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Evaluation of Climate Change Impacts and Effectiveness of Adaptation Options on Crop Yield in the Southeastern United States

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Abstract

The Environmental Policy Integrated Climate (EPIC) model was used to assess the impacts of climate change and proposed adaptation measures on yields of corn (*Zea mays* L.) and soybean (*Glycine max* L.) as well as aggregated yields of C_3 [soybean, alfalfa (*Medicago sativa* L.), winter wheat (*Triticum aestivum* L.)] and C_4 [corn, sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L.)] crop types from representative farms in ten Southeastern US states. Adaptations included annual biochar applications and irrigation. Historical baseline (1979 – 2009) and future (2041 – 2070) climate scenarios were used for simulations with baseline and future CO_2 concentrations of 360 ppmv and 500 ppmv, respectively. Four regional climate models (RCMs) nested within global climate models (GCMs) were used to run future simulations. The experiment was analyzed as randomized complete block design with split-plots in time for baseline vs. future comparisons, and as a randomized complete block design with repeated measures for comparisons between future periods within each RCM_GCM model. Compared to historical baseline scenario, increases in near future corn yield ranged between 36 to 83%, but future yields decreased by 5-13% towards 2066-2070 due to temperature stress. Future soybean yields decreased by 1-13% due to temperature and moisture stresses. Future aggregated C_4 crops produced higher yields compared to historical C_4 yields. There were no differences between future aggregated and historical C_3 crop yields. Both crop types were negatively affected by progressing climate change impacts towards the end of 2066-2070 simulation period. Reductions in future aggregated C_3 crop yields ranged between 10 to 22%, and between 6 to 10% for C_4 crops. We explained lower reductions in C_4 compared to C_3 crops due to a lesser degree of photorespiration, better water use efficiency, and better heat tolerance under conditions of high light intensities and increased temperatures in C_4 crops. Irrigation resulted in increased future corn yields between 29 to 33%, and 3 to 38% of aggregated C_4 crop yields, with no effect on soybean or aggregated C_3 crop yields. In some regions, biochar applications caused significant yield reductions of 9.5-20% for corn, 5 to 7% for aggregated C_3, and 3 to 5% for aggregated C_4 crops, depending on the model. Yield reductions were ascribed to alterations in plant nutrient availability. It was concluded that under drier weather scenarios, irrigation may be a promising adaptation strategy for agriculture in the Southeastern US.

Keywords: Climate change, Southeastern US, adaptation, mitigation, biochar, irrigation

1. Introduction

Climate change has gained significant international attention due to concerns of negative long-term impacts on agriculture and environmental quality (Chavas et al., 2009). Simulations with global climate models (GCMs) suggest that the projected increase in CO_2 will modify the global climate (IPCC, 2007; IPCC, 2014). Climate change is expected to have direct impacts on a wide range of ecosystems including agriculture. World demand for agricultural products in 2050 is predicted to increase by one third of demands in 2010 (Alexandratos and Bruinsma, 2012). Arable land area in the world will need to be expanded by an additional 70 million ha, in order to meet future needs for agricultural products (FAO, 2002; Alexandratos and Bruinsma, 2012). An apparent benefit of climate change is that under optimum conditions the increased CO_2 concentrations that accompany climate change produces a "fertilization effect" that may increase crop yields, improve water use efficiency, and reduce transpiration (Allen et al., 1998; Makino and Mae, 1999; Maroco et al., 1999; Izaurralde et al., 2003). However, research indicates that this positive crop response will slow as the concentration of CO_2 continues to rise and other resources such as water and nitrogen (N) become limiting (Bowes, 1993; Makino and Mae, 1999). In addition, research that has evaluated the effects of increased CO_2 concentrations on crop growth have shown that the accelerated rate of photosynthesis that accompanies higher CO_2 concentrations leads to reduced nutrient and protein contents in grain and forage crops (Thomson et al., 2005a).

In the past, researchers have used global and national contexts to evaluate the possible changes caused by climate change on agriculture by utilizing GCMs (Parry et al., 1999; Reilly et al., 2003). However, the resolution scale at which national and global scale simulations have been performed are seen as too coarse for detailed analysis of implications of climate change impacts (Gates, 1985; Thomson et al., 2005b). Regional impacts of climate change may not be sufficiently detailed using a resolution of several hundred kilometers that is typical for most GCMs. This lack of resolution becomes troublesome when evaluating climate change impacts at the regional level because GCMs were unable to capture the effects of local forcings, for example complex topography, which modulates the models' climate signal on the regional, sub-regional, and local levels (Rawlins et al., 2012). Climate change simulations using Regional Climate Models (RCMs) is currently and commonly being utilized for large domains such as North America since these RCMs operate at higher scales of resolution (~ 50 km) than GCMs and allows the implications of climate change to be considered on the regional and sub-regional levels. The utilization of RCMs in climate impact studies accounts for topographic complexities and finer-scale atmospheric dynamics due to a higher spatial resolution. The use of several RCMs and GCMs, or multi-RCM-GCMs ensembles in climate change impact studies is important because it helps to quantify various uncertainties associated with different RCM projections (Khaliq et al., 2014). Such coupled multi-RCM-GCM ensembles (further referred to as RCM_GCM models or RCM_GCM pairs in this article) are now available for North America through the North American Regional Climate Change Assessment Program (Mearns et al., 2009; Mearns et al., 2012). Bukovsky (2012) confirmed that RCMs utilized for climate projections over the North American domain that cover US and Canada may be used to reproduce observed trends in temperature. Accurate predictions of climate change-induced temperatures may be relevant to the models ability to credibly simulate anthropogenic climate change under future emission scenarios.

Given the uncertainty regarding the regional distribution of changes in climate, the vulnerability of crop yields to climatic variability is a matter of increasing concern (Luo and Lin, 1999; Reilly and Schimmelpfennig, 1999). If extreme changes in regional climate occur, the current agricultural production in some areas will be vulnerable and adaptations will be necessary. New technologies have been developed and successfully applied to help mitigate the negative impacts of climate change on agriculture. These technologies are broadly categorized into two groups – "adjustments" and "adaptations". Adjustments are easy, low cost strategies which are currently available to reduce the impacts of climate change. Examples include planting a mix of cultivars with different pollination times, changing the timing of field operations to accommodate crops with different maturity classes, and improving the use and efficiency of pesticides to control the higher pest pressures that are anticipated. Adaptations are major changes in practices and in the use of production technologies which aim to ameliorate the impacts of climate change over a long period of time. Examples include developing and using disease-resistant crop species, adopting specific conservation measures for soil moisture to minimize water shortages, as well as changing livestock breeding practices and shifting grazing patterns (United States Environmental Protection Agency, 2015). In addition, adaptations cross the full range of spatial scales from farm-level production to the level of international trade (Easterling, 1996).

In recent years, biochar applications have been viewed by many researchers as a potential long-term regional and/or global climate adaptation/mitigation technique to reduce greenhouse gas (GHG) emissions, improve soil physical properties, sequester soil carbon (C), and increase crop yields (Lehmann, 2007; Joseph et al., 2010; Laird et al., 2010a; Laird et al., 2010b; Major et al., 2010; Roberts et al., 2010; Herath et al., 2013; Lychuk et al., 2014; Lychuk, 2014). Biochar is a by-product of vegetative biomass and/or animal manures that have undergone pyrolysis and may consist of up to 90% recalcitrant C. Kuzyakov et al. (2009) estimated the half-life of biochar under natural soil conditions to be approximately 1400 years. Biochar possesses a number of distinctive beneficial characteristics which include a cation exchange capacity of 40-190 $cmol_c$ kg^{-1}, high porosity in comparison to soil, polyaromatic complex chemistry compounds, and a high surface area with increased reactivity (Lehmann et al., 2006; Atkinson et al., 2010; Laird et al., 2010b). These properties, when acting together, result in biochar attraction for plant micro- and macronutrients, causing increased soil pH, increased soil porosity, and improved water holding capacity.

This article discusses high-resolution regional modeling simulations of future climate change impacts and the effectiveness of proposed adaptation practices (biochar application and irrigation) to alleviate the impacts of climate change on corn (*Zea mays* L.) and soybean (*Glycine max* L.) as well as the aggregated yields of three C_3 [soybean, alfalfa (*Medicago sativa* L.), winter wheat (*Triticum aestivum* L.)] and three C_4 [corn, sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L.)] crops in the Southeastern United States. This modeling study was implemented on representative farms located in Alabama, Arkansas, Missouri, Mississippi, Florida, Kentucky, Louisiana, Texas, Georgia, and Tennessee. The objectives of this study were to (1) compare differences between average historical baseline (1979-2009) and future (2041-2070) predicted yields of corn, soybean, and aggregated yields of the three C_3 and three C_4 crops and (2) compare differences of the future (2041-2070) predicted corn, soybean, and aggregated yields of three C_3 and three C_4 crops between average 5-yr periods within each future climate scenario projected by the four RCM_GCM models, and assess the effects of biochar applications and irrigation on future yields.

2. Materials and Methods

2.1 Description of the simulation model

The Environmental Policy Integrated Climate (EPIC) model (Williams, 1995) was used for simulating impacts of climate change on yields of target crops. The model uses the concept of radiation-use efficiency (RUE) by which a fraction of daily photosynthetically active radiation is intercepted by the crop canopy and converted into crop biomass. In addition to solar radiation, other weather variables, such as temperature, precipitation, relative humidity and wind speed are inputs used for the simulations. The EPIC model can simultaneously model the growth of about 100 plant species including crops, native grasses, and trees; in addition to inter-crop, cover-crop mixtures, and/or similar scenarios can be simulated. Crops can be grown in complex rotations and can include management operations, such as tillage, irrigation, fertilization and liming (Williams, 1995). The model accounts for the effects of tillage practices on surface residue; soil bulk density; mixing of residue and nutrients in the surface layer; water and wind erosion; soil hydrology; soil temperature and heat flow; C, N, and P cycling; the effects of fertilizer and irrigation on growth of many crops; the fate of pesticides; and the economics associated with crop growth and land management. Stockle et al. (1992) modified EPIC to account for the CO_2 fertilization effect on the growth of C_3 and C_4 crops. A comprehensive description of the EPIC model applications and development was presented by Gassman et al. (2005).

The EPIC model has been successfully validated at the global scale with favorable results, as well as in many regions of the world under varying climates, soils, and management environments including China, Argentina, the United States, Italy, Canada, and other countries (Diaz et al., 1997; Costantini et al., 2005; Edmonds and Rosenberg, 2005; Thomson et al., 2006; Apezteguia et al., 2009; Chavas et al., 2009; Lychuk et al., 2017b; Lychuk et al., 2017c). In a previous publication (Lychuk et al., 2014), the original EPIC model was updated with algorithms describing the influence of biochar amendments on crop yields and important soil properties. The EPIC model performance has been verified for predicting the short and long term impacts of using biochar amendments for crop production. This newly updated, biochar-enhanced version of the EPIC model was used in this modeling study.

2.2 Climatic input data and scenario runs

We followed the standard approach to determine the impacts of climate change on crop yields by comparing the results based on historical baseline weather data and future predicted weather influenced by climate change. Historical and scenario-driven approaches were used for designing and conducting simulation runs. Historical weather temperature, precipitation, solar radiation, relative humidity and wind speed data from 1979 to 2009 were obtained from the National Oceanic and Atmospheric Administration's (NOAA) North American Regional Reanalysis (NARR) database (Mesinger et al., 2006). The NARR (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr, accessed in August, 2017) is a long-term, consistent high-resolution climate dataset for the North American domain and is a major improvement in both resolution and accuracy in comparison to the earlier global reanalysis datasets.

Climatic 3-hour-based data for the future scenario runs from 2041 to 2070 were obtained from the North American Regional Climate Change Assessment Program (NARCCAP) for the four RCMs and their driving GCMs. The NARCCAP project provides high resolution future climate scenario data for most of the North America continent using RCMs, coupled GCMs, and time-slice experiments (Mearns, 2007, updated 2012). The NARCCAP project objective was to run each RCM with National Center for Environmental Prediction (NCEP) reanalysis followed by two GCMs under the A2 scenario for the IPCC's Special Report on Emissions Scenarios (SRES) (Mearns et al., 2009; Mearns et al., 2012; Mearns et al., 2013) at a spatial resolution of 50 km. Under the A2 emissions scenario, the heterogeneous growth of global population is envisioned rising to more than 10 billion people by 2050. The projected atmospheric CO_2 concentrations are expected to reach 575 ppmv by the middle of the 21st century and 870 ppmv by its end. The A2 SRES high-emission scenario provides more information from an adaptation and mitigation perspective than a low-emission scenario and it was the primary reason why the A2 scenario was chosen by the NARCCAP group (Sobolowski and Pavelsky, 2012). Please refer to the NARCCAP Web site at http://www.narccap.ucar.edu for a complete description of its various experiments for the past and future climate simulations and http://www.narccap.ucar.edu/data/rcm-characteristics.html for the individual descriptions of the RCMs.

We derived daily means from the archived 3-hour NARCCAP climate data for maximum and minimum temperatures, precipitation, solar radiation, relative humidity, and wind speed for the four RCMs and their driving GCMs. The information about RCMs and their driving GCMs used in this modeling study is given in Table 1. We will refer to the RCM-GCM weather simulations as 'RCM_GCM', where RCM stands for the acronym of the RCM and GCM for the driving boundary conditions of the global climate model. For example, CRCM simulation driven by CGCM3 global climate model will be referred to as CRCM_CGCM3.

The year 2041 was selected as a starting point for future simulations because climate change effects are predicted to cause notable impacts beginning in the late 2030's to the early 2040's (IPCC, 2007; IPCC, 2014). It is important to note that the stochastic weather predicting models used in this simulation study have limitations in that they do not predict the occurrence of extreme events like droughts, days with extremely high (heat peaks) or low temperatures, and occurrence of very intense rainfalls. Instead, these models operate with weather patterns on an average basis, i.e. they envisage the occurrence of droughts and extreme rainfall events, however, the extreme temperatures and precipitation would be averaged and spread across all years of the simulation period.

Simulations using historic weather data were conducted under a CO_2 concentration of 365 ppmv. The future weather simulations were conducted under a CO_2 concentration of 500 ppmv. The adaptation practices evaluated were annual additions of biochar in the amount of 5 Mg ha^{-1} and irrigation occurring prior to plant stress (crop available water deficit in the root zone). Plant available water deficit in the root zone (- 65 mm depth) was used as a parameter to trigger irrigation. Depending on the severity of the plant available water deficit in the root zone, the amount of water applied varied between 25 and 75 mm each time irrigation occurred. The delivery system for the irrigation depended on the irrigation practices established at each representative farm.

The biochar used in the simulations was a traditionally kiln-produced hardwood biochar. Cation exchange capacity (CEC) of the biochar was 187 cmol$_c$ kg^{-1}. Carbon content of the biochar was 72.9%, total N content was 0.76% with the C:N, H:C, and O:C ratios being 120, 0.018 and 0.26, respectively. Ash content of the biochar was 4.6%. The pH (H_2O) and pH (KCL) of the biochar were 9.20 and 7.17, respectively. The biochar was incorporated into the soil with a single pass of a disc harrow to a depth of 5 cm one month prior to planting. The EPIC model was updated with algorithms describing the influence of biochar amendments on crop yields and important soil properties, as specified in Lychuk et al. (2014). For this particular modeling study, the model was initialized with biochar properties and application methods specified above.

For future weather simulations, three RCMs were used that had boundary conditions defined by three GCMs (four RCM_GCM pairs total). These pairs, also referred to as models in this paper, projected different patterns of changes in air temperatures, precipitation, and solar radiation that are expected to occur over time.

The RCM_GCM pairs used in this study were:

- The Canadian Regional Climate Model with the Third Generation Coupled Climate Model (CRCM_CGCM3)
- The Hadley Regional Model with the Hadley Coupled Model version 3 (HRM3_HadCM3)
- The Regional Climate Model Version 3 with the Third Generation Coupled Climate Model (RCM3_CGCM3)
- The Regional Climate Model Version 3 with the Geophysical Fluid Dynamics Laboratory GCM (RCM3_GFDL).

Table 2 summarizes the regional distribution of air temperatures and precipitation under baseline (NARR) conditions and deviations in the future climate scenarios predicted by the four RCM_GCM pairs from the historical baseline.

The representative farms approach, as proposed by Easterling et al. (1993) and Easterling et al. (1992) was used to select typical farms within the Southeastern US with typical farming systems representing homogenous climates, soils, vegetation, and land uses within the study region.

Representative farms were located in Alabama, Arkansas, Missouri, Mississippi, Florida, Kentucky, Louisiana, Texas, Georgia, and Tennessee. The predominant soil mapped at each farm location was used in the simulation. Simulations were performed on farms using typical existing technologies and management practices. Due to its design and model structure, the EPIC model could not account for the effects of micro-topography in the farm fields apart from unified slope, a steepness factor, and the field aspect, however the model did account for the available moisture content, nutrient transport, and other soil processes as a result of timing, the type and intensity of field operations, and crop rotations. Soil types and their properties used in the simulations are shown in Table 3.

Soil databases from the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) Soil Survey Geographic Database were used to input the required soil properties into the EPIC model. Simulations were performed for the upper 150 cm of the soil profile in 10 cm increments. The total number of independent simulations was 1200 (10 farms x 6 crops x 5 scenarios x 2 CO_2 levels x 2 treatments/adaptations). Land management and fertilizer application rates were based on a "no stress" approach to represent potential past and future yields. Up to 200 kg ha^{-1} of N, 50 kg ha^{-1} of P, and the best favorable planting and harvesting days were used for model simulations. Applications of potassium and sulfur fertilizer as well as micronutrients were not included in the simulations. The simulated land area at each farm was 10 hectares. The response variables were corn and soybean yields, as well as the aggregated yields of three C_3 (soybean, alfalfa, winter wheat) and three C_4 (corn, sorghum, pearl millet) crop types.

2.3 Statistical Analysis

The experiment was analyzed as a randomized complete block design with split-plots in time for the baseline vs. future comparisons, and as a randomized complete block design with repeated measures for comparisons between the averaged 5-year periods within each future climate scenario predicted by the RCM_GCM models. Experimental units consisted of 10 farms that were placed into one of three regions that allowed regional comparisons to be made. The farms and groupings were 3 in the South (Florida, Georgia, Alabama), 3 in the West (Texas, Louisiana, Mississippi) and 4 in the North (Arkansas, Missouri, Tennessee, Kentucky). Farms within regions were used as blocks (Izaurralde et al., 2003) within which the main plots were assigned to a 2 x 2 factorial combination of biochar and irrigation. The sub-plot factors were corn or soybean yields and the aggregated yields of C_3 or C_4 crops. For cases involving temporal data on the same experimental units, appropriate repeated-measures analyses were performed. Five different climate scenarios were used for comparisons: one historical baseline scenario (1979 – 2009) and four future climate scenarios (2041 - 2070) projected by the four RCM_GCM models. Periods within each individual future scenario were averaged in 5 year intervals and were treated as repeated measures. Comparisons were made (1) between historical baseline and future scenarios and (2) between the 5 year periods within each of the four future (2041 – 2070) climate scenario defined by the four RCM_GCM models. All statistical analyses were performed using the MIXED Procedure in SAS v. 9.3 (SAS Institute, 2013).

In total, there were five groups of comparisons made in this study:

1. Comparison between past (historical baseline) and future corn and soybean yields under the four future climate scenarios projected by the RCM_GCM models *(Section 3.1).*
2. Comparisons between future corn yields under future climate scenarios projected by the four RCM_GCM models. The future corn yields were compared among the 5-year periods within each future climate scenario predicted by the RCM_GCM models *(Section 3.2).*
3. Comparisons between future soybean yields under future climate scenarios projected by the four RCM_GCM models. The future soybean yields were compared among the 5-year periods within each future climate scenario predicted by the RCM_GCM models *(Section 3.3).*
4. Comparison between past (historical baseline) and future aggregated yields for three C_3 and three C_4 crops under the four future climate scenarios projected by the RCM_GCM models *(Section 3.4).*
5. Comparisons between the future aggregated yields for three C_3 and three C_4 crops under the future climate scenarios projected by the four RCM_GCM models. The future aggregated yields of C_3 and C_4 crops were compared among the 5-year periods within each future climate scenario predicted by the RCM_GCM models *(Section 3.5).*

3. Results

3.1 "Corn – Soybean" Historical Baseline Yield vs. Future Yield Comparison

Future corn yields increased in three of the four climate change scenarios when compared to historical yields. The greatest yield increases were predicted by the CRCM_CGCM3 model (83% increase), followed by a 60% increase under the HRM3_HadCM3 model, and a 36% increase under the RCM3_GFDL model (Tukey HSD test, $P < 0.05$, Table 4). There was a declining trend for future soybean yields under all future climate scenarios simulated by all RCM_GCM models (Table 4).

There were significant region x model interactions for future corn and soybean yields simulated the RCM3_CGCM3 model. The occurrence of interactions required that yield data be analyzed based on each region and model (Fig. 1 and Fig. 2). The future corn yields in the South region were higher by 64% compared to the values under the historical baseline (10.1 Mg ha^{-1} vs. 6.15 Mg ha^{-1}) scenario and by 120% when compared to the values in the West region (13.5 Mg ha^{-1} vs. 6.13 Mg ha^{-1}) (Tukey HSD test, $P < 0.05$). The yield differences were not significant for the North region (Fig. 1).

In the North region, the future soybean yields simulated under the RCM3_CGCM3 model displayed a 23% yield reduction compared to historical values (Fig. 2) (0.78 Mg ha^{-1} vs. 1.01 Mg ha^{-1}) (Tukey HSD test, $P < 0.05$). The future soybean yields were lower than the historical yields in the South region, but the difference was not significant. In the West region, the future soybean yields displayed a 41% increase compared to the historical baseline yields (1.12 Mg ha^{-1} vs. 0.79 Mg ha^{-1}) (Tukey HSD test, $P < 0.05$) (Fig. 2).

3.2 Climate and Adaptation Effects on Future Predicted Corn Yields

Significant region x model interactions were detected for all future climate scenarios predicted by the models. The occurrence of significant interactions required that corn yield data be analyzed based on each region and model. The average corn yield declined in 2066-2070 compared to the yields in 2041-2045 with the reductions ranging between 5% (HRM3_HadCM3 model, West region) to 13% (RCM3_CGCM3 model, West region) (Table 5).

The effects of irrigation on future corn yields were significant in the North (33% increase) and South regions (29% increase) under the future climate projected by the RCM3_CGCM3 and RCM3_GFDL models, and in the South (29% increase) region under the RCM3_GFDL scenario (Table 5). The future corn yields under irrigation in the other regions were not different than yield values grown under no irrigation (Table 5).

There were no effects for biochar on future corn yields in the North region across all future climate scenarios, the West region for the HRM3_HadCM3 and the RCM3_GFDL, and the South region for the RCM3_CGCM3 and the RCM3_GFDL (Table 5). For all the other regions under future climate projected by the remaining RCM_GCM models, there were significant period x biochar interactions. In the South region under the CRCM_CGCM3 model, there was a significant reduction (Tukey HSD test, $P < 0.05$) in corn yields by 9.5% from 12.45 Mg ha^{-1} (2041-2045 5-yr average) to 11.26 Mg ha^{-1} (2066-2070 5-yr average) that was attributed to biochar amendments. In the West region, under the CRCM_CGCM3 climate projection, there was a significant yield reduction (Tukey HSD test, $P < 0.05$) of 12% from 12.54 Mg ha^{-1} (2041-2045 5-yr average) to 11.06 Mg ha^{-1} (2066-2070 5-yr average) attributable to biochar. In the same region, under the RCM3_CGCM3 scenario, there was a significant yield reduction (Tukey HSD test, $P < 0.05$) of 20% from 14.03 Mg ha^{-1} (2041-2045 5-yr average) to 11.16 Mg ha^{-1}

(2066-2070 5-yr average). There were no biochar effects on future corn yields in the South region under the HRM3_HadCM3 model (data not shown).

3.3 Climate and Adaptation Effects on Future Predicted Soybean Yields

Similar to the effects of climate change on future corn yields, there were significant region x model interactions for all the future climate scenarios predicted by the RCM_GCM models. The occurrence of significant interactions required that the soybean yield data be analyzed based on each region and model. The average reductions in 5-yr yields between the beginning (2041-2045) and the end (2066-2070) of future simulation periods ranged between 1 to 13% (Tukey HSD test, $P < 0.05$). For example, under the CRCM_CGCM3 scenario in the North region, the yield reduction was 6% from 1.01 Mg ha^{-1} to 0.95 Mg ha^{-1} and 3% under the HRM3_HadCM3 from 0.91 Mg ha^{-1} to 0.88 Mg ha^{-1}. For the future climate scenario predicted by the RCM3_GFDL model, the reduction in the future soybean yields was 10%, from 0.87 Mg ha^{-1} to 0.78 in the South and 13% from 1.00 Mg ha^{-1} to 0.87 Mg ha^{-1} in the West region. The yield reduction under the RCM3_CGCM3 model in the South region was 8% from 0.96 Mg ha^{-1} to 0.88 Mg ha^{-1}. For the remaining scenarios predicted by the RCM_GCM models for the other regions, the yield reductions were not significant (data now shown). Neither irrigation nor biochar had any effects on the future soybean yields under any scenario across all the regions.

3.4 Aggregated C_3 and C_4 Crop Types: Historical Baseline Yield vs. Future Yield Comparisons

RCM3_CGCM3 (future) vs. NARR (baseline) comparison: There was a significant region x model interaction which required analyzing yield data based on each model (RCM3_CGCM3 and NARR) and region (North, South, and West). The crop type effect was not significant for any of the RCMs. This lack of significance allowed the yields of both crop types to be combined and then the yields between the RCM3_CGCM3 and NARR were compared based on each region. In the *North* region, the differences between the historical (3.74 54 Mg ha^{-1}) and future yields (3.54 Mg ha^{-1}) were not significant. Similarly, in the *South* region, the differences between the historical baseline (4.2 Mg ha^{-1}) and future yields (4.65 Mg ha^{-1}) were not significant. In the *West* region, there was a significant model x crop type interaction. This interaction required a separate analysis for the comparisons of the yields for each model (RCM3_CGCM3 and NARR) and the aggregated yields of each crop type (C_3 and C_4) (Fig. 3). The aggregated yields of the three C_4 crops under the future climate scenario predicted by the RCM3_CGCM3 model were almost doubled compared to the aggregated yields of the three C_4 crops under the historical baseline (8.8 Mg ha^{-1} vs. 4.8 Mg ha^{-1}, an 83% increase (Tukey HSD test, $P < 0.05$) (Fig. 3). There was a slight increase in the future aggregated yields of the three C_3 crops compared to the historical baseline, but the differences were not significant (Fig. 3).

RCM3_GFDL (future) vs. NARR (baseline) comparison: There was a significant model x crop type interaction which required analyzing the yield data based on each model and crop type (Fig. 4). The future aggregated yields of the three C_4 crops increased by 39%, from the historical yields, 5.47 Mg ha^{-1} to 7.64 Mg ha^{-1}, in the future ($P < 0.05$, Tukey HSD test). For the future aggregated C_3 crops, the increases were not significant compared to historical yields (Fig. 4).

CRCM_CGCM3 (future) vs. NARR (baseline) comparison: There was a significant model x crop type interaction which required analyzing the yield data by each model (CRCM_CGCM3 and NARR) and crop type (C_3 and C_4). The aggregated C_4 crop yields increased by 57%, from 5.3 Mg ha^{-1} under the historical climate to 8.3 Mg ha^{-1} under the future climate (Tukey HSD test,

$P < 0.05$). The increase in future aggregated yields compared to the historical yield of C_3 crops was not significant (Fig. 5).

HRM3_HadCM3 (future) vs. NARR (baseline) comparison: There was a significant model x crop type interaction which required analyzing the yield data based on each model (HRM3_HadCM3 and NARR) and crop type (C_3 and C_4). The aggregated C_4 crop yields increased by 41%, from 5.3 Mg ha^{-1} under the historical climate to 7.5 Mg ha^{-1} under the future climate ($P < 0.05$, Tukey HSD test). The differences between the historical and the future aggregated C_3 crop yields were not significant (Fig. 6).

3.5 Climate and Adaptation Effects on Future Aggregated C_3 and C_4 Crop Yields

There were significant region x model and period x crop type interactions for all future climate scenarios. These interactions required the yield data to be analyzed separately for each region, climate change scenario, 5-yr average period, and crop type (Table 6 and Table 7). The future aggregated C_3 crop yields were negatively affected under climate scenarios projected by all RCM_GCM models in all regions, except for the South region under the HRM3_HadCM3, RCM3_CGCM3, and RCM3_GFDL models and in the North region under the future climate predicted by the CRCM_CGCM3 model (Tukey HSD test, $P < 0.05$). The yield reductions ranged between 10% (in the North region under the HRM3_HadCM3 model) to 22% (in the North region under the RCM3_CGCM3 model) (Table 6) for comparisons between 2041-2045 and 2066-2070 5-yr average yields, respectively (Tukey HSD test, $P < 0.05$).

The reductions in the future aggregated C_4 crop yields varied between 6% in the West region under the future climate scenario predicted by the CRCM_CGCM3 model to 10% in the West region under the RCM3_CGCM3 model (Tukey HSD test, $P < 0.05$) (Table 7), when 2041-2045 and 2066-2070 5-yr average yields were compared. The reductions were also significant in the South and West regions for the CRCM_CGCM3 and the RCM3_CGCM3 models, and in the North region for the HRM3_HadCM3 model. In all other regions under all other future climate scenarios, there was a non-significant declining yield trend. Compared to the C_3 crops, the future aggregated yields of C_4 crops showed less reduction in projected yields as climate change progressed toward the final (2066-2070) 5-yr simulation period. This smaller reduction was obvious in (1) the magnitude of the reduction (10 to 22% reductions for C_3 vs. 6 to 10% reductions for C_4 crops), and in (2) the number of times the future yield reductions were found significant (8 times for aggregated C_3 crops and 5 times for aggregated C_4 crops) (Tables 6 and 7).

There were significant region x irrigation and model x crop type interactions detected. There was a positive response of future aggregated C_3 crop yields to irrigation, but the differences were not significant compared to the no irrigation treatment (Table 6). The future aggregated yields of the C_4 crops were greater under the irrigation treatment compared to the no irrigation treatment in almost all regions under all future climate scenarios (Tukey HSD test, $P < 0.05$) (Table 7). The yield increases ranged between 3% in the South region under the HRM3_HadCM model to 22% in the South region under the RCM3_CGCM3 and RCM3_GFDL models, and to 38% in the North region under the RCM3_CGCM3 model (Tukey HSD test, $P < 0.05$).

There were significant region x biochar and model x crop type interactions. Contrary to our expectations, the biochar applications negatively affected future yields. For the C_3 crops, the yield reductions due to biochar treatments varied between 5 to 7%, depending on the region and the model (Table 6). For the C_4 crops, the yield reductions varied between 3 to 5% (Table 7). For all other regions and models, there was a declining yield trend after biochar applications, but the differences were not significant (Tables 6 and 7).

4. Discussion

The four future climate scenarios predicted by the RCM_GCM models displayed a wide range of differences in maximum and minimum air temperatures and precipitation in the regions of interest. Generally, the CRCM_CGCM3 and HRM3_HadCM3 models predicted increased maximum daily air temperatures, while the RCM3_CGCM3 and the RCM3_GFDL models predicted decreased values. All scenarios except for the HRM3_HadCM3 model predicted decreased minimum daily air temperatures. In some individual states that comprised the North, West, or South regions, there was an increase in the future maximum daily temperature up to 3.3°C, depending on the RCM_GCM model. In some states, reductions in the future precipitation quantities compared to the historical values ranged between 8 to 28%. However, the average future precipitation throughout the Southeastern US was projected to increase by 3%, 10%, and 4% under the HRM3_HadCM3, RCM3_CGCM3, and RCM3_GFDL models, respectively, and to be reduced by 8% under the CRCM_CGCM3 model. We speculate that it is the average increase in the future precipitation which explained a weaker than expected crop response to irrigation under the future climate scenarios predicted by some of the models.

4.1 Corn

The future corn yields were initially predicted to increase when compared to yields under the historical baseline scenario. Our findings on increased future corn yields were similar to results reported by Hatch et al. (1999) who showed increased future corn yields simulated with the DSSAT model by as much as 27% in 2090 compared to a 1975 – 1995 historical baseline in

Georgia under the Hadley Center Model. Our findings were also in agreement with results reported by the Izaurralde et al. (2003), who simulated effects of climate change on corn yields in the United States using the Hadley Center Model. Depending on the sub-region, they found up to a 10% increase in future corn yields in the Southeastern US. However, as climate change progressed into the future, the corn yields decreased. In our study, the decreased future corn yields by the end of the 2066-2070 simulation period were primarily associated with an increased number of days with temperature stress due to increased daily maximum and minimum temperatures (Table 2). This temperature stress explained future corn yield declines in the North region under the future climate simulated by the CRCM_CGCM3, RCM3_CGCM3, and HRM3_HadCM3 models, and in the West region by the HRM3_HadCM3 model. The combination of temperature or moisture stress (deficit or excess) was the reason behind the yield reductions in the South region predicted by the RCM3_CGCM3 and RCM3_GFDL models, and in the North region by the RCM3_CGCM3 model (Table 2 and Table 5). These results were in agreement with Tsvetsinskaya et al. (2003) who investigated the regional impacts of climate change on corn yields in the Southeastern US. They reported projected reductions in corn yields ranging between 0 to 34%, depending on the scenario and the sub-region within the Southeastern US. Similarly, Easterling et al. (2003) found 10 to 30% corn yield reductions in the Southeastern US when no adaptations were taken to alleviate climate change impacts. We ascribed weaker than expected response to irrigation in corn due to the weakness in predicting extreme events like droughts, days with extreme heat temperatures (heat peaks), and very intense rainfalls by the RCM_GCM models. These models are stochastic in nature and they operate with weather patterns on an average basis. In addition, three of the four future climate scenarios predicted general increases in average annual precipitation rates (Table 2) for the 10 states covered in this study. This increased precipitation may also help explain the lack of a statistically significant uniform positive response to irrigation. Reductions in the future corn yields as a result of biochar applications were ascribed to alterations in pH levels and availability of soil nutrients such as Ca and Mg, and the availability of micronutrients such as B and Mo, which are important elements for biological N fixation. It should be noted that this modeling study utilized biochar with a C:N ratio of 120, thus the annual biochar applications may have resulted in decreased plant N availability due to N immobilization.

4.2 Soybean

The declining trends in the future soybean yields compared to the historical baseline reported in this study were in agreement with Izaurralde et al. (2003), who found that future climate change in the Southeastern US would result in decreased yields and Paudel and Hatch (2012), who reported reductions in soybean yields under the future climate simulated by the Hadley Center HadCM2 model. The temperature stress due to the increased future maximum and minimum temperatures was thought to be a primary reason for the declined future soybean yields, as soybeans are well known for their low tolerance to high temperatures. For example, as the future climate progressed towards the end of the simulation period (2066-2070), soybean grown in the North region under the future climates simulated by the CRCM_CGCM3 and HRM3_HadCM3 scenarios decreased due to increased daily maximum and minimum temperatures (Table 2). Deficit or excess moisture stress was also a factor for some regions and models. The excess moisture stress was due to as much as 57% increased future precipitation and was the primary reason for the declined soybean yields in some states within the South region predicted by the RCM3_CGCM3 and RCM3_GFDL models (Table 2). In our modeling study, the lack of irrigation effects on soybean was attributed to the increased average annual precipitation rate across the 10 states in this study. The increase in available moisture created soil conditions such that the soybean crops were not subjected to water stress, and irrigation was not required.

4.3 Aggregated Yields of C_3 and C_4 Crops

The average increase between future and historical aggregated C_4 crop yields varied between 39 to 83%, depending on the region and model. There was a numerical, but not statistically significant increase in the future aggregated C_3 crop yields compared to the historical baseline. As climate change progressed, both crop types were negatively affected and future yields were reduced. However, compared to the C_3 crops, the future aggregated yields of C_4 crops showed less reduction in projected yields towards the final 5-yr simulation period (2066-2070). Even though both crop types were negatively affected by progressing climate change, we concluded that generally C_4 crops are better adapted to stresses associated with climate change in comparison to C_3 crops due to: (1) better deficit moisture tolerance that was attributable to improved water use efficiency; (2) better assimilation of available moisture due to higher seasonal mean crop growth rates in C_4 compared to C_3 crops, and the C_4 crops increased moisture demands during the growth of larger biomass quantities; (3) better heat stress tolerance of C_4 crops compared to C_3 crops and (4) a lesser degree of photorespiration in C_4 compared to C_3 crops under conditions of high light intensities, increased atmospheric CO_2, and increased temperatures.

Our findings were in agreement with Vogan and Sage (2011) who concluded there was approximately 1.5 to 4 times greater photosynthetic water-use efficiency in C_4 compared to C_3 crops. In addition, Monteith (1978) compared the length of the growing season and the standing dry weight between a group of C_4 (bulrush millet, corn, sorghum, and sugar cane) and C_3 crops (kale, potatoes, sugar beet, rice, cassava, and oil palm). They reported the mean seasonal crop growth rate for the C_4 group was 22 ± 3.6 g m^{-2} d^{-1} and 13 ± 1.6 g m^{-2} d^{-1} for the C_3 group. Finally, Schmitt and Edwards (1981) found that at 30°C, corn (C_4 crop) had a higher rate of CO_2 assimilation and soluble protein contents than either rice or wheat (C_3 crops).

The yield reductions in C_3 crops were primarily associated with temperature stress due to the increased daily maximum air temperatures and reductions in future precipitation rates, which was in agreement with research on the effects of temperature and precipitation on long-term yields (Lychuk et al., 2017a; Lychuk et al., 2017b). For example, in the states comprising the North region, the projected increases in the future mean annual daily temperatures were almost 2°C under the RCM3_CGCM3 model, 2.6°C in the states comprising the West region under the HRM3_HadCM3 model, and 3.3°C in the states comprising the West region under the CRCM_CGCM3 model (Table 2). In individual states comprising North, West, or South regions, the reductions in future precipitation rates ranged between 8 to 28% compared to the historical values.

No statistically significant differences were detected on future aggregated C_3 crop yields in response to the irrigation treatment. However, the future aggregated yields of the C_4 crops were found to be significantly greater under the irrigation treatment in almost all regions under all future climate conditions, with yield increases ranging between 3 to 38% depending on the region and model. We ascribed the positive responses to irrigation in C_4 crops used in this study due to their increased moisture demand for greater biomass development (especially corn) and greater mean growth rates compared to C_3 crops.

Contrary to our expectations, in some regions the biochar applications resulted in significant decreases of the future aggregated yields in both crop types and varied between 5 to 7% for the

C_3 and 3 to 5% for the C_4 crops, depending on the model. The declines in future yields were ascribed to N immobilization and the expected reductions in plant N availability due to the high C:N biochar ratio used in this modeling study. Another possible reason for yield reductions is alteration in the rates and timing of seed germination, which would influence plant emergence and growth and yield due to the timing of precipitation and accumulation of thermal heat units, as a result of biochar application (Spokas et al., 2012). Further research is needed to simulate the effects of other types of biochar made from different types of feedstock materials on C_3 and C_4 crop yields in the Southeastern US under future climate projections.

5. Conclusions

The results of this study demonstrated that climate change is expected to affect the regions of the Southeastern US differently. Compared to the historical baseline scenario, the increased future corn yields ranged between 36 to 83%, but the future yields decreased by 5-13% towards 2066-2070 due to temperature stress. The future soybean yields decreased by 1-13% due to temperature and moisture stresses. The future aggregated C_4 crops produced higher yields compared to the historical C_4 yields. There were no differences between future aggregated and historical C_3 crop yields. Both crop types were negatively affected by progressing climate changes towards the end of the 2066-2070 simulation period. The reductions in the future aggregated C_3 crop yields ranged between 10 to 22%, and between 6 to 10% for C_4 crops. We attributed the lower yield reductions in C_4 compared to C_3 crops due to a lesser degree of photorespiration, better water use efficiency, and better heat tolerance under the conditions of high light intensities and increased temperatures in C_4 crops. The annual biochar applications were not effective in increasing corn, soybean or aggregated yields of C_3 and C_4 crop types, and under some future climate scenarios caused significant yield reductions. There were indications that irrigation may be an effective adaptation technique for alleviating climate change effects on the yields of corn and C_4 crops in the Southeastern US, with a mixed signal regarding the effects of irrigation on the yields of future soybean and C_3 crops. The effects of irrigation will be more or less pronounced depending on the region and the future climate scenario. Further research is needed to identify other adaptation practices for agriculture in the Southeastern US and quantify their effectiveness on alleviating climate change impacts on future crop yields in the region.

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Fig. 1 Corn yields for the North (N), South (S), and West (W) regions under the 1979 – 2009 NARR historical baseline and the future yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Fig. 2 Soybean yields for the North (N), South (S), and West (W) regions under the 1979 – 2009 NARR historical baseline and the future yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Fig. 3 Aggregated yields in the West region for the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Fig. 4 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Regional Climate Model Version 3 with the Geophysical Fluid Dynamics Laboratory Global Climate (RCM3_GFDL) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Fig. 5 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Canadian Regional Climate Model with the Third Generation Coupled Climate Model (CRCM_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Fig. 6 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Hadley Regional Model with the Hadley Coupled Model version 3 (HRM3_HadCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

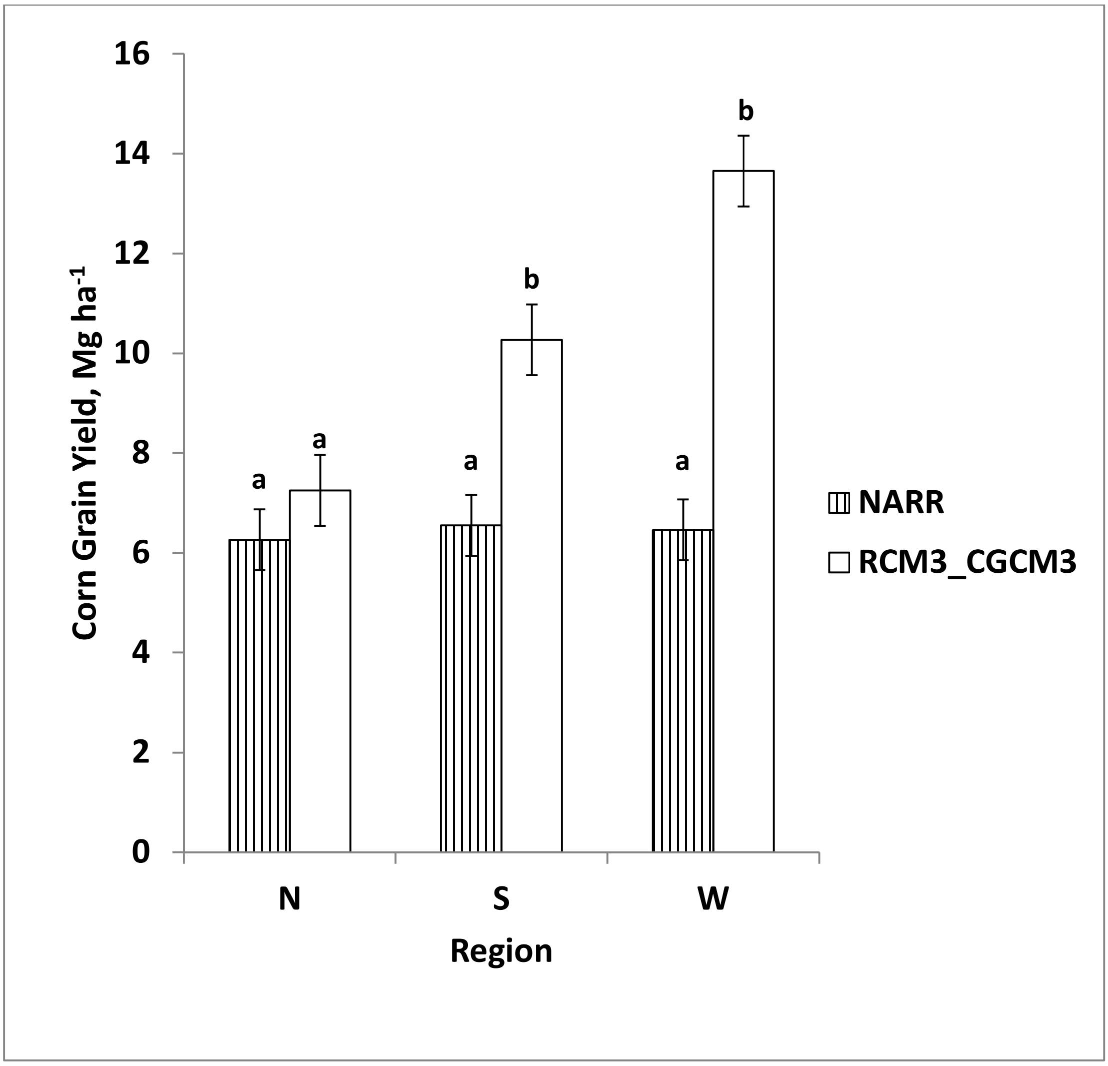

Fig. 1 Corn yields for the North (N), South (S), and West (W) regions under the 1979 – 2009 NARR historical baseline and the future yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

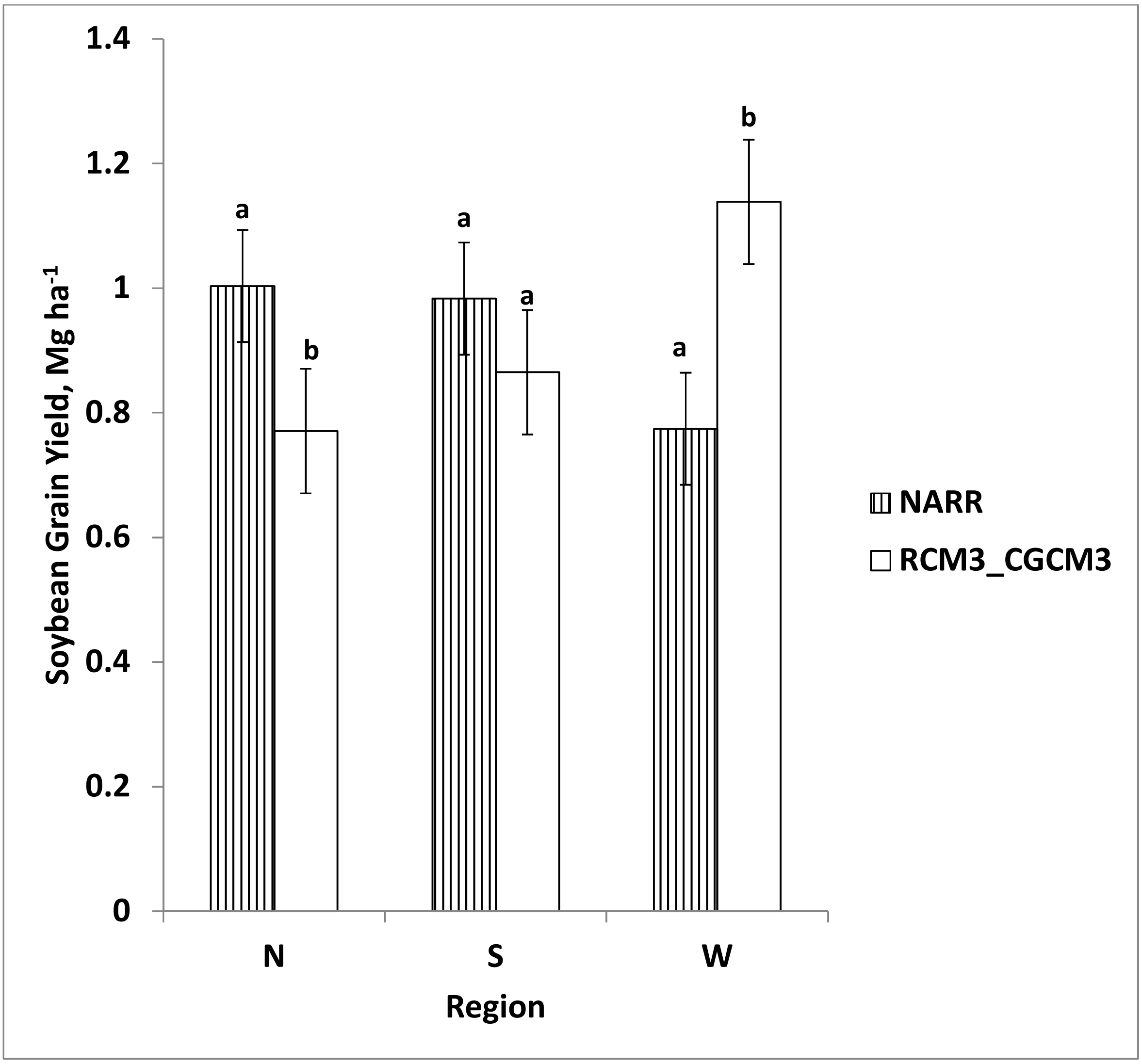

Fig. 2 Soybean yields for the North (N), South (S), and West (W) regions under the 1979 – 2009 NARR historical baseline and the future yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

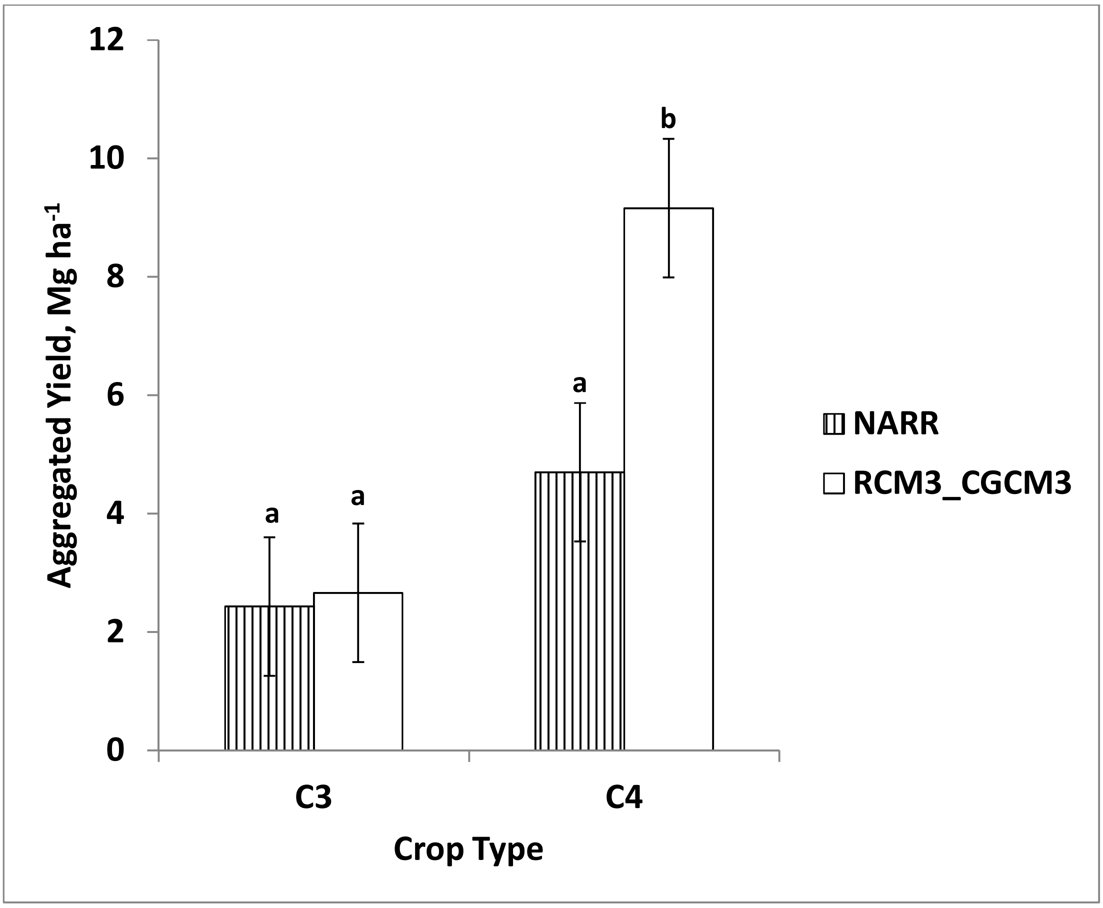

Fig. 3 Aggregated yields in the West region for the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Regional Climate Model Version 3 with the Third Generation Coupled Climate (RCM3_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

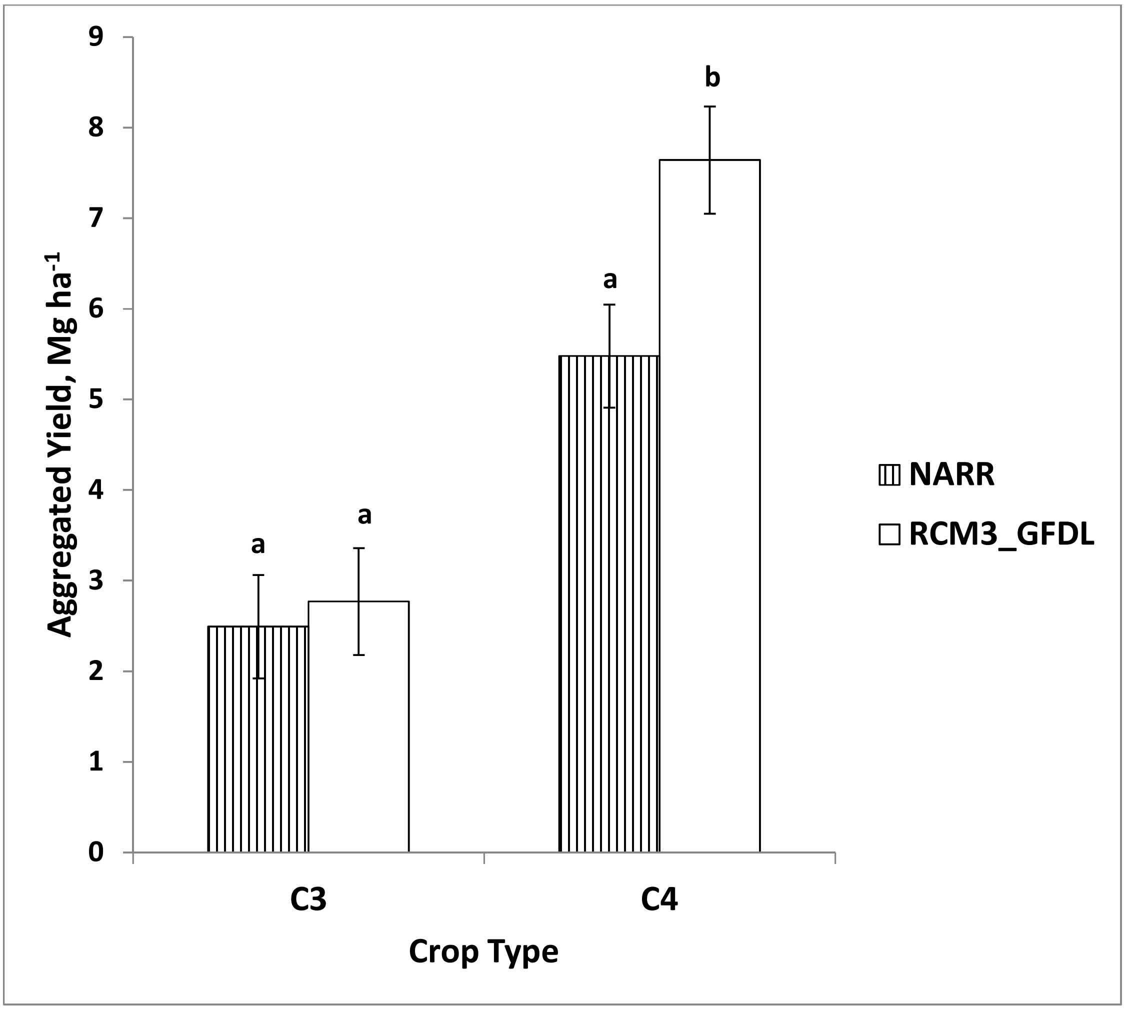

Fig. 4 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Regional Climate Model Version 3 with the Geophysical Fluid Dynamics Laboratory Global Climate (RCM3_GFDL) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

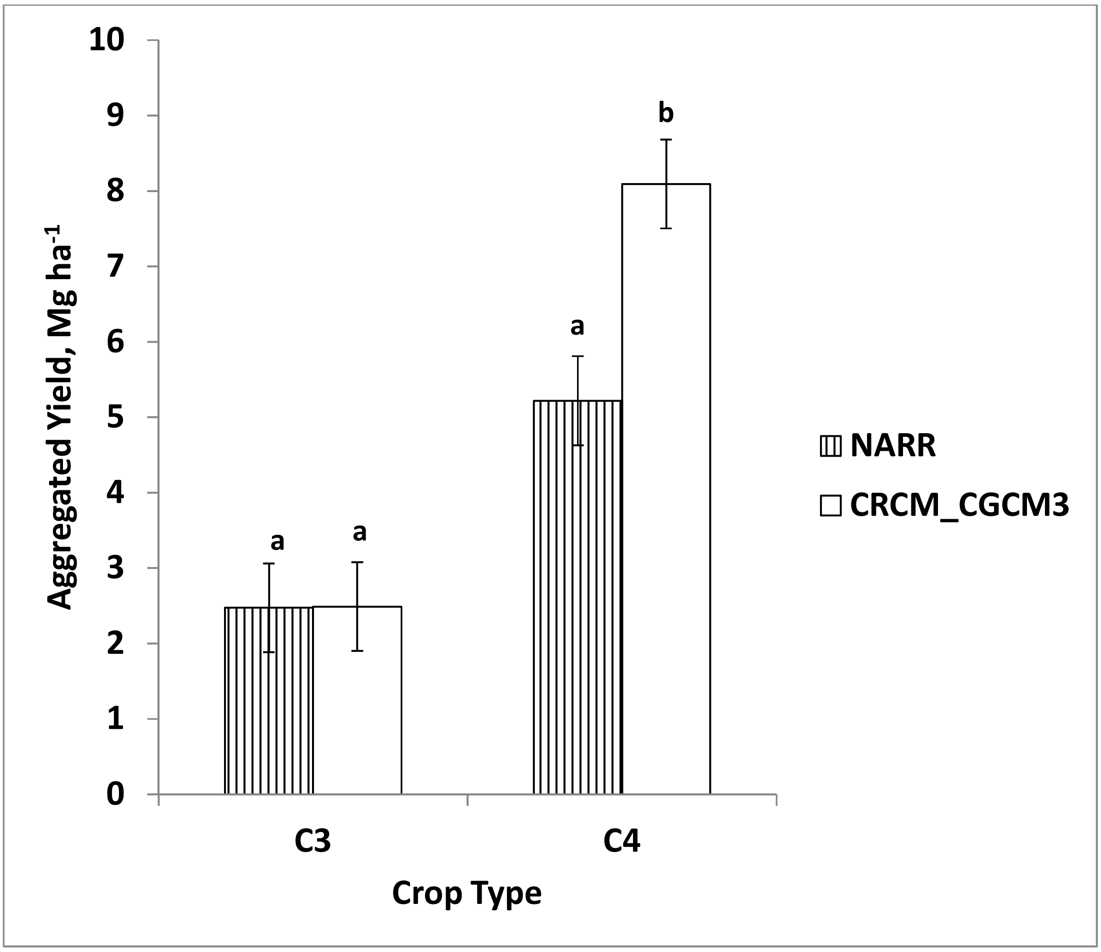

Fig. 5 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and future aggregated yields under the Canadian Regional Climate Model with the Third Generation Coupled Climate Model (CRCM_CGCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

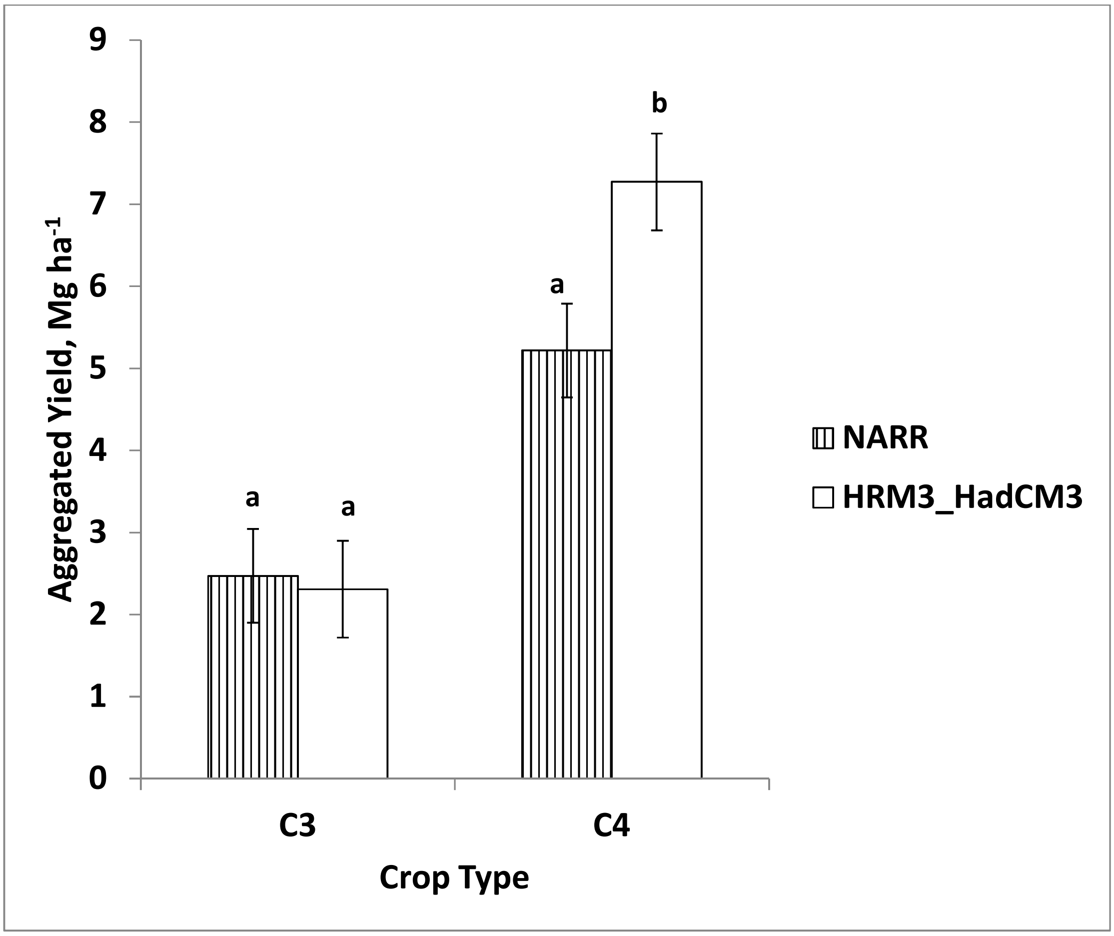

Fig. 6 Aggregated yields of the C_3 and C_4 crops under the 1979 – 2009 NARR historical baseline and the future aggregated yields under the Hadley Regional Model with the Hadley Coupled Model version 3 (HRM3_HadCM3) model. Letters indicate Tukey HSD mean differences at $P < 0.05$. Error bars represent standard error of the mean.

Table 1. Information about NARCCAP Regional Climate Models (RCMs) and their driving Global Climate Models (GCMs) set as boundary conditions used in this study† (adapted from Khaliq *et al.* (2014) Monette *et al.* (2012) Mailhot *et al.* (2012).

RCM	Driving GCM	Acronym of GCM driven RCM simulation	Simulation period
Canadian Regional Climate Model: CRCM	Canadian Global Climate Model, version 3: CGCM3	CRCM_CGCM3	2041-2070
Hadley Regional Climate Model: HRM3	Hadley Centre Climate Model, version 3: HadCM3	HRM3_HadCM3	2041-2070
Regional Climate Model 3: RCM3	Geophysical Fluid Dynamics Laboratory Model: GFDL	RCM3_GFDL	2041-2070
	CGCM3	RCM3_CGCM3	2041-2070

† Historical weather data from 1979 to 2009 were obtained from National Oceanic and Atmospheric Administration's (NOAA North America Regional Reanalysis (NARR) database. Source: (Mesinger, 2004)

Table 2. Regional distribution of air temperatures and precipitation under the historical baseline North America Regional Reanalysis (NARR, 1979 - 2009) conditions and the deviations from the baseline predicted by the pairs of four regional climate models (RCMs) and their boundary conditions defined by the Global Climate Models (GCMs) over the future 30-year simulation period (2041 – 2070). Models are listed in Table 1.

Model	Representative farms in									
	AL	AR	FL	GA	KY	LA	MS	MO	TN	TX
Maximum daily air temperature (°C)										
NARR	20.5	20.8	24.5	23.6	17.2	24.1	22.7	16.7	20.1	25.1
CRCM_CGCM3	2.3	3.3	1.6	1.9	2.4	2.6	3.3	3.2	3.0	2.6
HRM3_HadCM3	0.2	2.6	1.0	1.4	2.9	2.2	2.6	4.1	3.1	1.8
RCM3_CGCM3	0.5	0.4	-1.6	-1.4	0.4	-0.9	-0.3	1.7	0.7	-1.2
RCM3_GFDL	-1.1	-1.4	-2.7	-2.7	-1.3	-2.0	-1.7	-0.5	-0.9	-3.6
Minimum daily air temperature (°C)										
NARR	12.2	11.7	16.1	14.8	9.2	15.5	13.6	8.03	11.4	15.1
CRCM_CGCM3	-1.5	-0.5	-1.6	-1.1	-1.0	-0.1	-0.4	-0.1	-0.5	-2.0
HRM3_HadCM3	-1.3	1.96	0.2	0.6	0.9	1.5	1.8	2.9	2.1	1.5
RCM3_CGCM3	-1.0	-0.8	-2.1	-1.2	-1.1	-1.2	-1.1	0.1	-0.6	-2.2
RCM3_GFDL	-2.7	-2.2	-3.1	-2.4	-2.9	-2.5	-2.2	-1.8	-2.1	-3.8
Precipitation (mm)										
NARR	1328	1202	992	1220	1217	1503	1311	953	1281	853
CRCM_CGCM3	-87	-80	107	-141	211	-432	-199	-15	-66	-194
HRM3_HadCM3	51	69	262	67	254	-360	-59	97	-7	4
RCM3_CGCM3	42	68	631	265	126	-186	-99	232	40	25
RCM3_GFDL	-48	-28	494	204	105	-188	-157	81	-60	101

Table 3. Soil types and their properties used in the Environmental Policy Integrated Climate model simulations.

Representative farms in the Southeastern US states:	Soil type	Organic carbon content, %	Bulk density, g cm^{-3}	CEC, $cmol_c$ kg^{-1}	pH
Alabama	Fine, kaolinitic, thermic, rhodic paleudult	0.75	1.37	2.7	5.5
Arkansas	Fine-silty, mixed, active, thermic typic endoaqualfs	0.93	1.35	10.1	5.9
Florida	Fine-loamy, kaolinitic, thermic typic kandiudults	0.69	1.39	4.0	5.6
Georgia	Fine-loamy, kaolinitic, thermic plinthic kandiudults	1.1	1.38	3.5	5.4
Kentucky	Fine-silty, mixed, active, thermic ultic hapludalfs	1.3	1.31	2.9	6.1
Louisiana	Fine, smectitic, thermic typic albaqualfs	1.6	1.40	8.3	6.0
Mississippi	Fine, smectitic, thermic typic endoaqualfs	1.5	1.37	9.9	5.8
Missouri	Fine, smectitic, mesic aquertic argiudolls	3.6	1.29	19.4	6.6
Tennessee	Fine-silty, mixed, active, thermic ultic hapludalfs	1.2	1.35	9.4	5.9
Texas	Fine, smectitic, thermic udertic paleustalfs	1.0	1.30	8.9	6.1

Table 4. Comparisons between the predicted corn and soybean yields under the historical baseline and the future climate scenarios predicted by the regional climate models (RCMs). Models are listed in Table 1. Letters within the same column indicate Tukey HSD mean differences at $P < 0.05$

Model	Crop Yield (Mg ha^{-1})	
	Corn	Soybean
NARR (baseline)	6.43a	0.92a
CRCM_CGCM3	11.78b	0.96a
HRM3_HadCM3	10.31b	0.84a
RCM3_GFDL	8.77b	0.82a

Table 5. Climate and adaptation effects on the predicted corn yields (Mg ha^{-1}) under the four future climate scenarios predicted by the regional climate models (RCMs). Models are listed in Table 1. Letters within the same column for each effect indicate Tukey HSD mean differences at $P < 0.05$.

Effect		Model											
		CRCM_CGCM3			HRM3_HadCM3			RCM3_CGCM3			RCM3_GFDL		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Period (years)	2041-2045	11.14a	12.44a	12.73a	10.73a	11.49a	9.76a	8.53b	11.84a	14.02a	8.36abc	11.26ab	11.07a
	2046-2050	10.9ab	12.11ab	12.56ab	10.33ab	11.26a	9.12b	9.07a	11.22b	13.81a	7.91bc	10.72bc	9.24cd
	2051-2055	10.31cd	12.11ab	12.54ab	10.33ab	11.53a	9.72a	7.82c	11.3b	13.73a	8.4ab	11.6a	10.28b
	2056-2060	10.15cd	11.94ab	12.40ab	10.2b	11.33a	9.92a	8.38b	10.51c	13.43ab	8.45ab	11.25ab	9.3cd
	2061-2065	10.48bc	11.72ab	12.06ab	10.4ab	10.74a	8.72c	8.46b	10.98bc	12.83ab	8.66a	10.58cd	8.74d
	2066-2070	9.82d	11.63b	11.85b	9.59c	10.96a	9.25b	7.89c	11.05b	12.16b	7.78c	10.1d	9.74bc
Irriga-tion	No	10.19a	11.9a	12.3a	10.24a	11.4a	9.09a	7.17a	10.14a	13.3a	7.65a	9.96a	8.41a
	Yes	10.74a	12.0a	12.4a	10.29a	11.0a	9.74a	9.55b	13.16b	13.3a	8.87a	12.88b	11.05a
Bio-char	No	10.79a	-	-	10.52a	-	9.49a	8.50a	11.4a	-	8.37a	11.04a	9.88a
	Yes	10.14a	-	-	10.01a	-	9.34a	8.22a	10.9a	-	8.15a	10.8a	9.57a

Table 6. Climate and adaptation effects on the future aggregated C_3 crop yields (soybean, alfalfa, winter wheat) (Mg ha^{-1}) under the four future climate scenarios predicted by the regional climate models (RCMs). Models are listed in Table 1. Letters within the same column for each effect indicate Tukey HSD mean differences at $P < 0.05$

Effect		Model											
		CRCM_CGCM3			HRM3_HadCM3			RCM3_CGCM3			RCM3_GFDL		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Period (years)	2041-2045	2.33ab	2.59ab	2.74a	2.20ab	2.35a	2.60a	2.59a	2.73a	2.80a	2.29a	2.67a	2.93a
	2046-2050	2.41a	2.60a	2.76a	2.21a	2.36a	2.63a	2.49a	2.73a	2.79a	2.26ab	2.58a	2.86a
	2051-2055	2.31ab	2.46abc	2.74a	2.14abc	2.33a	2.57a	2.39ab	2.58a	2.74a	2.22ab	2.46a	2.76ab
	2056-2060	2.27ab	2.38abc	2.59ab	2.12abc	2.21a	2.46ab	2.33abc	2.41a	2.57ab	2.15ab	2.35a	2.76ab
	2061-2065	2.16ab	2.26bc	2.37bc	2.01bc	2.11a	2.28bc	2.18bc	2.29a	2.41bc	2.15ab	2.32a	2.51bc
	2066-2070	2.12b	2.25c	2.29c	1.98c	2.15a	2.16b	2.02c	2.33a	2.29c	1.96b	2.33a	2.41c
Irrigation	No	2.27a	2.43a	2.59a	2.10a	2.25a	2.45a	2.33a	2.50a	2.61a	2.24a	2.43a	2.69a
	Yes	2.26a	2.43a	2.58a	2.11a	2.25a	2.46a	2.35a	2.52a	2.59a	2.12a	2.47a	2.72a
Biochar	No	2.33a	2.50a	2.63a	2.15a	2.30a	2.49a	2.42a	2.56a	2.66a	2.25a	2.50a	2.76a
	Yes	2.20b	2.35b	2.54a	2.07a	2.22a	2.41a	2.25b	2.47a	2.53b	2.09b	2.41a	2.64b

Table 7. Climate and adaptation effects on the future aggregated C_4 crop yields (corn, sorghum, pearl millet) (Mg ha^{-1}) under the four future climate scenarios predicted by the regional climate models (RCMs). Models are listed in Table 1. Letters within the same column for each effect indicate Tukey HSD mean differences at $P < 0.05$

Effect		Model											
		CRCM_CGCM3			HRM3_HadCM3			RCM3_CGCM3			RCM3_GFDL		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Period (years)	2041-2045	7.47a	8.62a	8.71a	7.41a	8.23a	6.96a	5.57a	7.89a	9.37a	5.26a	7.35a	7.41a
	2046-2050	7.42a	8.47ab	8.68a	7.24ab	8.15a	6.50a	5.96a	7.44ab	9.33a	5.11a	7.08a	6.25a
	2051-2055	6.96a	8.36ab	8.79a	7.18ab	8.20a	6.94a	5.21a	7.60ab	9.14a	5.34a	7.60a	6.82a
	2056-2060	6.82a	8.16ab	8.75a	6.95ab	7.98a	7.11a	5.50a	7.05ab	8.89ab	5.27a	7.29a	6.26a
	2061-2065	7.21a	8.21b	8.43ab	7.31ab	7.82a	6.30a	5.68a	7.56ab	8.86ab	5.68a	7.14a	5.95a
	2066-2070	6.65a	8.12b	8.21b	6.71b	7.83a	6.58a	5.31a	7.27b	8.41b	5.03a	6.77a	6.68a
Irrigation	No	6.89a	8.32a	8.56a	7.11a	7.91a	6.49a	4.64a	6.71a	9.01a	4.93a	6.49a	5.57a
	Yes	7.29b	8.33a	8.62a	7.16a	8.17b	6.97b	6.43b	8.23b	8.99a	5.63b	7.92b	7.55b
Biochar	No	7.27a	8.47a	8.72a	7.27a	8.16a	6.77a	5.61a	7.58a	9.16a	5.34a	7.27a	6.63a
	Yes	6.91b	8.18b	8.47b	7.01b	7.91b	6.69a	5.46a	7.35a	8.84b	5.22a	7.14a	6.49a