop water demands in most years, farmers in this region rely on irrigation for meeting cotton water requirement. Nielsen-Gammon (2011) has predicted warmer summers in the future for this region, which will necessitate larger groundwater withdrawals to meet higher crop evapotranspiration needs. Studying the effects of climate change on cotton yields under current and future climate change scenarios, is therefore important for the TRP region as cotton is one of the major revenue contributors to the local economy. The overall objective of this study was to assess the impacts of climate variability and change on seed cotton yields at Chillicothe in the TRP region using our previously calibrated DSSAT CSM, CROPGRO-Cotton model (Modala et al., 2014).

Materials and Methods

The methodology adopted in this study is shown in a flow chart (Figure 1). The CSM-CROPGRO-Cotton model was previously evaluated for the TRP region using the observed data from cotton experiments at Chillicothe research station (34.25° N, 99.51° W, 447 m above sea level) in the Hardeman County in the TRP region (Modala et al., 2014). The model was initially calibrated and validated using the observed data collected from four irrigation scheduling treatments (100% ET replacement, 75% ET replacement, tensiometer based, and soil moisture based irrigation scheduling) implemented during the year 2012 (Rajan et al., 2013). Data from the 100% ET experiment was used for model calibration and the data from the other treatments was used for model validation. Data related to crop growth (leaf area index (LAI) and canopy height), crop development (phenology and number of main stem nodes) and crop yields that was collected during this experimental study, was used in the model calibration effort. The model was further evaluated by comparing the simulated seed cotton yields with the observed yields in a 3-year (2008-2010) cotton irrigation and tillage experiment (DeLaune et al., 2012; Modala et al., 2014).

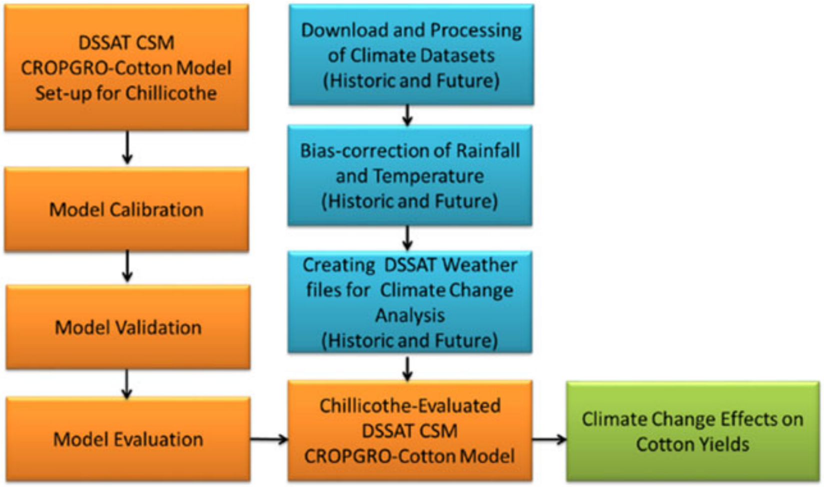

Figure 1. Methodology adopted in this study.

The projected historic (1971-2000) and future (2041-2070) climate datasets were downloaded from the North American Regional Climate Change Assessment Program (NARCCAP) website (Mearns et al., 2007; 2009). The NARCCAP climate datasets were generated by the Regional Climate Models (RCMs), which were driven by a set of ocean-atmospheric Global Climate Models (GCMs) that are forced with the A2 Special Report on Emission Scenarios (SRES) (Nakicenvoic et al., 2000). In general, RCMs are used to downscale the GCM predictions to a smaller scale (25–50 km^2). In the process of downscaling, systematic biases are incorporated into the data due to scaling issues (spatial averaging at grid level) and errors due to immature/incomplete concepts (Teutschbein and Seibert, 2012). Typical biases in the RCM climate data include incorrect estimation of extreme temperatures (Ines and Hansen, 2006), and incorrect seasonal variations in rainfall (Teutschbein and Seibert, 2010). Distribution mapping technique, also known as quantile-quantile mapping was used to remove the bias from the climate variables. This method involves creation of a transfer function to correct the distribution function of the simulated historic values to match the distribution function of the observed historic values. Precipitation datasets were bias corrected using the Gamma distribution mapping technique (Figure 2a) and the temperature datasets were bias corrected using the Gaussian distribution mapping technique (Figure 2b). In this approach, it was assumed that the bias is stationary under climate change, and the the scaling parameters that were obtained during the bias correction of model simulated historical precipitation and temperature were used to bias correct future climate datasets.

The calibrated CSM-CROPGRO-Cotton model was used to study the impacts of climate change on seed cotton yields at Chillicothe in the TRP. Bias corrected historic (1971-2000) and future (2041–2070) daily rainfall, maximum temperature and minimum temperature data as predicted by three regional climate models (RCM3-GFDL, RCM3-CGCM3, CRCM-CCSM) for the Hardeman County were used as inputs for simulating historic and future climate scenarios in the CSM-CROPGRO-Cotton model. The calibrated cultivar parameters (including ecotype and species parameters) from the Chillicothe-evaluated CROPGRO-Cotton model (Modala et al., 2014) were used in the above DSSAT projects. All management practices were assumed to be the same as those adopted for the 2012 100% ET replacement experiment at Chillicothe, except for irrigation. Automatic irrigation method was used in the model. Whenever the soil water content was below 50% of the available water (difference of field capacity and permanent wilting point soil moisture contents), irrigation was triggered until the available soil water content reached 85% level (deficit irrigation strategy). The soil properties that were used in the calibrated CROPGRO-Cotton model were also maintained the same for the simulations under future climate change scenarios.

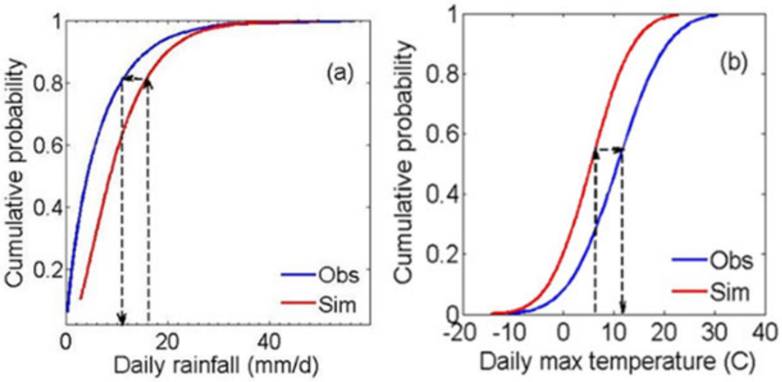

Figure 2. a) Bias correction of precipitation data using Gamma distribution mapping technique, and b) Bias correction of temperature data using Gaussian distribution mapping technique.

For the future (2041-2070) simulations, we have considered two scenarios: 1) no change in the future CO_2 concentrations when compared to the 2012 concentrations, and 2) the projected increases in CO_2 concentration in the future. In this study, we adopted the CO_2 concentration increases as projected under the A2 emission scenario, and increased the CO_2 concentration from 493 ppm (in year 2041) to 635 ppm (in year 2070).

Results and Discussion

The model calibration and validation results showed a good performance of the CSM-CROPGRO-Cotton model as indicated by a good agreement between the simulated and observed seed cotton yields (Table 1). The percent error in seed cotton yield prediction was within the acceptable range (< 10%). The model was also able to satisfactorily simulate the crop growth, development and crop phenology stages during both model calibration and validation (Modala et al., 2014).

Table 1. Comparison of observed and simulated seed cotton yields during the model calibration and validation.

Treatments	Observed yield (kg ha^{-1})	Simulated yield (kg ha^{-1})	Percent error
Calibration			
100% ET replacement	4781	4831	1.0
Validation			
75% ET replacement	4783	4402	-7.9
Tensiometer based	4613	4188	-9.2
Soil moisture based	4279	4217	-1.4

The bias correction procedure adopted in this study has effectively removed bias from the climate model-projected data. For example, the projected bias-corrected historic mean monthly rainfalls matched fairly well with the observed historic mean monthly rainfalls for the Hardeman County (Figure 3). The bias corrected, climate model-projected daily minimum and maximum temperature have also closely matched with observed mean temperatures over the period of 1971-2000 (data not shown).

Future climate change assessment using the three RCMs for both Texas Rolling Plains and Texas High Plains regions in west Texas showed: i) a decrease in average annual rainfall within a range of 30 to 127 mm, ii) a decrease in the number of rainfall events by 6% to 10%, iii) an increase in the intensity of rainfall by about 3% to 8%, and iv) an increase in the extreme events, in the future (2041-2070) when compared to the historic period (1971-2000). For the Hardeman County in which Chillicothe is located, the three RCMs predicted an average decrease in rainfall in the range of 11.4 to 67 mm, increase in the maximum temperature in the range of 2.3 ºC to 2.7 ºC, and an increase in the minimum temperature in the range of 2.2 ºC to 2.5 ºC in the future.

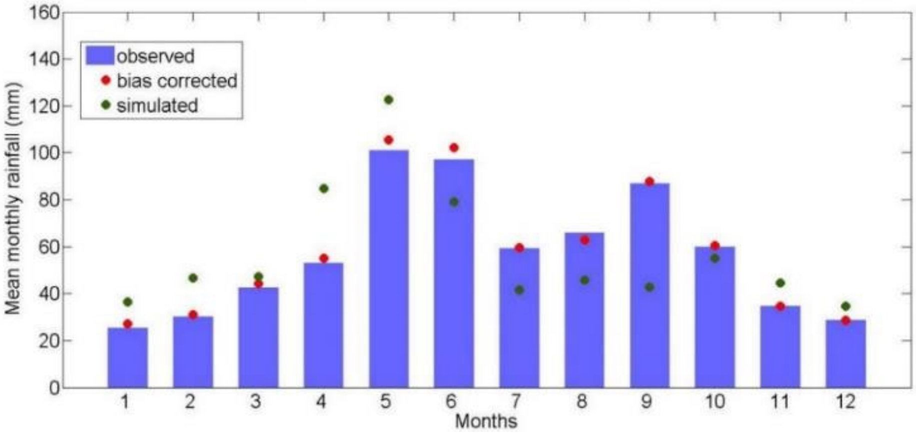

Figure 3. Comparison of bias-corrected RCM3-GFDL (Regional Climate Model Version3–Geophysical Fluid Dynamics Laboratory) model predicted monthly rainfall data with uncorrected and observed monthly mean rainfall for the period 1971-2000 for Hardeman County, TX.

Under the RCM-GFDL projected climate scenario and without considering the projected increase in CO_2 concentration, the CROPGRO-Cotton model simulated a decrease in seed cotton yield within a range of 2% to 14.9% (Figure 4). The reductions in seed cotton yield can be attributed to the combined effect of increase in average minimum and maximum temperature, and decrease in average annual rainfall in this region. When the projected increase in CO_2 was considered in the model simulations, the CROPGRO-Cotton model simulated an increase in seed cotton yield with in a range of 30 to 52%, indicating the huge impact of CO_2 concentration levels on seed cotton yields (Table 2).

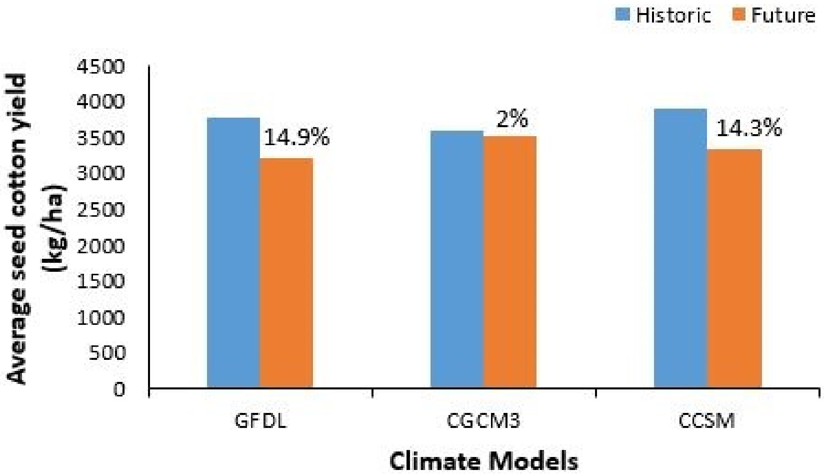

Figure 4. Effect of Climate Change on Seed Cotton Yields – Chillicothe (without considering CO_2 increase).

Table 2. Effect of Climate Change on Seed Cotton Yields – Chillicothe (considering increase in CO_2 concentration).

Climate Model	Historic average (1971-2000) seed cotton yield (kg ha^{-1})	Future average (2041-2700) seed cotton yield (kg ha^{-1})	Percent Change
GFDL	3769	4901	30
CGCM3	3603	5498	53
CRCM	3900	5169	32

Our predictions of future seed cotton yields under the influence of projected increases in CO_2 concentrations are in agreement with the results from previous free air CO_2 enrichment (FACE) experiments. For example, Smith et al. (1989) reported a 3% to 41% increase in seed cotton yield in an experiment in California and Kimball et al. (2002) reported a 40% increase in seed cotton yield at Maricopa in Arizona. The increase in cotton yields can be attributed to an increase in photosynthetic activity in cotton due to suppression of photorespiration caused by an increase in CO_2 concentration. Increase in CO_2 levels decrease transpiration rates in cotton.

Summary

A well-calibrated CSM-CROPGRO-Cotton model was successfully established for Chillicothe in the TRP region. When compared to historic (1971-2000) period, the RCMs predicted a reduction in average annual rainfall (11.4 to 67 mm) and an increase in maximum temperature (2.3 º C to 2.7 º C) and minimum temperature (2.2 º C to 2.5 º C) in the future (2041-2070) for the Hardeman County in which Chillicothe is located. The seed cotton yield predictions by the CSM-CROPGRO-Cotton model at Chillicothe over the future climate period (2041-2070) showed an average decline in the range of 2% (RCM3-CGCM3) to 14.9% (RCM3-GFDL) when projected increase in future CO_2 concentration was not considered, and an increase in seed cotton yields with in a range of 30 to 53% when a projected increase in CO_2 concentration was considered.

Acknowledgements

We thank the Cotton Incorporated and the Texas A&M AgriLife Research Cropping Systems Initiative for providing funding support for this study. We thank Seth McGinnis, Associate Scientist at National Center for Atmospheric Research-University Cooperation for Atmospheric Research (NCAR-UCAR) for providing assistance related to NARCCAP climate datasets. We also would like to thank Paul DeLaune, Edward Barnes, and Shyam Nair for their valuable contributions to our previous model evaluation efforts.

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