ABSTRACT

Title of Document:	EVALUATION OF BIOCHAR APPLICATIONS AND IRRIGATION AS CLIMATE CHANGE ADAPTATION OPTIONS FOR AGRICULTURAL SYSTEMS
	Taras Lychuk, Doctor of Philosophy, 2014
Directed By:	Professor Robert L. Hill, Department of Environmental Science and Technology Professor Roberto C. Izaurralde, Department of Geographical Sciences

The Environmental Policy Integrated Climate (EPIC) model was updated with algorithms to determine the effects of biochar applications on crop yields and selected soil properties. EPIC was validated using the results of a 4-yr field experiment performed on an Amazonian Oxisol amended with biochar. Simulations were conducted for 20-yr into the future and predicted increased values of soil cation exchange capacity, pH, soil C content, and decreased soil bulk density values after biochar applications. EPIC was then used to evaluate climate change impacts and effectiveness of annual biochar applications and irrigation as adaptation options on yields of C_3 and C_4 crops from representative farms in 10 Southeastern US states. Simulations were conducted for 1979- 2009 historical baseline climate data and 2038-2068 time periods using four regional climate models (RCM). Future corn (*Zea mays* L.) yields initially increased, but corn and soybean (*Glycine max* L.) yields had decreased by 2068. Future C_4 crops generally produced higher yields compared to the historical yields of C_4 crops. Historical baseline yields of C_3 crops and future C_3 crop yields were not significantly different. Biochar amendments had no effects on yields and in some cases resulted in significant yield decreases. Irrigation caused increases in corn yields, but not for soybean yields. Irrigation did result in increased C_3 and C_4 crop yields for some farms that were typically in drier areas. Further EPIC simulations were conducted to estimate the effects of climate change impacts and adaptations on microbial respiration, soil C content, and nitrate losses in runoff and leachate. Microbial respiration was higher under C_4 crops than under C_3 crops. Biochar amendments increased microbial respiration, although the relative relationship of $C_4 > C_3$ microbial respiration was maintained. Nitrate losses were significantly higher in the future and followed a $C_3 > C_4$ pattern. The greatest nitrate losses were observed under C_3 crops with even greater losses due to irrigation. Biochar amendments resulted in reduced losses for nitrate in leachate, but not in runoff. C sequestration increased under C_4 crops and biochar applications. Under some RCM weather scenarios, biochar applications and irrigation are promising adaptation strategies for agriculture in the Southeastern US.

EVALUATION OF BIOCHAR APPLICATIONS AND IRRIGATION AS CLIMATE CHANGE ADAPTATION OPTIONS FOR AGRICULTURAL SYSTEMS

By

Taras Lychuk

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2014

Advisory Committee:
Professor Robert L. Hill, Chair
Professor Roberto C. Izaurralde
Professor Robert J. Kratochvil
Professor Adel Shirmohammadi
Professor Richard A Weismiller

Dedication

I would like to dedicate my doctoral studies and dissertation to my Lord and Savior, Jesus Christ; my grandmother, Zoya; my wife, Olha Kushnir, and my daughter, Marie Lychuk; my beloved parents, Yevheniya and Yevheniy Lychuk and Vladimir Danyushin; my mother-in-law, Tetiana Kushnir; Robert and Anne Hill; and the Stanton, Lindemann, Ingalls, and Harris families. Without the help and support of these individuals and families, the completion of my doctoral studies and dissertation would not have been possible.

Acknowledgements

I would like to recognize and thank the following organizations and individuals for their assistance over the past 5 years.

I would like to acknowledge the Fulbright Commission, the Department of Environmental Science and Technology, the Joint Global Change Research Institute (JGCRI)/Pacific Northwest National Laboratory (PNNL), and the Department of Energy (DOE) Office of Science for providing financial support for this investigation.

I am extremely grateful for the guidance, encouragement, patience, knowledge, sharing and countless hours of advising from Dr. Robert L. Hill, who served as doctoral advisor on my Ph.D. program. I am very grateful for the guidance, patience and support from my co-advisor Dr. Roberto Cesar Izaurralde who introduced me to the EPIC model and the world of modeling. I am also grateful for the advice and guidance of my committee members: Dr. Robert J. Kratochvil, Dr. Adel Shirmohammadi, and Dr. Richard A. Weismiller. I especially would like to thank ENST professor Dr. Bahram Momen for his invaluable help with the statistical analyses of this research.

I would like to express my appreciation for the help of individuals from PNNL in regards to this project. I would like to thankfully acknowledge Dr. James Amonette and Allison Thomson for internal review of my manuscripts and for sharing their expertise with me. I would like to thank Meredydd Evans for the resources and opportunities she provided during difficult phases of this project. I am thankful for the technical assistance from Dr. Prasad Bandaru, Ritvik Sahajpal, David Manowitz, and Xuesong Zhang.

I am thankful for the tireless support of my family and friends from Ukraine and my mother-in-law, Tetiana, who came three times all the way from Ukraine to help and stay with us for extended periods. I am especially thankful to my grandmother, Zoya, for her emotional and spiritual support of my educational pursuits and experiences throughout my life, and her encouragement for me to learn foreign languages. I would like to thank my wife, Olha Kushnir, and my daughter, Marie Lychuk, who supported and put up with an ill-tempered, nerve shot husband and father during the hard years of this research. I would like to acknowledge all the help and support from Anne Willis, and the Stanton, Lindemann, Ingalls, and Harris' families who became our extended family in the United States.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Many sectors of the world economy, including agriculture, are being impacted by global climate change and projections suggest that this impact will continue to be increased. According to the Food and Agriculture Organization (FAO, 2002b), world demands for agricultural products in 2030 will have increased by one third in comparison to the demands in 2010. Mankind must take action to meet the growing food demands from an ever increasing world population that is expected to reach over 9 billion people by 2050 according to a recent United Nations report (United Nations, 2004). Even if the emissions of all greenhouse gases (GHG) were stopped at the present time, the GHG already emitted into the global atmosphere will continue to impact the Earth's climate for many years to come. However, people can partially alleviate the climate change impacts on agriculture and other sectors of the world economy with a set of collective actions that are called *adaptations*.

This dissertation presents the results of several modeling studies on evaluating the impacts of climate change on agriculture in the Southeastern United States and the effectiveness of adaptation strategies to counteract those impacts. The second chapter is a literature review that summarizes current climate change knowledge and some adaptation strategies. Original research studies are described and the results presented in chapters three to five. Chapter 6 summarizes the significant results of all three studies. Additional information on chapters 2 to five are briefly discussed in the following paragraphs of this introduction.

The literature review discusses climate change and its impacts on agriculture in the United States. Previous research is discussed concerning the use of regional climate change modeling as an effective tool to model the impacts of climate change and the effectiveness of adaptation options. The use of biochar soil amendments as a potential climate change adaptation tool is specifically discussed. The chapter concludes with a discussion of using the Environmental Policy Integrated Climate (EPIC) model approach to simulate climate change impacts and test the effectiveness of adaptation options.

Chapter three discusses how the EPIC model was modified with algorithms to determine the impacts of biochar applications on corn yields and selected soil properties. The main objectives for that modeling study was to (1) develop new algorithms in the EPIC model to quantify the influence of biochar additions to soil on fundamental soil properties (CEC, pH, bulk density and C dynamics) and crop productivity; (2) validate EPIC simulations using data from a 4-yr biochar amendment study on an Amazonian Oxisol; and (3) evaluate the stability and performance of the updated EPIC model when used in a 20-yr long term simulation. We hypothesized that biochar soil amendments will increase corn (*Zea mays* L.) yields and favorably affect selected soil physical properties.

The fourth chapter addresses climate change impacts and the effectiveness of adaptation options on sustaining or improving crop yields in the Southeastern US. The EPIC model was used to simulate the potential impacts of climate change and evaluate adaptations on the yields of three C_3 [alfalfa (*Medicago sativa* L.), soybean (*Glycine max* L.), winter wheat (*Triticum aestivum* L.)] and three C_4 (corn, sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L.)] crops from representative farms in 10 Southeastern US states. The objectives of this modeling study were to (1) evaluate how future climate change as predicted using four regional climate models (RCMs) affect different regions of the Southeastern US; (2) compare differences in historical baseline and predicted corn and soybean yields, as well as aggregated yields of C_3 and C_4 crops for the four RCMs; (3) compare the predicted corn and soybean yields as well as aggregated yields of C_3 and C_4 crops for the four RCMs during the 2038 – 2068 period; and (4) evaluate the effectiveness of the biochar applications and irrigation for the different RCMs on corn and soybean yields as well as aggregated yields of C_3 and C_4 crops. It was hypothesized that climate change will have different impacts on different regions of the Southeastern US. We also hypothesized that climate change and adaptations will each have effects on crop yields. Adaptations that were evaluated included annual applications of biochar and irrigation.

Chapter five addresses the impacts of climate change and the effectiveness of biochar applications and irrigation on microbial respiration, soil carbon (C) content, and nitrate losses in runoff and leachate from the same representative farms in the Southeastern US. The specific objectives of this modeling study were to (1) compare differences in historical baseline and future predicted values of nitrate losses, microbial respiration and soil carbon content trends, as well as the influence of the aggregated impacts of C_3 and C_4 crops on these parameters in the past and in the future; (2) compare the predicted nitrate losses, microbial respiration and soil C content trends for the four RCMs during the 2038 – 2068 period; and (3) evaluate the effectiveness of biochar applications, irrigation, and the influence of C_3 and C_4 crops on nitrate losses, microbial respiration and soil C content trends for the four RCMs. We hypothesized that climate change will have impacts on the response variables mentioned above, and that biochar applications, irrigation and crop types will differ in their influence.

The sixth chapter summarizes the results of all three modeling studies and attempts to draw some general conclusions from the research work presented in this dissertation.

Chapter 2: Literature Review

Climate Change

Scientific consensus is that the anthropogenic effects of climate change are already occurring and the impacts will be substantial (IPCC, 2007b; IPCC, 2014). Numerous studies, reports, and well-documented observations show that the burning of fossil fuel, deforestation, and other industrial processes are rapidly increasing the atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases. Atmospheric CO_2 concentrations have risen by more than 30% since pre-industrial times, from equilibrium levels of about 280 ppmv in 1880, to the currently observed levels of 392 ppmv (Tubiello et al., 2000). Current anthropogenic CO_2 emissions are about 8 GT C year^{-1} with atmospheric yearly increases being around 0.5% per year. It is predicted that atmospheric CO_2 concentration levels will be doubled by the end of the 21st century (Tubiello et al., 2000).

Climate change has gained significant international attention due to concerns of negative long-term impacts on agriculture, as well as water supply and human welfare. Change and variability are persistent features of climate, however, the climate change due to anthropogenic effects accompanies a millennia of strictly natural climate change and variability (Backlund et al., 2008). Little doubt exists that human influence inputs to the atmosphere will continue to alter Earth's climate throughout the 21st century. The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) (IPCC, 2007b) presents strong evidence that changes in atmospheric composition will result in further increases in global average temperature and sea level rise, as well as declines in snow cover, land ice, and sea ice extent. In its most recent IPCC Summary for Policy Makers to AR5 issued by Working Group II, the extents of the detrimental influences of climate change on human economy and population are projected to increase even further (IPCC, 2014). Similarly, it is expected that global average rainfall, its variability, and the occurrence of heat waves and extreme droughts will become more frequent (Backlund et al., 2008).

Climate Change Impacts on the United States

Based on temperature and precipitation records, the global-scale changes previously discussed are generally consistent with the predicted impacts of climate change in the United States. The degree of warming varies by region in the United States, but overall the country has warmed significantly. For example, the northern portion of the continental US and Alaska have experienced significant warming. The Southeastern US has recently received more average precipitation than 100 years ago while the Southwestern US has received less precipitation (Backlund et al., 2008; IPCC, 2007b).

Climate conditions in the US are predicted to continue to change throughout the 21st century. Depending on the high or low emission scenarios (IPCC, 2000), the effects of future greenhouse gas emissions will be much more noticeable near the end of the century. IPCC 4th Assessment Report predicts that the entire United States will warm substantially over the next 30 years with an increase of 1-2°C over much of the country (IPCC, 2007b). This rate of change would be significantly greater than the observed increases over the course of the 20th century. By the 2080s, a low emissions scenario predicts summer temperatures will have increased by 3-4°C in the interior West with warming of 2-3°C everywhere else in the country (IPCC, 2007b). A high emissions scenario predicts increased temperatures of 5-6°C in the interior West and Midwest with warming of 3-5°C in the Southeastern and far Western United States.

Changes in precipitation rates for the United States are more uncertain due to precipitation's sensitivity to both local conditions and shifts in the large-scale circulation of the atmosphere (Walthall et al., 2013). Projections based on the ensemble of the 16 regional climate models utilized to evaluate impacts of climate change on the conterminous United States agree that over the next 25-30 years the Northwest will experience reductions of 15-25% in summertime rainfall. Over the same time period, a 5% decrease in precipitation is predicted for the central South region with increased precipitation of 5-15% for the North Central, the Eastern, and the Southeastern US (Backlund et al., 2008; IPCC, 2007b; Walthall et al., 2013).

Despite increased precipitation envisioned for both the low and high emissions scenarios, there may not necessarily be increased crop yields as a result of predicted increases in available moisture. At the same time when increased precipitation is predicted, elevated temperatures would result in earlier melt and runoff of water stored in snow cover and would lead to increased plant evapotranspiration. Due to changes in the rainfall patterns, more precipitation is expected to fall in the form of intense, short duration storms that will result in rapid runoff. Even though the mean precipitation rates are expected to increase, the timing of precipitation will change such that there are prolonged dry periods, and plants may suffer from water stress immediately after planting and during other important stages of plant development. All of these factors may offset the projected increase in mean precipitation in the US and lead to less crop available moisture.

Climate Change Impacts on Agriculture in the United States

Due to the differences between photosynthetic pathways between C_3 and C_4 plants, C_3 and C_4 crops differ in the way they react to the increased ambient CO_2 concentration or so-called CO_2 fertilization effect. The C_3 metabolic pathway of carbon fixation is named after a three-carbon compound that is the first stable product of carbon fixation. In C_3 plants, increasing atmospheric CO_2 stimulates photosynthesis over a wide concentration range. C_3 plants close their stomata in response to increased CO_2 concentration which results in a greater water use efficiency (provided water supply is not limited). In situations of high light intensity and high temperatures, C_3 plants are subjected to photorespiration, which is a process that involves the rubisco enzyme responsible for photosynthesis. During photorespiration, rubisco utilizes oxygen instead of carbon dioxide, thus causing a slowing of the production of sugars from photosynthesis. Crops that utilize C3 carbon fixation grow best where the sunlight intensity is moderate, temperature is moderate and CO_2 concentrations are around 200 ppmv or higher, and where water supply is not limited. The C4 metabolic pathway of carbon fixation is named for the 4 carbon atoms present in the first product of carbon fixation in these plants. C_4 crops benefit less from the CO_2 fertilization effect because C_4 photosynthesis is a biochemical adaptation to a CO_2 limited atmosphere in the past, therefore, they take little advantage of increased CO_2 concentrations. C_4 plants have a competitive advantage over plants possessing the more common C3 carbon fixation pathway under conditions of drought, high temperatures, and nitrogen or CO_2 limitations. This advantage is because C_4 plants photosynthesize faster than C_3 plants under high light intensity and high temperatures because the CO_2 is delivered directly to the rubisco enzyme, not allowing it to utilize oxygen and undergo photorespiration.

Agriculture in the United States will be affected due to rising temperatures, changing precipitation patterns, and rising concentrations of atmospheric CO_2. Projected temperature increases will affect crop production by influencing variations in a crop's minimum, maximum, and optimum temperatures. Beyond a threshold, higher air temperatures adversely affect crop growth, pollination, and reproductive processes. Exposure to high air temperatures during pollination can greatly reduce crop yields and increase the risk of total crop failure. Increased temperature causes crops to mature and to complete their development stages at a more rapid rate (Easterling et al., 1993) that may result in stunted crop growth. Because of the accelerated growth, soil may not be able to supply water and/or nutrients at the required rates and, thus, grain, forage, fruit, or fiber production may be reduced. Additionally, increased temperatures may accelerate the rate of crop water use and result in increased crop water stress in areas with variable precipitation. For the majority of vegetable varieties grown in the US, exposure to temperature increases in the range of 1-4°C

(1.8° - 7.2°F) cause a moderate decrease in biomass growth. However, if vegetables are exposed to the temperature increases more than 5-7°C (9 – 12°F) above the optimal range, severe production losses frequently occur. Perennial cropping systems will be affected by impacts on their plant-chilling requirements due to increased winter temperatures.

Precipitation is projected to increase for some areas of the United States and decrease for other areas. Irrigation systems will be challenged to deliver water to crops in a timely manner because of changes in the timing, intensity, and amount of rain/snow mixtures occurring in the precipitation. A greater occurrence of flooding events may be triggered by excess precipitation resulting in increased erosion and decreased soil quality. Increased evapotranspiration is expected as a result of increased temperatures which will likely result in greater water demand by crops, leading to water stress even in areas where precipitation amounts have increased, especially for areas in which the soils have limited soil water holding capacity. Timing of these important factors will be critical for crop development. For example, excess water during corn's early growing stages may result in crop failure due to disturbed oxygen balance of the root zone, roots drowning, and increased microbial growth which can cause the formation of sulfides and butyric acid that are toxic to plants. At the same time, soil water deficits may lead to less growth and reduced yields if the stress occurs during the grain filling stage. Erosion will most likely be increased due to the predicted increased rainfall intensities and the resulting increased erosive potentials of higher intensity rainfalls. Due to changes in rainfall patterns and intensities, climate change will alter the balance of the hydrologic cycle which will have consequences for agricultural production and soil conservation across many US regions. Drought frequency and severity will increase, rain-free periods will lengthen, and individual precipitation events will become more erratic and intense leading to more runoff. Crop-water requirements, crop-water availability, potential crop productivity, and the increased cost of water access will all change and result in differential impacts across the agricultural landscape. These increased pressures on crop production will likely cause changes in cropland allocations and production systems in the United States.

As for the increasing CO_2 concentrations, the effects of this increase on crop growth are complex and variable depending on the species. Crops with a C_3 photosynthetic pathway are likely to respond more strongly than crops with a C_4 photosynthetic pathway. Controlled free-air concentration enrichment (FACE) studies have shown that elevated CO_2 levels can increase crop growth while decreasing soil water-use rates (Kimball et al., 1995; Leakey et al., 2004; Nowak et al., 2001; Rogers et al., 2004) . However, the magnitude of the growth simulation effects of elevated CO_2 under field conditions considering changing water, nutrient constraints, and plant competition, remains uncertain. Changing climate conditions may be offsetting the positive effects of elevated CO_2 on crop water use efficiency. For example, increased temperatures will increase crop water demand and reduce available soil moisture through evaporation from the soil surface, thus, resulting in reduced crop available moisture. Additionally, the quality of agricultural products may be altered by elevated CO_2 levels. Where increased CO_2 levels have been shown to reduce the nitrogen content in grain products, it may also cause reductions in the quantities of quality feed stocks and/or forage (Bowes, 1993; Makino and Mae, 1999; Thomson et al., 2005). The regional climate may be severely impacted by increased temperatures and/or CO_2 concentrations or changes in precipitation patterns. These factors when considered individually or in combination will expose the current vulnerability in crop production systems in some areas and will necessitate that adaptations be adopted to deal with these climate change impacts.

Adapting US Agriculture to Climate Change

Climate change will force farmers in the United States and their supporting institutions to take steps to minimize crop yield losses from the negative impacts of climate change and to maximize gains in crop yields from beneficial impacts. The general populace will need to utilize mitigation and/or adaptation practices to compensate for the change in environmental conditions attributed to climate change. *Mitigation* is the use of current and/or future technologies to counteract emissions of greenhouse gases and thus contribute to their stabilization in the atmosphere. *Adaptations* are a set of actions that are designed to lessen the adverse impacts of climate change on human and natural systems. In an agricultural setting, the main goal of adaptation is to reduce the vulnerability of agriculture to the harm that may be caused by climate change. This dissertation concentrates on agricultural climate change adaptation strategies and, therefore, adaptation strategies will be discussed in greater detail.

Adaptation strategies that are commonly in use by US farmers include selecting crop cultivars that are more adaptable to the current climate conditions, changing the timing of field operations, and the increased use of pesticides to control higher pest pressures. To adapt to changes involving crop pest management challenges, strategies for preventing rapid evolution of pest resistance to chemical control agents, development of new pesticide products, crop biodiversity, the management of biodiversity at field and landscape scales to suppress pest outbreaks and pathogen transmission, as well as improved pest forecasting, are being utilized. Research on adaptations performed in California's Central Valley found that an integrated set of changes in crop mix, irrigation methods, fertilization and tillage practices and land management were most effective to manage projected climate change in the near future. Considering the projected effects of climate change, US agricultural systems currently operate at their marginal limits and those farming operations that currently depend on irrigation will have to become more adaptive and go through transformative changes to remain productive and profitable.

To make agricultural systems more productive under climate change conditions, additional adaptation strategies may have to be utilized. They include developing crop and livestock production systems that are robust to drought, pest, and heat stress; diversifying crop rotations; integrating livestock with crop production systems; improving soil quality; and minimizing the off-farm flow of nutrients and pesticides. For example, drought and stress-resistant crops and livestock may improve a farmer's ability to cope with the increased variability of temperature and precipitation projected through the mid-century. Also, under conditions of variable and extreme weather events, production practices that enhance the ability of healthy soils to regulate water resources at the farm and watershed scales will be particularly critical.

Regional Modeling, Adaptation, and Climate Change

Simulation modeling driven by historical and future climate scenarios have been essential tools for testing hypotheses concerning the impacts of climate change on agricultural production and water resources (Rosenberg, 1992). In the past, by utilizing general circulation models (GCMs), researchers have routinely used global and national contexts to evaluate the possible changes caused by climate change on agriculture (Parry et al., 1999; Reilly et al., 2003; Reilly and Schimmelpfennig, 1999; Rosenberg, 1992).

Depending on the GCM used and the region studied, prior simulated model-based assessments of agricultural responses to climate change show variable responses. For example, an assessment of corn and winter wheat in their present US growing regions found that the regional impacts of climate change could be dramatic and varied, with declines in production of up to 76% in extreme cases, and increases in production approaching 31% with benign changes in climate (Luo and Lin, 1999; Reilly and Schimmelpfennig, 1999). On the other hand, Webster et al. (2003) applied an earth systems model to describe the uncertainty in climate projections under two different policy scenarios. Their study illustrated an internally consistent uncertainty analysis of one climate assessment modeling framework, propagating uncertainties in both economic and climate components, and constraining climate parameter uncertainties based on observation. They found that in the absence of greenhouse gas emissions restrictions, there is a one in forty chance that global mean surface temperature change will exceed 4.9°C by the year 2100. As a policy case with aggressive emissions reductions implemented over time, the temperature change would be lowered to a one in forty chance of exceeding 3.2°C, thus reducing but not eliminating the chance of substantial warming. Under these scenarios, the production of some crops will likely benefit from climate change, particularly the enhanced atmospheric concentration of CO_2.

The resolution scale used in previous studies involving GCM and also at which national and global scale simulations have been performed were seen as too coarse for making detailed assessments of climate change impacts (Gates, 1985). Thomson et al. (2005) showed that regional agriculture will be affected by climate change with consequences for regional, national, and global food production. The main concern with using GCMs for regional predictions of climate change impacts is the regional impacts of climate change may not be fully embraced by the typically employed resolution (e.g. 100 kilometers) of most GCMs. This typical resolution becomes a problem when making conclusions regarding climate change impacts at the regional level. The regional climate change modeling that is currently and commonly being utilized uses a much higher scale of resolution (e.g.100 meters) and allows the implications of climate change to be considered on the local level.

One of the first regional modeling studies that considered adaptations to climate change was performed in 1992 (Easterling et al., 1992a; Easterling et al., 1992b). In these studies, the MINK region (Missouri, Iowa, Nebraska, Kansas) was used to model the impacts of 1930's historic climatic data on agriculture and the effectiveness of possible adaptations to counteract the climate impacts during the Dust Bowl period (i.e. the area was known as the Dust Bowl for its persistent drought and erosion). It was found that some suggested adaptations, such as early planting, long-season cultivars, planting density, and cultivars with improved radiation use efficiency and stress tolerance were able to partially alleviate yield losses induced by climate change during the Dust Bowl period.

A different study (Rosenberg et al., 2003) applied results of the Hadley Climate Model 2 General Circulation Model (HadCM2 GCM) and the Environmental Policy Integrated Climate (EPIC) model to evaluate climate change impacts on crop yields and ecosystem processes. EPIC was implemented to run the main crops (with and without irrigation) grown in the United States using the historic 1961–1990 weather data and using predicted weather data for two future climate scenarios (2025–2034, 2090–2095). The simulation runs were implemented at two CO_2 concentrations (365 and 560 ppmv). The simulation results revealed a high spatial dependence driven mainly by regional changes in temperature and precipitation. Wheat yields in the Northern Plains region remained relatively unchanged during the two future periods, but the crop benefited from the CO_2 fertilization effect. In the Southern Plains, the increased temperature would reduce yields during the future periods, but these losses would be partially compensated by the positive CO_2 effect. This CO_2 effect was found to have less effect in maize than in wheat crops. Water use efficiency was reduced in response to increased temperatures for both crops, but again, the CO_2 fertilization effect helped attenuate these decreases.

Reilly et al. (2003) in their regional climate change study examined the impacts of transient climate change on US agriculture and historical shifts and trends in the locations of corn, soybean, and wheat. While it was concluded that technological and management adaptations may have overwhelmed the impacts of climate change in the analysis of the historical crop yields, it was not clearly concluded whether the north and northwest migrations that were historically observed for these crops were independent of the climatic factors associated with climate change.

Tsvetsinskaya et al. (2003) performed a modeling study in the Southeastern US to assess the effect of different spatial scales of climate change scenarios on the simulated yield changes in maize, winter wheat, and rice. For the majority of cases on the state level, significant differences in corn yields were found as the climate changed. When the coarse scale scenario was used, there were smaller decreases and increases in corn yields that were not as likely to be significantly different. The scale of the scenarios modeled seem to have produced little or no differences in the wheat yields. The differences in the scenario scales resulted in significant differences in the rice yields. The climate variable that was primarily responsible for the significant differences in the corn yields was the precipitation during grain fill which resulted in different water stress levels. Using adaptation practices, it was possible to reduce, but not entirely remove the significant yield differences for all crops produced by the different scale scenarios. The results of this regional modeling study indicated that the spatial resolution of climate change scenarios can be an important component of uncertainty in climate change impact assessments.

Carbone et al. (2003) examined the soybean and sorghum yield responses in the Southeastern US using a coarse global circulation model (i.e. 300-km, GCM) in comparison to a fine regional climate model (i.e. 50-km, RCM) with different climate change scenarios and adaptations. Soybean yields under a coarse scale-scenario decreased by 49% in response to predicted temperature and precipitation-based climate change responses, but the yield decreases were only 26% when the CO_2 fertilization impacts were taken into consideration. By contrast, the fine-scale scenario exhibited higher temperatures and lower precipitation than the coarse-scale scenario and resulted in corn yield decreases of 69% for climate change alone and 54% when the CO_2 fertilization impact was considered. By using adaptation strategies such as changing the planting dates and utilizing better adapted cultivars, the climate change impacts were partially mitigated, but yields still decreased by 8% and 18%, respectively, for the coarse and fine scale climate change scenarios. It was concluded that adaptation strategies tempered the impacts of moisture and temperature stress during pod-fill and grain-fill periods, but that the impacts differed with respect to the scale of the climate change scenarios.

Easterling et al. (2003) implemented a regional modeling study for the Southeastern US which tested the impacts of climate change on corn yields, the effectiveness of optimizing planting dates, and the use of hybrids with maturity ratings of different lengths as adaptations to help address climate change impacts. They concluded that simple substitutions of existing agronomic practices in response to climate change sooner or later will lose effectiveness in dealing with climate change. The effectiveness of the previously mentioned adaptation strategies declined over time as the increasing heat stress overcame the value of planting longer season hybrids. It was concluded that new fundamental adaptive knowledge and technology is required to cope with the unprecedented future climate challenges.

Biochar as a Climate Change Adaptation Tool

Application of biochar to soil has recently received widespread attention as a potential climate change adaptation and mitigation tool. There were about a dozen articles on biochar published in 2000, but, in 2012 over 3000-plus articles were published that addressed a wide range of topics (Maddox, 2013). The International Biochar Initiative (International Biochar Initiative, 2014a) defines biochar as fine-grained charcoal high in organic carbon and largely resistant to decomposition. It's use as a soil amendment is viewed as a potential long-term regional and/or global climate adaptation technique to reduce GHG emissions, improve soil physical properties, sequester soil carbon, and increase crop yields (Herath et al., 2013; Joseph et al., 2010; Laird et al., 2010a; Laird et al., 2010b; Lehmann, 2007; Liang et al., 2006; Major et al., 2010; Roberts et al., 2010). Biochar is rich in carbon and is produced by the pyrolysis process of heating the biomass in a low-oxygen environment. Pre-Columbian Amazonian farmers were the first farmers to use biochar amendments to enhance soil productivity. Although biochar is typically derived from plants and other waste feedstocks in which the carbon may have been readily available, after pyrolysis the resultant biochar may consist of up to 90% recalcitrant carbon. When applied to soil as an amendment, biochar creates a recalcitrant soil carbon pool which is carbon-negative in nature. This net withdrawal of atmospheric CO_2 is stored in the soil carbon stocks and is very resistant to decomposition. Kuzyakov et al. (2009) concluded that the half-life of biochar under natural soil conditions is about 1400 years.

Biochar possesses a number of distinctive beneficial characteristics including high cation exchange capacity (CEC) of 40 to 190 $cmol_c\ kg^{-1}$; high porosity in comparison to soil; possession of polyaromatic complex chemical compounds; and a high surface area and reactivity (Atkinson et al., 2010; Laird et al., 2010b; Lehmann et al., 2006). These properties when considered together, result in biochar possessing an attraction for plant micro- and macronutrients, causing increased soil pH, increasing soil porosity, and improving water holding capacity.

The quality of biochar is highly dependent on the choice of feedstock (organic waste such as sewage sludge and manures, crop residue, wood chips, municipal waste, etc.) and on the temperature, and time and presence of oxygen during pyrolysis (Lehmann et al., 2006; Sohi et al., 2009). When lower temperatures are used, more biochar is created per unit biomass (Winsley, 2007) and this biochar has higher pH-dependent CEC values (Mukherjee et al., 2011). However, the overall quality of the lower temperature biochar is considered to be less than when higher temperatures are used in production. Roberts et al. (2010) indicated that coupling pyrolysis with the biochar application makes the system carbon negative, because more carbon is sequestered than later emitted in the form of greenhouse gas emissions (GHG).

Since biochar does not possess an appreciable quantity of readily available plant nutrients, it is often applied in combination with fertilizer (DeLuca et al., 2009; Lee et al., 2010; Zheng et al., 2012). When used in combination with fertilizer, biochar application improves soil nutrient regimes by increasing bioavailability and plant uptake of nitrogen (N) and phosphorus (P) (DeLuca et al. 2009). According to the International Biochar Initiative (International Biochar Initiative, 2014a), biochar application potentially reduces fertilizer requirements because it attracts and retains soil nutrients. As a result, costs associated with fertilization are minimized when used in combination with biochar amendments because fertilizer may be retained in the soil for longer periods due to the biochar's retention capability. Biochar could be added to soils with the aim of sequestering carbon, improving soil quality, increasing plant growth (Glaser et al., 2002; Joseph et al., 2010; Major et al., 2010; Woolf et al., 2010) and reducing greenhouse gas emissions, such as CO_2 (Lehmann, 2007), CH_4 (Rondon et al., 2005) and N_2O (Roberts et al., 2010; Rondon et al., 2005). Research also shows that biochar application may decrease nutrient leaching and sediment losses, such as various forms of N and P, from agricultural soils (Laird et al., 2010a;

Lehmann et al., 2003). It is thought that the high surface charge density of biochar enables it to retain cations by cation exchange and anions by adsorption (Liang et al., 2006). Once incorporated into soil, biochar is very slowly oxygenated and transformed into a physically-stable but chemically-reactive humus. By contrast, if plant or animal residues are returned directly to the soil, the carbon content in them will be reduced within a period of several months to a few years. Consequently, when added to soil, biochar can sequester carbon for a long time, usually from hundreds to thousands of years and significantly reduce the release of GHG to the atmosphere, while at the same time improving soil physical properties and nutrient regimes (Herath et al., 2013; Laird et al., 2010a; Laird et al., 2010b). Due to the recalcitrant nature of carbon and its high content in biochar, application of biochar to soils leads to increased soil organic matter contents (Major et al., 2010). For its ability to sequester carbon and to have a positive influence on crop yields and soil properties, biochar application to soil has received considerable interest as a potential tool to slow global warming.

In spite of the potential benefits of biochar amendments, there are limited studies evaluating the use of biochar as a soil amendment when used in field studies and the few studies that have been published have been limited to evaluation of biochar additions on highly weathered tropical soils (Gaskin et al., 2010; Glaser et al., 2002; Major et al., 2010). In addition, no modeling studies have been implemented to evaluate biochar application as an adaptation tool to test its short- and long-term effects on crop yields, in reducing nitrate losses and its effects on microbial respiration and soil carbon. Modeling can provide a useful means to examine the potential effects of biochar additions to soil on crop productivity and soil properties over long time periods. Previously, there were no environmental simulation models that could describe the impacts of using biochar amendments for soils. A result of our current research is an enhanced version of the Environmental Policy Integrated Climate (EPIC) model that simulates the use of biochar soil amendments over short and long time periods (Lychuk et al. 2014).

Environmental Policy Integrated Climate (EPIC) Model

The Environmental Policy Integrated Climate Model was originally created in 1984 to quantify the effects of erosion on soil productivity. This model has evolved into a single-farm biophysical process model that can simulate crop/biomass production, soil evolution, and their mutual interactions given detailed farm management practices and input climate data (Williams, 1995). The EPIC flowchart diagram is shown on Fig. 2.1 with a brief description of each component of the model.

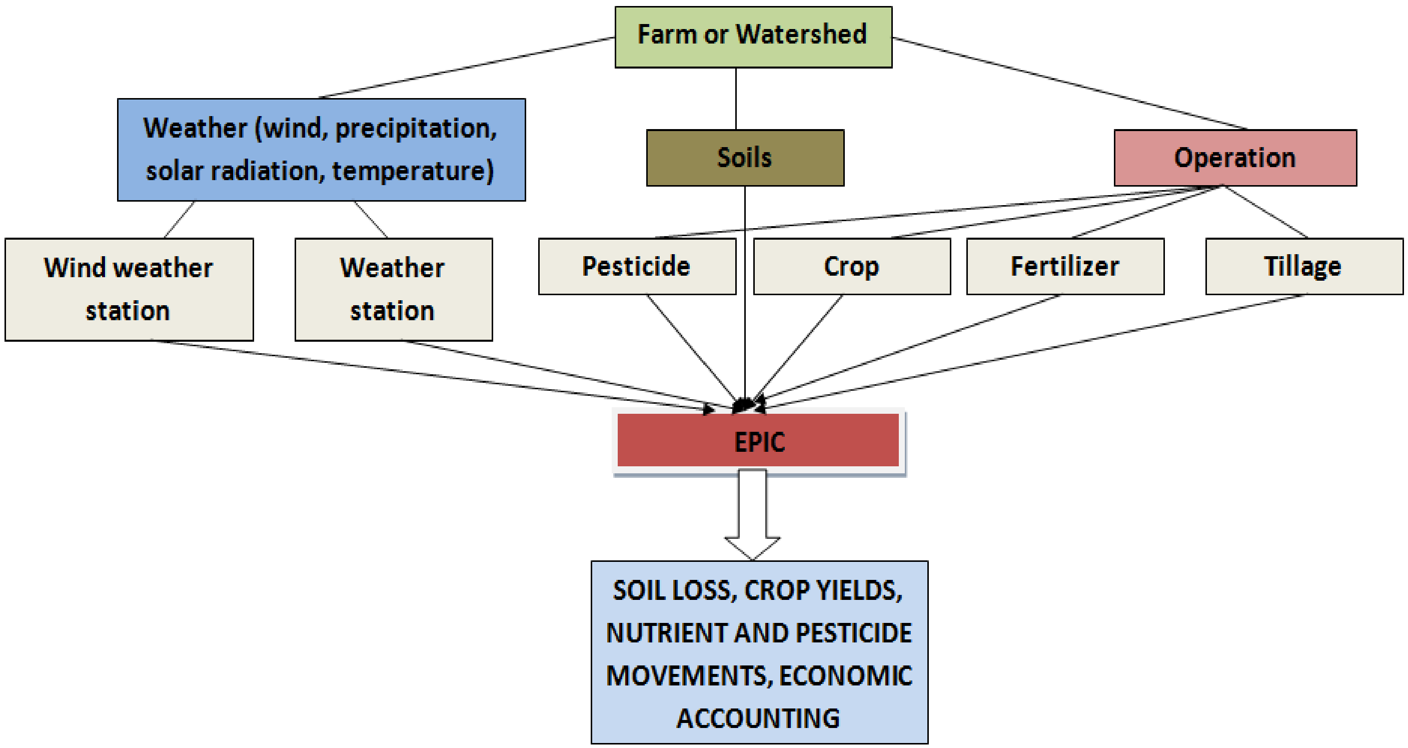


Fig. 2.1 A flowchart of inputs and subroutines in the Environmental Policy Integrated Climate Model. The model operates on a daily basis and each subroutine updates daily. Three main input components of the EPIC model are weather, soils, and operations schedule. The weather component requires data on maximum and minimum daily temperature, wind speed and direction, and the amount of daily solar radiation in MJ m^{-2}. The soils component requires information on soil carbon content, soil pH, CEC, bulk density, as well as sand, silt, and clay content. The operation schedule component requires data on kind and timing of field operations like tillage, planting and harvesting days, type of fertilizer and pesticide use and their application rates. The model processes all input data in EPIC executable file and provides information on response variables of interest in the output file.

In its most recently released version (EPIC version 1102, October 2012), the EPIC model can simulate the growth and development of over 100 plant species including all major crops, grasses, legumes, and some trees (Izaurralde et al., 2012). The model uses the concept of radiation-use efficiency (RUE) to simulate crop growth by calculating the potential daily photosynthetic production of biomass. Stress indices for water, temperature, N, P, and aeration are calculated daily using the value of the most severe of these stresses to reduce potential plant growth and crop yield (Williams, 1995). Stress factors for soil strength, temperature, and aluminum toxicity are used to adjust potential root growth.

EPIC also contains algorithms that allow this model to completely describe the hydrological balance on the scale of a small watershed. Processes taken into consideration are snowmelt, surface runoff, infiltration, soil water content, percolation, lateral flow, dynamics of the water table, and evapotranspiration. Daily weather can be input from historical records or it may be estimated from precipitation, air temperature, solar radiation, wind, and relative humidity parameters. Wind erosion is calculated on a daily time step based on wind speed distribution and adjusted according to soil properties, surface roughness, vegetative cover, while water erosion is computed as a function of the energy in rainfall and runoff. Values for soil properties including soil layer depth, texture, bulk density, and C concentration are needed to perform EPIC simulations. The mixing of nutrients and crop residues within the plow layer simulate and represent the tillage submodel in EPIC. This submodel also simulates changes in bulk density, considers ridge height and surface roughness, and converts standing residue to flat residue. EPIC computes crop growth by reducing the potential growth using the largest multiplicative stress factor of the following stresses: shortages of water, nitrogen, phosphorus, and potassium; temperature extremes; and inadequate soil aeration. Stockle et al. (1992) adapted EPIC to simulate the CO_2-fertilization effect on RUE and evapotranspiration (ET) to account for increased photosynthesis in C_3 crops and reduced ET in both C_3 and C_4 crops due to reduced stomatal conductance under conditions of elevated CO_2 concentrations which resulted in improved water use efficiency. A comprehensive description of the EPIC model application and development was presented by Gassman et al. (2004). EPIC dynamically accounts for soil C interactions in response to land use change, soil management, and climate change whose interactions have been verified with reasonable precision in long-term field experiments within the US and Canada (Izaurralde et al., 2005; Izaurralde et al., 2006). Izaurralde et al. (2006) modified the EPIC model with the introduction of a coupled carbon-nitrogen submodel based on the 2-litter and 3-soil carbon pools of the Century model (Parton et al., 1987) that simulates terrestrial carbon dynamics as effected by environmental and management factors. Soil C interactions are dynamically simulated in response to land use changes, soil management, and climate change.

The EPIC model has been applied extensively by a worldwide user community and has proven to be reliable in its accuracy to predict crop/biomass production based on climatic and other relevant data (Apezteguia et al., 2009; Chavas et al., 2009; Thomson et al., 2006). Users have successfully validated the EPIC model at the global scale with favorable results, in many regions of the world under varying climates, soils, and management environments, including the US, Canada, Argentina, Italy, China, and other countries (Apezteguia et al., 2009; Chavas et al., 2009; Costantini et al., 2005; Diaz et al., 1997; Edmonds and Rosenberg, 2005; Thomson et al., 2006). In the following chapters, we describe the algorithms and subroutines implemented into the EPIC model that consider the short- and long-term influences of biochar amendments on soil CEC and pH, organic carbon and bulk density dynamics (Lychuk et al., 2014). We then applied the model to predict climate change impacts on crop yields, nutrient losses and soil carbon trends in the Southeastern US and test the effectiveness of biochar application and irrigation as adaptation strategies to help alleviate climate change impacts.

References

Apezteguia, H.P., Izaurralde, R.C. and Sereno, R., 2009. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Cordoba, Argentina. Soil & Tillage Research, 102(1): 101-108.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil, 337(1-2): 1-18.

Backlund, P., Janetos, A. and Schimel, D., 2008. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. Report by the U.S. Climate Change Science Program and the Subcommittee on global change research.

Bowes, G., 1993. Facing the inevitable - plants and increasing atmospheric CO_2. Annual Review of Plant Physiology and Plant Molecular Biology, 44: 309-332.

Carbone, G.J. et al., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. Climatic Change, 60(1-2): 73-98.

Chavas, D.R., Izaurralde, R.C., Thomson, A.M. and Gao, X.J., 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agricultural and Forest Meteorology, 149(6-7): 1118-1128.

Costantini, E.A.C., Castelli, F. and L'Abate, G., 2005. Use of the EPIC model to estimate soil moisture and temperature regimes for desertification risk in Italy. Advances in Geoecology, 36: 251-263.

DeLuca, T., MacKenzie, M.D. and Gundale, M.J., 2009. Biochar effects on soil nutrient transformations. In: J. Lehmann and S. Joseph (Editors), Biochar environmental management: Science and technology. Earthscan, Sterling, VA, pp. 251-268.

Diaz, R.A., Magrin, G.O., Travasso, M.I. and Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean Rolling Pampas. Climate Research, 9(1-2): 25-30.

Easterling, W.E., Chhetri, N. and Niu, X.Z., 2003. Improving the realism of modeling agronomic adaptation to climate change: Simulating technological substitution. Climatic Change, 60(1-2): 149-173.

Easterling, W.E. et al., 1993. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. Climatic Change, 24(1-2): 23-61.

Easterling, W.E., McKenney, M.S., Rosenberg, N.J. and Lemon, K.M., 1992a. Simulations of crop response to climate change - effects with present technology and no adjustments (the dumb farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 53-73.

Easterling, W.E., Rosenberg, N.J., Lemon, K.M. and McKenney, M.S., 1992b. Simulations of crop responses to climate change - effects with present technology and currently available adjustments (the smart farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 75-102.

Edmonds, J.A. and Rosenberg, N.J., 2005. Climate change impacts for the conterminous USA: An integrated assessment summary. Climatic Change, 69(1): 151-162.
Gaskin, J.W. et al., 2010. Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield. Agronomy Journal, 102(2): 623-633.
Gassman, P.W. et al., 2004. Historical Development and Applications of the EPIC and APEX Models, American Society of Agricultural and Biological Engineers.
Gates, W.L., 1985. The use of general-circulation models in the analysis of the ecosystem impacts of climatic-change. Climatic Change, 7(3): 267-284.
Glaser, B., Lehmann, J. and Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils, 35(4): 219-230.
Herath, H.M.S.K., Camps-Arbestain, M. and Hedley, M., 2013. Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. Geoderma, 209: 188-197.
International Biochar Initiative, 2014. http://www.biochar-international.org/biochar/soils.
IPCC, 2000. Special Report on Emission Scenarios.
IPCC, 2007. IPCC Fourth Assessment Report. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2014. Intergovernmental Panel on Climate Change Working Group II Assessment Report 5 Summary for Policy Makers: Climate Change 2014: Impacts, Adaptation, and Vulnerability, Available online at http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-TS_FGDall.pdf Retrieved April 11, 2014.
Izaurralde, R., McGill, W. and Williams, J., 2012. Development and application of the EPIC model for carbon cycle, greenhouse-gas mitigation, and biofuel studies. In: M.A. Liebig, A.J. Franzluebbers and R.F. Follett (Editors), Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate. Elsevier, Amsterdam, pp. 409-429.
Izaurralde, R.C., Thomson, A.M., Rosenberg, N.J. and Brown, R.A., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 6. Distribution and productivity of unmanaged ecosystems. Climatic Change, 69(1): 107-126.
Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J. and Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192(3-4): 362-384.
Joseph, S.D. et al., 2010. An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48(6-7): 501-515.

Kuzyakov, Y., Subbotina, I., Chen, H.Q., Bogomolova, I. and Xu, X.L., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biology & Biochemistry, 41(2): 210-219.

Laird, D., Fleming, P., Wang, B., Horton, R. and Karlen, D., 2010a. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158(3-4): 436-442.

Laird, D.A. et al., 2010b. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma, 158(3-4): 443-449.

Lee, J.W., Hawkins, B., Day, D.M. and Reicosky, D.C., 2010. Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy & Environmental Science, 3(11): 1695-1705.

Lehmann, J., 2007. A handful of carbon. Nature, 447(7141): 143-144.

Lehmann, J. et al., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, 249(2): 343-357.

Lehmann, J., Gaunt, J. and Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitigation and Adaptation Strategies for Global Change, 11: 403- 427.

Liang, B. et al., 2006. Black Carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70(5): 1719-1730.

Lychuk, T., Izaurralde, R., Hill, R., McGill, W. and WIlliams, J., 2014. Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated Climate (EPIC) model. Mitigation and Adaptation Strategies for Global Change. DOI 10.1007/s11027-014-9554-7

Luo, Q.Y. and Lin, E., 1999. Agricultural vulnerability and adaptation in developing countries: The Asia-Pacific region. Climatic Change, 43(4): 729-743.

Maddox, N., 2013. The promise and uncertainties of Biochar. CSA News Magazine, 58: 4 - 9.

Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil, 333(1-2): 117-128.

Makino, A. and Mae, T., 1999. Photosynthesis and plant growth at elevated levels of CO2. Plant and Cell Physiology, 40(10): 999-1006.

Mukherjee, A., Zimmerman, A.R. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. Geoderma, 163(3-4): 247-255.

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change-Human and Policy Dimensions, 9: S51-S67.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic-matter levels in great-plains grasslands. Soil Science Society of America Journal, 51(5): 1173-1179.

Reilly, J. et al., 2003. US agriculture and climate change: New results. Climatic Change, 57(1-2): 43-69.

Reilly, J.M. and Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Climatic Change, 43(4): 745-788.

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R. and Lehmann, J., 2010. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. Environmental Science & Technology, 44(2): 827-833.

Rondon, M., Ramirez, J. and Lehmann, J., 2005. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere, 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore.

Rosenberg, N.J., 1992. Adaptation of agriculture to climate change. Climatic Change, 21(4): 385-405.

Rosenberg, N.J., Brown, R.A., Izaurralde, R.C. and Thomson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States - I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agricultural and Forest Meteorology, 117(1-2): 73-96.

Sohi, S., Lopez-Capel, E., Krull, E. and Bol, R., 2009. Biochar's roles in soil and climate
change: A review of research needs. CSIRO Land and Water Science Report.

Stockle, C.O., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992. Estimation of the effects of CO_2 induced climate change on growth and yield of crops. Part I. Modification of the EPIC model for climate change analysis. Agricultural Systems, 38: 225-238.

Thomson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C. and Benson, V., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 3. Dryland production of grain and forage crops. Climatic Change, 69(1): 43-65.

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J. and He, X.X., 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China. Agriculture Ecosystems & Environment, 114(2-4): 195-209.

Tsvetsinskaya, E.A. et al., 2003. The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climatic Change, 60(1-2): 37-71.

Tubiello, F.N., Donatelli, M., Rosenzweig, C. and Stockle, C.O., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy, 13(2-3): 179-189.

Walthall, C.L. et al., 2013. Climate Change and U.S. Agriculture: an Assessment of Effects and Adaptation Responses, U.S. Department of Agriculture.

Webster, M. et al., 2003. Uncertainty analysis of climate change and policy response. Climatic Change, 61(3): 295-320.

Williams, J.R., 1995. The EPIC model. In: V.P. Singh (Editor), Computer Models of Watershed Hydrology. Water Resources Public, Highland Ranch, CO, USA, pp. 909 - 1000.

Winsley, P., 2007. Biochar and bioenergy production for climate change mitigation. New Zealand Science Review, 64: 5-10.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nature Communications, 1.

Zheng, J., Stewart, C.E. and Cotrufo, M.F., 2012. Biochar and Nitrogen Fertilizer Alters Soil Nitrogen Dynamics and Greenhouse Gas Fluxes from Two Temperate Soils. Journal of Environmental Quality, 41(5): 1361-1370.

Chapter 3: Biochar and Global Change Adaptation: Predicting Biochar Impacts on Crop Productivity and Soil Quality for a Tropical Soil with the Environmental Policy Integrated Climate (EPIC) Model

Accepted for publication in the ***Mitigation and Adaptation Strategies for Global Change Journal*** *on February 23, 2013. DOI 10.1007/s11027-014-9554-7*

Abstract

The Environmental Policy Integrated Climate (EPIC) model with newly-developed biochar algorithms was used to determine the impacts of biochar amendments on corn (*Zea mays* L.) yields, soil cation exchange capacity (CEC), pH, bulk density (D_b) and soil organic carbon (SOC) dynamics. The objectives were (1) to determine impacts of biochar applications on crop yields and soil properties of a tropical soil and (2) to evaluate biochar's potential as a climate change adaptation tool. EPIC was validated using results of a 4-yr experiment performed on an Amazonian Oxisol amended with biochar at rates of 0, 8, and 20 Mg ha^{-1}. Simulated yields of corn on biochar amended soil were significantly greater than control yields ($p<0.05$). Simulated soil pH increased from an initial 3.9 to 4.19, CEC increased from 9.76 to 11.5 cmol$_c$ kg^{-1}, and SOC also increased. After validation, EPIC was used to simulate the impacts of the same biochar rates applied at 4 year intervals on corn yields and soil properties over the next 20 years. Soil CEC increased from 11.1 cmol$_c$ kg^{-1} to 20.2 cmol$_c$ kg^{-1} for the highest biochar application rate. Soil pH increased from 3.9 to 5.64. SOC increased up to 2.59% for the highest biochar application rate with decreased topsoil D_b from 1.11 Mg m^{-3} to 0.97 Mg m^{-3}. Long-term corn yields were slightly decreased. Although the results are biochar-, dose-, and soil-specific, biochar additions to tropical soils hold promise as a climate change adaptation tool resulting in increased soil carbon sequestration and improved soil properties.

Keywords Biochar, bulk density, cation exchange capacity, crop productivity, Environmental Policy Integrated Climate Model (EPIC), modeling, pH, soil carbon dynamics, soil quality.

Introduction

Simulations with global climate models (GCMs) suggest that projected increases in atmospheric carbon dioxide (CO_2) will modify the global climate and bring about a series of changes such as: warming ocean temperatures, changes in cloud cover, rising surface air temperatures, increasing frequency of severe weather events (droughts, floods), and changes in the global hydrologic cycle (IPCC 2007). The above mentioned consequences of climate change will alter a wide range of ecosystems including agriculture (Chavas et al. 2009). Agriculture is likely to be more adaptable to climate change than less managed ecosystems provided farmers have access to appropriate technologies and resources (IPCC 2001). Climate change will force farming operations to take steps to minimize yield losses in response to detrimental changes in climate and to maximize yields using practices that are beneficial. In past decades, conceptual and practical technologies to help mitigate the impacts of climate change have been evaluated by agricultural researchers and policy makers (IPCC 2001; Smith et al. 2000; Easterling 1996; Hatfield et al. 2011). These technologies could be 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 mixture of varieties with different pollination times, increased planting depth, etc. Adaptations are more high cost, system wide major changes in crops grown and production technologies. In an agricultural setting, the main goal of adaptation is to reduce the vulnerability of agriculture to the harm that may be caused by climate change. Adaptations may be applied across the full range of spatial scales from farm-level production to the level of international trade (Easterling 1996). Recent studies of crop production have evaluated the impacts of adaptations to climate change using various simulation models. For example, a study conducted by Adams et al. (1998) found that advances in technologies and adaptation could potentially mitigate 50% of the simulated yield declines in sorghum (*Sorghum bicolor* L.) and hay (not specified) in the US. Carbone et al. (2003) reported that adaptations tempered the impacts of moisture and temperature stresses associated with climate change during soybean (*Glycine max* L.) pod-fill and sorghum grain-fill periods, and that adaptations lowered yield decreases in response to climate change. The overall thinking is that with land management and technology improvements through various adaptation technologies, agricultural productivity can be maintained or increased under climate change, with additional benefits of reducing greenhouse gas (GHG) emissions.

Biochar application is viewed as a potential long-term regional and/or global climate adaptation/ mitigation technique to reduce GHG emissions, improve soil physical properties, sequester soil carbon (C) and increase crop yields (Lehmann 2007; Roberts et al. 2010; Herath et al. 2013; Joseph et al. 2010; Liang et al. 2006; Major et al. 2010; Laird et al. 2010a, b). Biochar is rich in C and is produced by heating biomass in a low-oxygen environment (known as pyrolysis). Biochar was first used by pre-Columbian Amazonian farmers to enhance soil productivity. It has a high pH buffering capacity since it can possess a cation exchange capacity (CEC) up to 70 $cmol_c\ kg^{-1}$ at pH 7 (depending on the temperature of pyrolysis) (Mukherjee et al. 2011). Liang et al. (2006) and Stavi and Lal (2013) indicated that biochar's high CEC is due to carboxylic groups found on its surfaces and organic acids that biochar adsorbed during pyrolysis, both of which contribute negative charge to biochar surfaces.

The quality of biochar is highly dependent on the choice of feedstock (organic waste such as sewage sludge and manures, crop residue, wood chips, municipal waste, etc.) as well as the temperature, and the time and presence of oxygen during pyrolysis (Sohi et al. 2009; Lehmann et al. 2006). When lower temperatures are used, more biochar is created per unit biomass (Winsley 2007) that has higher pH-dependent CEC values (Mukherjee et al. 2011). However, the overall quality of the lower temperature biochar is considered to be less than when higher temperatures are used in its production. The C content of biochar may reach up to 80%, but usually varies around 55-70%, depending on pyrolysis conditions and the type of feedstock used (Antal and Grønli 2003).

Biochar is often applied in combination with fertilizer, as biochar does not carry a lot of readily available nutrients (DeLuca et al. 2009; Zheng et al. 2012; Lee et al. 2010). When used in combination with fertilizer, biochar application improves soil nutrient regimes in that it increases bioavailability and plant uptake of nitrogen (N) and phosphorus (P) (DeLuca et al. 2009). According to the International Biochar Initiative, biochar application potentially reduces fertilizer requirements because it attracts and holds soil nutrients. As a result, costs associated with fertilization are minimized because fertilizer may be retained in the soil for longer periods due to the biochar effect. Novak et al. (2009) indicated that depending on feedstock composition and pyrolysis conditions, biochars may be specifically designed to selectively improve soil chemical and physical properties of degraded soils. Once incorporated into soil, biochar is very slowly oxygenated and transformed into a physically-stable, but chemically-reactive humus. By contrast, if plant or animal residues are returned directly to the soil, the C content in them will be reduced within a period of several months to a few years. Consequently when added to soil, biochar can sequester C for a long time, usually from hundreds to thousands of years and significantly reduce the release of GHG to the atmosphere, while improving soil physical properties and nutrient regimes (Laird et al. 2010a; Herath et al. 2013). Application of biochar has been shown to reduce soil bulk density, increase soil pH, CEC, and water-holding capacity (Herath et al. 2013; Sohi et al. 2009; Laird et al. 2010a, b; Liang et al. 2006). Biochar may be added to soils with the intentions to sequester C, improve soil quality, increase plant growth (Glaser et al. 2002; Joseph et al. 2010; Major et al. 2010; Woolf et al. 2010), and reduce GHG emissions such as CO_2 (Lehmann 2007), CH_4 (Rondon et al. 2005) and N_2O (Roberts et al. 2010; Rondon et al. 2005). Due to the recalcitrant nature of C and its high content in biochar, application of biochar to soils increases soil organic carbon (SOC) and soil organic matter (OM) content (Major et al. 2010). According to Tejada and Gonzalez (2007) and the International Biochar Initiative, biochar application also increases soil aggregate stability through the negative charge that develops on its surfaces. Upon application to soil, biochar also effectively adsorbs ammonia (NH_3) reducing its loss through volatilization (Stavi and Lal 2013). Roberts et al. (2010) indicated that coupling pyrolysis and biochar application makes the system C negative, because more C is sequestered than later emitted in the form of GHG emissions. Hence it has received considerable interest as a potential tool to slow global change.

The economics of biochar range from unprofitable to economically feasible depending on the technology of biochar production. It is notable that historically biochar has not been produced for C sequestration purposes, but has been treated as an undesirable waste by-product created during the production of liquid and gas energy products (Spokas et al. 2011). Modern agricultural use envisions biochar production for the purposes of C sequestration and GHG reductions, as well as improved soil quality and increased crop yields. A study by McCarl et al. (2009) showed that the use of biochar amendments produced from corn (*Zea mays* L.) stover by fast and slow pyrolysis was not economically feasible. Roberts et al. (2010) indicated that biochar systems using corn stover or yard wastes as feedstocks were profitable at \$80 Mg^{-1} CO_2 equivalents. Gaunt and Lehmann (2008) demonstrated that corn stover used for biochar production and to be used as a soil amendment, was more feasible than either bio-coal production or leaving the residue in the field when the focuswas on the value of CO_2 reductions. In a study evaluating the profitability of adding biochar instead of agricultural lime in eastern Washington, US, Galinato et al. (2011) stated that at a GHG offset payment of \$31 Mg^{-1} CO_2 equivalents biochar addition is more profitable than lime ($CaCO_3$) addition for biochar prices less that \$96 Mg^{-1}. The studies cited above indicated that biochar production and its use as a soil amendment may or may not be economically feasible, depending on the goals of biochar use. Similarly, Herath et al. (2013) indicated that currently there is a lack of sound economic evidence for the true agronomic value of biochar. In the current situation, when the price of CO_2 is low, it is important that the agronomic value is high in order to offset the costs associated with biochar production. However, it is worth noting that with the current trends of price increases for C credits, biochar will become more and more economically attractive as a climate change adaptation option to sequester C and reduce GHG emission levels. It is not surprising that various research and scientific groups around the world have proposed to include biochar as a separate climate change adaptation mechanism, which may be implemented under the

Joint Implementation of the Clean Development Mechanisms proposed by the United Nations Framework Convention on Climate Change (UN FCCC) Kyoto Protocol.

Although formal studies have not been implemented in Colombia, the availability of cheap labor and low operational costs seems to support the economical feasibility of utilizing biochar as an amendment for agricultural soils. Field scale additions of biochar are economically feasible for farmers if the cost of biochar use is less than the breakeven value (Spokas et al. 2011). But the farmers may not be willing to invest in biochar additions, if the long term benefits of biochar on soil properties and crop yields are uncertain. Obtaining long term benefits data in this case is problematic because a majority of the existing studies involving biochar have been limited to less than 3 years. This short time period makes it hard for the farmer to forecast with certainty long-term annual benefits of biochar additions.

Despite the presence of cheap labor and lower operational costs in Colombia, given all the uncertainties, this modeling study assumes it is not economically feasible to produce biochar for the purposes of soil amendments. However, existing liquid and gas energy production systems in Colombia deliver biochar as a waste product, which can be added to agricultural lands at relatively low cost. As world governments get more involved with reducing GHG emissions to counteract global climate change, there are likely to be increased cost credits being assigned to C reductions that may make biochar production and use an attractive and cost effective adaptation strategy. An example of a current government initiative is the Carbon Farming Initiative in

Australia, under which farmers and land managers may earn C credits by storing C or reducing GHG. These credits can be sold to businesses wishing to offset their emissions (DCCEE 2012).

Field studies have differed in their estimates regarding impacts of biochar applications on crop yields. Spokas et al. (2011) reviewed fifty studies that involved the evaluation of biochar amendments to soil. Fifty percent of the reviewed studies reported increases in crop yields following biochar amendments, while thirty percent of the studies showed no yield impacts, and the remaining twenty percent indicated decreases in yields. However, studies that utilized traditional hardwood biochar produced in kilns or soil pits reported consistent yield increases when it was added to soils (Spokas et al. 2011). In spite of the potential benefits of biochar amendments , there are limited studies evaluating the use of biochar as a soil amendment and the few studies that have been published evaluated biochar additions on highly weathered tropical soils (Gaskin et al. 2010; Major et al. 2010; Glaser et al. 2002). Consequently, the need to conduct further research on this topic exists and the work reported here focuses on biochar additions to an Amazonian Oxisol since there is a better understanding of biochar amendment use in tropical soils. Modeling can provide a useful means to examine the potential effects of biochar additions to soil on crop productivity and soil properties over long time periods. Prior to this study, there were no environmental simulation models that could describe the impacts of using biochar amendments for soil.

The objectives of this study were (1) to determine the impacts of long term biochar amendments to a tropical soil and the subsequent effects on crop yields and soil properties and (2) to evaluate whether the subsequent impacts of biochar additions to a tropical soil can be a potential regional and/or global adaptation tool for climate change. In order to accomplish these objectives, it was necessary to develop algorithms for use in the Environmental Policy Integrated Climate (EPIC) model to simulate the impacts of adding biochar amendments on soil properties and crop yields. The EPIC model was then validated to compare predicted results with the results from observations reported in the literature of a 4-yr experiment performed on an Amazonian Oxisol amended with biochar at rates of 0, 8, and 20 Mg ha^{-1}. This particular field study was one of the best available longer-term experiments published that evaluated impacts of biochar application on crop yields and specific soil parameters of interest. Following validation, EPIC was used to simulate the impacts from applying biochar amendments once every four years for twenty years on corn yields, SOC dynamics, and soil properties.

Materials and Methods

Properties and functions of the EPIC model

The EPIC model is a widely tested model which was originally created to quantify the effects of erosion on productivity of soils. Created in 1984, this model has evolved into a single-farm biophysical process model that can simulate crop/biomass production, soil productivity, and their mutual interaction given detailed farm management practices and input climate data (Williams, 1995). In its most recently released version (EPIC version 1102, October 2012), the EPIC model can simulate the growth and development of over 100 plant species including all major crops, grasses, legumes, and some trees (Izaurralde et al., 2012). The model uses the concept of radiation-use efficiency (RUE) to simulate crop growth by calculating the potential daily photosynthetic production of biomass. Stockle et al. (1992) adapted EPIC to simulate the CO_2-fertilization effect on RUE and evapotranspiration (ET) to account for increased photosynthesis in C_3 plants and reduced ET and improved water use efficiency in both C_3 and C_4 plants due to reduced stomatal conductance under conditions of elevated CO_2 concentrations. Daily gains in plant biomass are affected by vapor pressure deficits and atmospheric CO_2 concentration. Wind erosion is calculated on a daily time step based on wind speed distribution and adjusted according to soil properties, surface roughness, vegetative cover, while water erosion is computed as a function of the energy in rainfall and runoff. Stress indices for water, temperature, N, P, and aeration are calculated daily using the value of the most severe of these stresses to reduce potential plant growth and crop yield (Williams, 1995). Izaurralde et al. (2006) modified the EPIC model with the introduction of a coupled C-N submodel based on the 2-litter and 3-soil C pools of the Century model (Parton et al., 1987) that simulates terrestrial C dynamics as affected by environmental and management factors.

EPIC considers landscape hydrological balance on the scale of a small watershed that includes snowmelt, surface runoff, infiltration, soil water content, percolation, lateral flow, dynamics of the water table, and evapotranspiration. Future daily weather can be generated by an EPIC weather generator subroutine by estimating precipitation, air temperature, solar radiation, wind, and relative humidity parameters. Historical weather can also be input into EPIC directly from historical records. Values for soil properties including soil layer depth, texture, bulk density, and C concentration are needed to drive the EPIC simulations. The tillage submodel mixes nutrients and crop residues within the plow layer, simulates changes in bulk density (D_b), determines ridge height and surface roughness, and converts standing residue to flat residue. The EPIC model has been applied extensively by a worldwide user community and has proven to be reliable in its accuracy to predict crop/biomass production based on climatic and other relevant data (Chavas et al., 2009; Apezteguia et al., 2009; Thomson et al., 2006). Soil C interactions are dynamically simulated in response to land use change, soil management, and climate change. Users have successfully validated the EPIC model at the global scale with favorable results, as well as in many regions of the world under varying climates, soils, and management environments including the US, Canada, Argentina, Italy, China, and other countries (Chavas et al., 2009; Diaz et al., 1997; Edmonds and Rosenberg, 2005; Thomson et al., 2006; Costantini et al., 2005; Apezteguia et al., 2009).

Development of biochar algorithms in EPIC

Algorithms were developed and implemented into EPIC's modeling procedures that considered the influence of biochar amendments on soil CEC, pH, SOC, and D_b dynamics. For the soil CEC and pH subroutine, algorithms were developed that relate biochar's high surface area and charge density and the relationship of biochar additions to increases in soil CEC and pH. For the SOC subroutine, we allocated biochar to the slow, passive, and metabolic soil C pools and modeled corresponding changes in soil D_b and C sequestration rates. The implementation of the developed algorithms and corresponding modeling procedures in EPIC for soil pH, CEC, C dynamics, and D_b are shown in the following algorithms. The manner in which the algorithms were applied is shown in the biochar and soil interaction processes box of the conceptual diagram in Figure 3.1.

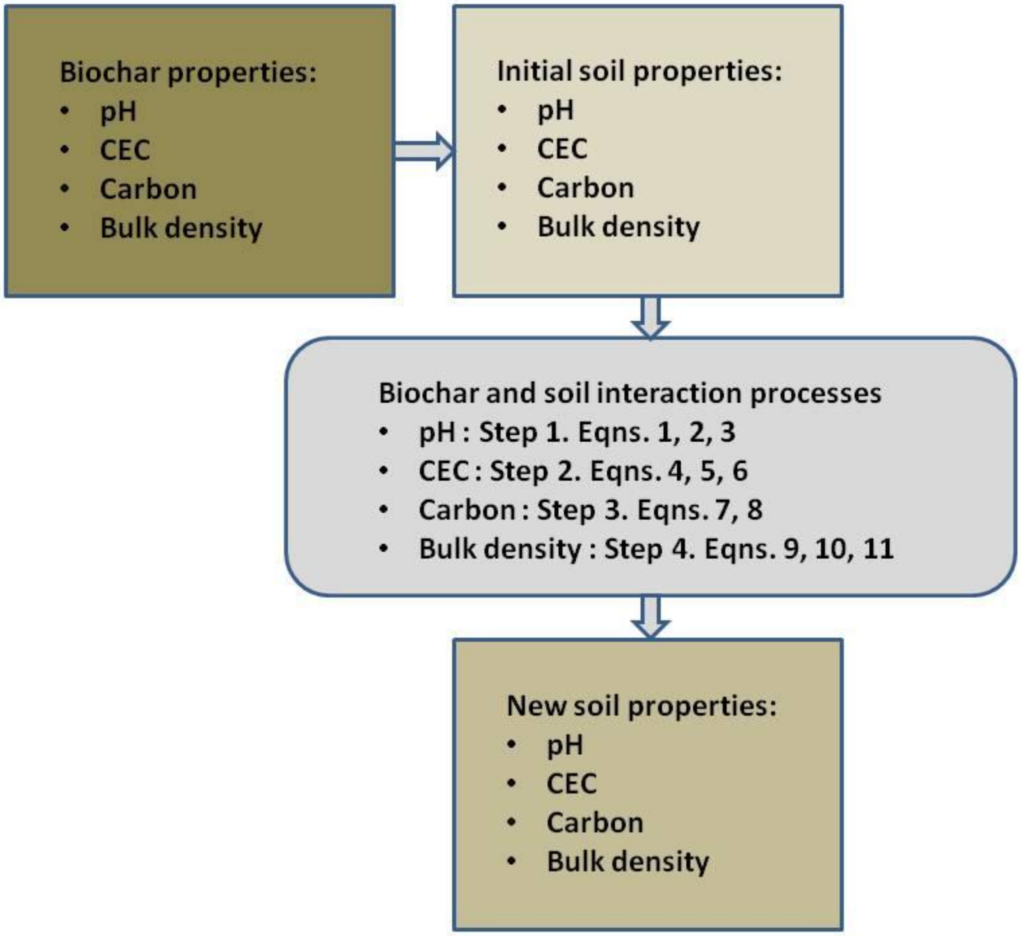


Fig. 3.1 Conceptual diagram describing inputs, outputs and processes used in the EPIC model to simulate the effects of biochar additions on soil pH, cation exchange capacity (CEC), soil carbon (C) dynamics, and bulk density (D_b). Equation numbers are indicated for each soil property. Among others, biochar has four important properties (CEC, pH, C content, and D_b) that, upon addition to soil, may influence essential soil properties such as soil CEC, pH, soil C, and soil D_b. Initial soil and biochar properties serve as main inputs for the biochar subroutine initiation. Processes between soil and biochar interactions are described by relevant steps and equations (see text). Outputs are presented as modified soil properties due to influence of biochar addition. The effect of biochar additions on soil pH, CEC, and D_b coupled with soil management will ultimately impact soil nutrient, moisture and air regimes, and resultant crop yields.

Algorithms for predicting the impacts of biochar additions on soil CEC and pH

According to DeLuca et al. (2009), the biochemical basis for the high CEC of biochar is most likely due to the presence of oxidized functional groups represented in the large surface area of biochar and its high charge density. We updated EPIC with an S-curve parameter definition for increases in CEC as a result of biochar additions and modeled its influence on increases in pH. It was a multi-step process, as outlined below and is presented in a conceptual diagram (Fig. 3.1) which describes inputs, outputs, and processes used in the EPIC model to simulate the effects of biochar additions on soil properties.

Step 1: We calculated the added CEC with biochar additions to soil in $mmol_c\ g^{-1}$ of biochar based on the following incremental procedure.

1a.) The CEC of the soil and the biochar mixtures were calculated in $cmol_c\ kg^{-1}$ according to the equation:

$$CECmix = \frac{CECsoil + \left(\frac{BCrate}{Msoil}\right) x\ CECbiochar}{1 + \left(\frac{BCrate}{Msoil}\right)} \qquad (1)$$

Where CEC_{mix} is the CEC of the soil and biochar mixtures in $cmol_c\ kg^{-1}$, *CECsoil* is the initial CEC of a soil in $cmol_c\ kg^{-1}$, *BCrate* is the rate of biochar addition in kg ha^{-1}, *Msoil* is the mass of a furrow slice of soil in 1 hectare (kg ha^{-1}); and *CECbiochar* is the CEC of biochar in $cmol_c\ kg^{-1}$.

1b.) The added positive charges from the biochar addition was calculated in $cmol_c\ kg^{-1}$ according to the equation:

$$Added(+) = CECmix - CECsoil \qquad (2)$$

Where $Added(+)$ is the added positive charge from the biochar addition in $cmol_c\ kg^{-1}$, CEC_{mix} is the CEC of the soil and the biochar mixtures in $cmol_c\ kg^{-1}$, and *CECsoil* is the initial CEC of a soil in $cmol_c\ kg^{-1}$.

1c.) The added CEC of the biochar addition was calculated in $mmol_c\ g^{-1}$ according to the equation:

$$CECadded = \frac{Added(+)*10}{OMcont.bc\&soil} \qquad (3)$$

Where $CECadded$ is the added CEC from the biochar addition in $mmol_c\ g^{-1}$, $Added(+)$ is the added positive charge from biochar addition in $cmol_c\ kg^{-1}$, *10* is the conversion factor from $cmol_c\ kg^{-1}$ to $mmol_c\ g^{-1}$ of the biochar, and *OMcont.bc&soil* is the organic matter content in grams within the new mixture of soil and biochar.

Step 2: The soil pH that resulted after biochar addition was calculated in the following manner.

2a.) The original soil equivalent base $mmol_c$ (*X*) for an Oxisol based on its original pH was calculated according to the equation:

$$X = T - \frac{1}{A}\left(ln\left(\frac{UpH-LpH}{pH-LpH}\right) - 1\right) \qquad (4)$$

Where X is the original soil equivalent base in $mmol_c$, UpH and LpH are the upper and lower Oxisol pH soil values (7.30055 and 3.495 for curve fitting purposes), respectively, and A and T are calculated from existing data for curve fitting purposes (A= 1.08 and T = 6.6).

2b.) The new equivalent base in $mmol_c$ of soil that resulted after biochar application was calculated according to the equation:

$$X_{new} = X + CECadded \qquad (5)$$

Where X_{new} is the new equivalent base in $mmol_c$ of soil, X is the original soil equivalent base in $mmol_c$, and $CECadded$ is the added CEC from biochar in $mmol_c\ g^{-1}$ as stated in equation (3).

2c.) The soil pH that resulted after biochar application was calculated using the X_{new} term in the logistic equation:

$$pH_{new} = \frac{UpH - LpH}{1 + e^{-a(X_{new} - T)}} + LpH \qquad (6)$$

Where pH_{new} is new soil pH as affected by biochar addition, UpH and LpH are the upper and lower Oxisol pH soil values (7.30055 and 3.495 for curve fitting purposes), respectively, A and T are calculated from existing data for curve fitting purposes (A= 1.08 and T = 6.6), and X_{new} is the new equivalent base in $mmol_c$ of soil.

Equation (6) is a modified version of the equation presented by Magdoff and Bartlett (1985) who developed a normalized curve to represent the pH-buffering effect of OM additions to soil. The S-shaped curves like the one in equation 6 are used to describe the behavior of many parameters in EPIC. The y-axis is scaled from 0-1 to express the effect of a range in the x axis variable on the process being simulated (in this case, the increase in CEC and pH as a result of biochar addition to soil). The S curve is described adequately by two points from existing data (*A* and *T*), normalized to the respective minimum and maximum terms of soil pH (*UpH* and *LpH*). The EPIC model uses these two points to solve the exponential equation for two parameters that guarantee the curve originates at zero, passes through the two given points, and *y* approaches 1.0 as *x* increases beyond the second point.

Two important assumptions have to be stated when considering the effects of biochar additions on soil CEC and pH: 1) biochar in essence is OM and 2) added CEC in $cmol_c$ kg^{-1} of biochar corresponds to $cmol_c$ kg^{-1} of OM in the Magdoff and Bartlett (1985) publication. The initial pH of the soil and its starting OM content, as well as the soil composition will largely guide the proportional increases in a soil's CEC and pH as a result of biochar additions due to a higher or lower extent of soil buffering. Additionally, factors such as the type of pyrolysis process used, biochar age, and its C and ash content will have an influence on soil CEC and pH values.

Algorithms describing soil C content dynamics

In the EPIC model, SOC is split into three compartments: microbial biomass, slow humus, and passive humus. Assuming that biochar mainly consists of OM, these compartments should have different turnover times ranging from days or weeks for a small percentage of biochar metabolic constituents to hundreds of years for slow and thousands of years for passive OM (Izaurralde et al. 2006). Hamer et al. (2004) reported a loss of 0.3-0.8 % of the initial C from biochar as CO_2-C that resulted from oxidation during a 60 day incubation at 20˚C. Baldock and Smernik (2002) found less than a 2% C loss from wood biochar over 120 days due to oxidation. These findings and other relevant literature give us a basis for assuming that C in biochar is mainly present in slow and passive forms. For EPIC modeling purposes and per the available literature (Joseph et al. 2009; Lehmann et al. 2009; Zimmerman 2010), there was 60% of the C in biochar allocated to the slow pool, 38% to the passive pool and 2% to the active/metabolic pool. C and N can also be leached or lost in gaseous forms, which EPIC also takes into account.

EPIC calculates the potential transformation of the slow humus compartment *(HSCTP)* as the product of the mass of C in slow humus *(HSC)*, the rate of transformation under optimal conditions *(HSR)* and a combined factor *(CS)* expressing the effects of temperature, soil water content, oxygen, and tillage (Step 3, Fig.1) (Izaurralde et al., 2006):

$$HSCTP = HSC \ x \ HSR \ x \ CS \qquad (7)$$

Passive humus is very slow to be transformed and is thought to be partially protected from transformation by being sorbed to clays. Hence clay content influences its formation (allocation of C to clay), and it has an exceedingly slow maximum decomposition rate (Parton et al., 1993). The potential transformation of the passive humus compartment is the product of the mass of C in the passive humus *(HPC)*, the rate of transformation under optimal conditions *(HPR)*, and the combined factor *(CS)* (Step 3, Fig.1) (Izaurralde et al., 2006):

$$HPCTP = HPC\ x\ HPR\ x\ CS \quad (8)$$

The reader is referred to the original article of Izaurralde et al. (2006) for the detailed equations of mechanisms of litter partitioning as well as potential and actual C and the allocation of transformed components in the EPIC model.

Algorithms for predicting changes in soil bulk density from biochar additions

Soil OM is inversely related to the soil D_b (Izaurralde et al., 2006). The EPIC model calculates the annual changes in D_b due to the changes in the SOC content using a modified version of the Adams equation (Adams, 1973):

$$Db = \begin{cases} \frac{100}{(SOC\ X 1.724/0.244+(100-SOC\ X\ 1.724)DBm}; & 0 \leq SOC < 58\ (g\ C\ kg^{-1}\ x\ 10^{-1}) \\ 0.244; & SOC = 58\ (g\ C\ kg^{-1}\ x\ 10^{-1}) \end{cases} \quad (9)$$

$$Db = \frac{100}{\frac{\%SOM}{0.244} + \frac{100 - \%SOM}{Dm}} \quad (10)$$

While the D_b of the soil organic matter is fairly constant (0.244 Mg m^{-3}) and the mineral bulk density (DB_m) is usually not known. EPIC estimates DB_m at the initiation of the run based on the initial values of D_b and *SOC*. Values of D_b are then updated annually based on the new calculations of the *SOC* for each layer. Adjustments are also made to the depth of each soil layer to accommodate the mass of mineral and organic matter according to the calculated D_b. EPIC also estimates changes in the soil D_b caused by changes in the *SOC* content, which are in turn influenced by soil respiration and erosion. In this way, EPIC explicitly treats changes in the soil matrix (density, porosity and water retention, based on the assumption that the biochar behaved similarly to normal soil OM) as well as changes in the soil constituents, such as organic C, thereby allowing feedback mechanisms to operate (Izaurralde et al., 2006; Williams, 1995).

To consider the effects of biochar additions on soil D_b, the original Adams equation (1973) has been further modified to the following form (Step 4, Fig.1):

$$Db = \frac{100}{\frac{SOM}{Dsom} + \frac{100-SOM-BC}{Dm} + \frac{BC}{DBc}} \quad (11)$$

Where *Dsom* is the bulk density of the soil OM (0.244 Mg m^{-3}) (Izaurralde et al., 2006), *BC* is the addition rate of the biochar to the soil, and *DBc* is the bulk density (0.64 Mg m^{-3}) of the biochar.

EPIC validation and subsequent simulations

The EPIC simulations describing the effects of biochar additions on corn yields, soil CEC, pH, bulk density, and SOC dynamics were validated using the results of a field experiment presented by Major et al. (2010). This field study reported the long-term effects of a single addition of biochar on corn – soybean yields, soil properties, and nutrient availability. The field experiment, located in Colombia at the Matazul farm (N 04° 10' 15.2'', W 072° 36' 12.9''), was performed on a soil that had never been tilled, cropped, or amended. Initial vegetation consisted of native savanna grasses. The soil was an isohyperthermic kaolinitic Typic Haplustox (Soil Survey Staff, 1994). Major et al. (2010) and Rippstein et al. (2001) indicated that this soil type developed from alluvial sediments originating from the Andes Mountains. The soil at the experimental site contained 20 g kg^{-1} organic C, 1.3 g kg^{-1} total N, 6 g kg^{-1} available P, 0.4 – 0.44 kg kg^{-1} clay, a pH (in KCl) of 3.9, and a CEC of 111.9 $mmol_c$ kg^{-1} in the upper 0.1 m soil depth. Soil D_b was 1.11 Mg m^{-3}. The average annual precipitation was 2,200 mm, with an average annual temperature of 26°C (Rippstein et al. 2001).

In December 2002, the experimental area was chisel plowed and lime (dolomite, [$CaMg(CO_3)_2$]) was applied at 2.2 Mg ha^{-1}, and incorporated to a 30-cm depth using two passes of a chisel plow. Nine days later, biochar was applied at rates of 0, 8 and 20 Mg ha^{-1} to plots arranged in a randomized complete block design with three replicates. The biochar was then incorporated with a single pass of a disc harrow to a depth of 5 cm. Lime and biochar were incorporated only on one occasion. There were a total of nine experimental plots, each measuring 4 by 5 m. Plots were separated by a 1 m buffer within blocks and a 2 m buffer between plots (Major et al. 2010). A no-tillage management system was implemented after biochar incorporation. Beginning in May 2003 and until December 2006, plots were cropped to a corn – soybean rotation. Seeding and fertilization of corn and soybean were done using hand tools and occurred at the same time that fertilizer was placed in a parallel furrow approximately 10 cm from the seed row. After seeding, all plots received side-dressed fertilizer being applied by hand onto the soil surface to the side of crop rows. According to Major et al. (2010), corn was seeded at 62,500 plants ha^{-1} (6.25 plants m^{-2}) on 22 May 2003 and 30 April 2004 (variety information unavailable), and hybrid Pioneer® 3041 was seeded on 17 May 2005 and 10 May 2006. Weeds, insects and fungal diseases were controlled as necessary using herbicides and pesticides according to local practices. Soybean yields were not reported because they were lost due to deer (*Odocoileus virginianus* L.) grazing. Wood biochar, commercially produced for cooking using the traditional mound kiln technique, was used in the study. Details on the feedstocks used to make the biochar and the production conditions were not available. C 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. Applications of N (as urea), potassium (as KCL), and P (as acidified rock phosphate) are noted in Table 3.1. The soil, operational management, fertilizer schedule, weather data and biochar properties data were converted to EPIC input files to accurately represent the conditions of the study site as described by Major et al. (2010).

Table 3.1. Fertilizer application rates (kg ha^{-1}) of nitrogen (N), phosphorus (P), and potassium (K) used for the Environmental Policy Integrated Climate model simulations.

Year	Crop	N (Urea)	P (Acidified rock phosphate)	K (KCL)
2003	Corn	165	43	86
2004	Corn	170	33	84
	Soybean	87	39	63
2005	Corn	156	30	112
	Soybean	16	10	110
2006	Corn	159	30	138
	Soybean	16	10	104

The 2.2 Mg ha^{-1} of lime application was not included as part of the simulations, since the original field study only reported on the biochar effects on soil pH and did not discuss the influence of lime applications. Additionally, climate and other data for the year 2006 were not included into the model simulations since major declines for crop yields were reported for 2006 with no plausible explanations presented in the Major et al. (2010) study. Therefore, the EPIC model could not have been updated with

relevant information to account for any major stresses that would have been responsible for yield declines in 2006, hence the year 2006 was omitted for yield predictions.

All simulations for corn yields and soil parameters were initially performed on the 4-year short term basis of the original field experiment and then extended to a 20-year long term basis. During the long term simulations, biochar was added at rates of 0, 8, and 20 Mg ha^{-1} to the soil once every 4 years with appropriate annual fertilizer applications as in the original study (Table 3.1). Historical weather data were obtained for a weather station approximately 32 km from the research plots using the recently announced Global Weather Data resource run by the NOAA National Center for Environmental Prediction (NCEP) (http://globalweather.tamu.edu/). Since Columbia is located fairly close to the equator, differences observed in climate are primarily due to landform differences in elevation. Since the weather station and the research plots were located on equivalent landform positions, the weather station data is thought to be representative of conditions at the research plots. We extracted a daily weather file of maximum and minimum temperature, precipitation, radiation, relative humidity, and wind speed data. The average monthly temperature, precipitation, wind speed and solar radiation values are given in Table 3.2.

Table 3.2. Average monthly values of historical climate data observed for the 2003 to 2006 period.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Ann.
Max. T (°C)	33.8	35.2	32.6	27.9	26.9	26.2	27.1	29.4	31.9	31.0	30.1	31.0	30.2
Min. T (°C)	22.7	24.3	23.4	21.2	21.1	19.9	19.9	20.5	21.4	22.1	22.0	21.7	21.7
Precipitation mm	66	74	205	524	395	178	126	140	201	369	379	123	2784
Wind speed ($m\ s^{-1}$)	1.47	1.24	0.67	0.81	0.90	0.95	0.99	0.94	0.82	0.68	1.06	1.39	0.99
Radiation ($J\ m^{-2}$) x 10^7	1.89	1.92	1.65	1.21	1.28	1.41	1.62	1.95	2.06	1.79	1.71	1.79	1.69

Statistical Analyses

Regression analyses were performed to verify the degree of association between observed and simulated values (Smith et al., 1996). The percent error was calculated as follows: (simulated - observed) × 100) / observed (Smith et al., 1996). In addition to regression analysis, we used the mean square deviation (MSD) statistics to evaluate the predictive accuracy of EPIC against measured data. Our approach was based on Gauch et al. (2003), in which MSD is partitioned into three components: squared bias (SB), non-unity slope (NU), and lack of correlation (LC) (Fig. 3.2). All three components relate to terms of the linear regression equation ($Y = a + bX$) and the regression coefficient (r^2).

Given a set of simulated (X) and observed values (Y), the MSD is defined as MSD = $\sum (X_n - Y_n)^2/N$ for $n = 1,2,\ldots,N$. The first component of MSD, SB, gives a measure of the inequality between the two means $\bar{X}$ and $\bar{Y}$ as SB = $(\bar{X} - \bar{Y})^2$. Gauch et al. (2003) indicated the second component NU measures the degree of the rotation of the regression line and is defined as NU = $(1 - b)^2$ x $\Sigma x_n^2 / N$, where b is the slope of the least-squared regression of Y on X and $b = \Sigma x_n y_n / \Sigma x_n^2$, $x_n = X_n - \bar{X}$, and $y_n = Y_n - Y$. Here, NU>0 occurred only when $b \neq 1$. The third component LC was calculated as LC = $(1 - r^2)$ x $\Sigma y_n^2 / N$ where r^2 is the square of the correlation $(\Sigma x_n y_n)^2 / (\Sigma x_n^2 \Sigma y_n^2)$. Here, LC > 0 only occurred when $r^2 \neq 1$.

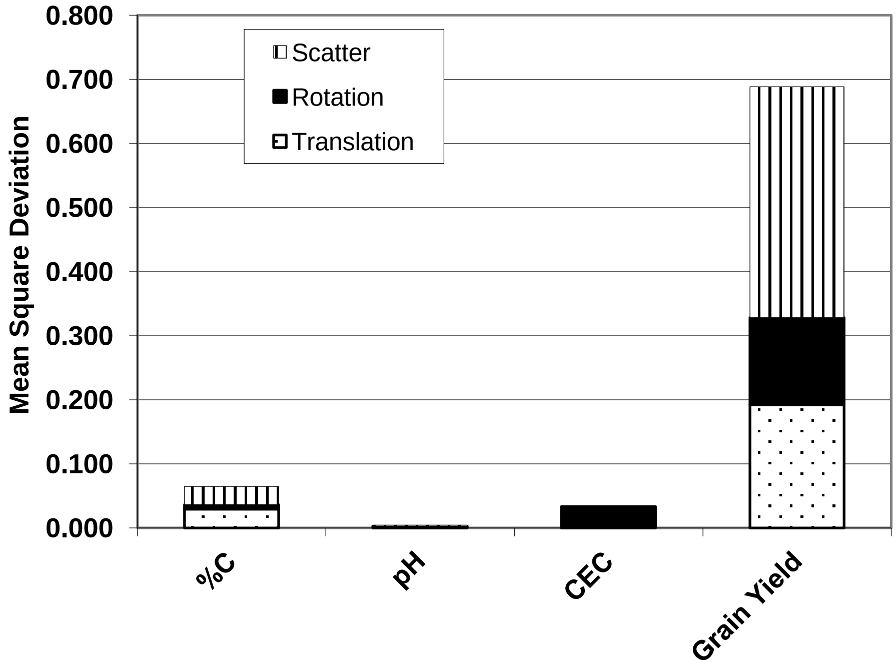


Fig. 3.2 Comparison of mean square deviations (MSD) between observed and simulated values for soil carbon (%C), pH, cation exchange capacity (CEC), and grain yield as affected by biochar additions. Scatter component of MSD provides a measure of the scatter (lack of correlation, LC) component in the data. The rotation (non-unity, NU) component contributes to MSD when the slope of the regression line between the simulated and observed values is ≠ 1. The measure of the inequality of the means is described by the translation (squared bias, SB) component of MSD.

Results and Discussion

Corn yields

We verified the performance of the model by comparing simulated vs. observed corn yields (Fig. 3.3). No significant effects on corn yield were observed in the first year after biochar addition in the original study. EPIC predicted the same trend for the control treatment, and explained about 70% of the variations in yields due to the biochar effects.

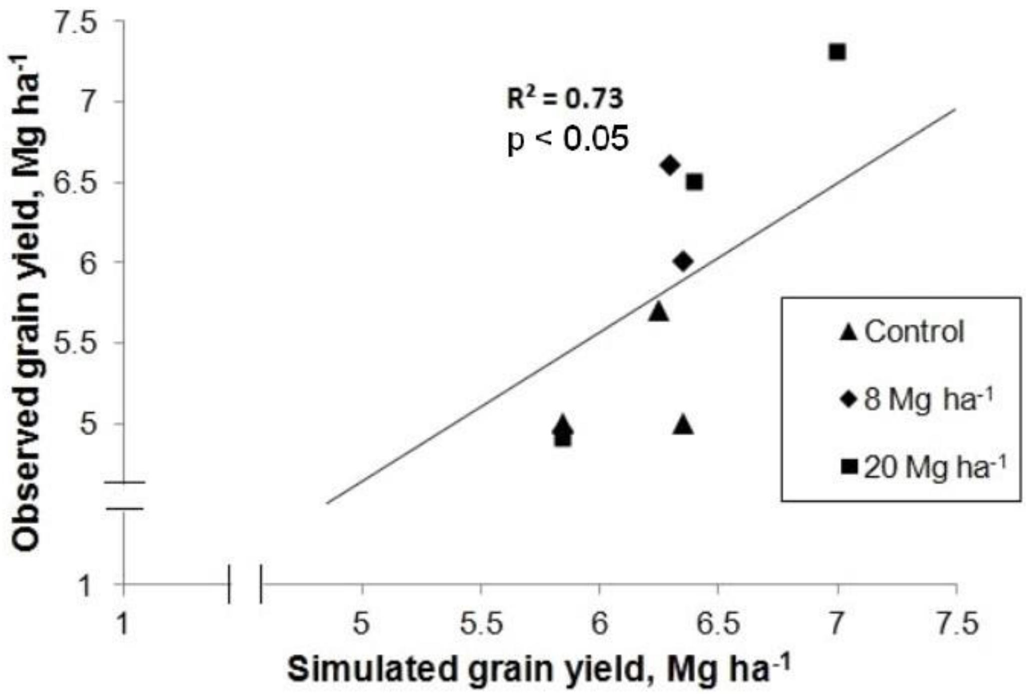


Fig. 3.3 Observed and simulated values of corn grain yield from the 2002 to 2005 study period as affected by different rates of biochar addition. The R^2 value indicates the coefficient of determination for the linear regression.

In subsequent years of the field study, corn yields increased with increases in biochar amendment rates and was most likely attributed to the slow oxidation of biochar and the improved nutrient regime that would result (Liang et al., 2006). There was good agreement between simulated and observed yields (R^2 = 0.73, p < 0.05) (Fig. 3.3). Yield results for 2006 were not included in the statistical analysis. Drastic declines in yields were observed during that year in comparison to previous years of the field experiment. Since the reasons for the decline were unclear, we could not update EPIC with the appropriate information and as a result EPIC predicted further increases in yields for the year 2006. The average error in estimation was about 30%. Still, the highest MSD value was observed (0.6885) for grain yield with most of the error due to LC or scatter. The results of the long term simulations of the biochar impacts on corn yields showed decreases in grain yields to the values of 4.6 Mg ha^{-1} (data not shown). Based on the simulation results, we surmised that high annual temperatures and precipitation regimes coupled with low activity clays characteristic of Oxisols increased nutrient leaching and microbial respiration rates thus outweighed the positive influence of biochar additions. Still, short-term crop yield predictions were promising. As will be described further, improvements in soil quality parameters as a result of biochar additions to the soil were significant and indicated the overall positive effects of biochar amendments on the soil environment, especially on the C sequestration dynamics.

Soil CEC and pH

Major et al. (2010) reported only a slight increase in topsoil CEC values after biochar additions. However, significant increases in pH values have been reported and linked to the increases in CEC (Herath et al., 2013; Sohi et al., 2009; Laird et al., 2010a, b; Liang et al., 2006). Given the properties and technological pyrolysis process of biochar production, it was assumed that the biochar used in the field study had a CEC of approximately 187 $cmol_c$ kg^{-1} based on the approach of Laird et al. (2010a), and this was the value used in the model simulations. After the first year of biochar additions, for the top 20 cm of soil, EPIC predicted increases of CEC from the original 9.76 $cmol_c$ kg^{-1} of soil to a value of 10.46 $cmol_c$ kg^{-1} for the 8 Mg ha^{-1}

biochar amendment rate. For the 20 Mg ha^{-1} rate, EPIC predicted a CEC of 11.5 cmol$_c$ kg^{-1} at the end of the simulation (Fig. 3.4). In other words, the EPIC model predicted that each addition of 8 Mg ha^{-1} of biochar added to the topsoil resulted in an additional 0.7 cmol$_c$ kg^{-1} (data on 8 Mg ha^{-1} biochar application was not reported in original field study). Similarly, an addition of 20 Mg ha^{-1} biochar increased CEC by 1.74 cmol$_c$ kg^{-1}. The simulated CEC values were in agreement with the observed results with an average error of less than 5%. The coefficient of determination (R^2) was 0.95 ($p < 0.05$).

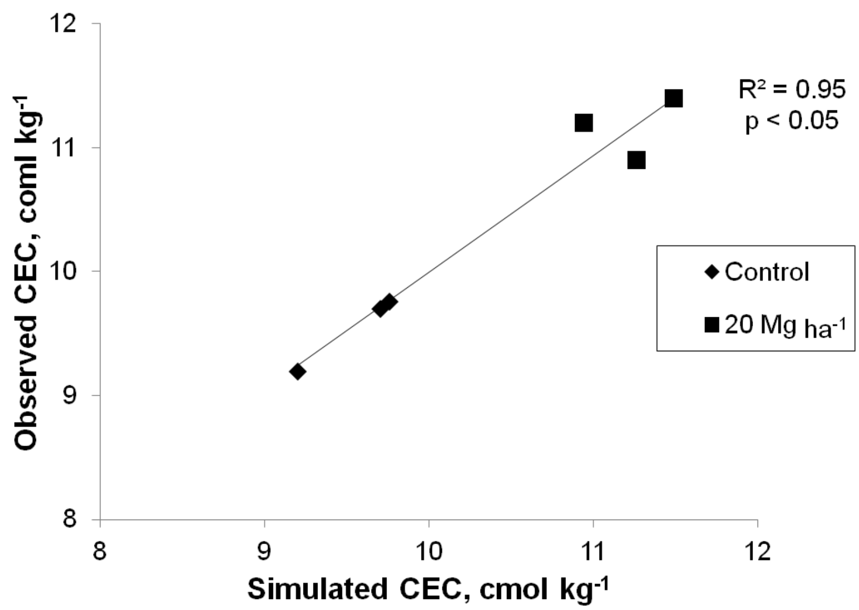


Fig. 3.4 Observed and simulated values of soil cation exchange capacity (CEC) within the upper 20-cm soil layer as affected by biochar addition from the 2002 to 2005 study period. The R^2 value indicates the coefficient of determination for the linear regression.

The calculated MSD value was 0.0342 with most of the error originating from the NU or the rotation component. EPIC further predicted CEC values at the end of the 20th year of simulation to be 13.96 $cmol_c$ kg^{-1} and 20.2 $cmol_c$ kg^{-1} for the above-mentioned rates (Fig. 3.5).

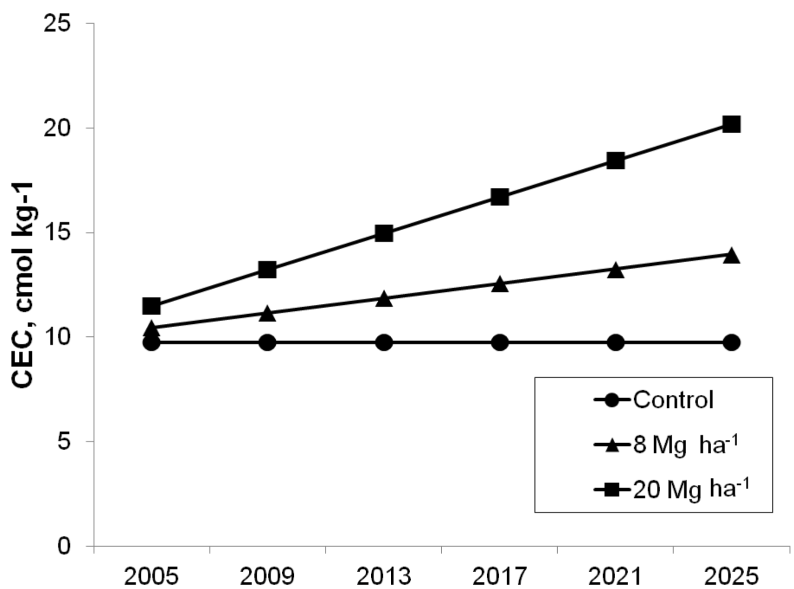


Fig. 3.5 Long-term effects of biochar additions on cation exchange capacity (CEC) of the upper 20-cm soil layer of an Amazonian Oxisol as predicted by the Environmental Policy Integrated Climate model. Biochar was added at the indicated rates once every four years during the 20-year model simulation.

Currently, the EPIC algorithms do not simulate increases in CEC as a result of biochar oxidation over time and this will be the subject of future research. In the original field study, topsoil pH increased significantly after biochar additions and the same trend was observed in the EPIC simulation results (Fig. 3.6). The coefficient of determination was 0.82 ($p < 0.01$). This was further confirmed by the smallest observed value of MSD (0.0044) with the amount of error being equally distributed between translation, rotation, and scatter components of the MSD.

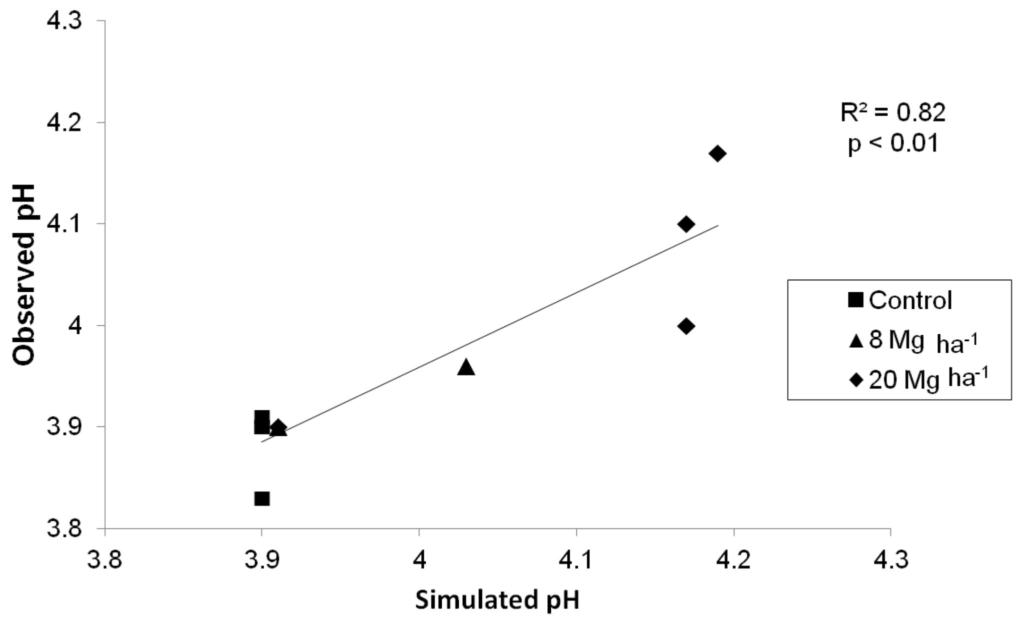


Fig. 3.6 Observed and simulated values of soil pH in the upper 20-cm soil layer as affected by biochar addition. The R^2 value indicates the coefficient of determination for the linear regression.

The average error for simulated pH values by EPIC was within 4% of the observed pH under field conditions. EPIC captured the pH trend and predicted increase in topsoil pH from 3.9 up to 4.03 and 4.19 for the 8 Mg ha^{-1} and 20 Mg ha^{-1} biochar amendment rates, respectively, which conforms to the results obtained by Major et al. (2010). The EPIC model also predicted that topsoil pH values would reach 4.68 and 5.64 for the 8 Mg ha^{-1} and 20 Mg ha^{-1} biochar amendment rates, respectively, by the end of the 20-yr simulation period (Fig. 3.7).

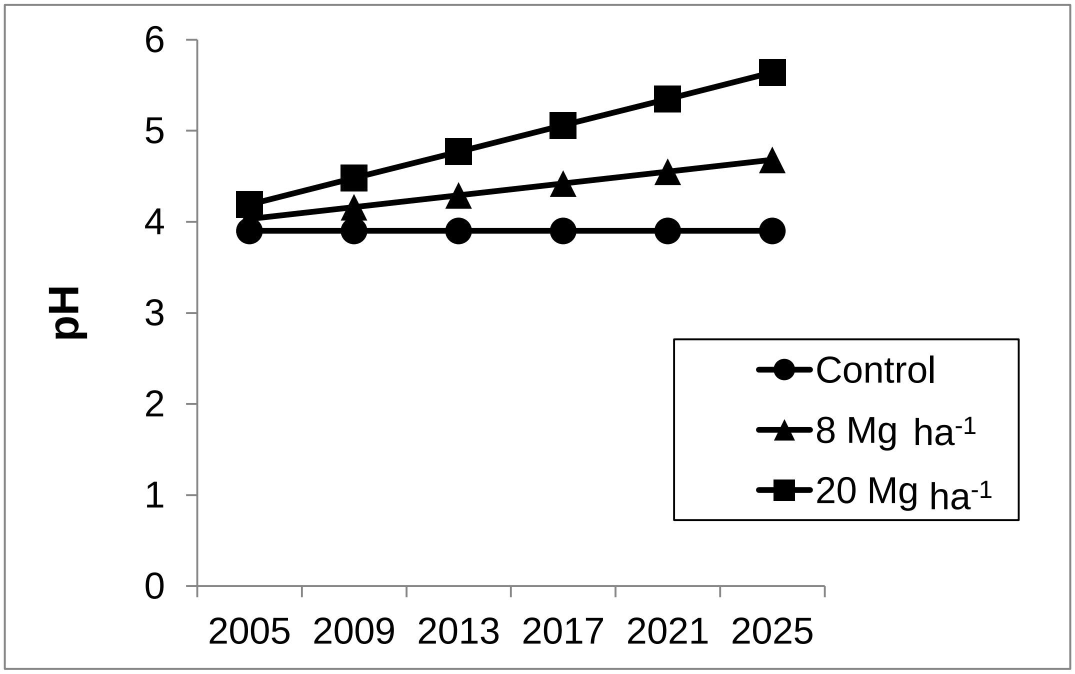


Fig. 3.7 Long-term effects of biochar additions on soil pH of the upper 20-cm soil layer of an Amazonian Oxisol as predicted by the Environmental Policy Integrated Climate model.

Soil C content dynamics

Biochar amendments resulted in increased amounts of total SOC accumulation in the upper 20 cm of the soil profile. Simulated topsoil SOC dynamics were in agreement with the field observations (R^2 = 0.77, p < 0.05) with an average error of about 8% between observed and simulated values (Fig. 3.8). The calculated MSD value was 0.0651 with most of the prediction error being equally associated with scatter and translation MSD components.

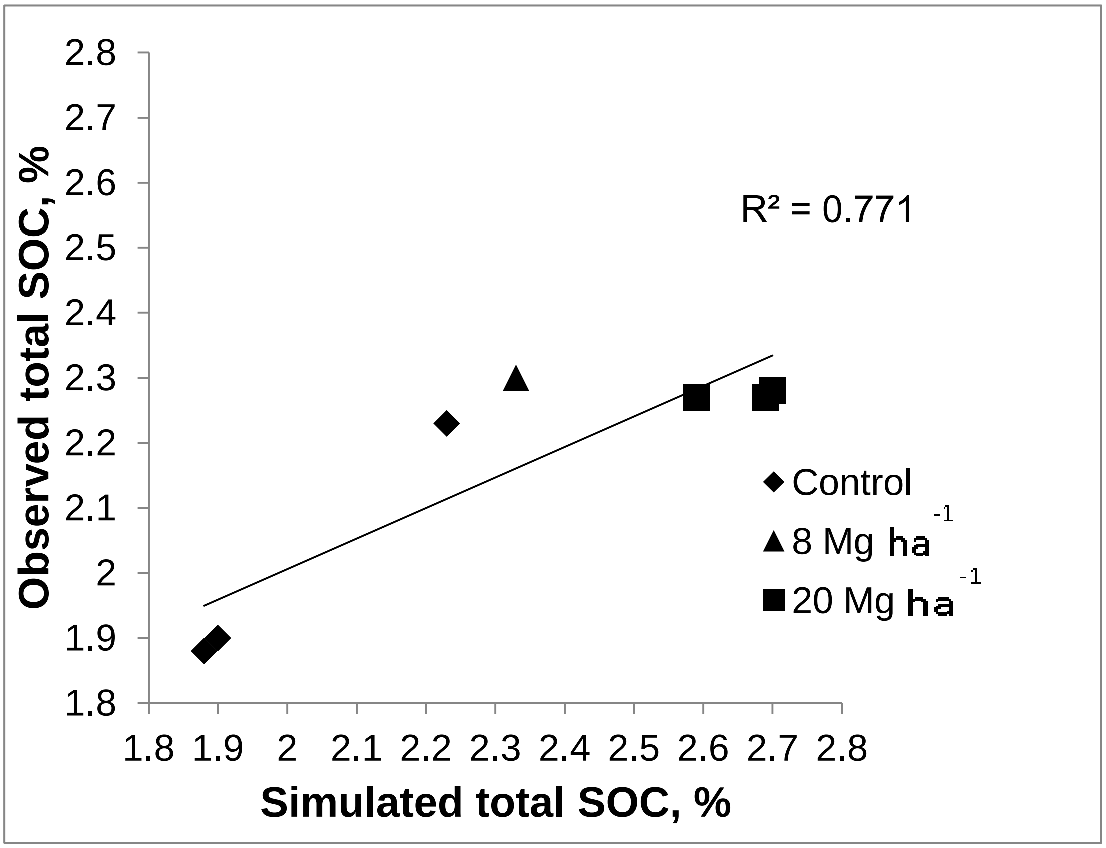


Fig. 3.8 Observed and simulated values of total soil organic carbon (SOC) within the upper 20-cm soil layer of an Amazonian Oxisol as affected by biochar addition from the 2002 to 2005 study period. The R^2 value indicates the coefficient of determination for the linear regression.

After 20 years of simulation, EPIC predicted increases in the SOC content for the entire 1.5-m soil profile - from initial values of 2.0% to 2.59% for the highest rate of biochar addition (Fig. 3.9).

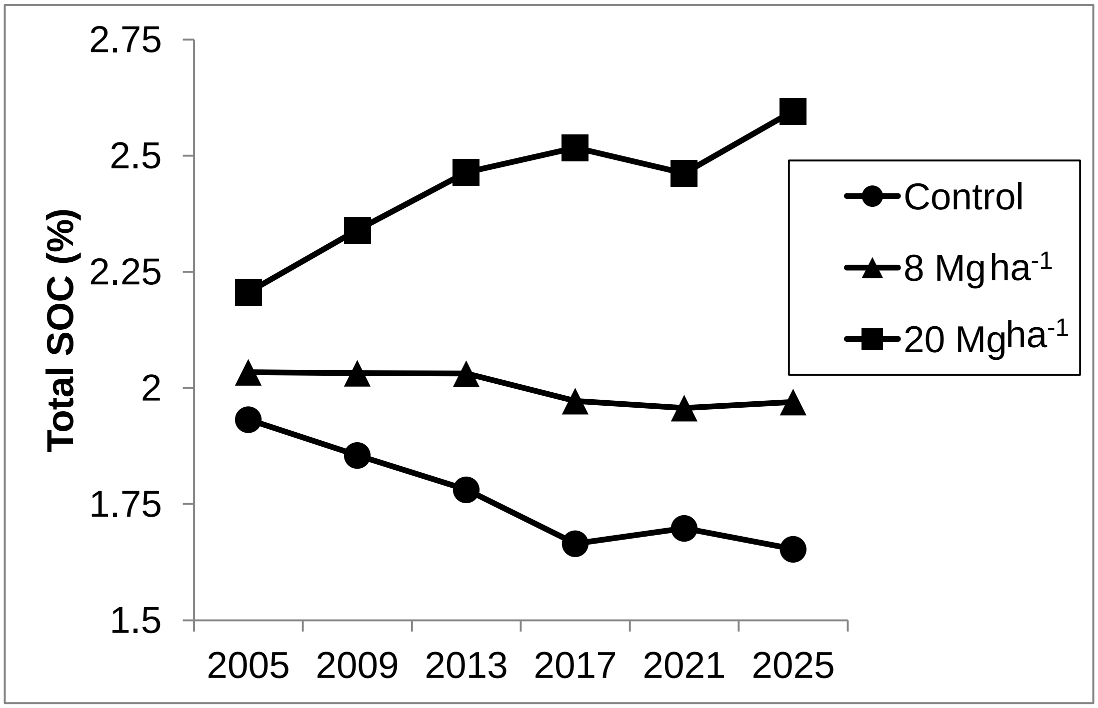


Fig. 3.9 Long-term effects of biochar additions on total soil organic carbon (SOC) within the 1.5-meter soil profile depth as predicted by the Environmental Policy Integrated Climate model. Biochar was added at the indicated rates once every 4 years during the 20-year model simulation.

Microbial respiration processes seemed to be accelerated in the region of the field study and were most likely due to the warm temperatures, as well as the high rainfall and humidity. For the 8 Mg ha^{-1} rate of biochar amendment, EPIC predicted the SOC losses were almost nullified. It was only with the 20 Mg ha^{-1} rate of biochar amendment that the SOC balance became positive in the EPIC simulations. Our calculations of the SOC dynamics indicated that this buildup was larger than what can be attributed to a simple addition effect of biochar to the soil. The increase was most likely attributed to the properties of the biochar that influenced soil physical and chemical properties (high surface area and high CEC, low D_b, high pH), as well as the microbial respiration processes in the soil. Positive SOC dynamics and subsequent increases in the soil C sequestration resulted from the increased application rates of biochar and are important findings of this modeling study. These results confirm that biochar application is effective in sequestering C on an Amazonian Oxisol and, thus, biochar amendments to soil holds promise as an effective climate change adaptation tool. Increased SOC storage also favorably increased the soil water field capacity from the original 0.353 to 0.411 $m^3 m^{-3}$ and the soil water holding capacity from 0.322 to 0.404 $m^3 m^{-3}$.

Bulk density

The EPIC model simulations predicted that the addition of biochar to the soil would result in decreased topsoil D_b. Values of D_b were not reported from the field study and, therefore, could not be included in the statistical analysis. Initial soil D_b was set as 1.1 Mg m^{-3} according to the Soil Survey Staff (1994) for the type of soil in the field study. The EPIC model predicted (Equation 11) the soil that had received biochar amendments would have lower D_b than the control (Fig. 3.10). Within the first year, the D_b within the upper 20-cm soil layer was reduced to 1.09 Mg m^{-3} and 1.06 Mg m^{-3} after addition of 8 Mg ha^{-1} and 20 Mg ha^{-1} of biochar, respectively. The 20-year EPIC simulations indicated that over time the biochar effects were amplified and by the end of the 20th year of the simulation the topsoil D_b was lowered by approximately 12% (Fig. 3.10). Soil D_b was further reduced to 1.06 Mg m^{-3} and 0.97 Mg m^{-3} for the above mentioned rates of biochar additions. Our findings conform to those reported by Laird et al. (2010a) who concluded that the magnitude of biochar effects on soil D_b was larger than can be explained by simple dilution of the soil from biochar amendments that characteristically have low D_b. As seen in Fig. 3.11, the topsoil D_b was directly proportional to the increased SOC content of the topsoil. The highest rate of biochar amendments corresponded to the lowest values in topsoil D_b.

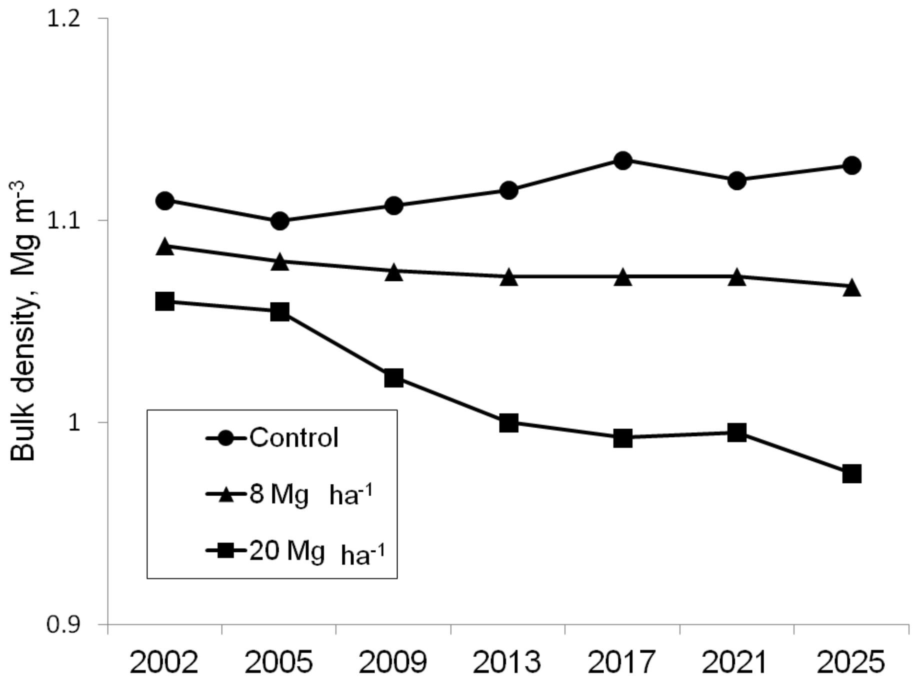


Fig. 3.10 Effects of biochar additions on soil bulk density within the upper 20-cm soil layer of an Amazonian Oxisol as predicted by the Environmental Policy Integrated Climate model during the short term (2002 – 2005) and long- term (2005 – 2025) study period. Biochar was added at the indicated rates once every 4 years.

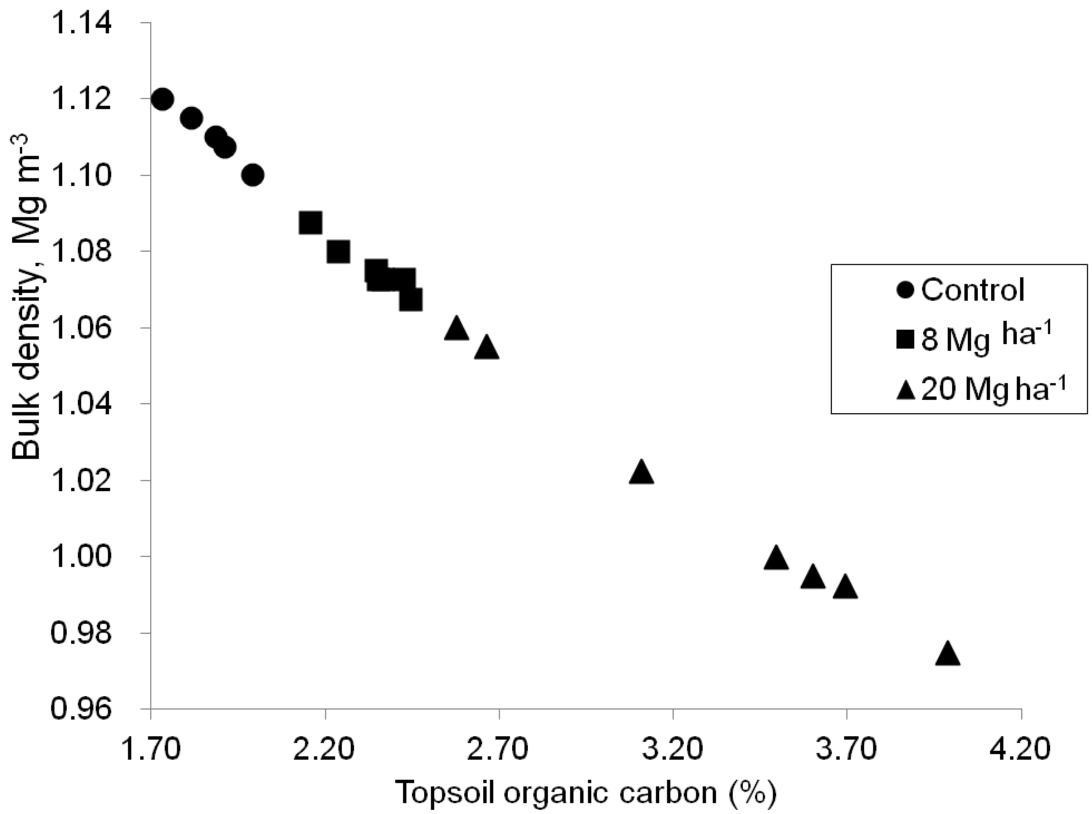


Fig. 3.11 The inverse relationship predicted by the Environmental Policy Integrated Climate model between topsoil organic carbon and bulk density within the upper 20-cm of an Amazonian Oxisol as affected by biochar additions.

Conclusions

Modeling can be a useful tool in evaluating the long term impacts of climate change on ecosystems, including agriculture. Modeling also allows the testing of potential adaptation strategies to evaluate their efficiency in coping with climate change impacts. This is particularly important as modeling will help optimize time, resources, and planning strategies for specific adaptation techniques prior to their practical implementation in the real world.

Previously, there have not been any environmental simulation models that could be used to describe the impacts of biochar amendments on soil properties and crop yields. We described and tested new algorithms in EPIC to simulate the impacts of biochar amendments being applied to soil on the resultant crop yields and soil properties. The biochar algorithms incorporated in the EPIC model were developed based on our current understanding of the effects of biochar additions to soil. The model was successfully validated and performed well in reproducing field observations of the impacts of biochar amendments on short-term crop yields and soil properties such as CEC and pH of an Amazonian Oxisol.

EPIC simulations were performed for a 20 year period to evaluate the potential long-term impacts of repeated applications of biochar amendments on soil properties, crop yields, and C sequestration. The EPIC model simulations reproduced observations of increased SOC in the field and predicted long term increased soil C sequestration and decreased soil D_b with increased rates of biochar amendments.

It should be noted that the simulation results are biochar-, dose-, soil-, and region-specific. Hence, indications are that the short and long term applications of biochar to tropical soils hold promise as a regional agricultural climate change adaptation tool in sequestrating C and reducing GHG levels, while at the same time improving soil properties important for crop growth. Future simulations to test biochar's impact on crop yields and changes in soil properties will be conducted as results of ongoing biochar experimental studies conducted on soil types other than an Amazonian Oxisol become available. Additional field studies and long term model simulations will help determine if biochar application is an effective climate change adaptation tool on other soil types represented in other regions of the world.

Acknowledgements

The project was supported by the DOE Office of Science under the Carbon Sequestration in Terrestrial Ecosystems (CSiTE), the Terrestrial Ecosystem Sciences Program, the Regional Climate Modeling Program, and by the Department of Environmental Science and Technology, University of Maryland, College Park. The senior author gratefully acknowledges the financial support from the Fulbright Commission. The authors are grateful to anonymous reviewers for their critical and constructive reviews. Authors also thankfully acknowledge James Amonette and Allison Thomson (PNNL) for internal review of the manuscript and the following colleagues for technical assistance: Ritvik Sahajpal (University of Maryland), David Manowitz (PNNL), Prasad Bandaru (PNNL), and Xuesong Zhang (PNNL).

References

Adams, R.M., McCarl, B.A., Sergeson, K. and Rosenzweig, C., 1998. Climate change and U.S. agriculture: Some further evidence. Electric Power Research Institute, Corvallis, OR USA.

Adams, W.A., 1973. Effect of organic matter on bulk and true densities of some uncultivated podzolic soils. Journal of Soil Science, 24: 10-17.

Antal, M.J. and Grønli, M., 2003. The art, science, and technology of charcoal production. Industrial Engineering and Chemistry, 42: 1619-1640.

Apezteguia, H., Izaurralde, R.C. and Sereno, R., 2009. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Córdoba, Argentina. Soil and Tillage Research, 102: 101–108.

Baldock, J.A. and Smernik, R.J., 2002. Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood. Organic Geochemistry, 33: 1093-1109.

Carbone, G.J., Kiechle, W., Locke, C., Mearns, L.O., McDaniel, L. and Downton, M.W., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the Southeastern United States. Climatic Change 60: 73-98

Chavas, D.R., Izaurralde, R.C., Thomson, A. and Gao, X., 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agriculture and Forest Meteorology, 149: 1118-1128.

Costantini, E.A., L'Abatei, G. and Fabio, C., 2005. Use of the EPIC model to estimate soil moisture and temperature regimes for desertification risk in Italy. Advances in Geoecology, 36: 251–263.

DeLuca, T., MacKenzie, M.D. and Gundale, M.J., 2009. Biochar effects on soil nutrient transformations. In: J. Lehmann and S. Joseph (Editors) Biochar environmental management: science and technology. Earthscan. Sterling, VA, p. 251-268.

Department of Climate Change and Energy Efficiency, 2012. An overview of the Carbon Farming Initiative. Available via http://www.climatechange.gov.au/reducing-carbon/carbon-farming-initiative Cited 14 Jan 2014

Diaz, R.A., Magrin, G.O. and Travasso, M.I., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean rolling pampas. Climate Research, 9: 25–30.

Easterling, W.E., 1996 Adapting North American agriculture to climate change in review. Agriculture and Forest Meteorology, 80: 1-53.

Edmonds, J. and Rosenberg, N., 2005. Climate change impacts for the conterminous USA: an integrated assessment summary. Climatic Change, 69: 151–162.

Galinato, S.P., Yoder, J.K. and Granatstein, D., 2011. The economic value of biochar in crop production and carbon sequestration. Energy Policy, 39: 6344 - 6350

Gaskin, J.W., Speir, R.A., Keith, H., Das, K.C., Lee, R.D., Morris, L.A. and Fisher, D.S., 2010. Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agronomy Journal, 102: 623-633.

Gauch, H.G., Hwang, J.T.G. and Fick, G.W., 2003. Model evaluation by comparison of the model-based predictions and measured values. Agronomy Journal 95:1442-1446

Gaunt, J.L. and Lehmann, J., 2008. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environmental Science and Technology, 42: 4152 - 4158.

Glaser, B., Lehmann, J. and Wolfgang, Z., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils, 35: 219-230.

Hamer, U., Marschner, B., Brodowski, S. and Amelung, W., 2004. Interactive priming of black carbon and glucose mineralisation. Organic Geochemistry, 35: 823-830.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A. and Wolfe, D.W., 2011. Climate impacts on agriculture: Implications for crop production. Agronomy Journal, 103:351-370.

Herath, H.M.S.K., Camps-Arbestain, M. and Hedley, M., 2013. Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. Geoderma, 209-210: 188-197.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (Editors) Cambridge University Press, Cambridge, UK, and New York

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (Editors) Cambridge University Press, Cambridge, United Kingdom and New York, NY

Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N. and Jakas, M., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192: 362-384.

Izaurralde, R.C., McGill, W.B. and Williams, J.R., 2012. Development and application of the EPIC model for carbon cycle, greenhouse-gas mitigation, and biofuel studies. In: M.A. Liebig, A.J. Franzluebbers, R.F. Follett (Editors) Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate. Elsevier, Amsterdam, p. 409-429

Joseph, S.D., Camps-Arbestain, M., Lin, Y., Munroe, P., Chia, C.H., Hook, J., Van Zwieten, L., Singh, B.P. and Lehmann, J., 2010. An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48: 501-515.

Joseph, S., Peacocke, C., Lehmann, J. and Munroe, P., 2009. Developing a biochar classification and test methods. In: J. Lehmann and S. Joseph (Editors) Biochar for environmental management: science and technology. Earthscan, London, p 107-125.

Laird, D.A., Pierce, F., Davis, D., Horton, R., Wang, B. and Douglas, K., 2010a. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158: 443-449.

Laird, D.A., Fleming, P., Wang, B., Horton, R. and Karlen, D., 2010b. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158: 436-442.

Lee, J.W., Hawkins, B., Day, D.M. and Reicosky, D.C., 2010. Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy and Environmental Science, 3: 1695 - 1705

Lehmann, J., 2007. A handful of carbon. Nature. 447:143-144

Lehmann, J., Czimczik, C., Laird, D., Sohi, S., 2009. Stability of biochar in the soil. In: J. Lehmann and S. Joseph (Editors) Biochar for environmental management: science and technology. Earthscan, London, p. 183-203

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitigation and Adaptation Strategies for Global Change, 11: 403-427.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B. and Skjemstad, J.O., 2006. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70: 1719-1730.

McCarl, B.A., Peacocke, C., Chrisman, R., Kung, C. and Sands, R.D., 2009. Economics of biochar production, utilization and greenhouse gas offsets. In: J. Lehmann and S. Joseph (Editors) Biochar for environmental management. Earthscan, London, p. 341 - 358

Magdoff, F.R. and Bartlett, R.J., 1985. Soil pH buffering revisited. Soil Science Society of America Journal, 49: 145-148.

Major, J., Rondon, V., Molina, D., Riha, S.J. and Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil, 333: 117-128.

Mukherjee, A., Zimmerman, A.R. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. Geoderma, 163:247–255

Novak, J., Lima, I., Xing, B., Gaskin, J., Steiner, C., Das, K.C. and Ahmedna, M., 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science, 3:195 - 206

NOAA National Centers for Environmental Prediction (NCEP). Cited January 14, 2014. http://globalweather.tamu.edu/

Parton,W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal, 51:1173–1179.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S. and Kirchner, T., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biochemistry Cycles, 7: 785-809.

Rippstein, G., Amezquita, E., Escobar, G. and Grollier, C., 2001. Condiciones naturales de la sabana. In: G. Rippstein et al (Editors) Agroecologia y

Biodiversidad de las Sabanas en los Llanos Orientales de Colombia. Centro Internacional de Agricultura Tropical (CIAT), Cali, 1–21

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R. and Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environmental Science and Technology, 44: 827 - 833

Rondon, M., Ramirez, J. and Lehmann, J., 2005. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In: Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, 21 - 24 March 2005

Smith, J., Smith, P. and Addiscott, T., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: D.S. Powlson, P. Smith, J.U. Smith (Editors) Evaluation of soil organic matter models using existing long-term datasets. Spinger-Verlag. Heidelberg, Germany, p.181-199

Smith, B., Burton, I., Klein, R. and Wandel, J., 2000. An anatomy of adaptation to climate change and variability. Climatic Change, 45: 223-251.

Sohi, S., Lopez-Capel, E., Krull, E., and Bol, R., 2009. Biochar's roles in soil and climate change: A review of research needs. CSIRO Land and Water Science Report

Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H.P., Boateng, A.A., Lima, I.M., Lamb, M.C., McAloon, A.J., Lentz, R.D. and Nichols, K.A., 2011. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality, 41: 973-989

Soil Survey Staff, 1994. Keys to Soil Taxonomy. Pocahontas Press, Blacksburg VA USA

Stavi, I. and Lal, R., 2013. Agroforestry and biochar to offset climate change: a review Agronomy and Sustainable Development, 33:81-96

Stockle, C., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992. A method for estimating direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops. Part I—Modification of the EPIC model for climate change analysis. Agricultural Systems, 38: 225–238

Tejada, M., Gonzalez, J.L., 2007. Influence of organic amendments on soil structure and soil loss under simulated rain. Soil and Tillage Research, 93: 197-205

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J. and He, X., 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai plain of China. Agriculture, Ecosystem, Environment, 114: 195–209.

Williams, J.R., 1995. The EPIC Model. In: V.P. Singh (Editors) Computer models of watershed hydrology. Water Resource Publications. Highlands Ranch, CO, p. 909–1000

Winsley, P., 2007. Biochar and bioenergy production for climate change mitigation. New Zealand Science Review, 64: 5-10.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nature Communications, 1:56

Zheng, J.Y., Stewart, C.E., Cotrufo, M.F., 2012. Biochar and nitrogen fertilizer alters soil nitrogen dynamics and greenhouse gas fluxes from two temperate soils. Journal of Environmental Quality, 41: 1361 - 1370

Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory-produced clack carbon (biochar). Environmental Science and Technology, 44:1295-1301

Chapter 4: Evaluation of Climate Change Impacts and Effectiveness of Adaptation Options on Crop Yields in the Southeastern United States

Abstract

Agricultural responses to climate change suggest an increased vulnerability of crop yields to elevated temperatures, decreased water availability, and increased nutrient stresses. The EPIC (Environmental Policy Integrated Climate) model was used to evaluate the potential impacts of climate change adaptations on yields of corn (*Zea mays* L.) and soybean (*Glycine max* L.), as well as C_3 and C_4 aggregated crop yields from representative farms in Alabama, Arkansas, Missouri, Mississippi, Florida, Kentucky, Louisiana, Texas, Georgia, and Tennessee that were grouped into North, South, and West regions. In this study, three C_3 crops were represented by combined yields of soybean, alfalfa (*Medicago sativa* L.), and winter wheat (*Triticum aestivum* L.), whereas C_4 crops were represented by combined corn, sorghum (*Sorghum bicolor* L.), and pearl millet (*Pennisetum glaucum* L.) yields. Adaptations included annual biochar applications and irrigation occurring prior to crop stress. Historical baseline (1979 – 2009) and future (2038 – 2068) climate scenarios were used for simulations with baseline and future CO_2 concentrations of 360 ppmv and 500 ppmv, respectively. Climatic data for baseline scenarios used NOAA's North American Regional Reanalysis (NARR) database. Climatic data for the future scenarios used the North American Regional Climate Change Assessment Program (NARCCAP)

database. Four regional climate models were used for the simulations to project different patterns of changes in air temperatures, precipitation, and solar radiation that are expected to occur over time. 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 periods of regional models. Results of this study indicated that climate change is affecting different regions of the Southeastern US differently. Compared to the historical baseline scenario, corn yields are projected to initially increase from 36% to 84% depending on the region. However, future corn yields show statistically significant decreases of 3-15% across the entire Southeastern US in 2038-2068, primarily due to temperature stress associated with future climate change. Compared to the historical baseline scenario, data trends suggest that soybean yields will decrease. Future soybean yields show statistically significant decreases in yields of 1-13% primarily due to temperature or combined temperature and moisture stresses. For comparisons between C_3 and C_4 historical baseline and future crop yields, it was found that C_4 crops generally produced higher yields compared to historical yields of C_4 crops, while C_3 crops historical baseline and future yields were not significantly different. Annual biochar applications did not have effects on corn, soybean, $C_{3,}$ or C_4 yields and caused significant yield reductions of 1-20% in the South and West regions using the CRCM (The Canadian Regional Climate Model with the Third Generation Coupled Climate) model, the South region using the HRM3 (The Hadley Regional Model and the Hadley Coupled Model version 3) model, and the West region using the RCM3C (The Regional Climate Model Version 3 and the Third Generation

Coupled Climate model). Irrigation caused significant increases in corn yields up to 33% for the South region, but no statistically significant increases were observed for soybean yields. Irrigation also resulted in increases of combined C_3 and C_4 crop yields for all regions for the RCM3G (The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate model), the South region for the RCM3C model and the West region for the HRM3 model. Irrigation caused yield increases of 2 - 35%. For all other regions and models, data trends indicated increased crop yields in response to irrigation, however no statistical significance was detected. Under some weather scenarios, irrigation may be a promising potential adaptation strategy for agriculture in the Southeastern US.

Introduction

Climate change

Climate change has gained significant international attention due to concerns of negative long-term impacts on agriculture and environmental quality (Chavas et al., 2009). Atmospheric carbon dioxide (CO_2) concentrations have risen by more than 30% since pre-industrial times from equilibrium levels of about 280 ppmv in 1880 to the currently observed levels of 392 ppmv (Tubiello et al., 2000). These increases are the direct results of human activities, primarily the burning of fossil fuels, cement production, and modified land-use patterns (IPCC, 1996). Although the magnitude of future changes is uncertain, further changes in climate over this century are almost certain.

Current anthropogenic CO_2 emissions are about 8 GT C $year^{-1}$ with an atmospheric yearly increase of around 0.5% per year. At the current rate of CO_2 increases, atmospheric CO_2 concentrations will be doubled by the end of the 21^{st} century (Tubiello et al., 2000). Simulations with global climate models (GCMs) suggest that the projected increase in CO_2 will modify the global climate through warming of the ocean, change in the degree of cloud cover, rising of surface air temperatures, increasing frequency of severe weather events (droughts, floods) and altering the global hydrologic cycle (IPCC, 2007a). The above mentioned negative consequences of climate change will have direct impacts on a wide range of ecosystems including agriculture. Agriculture is a highly managed ecosystem and given appropriate technologies and resources, agriculture is likely to be more adaptable than less managed ecosystems (IPCC, 2001a).

Climate change impacts on agriculture

The potential impact of climate change on agriculture is a major public concern if we are to maintain our current quality of life. Agricultural crop production might be significantly impacted by climate change and elevated CO_2 concentrations to an extent that will affect global food supplies. The response of agricultural systems to climate change will be strongly influenced by changes in our current management practices.

World demand for agricultural products in 2030 is predicted to increase by one third of what it was in 2010 (FAO, 2002a). To meet future needs for agricultural products, an additional 120 million ha of land will need to be converted to cropland by 2030 (FAO, 2002b). During this time period, the need for urban land will continue to grow and it is thought that the additional land for crop production will come from forest land that will be cleared (FAO, 2002b). One of our most important societal goals is to create solutions where agriculture can satisfy the food demands for an increasing world population and at the same time maintain environmental quality.

Climate change has already begun affecting the sustainability of agricultural systems through it impacts on decreasing crop yields, decreasing water availability, and increasing pest pressures (Reilly et al., 2003; Reilly and Schimmelpfennig, 1999; Rosenberg et al., 2003; Smith et al., 2005; Thomson et al., 2005). In response to climate change, we have already seen an earlier initiation of the spring green-up of perennial crops in the Northern Hemisphere. Crops have experienced increased moisture stress because of reduced amounts of precipitation and there has been an increase in the frequency of forest fires in North America and the Mediterranean Basin. Global climate models predict that these events will become more frequent as climate change impacts become more pronounced (ASA, 2011). 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; Izaurralde et al., 2003; Makino and Mae, 1999; Maroco et al., 1999). However, research rationalizes that this positive crop response will slow as the concentration of CO_2 continues to rise and other resources such as water and nitrogen become limiting

(Bowes, 1993; Makino and Mae, 1999). Additional 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., 2005). It has also been shown that the positive crop response to CO_2 that may occur is determined in part by the soil-water availability such that when grown under drought conditions the crop response is reduced (IPCC, 2001b).

There is little doubt that the increased concentrations of GHG will alter global weather patterns and, therefore, regional weather patterns will be also influenced. It is thought that temperature and precipitation will change from conditions to which crops are currently adapted and that changes in cloudiness will alter the timing, quality (i.e. how “active and efficient” the sun will be), and quantity (i.e. how long the sun is going to stay “active and efficient”) of solar irradiance. Regional agriculture will be affected by these changes with consequences for regional, national, and global food production (Thomson et al., 2005). Given the uncertainty regarding the regional distribution of climate change, 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, current agricultural production in some areas will be vulnerable and adaptations will be necessary.

Adaptations

Climate change will force farmers to take steps to minimize yield losses from the deleterious impacts of climate change and to maximize yield gains from beneficial climate change impacts. 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 the manner that we grow crops and the use of production technologies which aim to ameliorate the impacts of climate change over a long period of time. Adaptations cross the full range of spatial scales from farm-level production to the level of international trade (Easterling, 1996).

Biochar as a climate change adaptation tool

Biochar is a by-product of vegetative biomass and/or animal manures that have undergone pyrolysis and may consist of up to 90% recalcitrant carbon. Kuzyakov et al. (2009) concluded 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 having a high surface area and reactivity (Atkinson et al., 2010; Laird et al., 2010b; Lehmann et al., 2006). These properties when considered together results in biochar having an attraction for plant micro- and macronutrients, causing increased soil pH, increased soil porosity, and improved water holding capacity. Novak et al. (2009) suggested a methodology that alters feedstocks and pyrolysis conditions in order to create designer biochars that have specific chemical characteristics matched to selective chemical and physical issues of a degraded soil.

There are various hypotheses about biochar's impacts on crop productivity upon its application to soil. Researchers primarily agree that when used in combination with fertilizer management, biochar application improves the bioavailability and plant uptake of nitrogen and phosphorus (DeLuca et al., 2009). According to the International Biochar Initiative (International Biochar Initiative, 2014b), upon application to soil, biochar attracts and holds soil nutrients because of its high surface area, its complex pore structure that serve as habitats for myriads of soil microorganisms, and its negative surface charge. Nesbitt (1997) reported that nutrients in biochar may be directly available through solubilization of the solid biochar residue and the utilization of the labile carbon component that is readily available for microbial uptake. After performing a meta-analysis to quantify the effects of biochar amendments on crop productivity, Jeffery et al. (2011) reported, in addition to enhanced nutrient availability that increased crop yields could be attributed to improved soil water holding capacity and an increase in soil pH especially for biochar amendments applied to acidic soils. Despite the existence of many field studies that have confirmed an increase in crop yields after the use of biochar amendments, Spokas et al. (2012) in a review of fifty studies involving the evaluation of using biochar amendments to soil found that although fifty percent of the reviewed studies reported increased crop yields following biochar amendments, thirty percent of the studies showed no yield impacts, and the remaining twenty percent indicated decreased yields.

Why regional modeling may be helpful

Utilizing general circulation models (GCMs), previous researchers have routinely used global and national contexts to evaluate the possible changes caused by climate change on agriculture (Parry et al., 1999; Reilly et al., 2003; Rosenberg, 1992). However, the resolution scale at which national and global scale simulations have been performed are seen as too coarse for detailed implications of climate change impacts (Gates, 1985). The main concern with using GCMs for regional predictions of climate change impacts arises since regional impacts of climate change may not be sufficiently detailed using a resolution of 100 kilometers that is typical for most GCMs. This lack of resolution becomes troublesome when evaluating climate change impacts at the regional level.

This article will discuss high-resolution regional modeling simulations used in an evaluation of future climate change impacts and the effectiveness of proposed adaptation practices (biochar application and irrigation) to alleviate the impacts on C_3 and C_4 crop yields 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 US Department of Energy funded this project and selected the ten Southeastern US states, in which representative farms were located and for which simulations were performed.

Research objectives

The objectives of this study were:

1. Evaluate how future climate change as predicted using four regional climate models (RCMs) affect temperature and precipitation in different regions of the Southeastern United States.
2. Compare differences in historical baseline and predicted corn (*Zea mays* L.) and soybean (*Glycine max* L.) yields, as well as aggregated yields of C_3 and C_4 crops for the four RCMs.
3. Compare the predicted corn and soybean yields as well as aggregated yields of C_3 and C_4 crops for the four RCMs during the 2038 – 2068 period
4. Evaluate the effectiveness of biochar soil amendments and irrigation on corn and soybean yields within the different RCMs as well as on the aggregated yields of C_3 and C_4 crops.

Materials and Methods

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 and selected soil physical properties. EPIC is a widely tested model originally built to quantify the effects of soil erosion and agricultural productivity. EPIC operates on a daily time step and can perform long-term simulations (hundreds of years) on watersheds up to 100 ha. Since its inception, the EPIC model has evolved into a comprehensive agro-ecosystem model. 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. EPIC can simultaneously model the growth of about 100 plant species including crops, native grasses, and trees; in addition 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 application and development was presented by Gassman et al. (2004).

EPIC has undergone many improvements and intensive testing under diverse climate, soil, and management environments. Recently, several improvements have been made in EPIC and include the implementation of a coupled carbon-nitrogen submodel to simulate terrestrial carbon dynamics as effected by environmental and management factors. A detailed description of the new C and N algorithms can be found in Izaurralde et al. (2006).

Among a variety of available simulation models, EPIC has proven to be one of the most reliable in its accuracy to predict crop/biomass production based on climatic, soil, operational management, and other relevant data. Long-term field experiments have verified reasonable precision in representing these interactions in the US and Canada (Izaurralde et al., 2005; Izaurralde et al., 2006). EPIC 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, and other countries (Apezteguia et al., 2009; Chavas et al., 2009; Costantini et al., 2005; Diaz et al., 1997; Edmonds and Rosenberg, 2005; Thomson et al., 2006).

In a previous publication (Lychuk et al., 2014), we updated the original EPIC model with algorithms describing the influence of biochar amendments on crop yields and important soil properties, and verified EPIC's performance for predicting the short and long term impacts of using biochar amendments for crop production. For this modeling study, this newly updated biochar enhanced version of the EPIC model was used.

Climatic input data and scenario runs

For this study, 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 data from 1979 to 2009 were obtained from NOAA's North America Regional Reanalysis (NARR) database (Mesinger, 2004). NARR is a long-term, consistent high-resolution (on a scale of about 100 meters) 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 data for the future scenario runs of 2038 to 2068 were obtained from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP provides high resolution future climate scenario data for most of the North America continent using regional climate models, coupled global climate models, and time-slice experiments (Mearns, 2007, updated 2012). The year 2038 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, 2007a). 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 and 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 ppm. The future weather simulations were conducted under a CO_2 concentration of 500 ppm. 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). The biochar was incorporated in the soil with a single pass of a disc harrow to a depth of 5 cm one month prior to planting. Biochar used 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. 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.

For future weather simulations, four regional climate models (RCMs) were used that had boundary conditions defined by global models. The RCMs used in this study were:

- The Canadian Regional Climate Model with the Third Generation Coupled Climate Model (CRCM CGCM3)
- The Hadley Regional Model and the Hadley Coupled Model version 3 (HRM3 HADCM3)
- The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model (RCM3 CGCM3)
- The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory GCM (RCM3 GFDL).

Table 4.1 summarizes the regional distribution of air temperatures and precipitation under baseline (NARR) conditions and deviations from the historical baseline predicted by the four RCMs.

Table 4.1. Regional distribution of air temperatures and precipitation under historical baseline North America Regional Reanalysis (NARR, 1979 - 2009) conditions and deviations from the baseline predicted by the four regional climate models* (RCMs) over the future 30-year simulation period (2038 – 2068).

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	2.3	3.3	1.6	1.9	2.4	2.6	3.3	3.2	3.0	2.6
HRM3	0.2	2.6	1.0	1.4	2.9	2.2	2.6	4.1	3.1	1.8
RCM3C	0.5	0.4	-1.6	-1.4	0.4	-0.9	-0.3	1.7	0.7	-1.2
RCM3G	-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	-1.5	-0.5	-1.6	-1.1	-1.0	-0.1	-0.4	-0.1	-0.5	-2.0
HRM3	-1.3	1.96	0.2	0.6	0.9	1.5	1.8	2.9	2.1	1.5
RCM3C	-1.0	-0.8	-2.1	-1.2	-1.1	-1.2	-1.1	0.1	-0.6	-2.2
RCM3G	-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	-87	-80	107	-141	211	-432	-199	-15	-66	-194
HRM3	51	69	262	67	254	-360	-59	97	-7	4
RCM3C	42	68	631	265	126	-186	-99	232	40	25
RCM3G	-48	-28	494	204	105	-188	-157	81	-60	101

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

For simplicity, we will refer to these regional climate models as CRCM, HRM3, RCM3C, and RCM3G. Regional climate models are used to project different patterns of changes in air temperatures, precipitation, and solar radiation that are expected to occur over time. All future weather simulations were part of the A2 scenario from the Special Report on Emissions Scenarios (SRES) (IPCC, 2000). The A2 scenario assumes a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in some other scenarios.

The representative farms approach, as proposed by Easterling et al. (1993) 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. Soil types and their properties used in the simulations are shown in Table 4.2

Table 4.2 Soil types and their properties used in Environmental Policy Integrated Climate model simulations

Representative farms located in the following 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

Simulations were performed on farms using typical existing technologies and management practices. The EPIC model was updated with crop varieties used in simulations according to the region in which they were grown. All representative farms in the Southeastern region drain to the Mississippi river or directly to the Gulf of Mexico. 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 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 nitrogen, 50 kg ha^{-1} of phosphorus 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 crops (soybean, alfalfa (*Medicago sativa* L.), and winter wheat (*Triticum aestivum* L.)) and three C_4 crops (corn, sorghum (*Sorghum bicolor* L.), and pearl millet (*Pennisetum glaucum* L.).

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 periods of the regional 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 2 x 2 factorial combinations of biochar and irrigation. The subplot factors were corn or soybean and 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 (2038 - 2068). Periods for the future scenarios were averaged for 5 year interval periods and were treated as repeated measures. Future scenarios were not statistically compared across RCMs because one of the reasons the regional climate models were created were to have statistically different weather scenarios. A second reason that the regional climate models were not included into the statistical analyses were that their inclusion created an excessive number of complex interaction effects that made data analysis and interpretation impossible. Comparisons were made (1) between baseline and future scenarios and (2) between the 5 year periods within each future climate scenario.

All statistical analyses were performed using the MIXED Procedure in SAS v. 9.3 (SAS Institute, 2013). We evaluated the crop yields as response variables. The LSD-adjusted significant differences (following a significant F test) were used for multiple mean comparisons.

In total, there were six groups of comparisons made in this study.

1. Comparison between past (baseline) and future corn yield predicted by the four regional climate models/scenarios.

2. Comparison between past (baseline) and future soybean yield predicted by the four regional climate models/scenarios.
3. Comparison between past (baseline) and future yield for C3 and C4 crop types predicted by the four regional climate models/scenarios.
4. Comparisons between future corn yields predicted by the four regional climate models/scenarios.
5. Comparisons between future soybean yields predicted by the four regional climate models/scenarios.
6. Comparisons between future yields for C3 and C4 crop types predicted by the four regional climate models/scenarios.

Results and Discussion

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

Three of the four RCM models predicted statistically significant differences between the baseline and the future corn yields with yield increases from 36 to 84% when compared to the baseline scenario (Table 4.3). The reasons for these increases in corn yields were associated with greater availability of soil moisture resulting from greater rates of precipitation. There was a statistically significant region x climate model interaction in case of the RCM3C model that indicated that all the regions did not behave in the same manner for this regional climate model. This finding is in agreement with Izaurralde et al. (2003) who simulated effects of climate change on corn yield in the United States using the Hadley Center model. They found that corn yields in the Southeastern US will increase, compared to historical baseline scenario, with an average value of about 10%, depending on the region. For the soybean yields, there was a trend in the data that suggested decreased soybean yields for all RCM models when compared to the baseline yields, but no statistically significant differences were detected (Table 4.3). This finding was also similar to the conclusions reached by Izaurralde et al. (2003) who found that future climate change impacts on soybean yields in the Southeastern US would result in yield decreases.

Table 4.3 Comparisons between predicted corn and soybean yields using historical baseline climate data and regional climate models* data. Letters within the same column indicate LSD mean differences at $P < 0.05$

Model	Crop Yield (Mg ha^{-1})	
	Corn	Soybean
NARR (baseline)	6.43a	0.92a
CRCM	11.78b	0.96a
HRM3	10.31b	0.84a
RCM3G	8.77b	0.82a

*(NARR – Historical baseline climate scenario; CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - The Hadley Regional Model and the Hadley Coupled Model version 3; RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

Different regions exhibited different corn yield responses. For example, the RCM3C model displayed statistically significant increases in corn yields for the South and West regions, but not for the North region (Fig. 4.1). When examining soybean yields for the RCM3C model, the North region displayed a 20% decreased yield that was statistically significant, the South region displayed no significant differences in yields, and the West region displayed a 35% yield increase that was statistically significant (Fig. 4.2). These differences resulted from variations in moisture availability and temperature stresses in different regions.

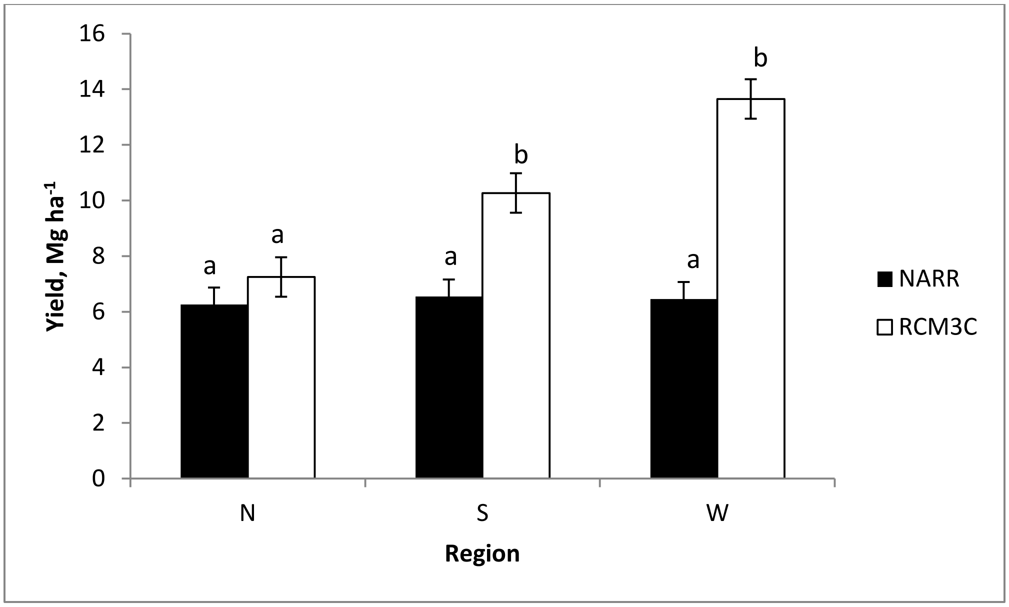


Fig. 4.1 Comparison of corn yields for the North (N), South (S), and West (W) regions using the 1979 – 2009 the NARR (Historical baseline climate scenario) data and predicted yields for the RCM3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate model. Letters indicate LSD (Least significant differences) mean differences at $P < 0.05$.

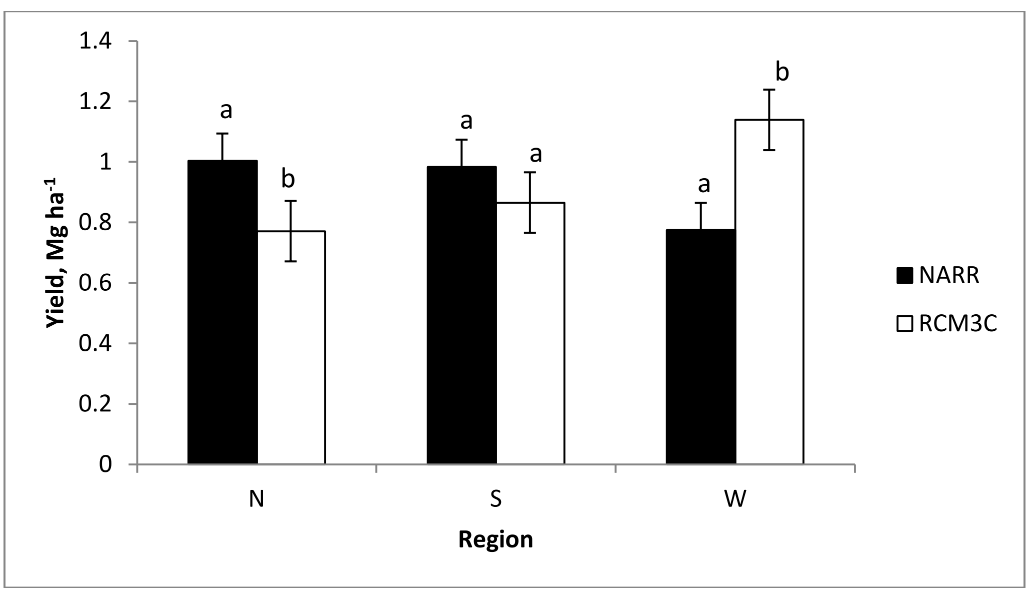


Fig. 4.2 Comparison of soybean yields for the North (N), South (S), and West (W) regions using the 1979 – 2009 the NARR (Historical baseline climate scenario) data and predicted yields for the RCM3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate model. Letters indicate LSD (Least significant differences) mean differences at $P < 0.05$.

C_3 and C_4 Crop Types: Historical Baseline Yield vs. Future Yield Comparison

There was a significant region x RCM interaction for the RCM3C model. Differences in crop yields were not statistically significant between the historical baseline and future climate predicted by the RCM3C model for the North and South regions (Table 4.4).

Table 4.4 Comparison between historical baseline and future combined crop yields using the RCM3C regional climate model. Crop yields are reported based on combined yields due to the absence of significant interactions between crop type and model. Letters within the same column indicate LSD mean differences at $P < 0.05$.

Model*	Aggregated Crop Yields, Mg ha^{-1}	
	North Region	South Region
NARR (baseline)	3.74a	4.22a
RCM3C	3.54a	4.65a

*(NARR – Historical baseline climate scenario; RCM3C - The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; LSD – Least significant differences)

Significant yield differences were displayed for the RCM3C model's North and South regions simulations (Table 4.5) with C_4 crops producing significantly higher aggregated yields in comparison to the C_3 crops.

Table 4.5 Aggregated crop yields of C_3 and C_4 crops for the North and South regions across RMC3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate model. Letters within the same column indicate LSD* mean differences at $P < 0.05$.

Crop Type	Aggregated Crop Yields, Mg ha^{-1}	
	North Region	South Region
C_3	2.42a	2.54a
C_4	4.86b	6.33b

*(LSD – Least significant differences)

For the West region, there was a significant RCM x crop type interaction for the RCM3C model with significant increases of up to 85% in aggregated crop yields for the C_4 crops in comparison to the historical baseline scenario. No significant differences were detected between baseline and future aggregated yields for the C3 crops (Fig. 4.3).

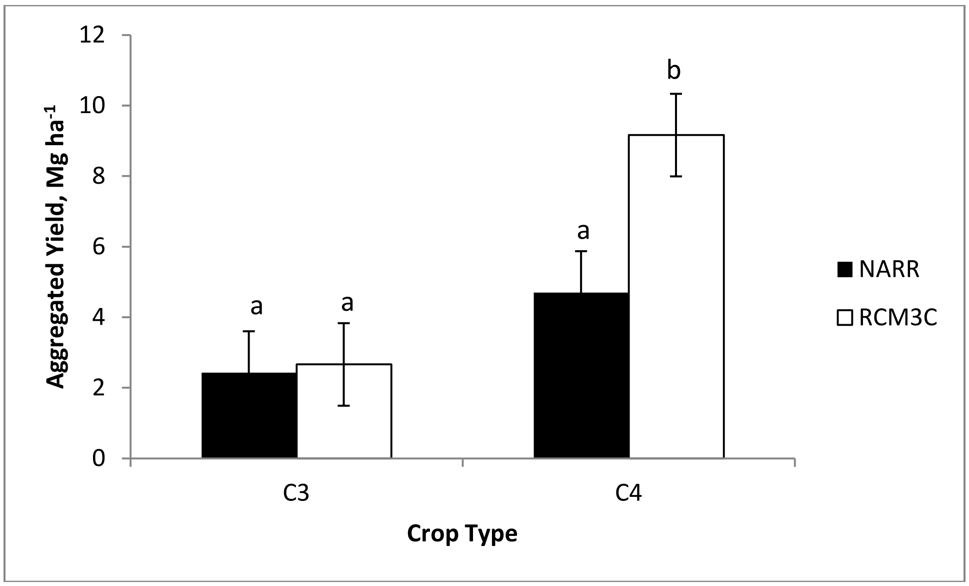


Fig. 4.3 Comparison of aggregated yields in the West region for C_3 and C_4 crops using the NARR (historical baseline climate scenario) and future climate predicted by the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate model. Letters indicate LSD (Least significant differences) mean differences at $P < 0.05$.

Significant interactions did not exist between crop type and model indicating that aggregated yields for C_3 and C_4 crops behaved similarly across all RCMs. For example, differences in aggregated yields for C_3 and C_4 crop types were not statistically significant between the historical baseline and the future climate predicted by the RCM3G model across all regions based on the model main effects. However, the crop type main effect was significant, with C_4 crops producing more than twice the aggregated yield compared to C_3 crops in the case of RCM3G regional climate model (Fig. 4.4). We concluded that C_4 crops may be better adapted to heat and moisture stresses associated with climate change due to their better tolerance of higher temperatures and high light intensities when compared to C_3 crops.

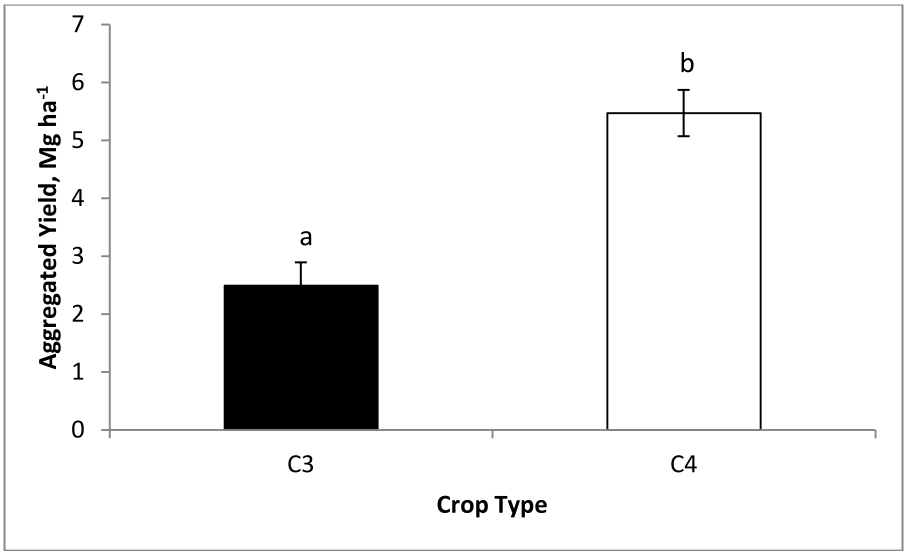


Fig. 4.4 Comparison of aggregated yields for C_3 and C_4 crops using the NARR (Historical baseline climate scenario) and future climate predicted by the RCM3G (The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) regional climate model. Letters indicate LSD (Least significant differences) mean differences at $P < 0.05$.

When comparing aggregated yields for the CRCM and HRM3 regional climate models in comparison to the historical baseline scenario, there were significant RCM x crop type interactions with significantly increased aggregated yields of up to 50% for the C_4 crops under the CRCM regional climate model and significantly increased aggregated yields of up to 45% for the C_4 crops under the HRM3 regional climate model. No significant differences were detected between baseline and future aggregated yields for the C_3 crops (Fig. 4.5 and 4.6).

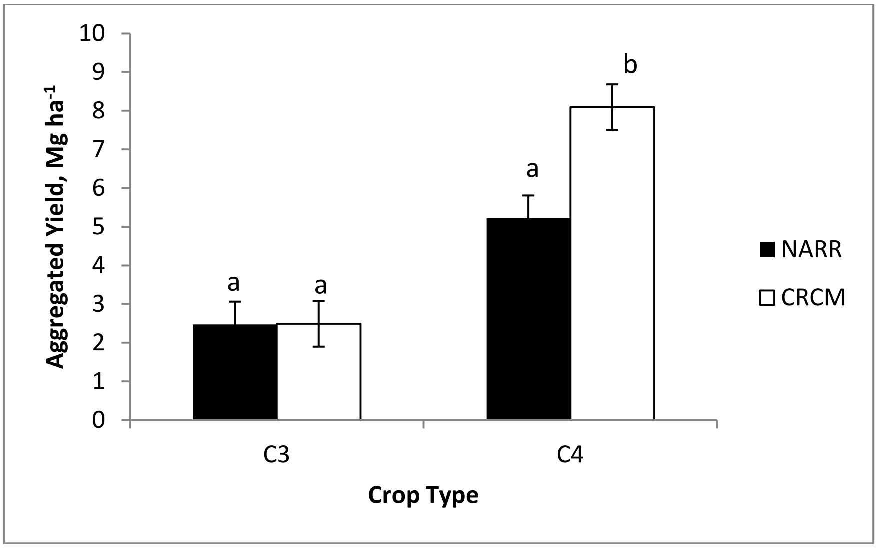


Fig. 4.5 Comparison of aggregated yields for C_3 and C_4 crops using the NARR (historical baseline climate scenario) and future climate predicted by the CRCM (the Canadian Regional Climate Model with the Third Generation Coupled Climate Model) regional climate model. Letters indicate LSD (Least significant differences) mean differences at P < 0.05.

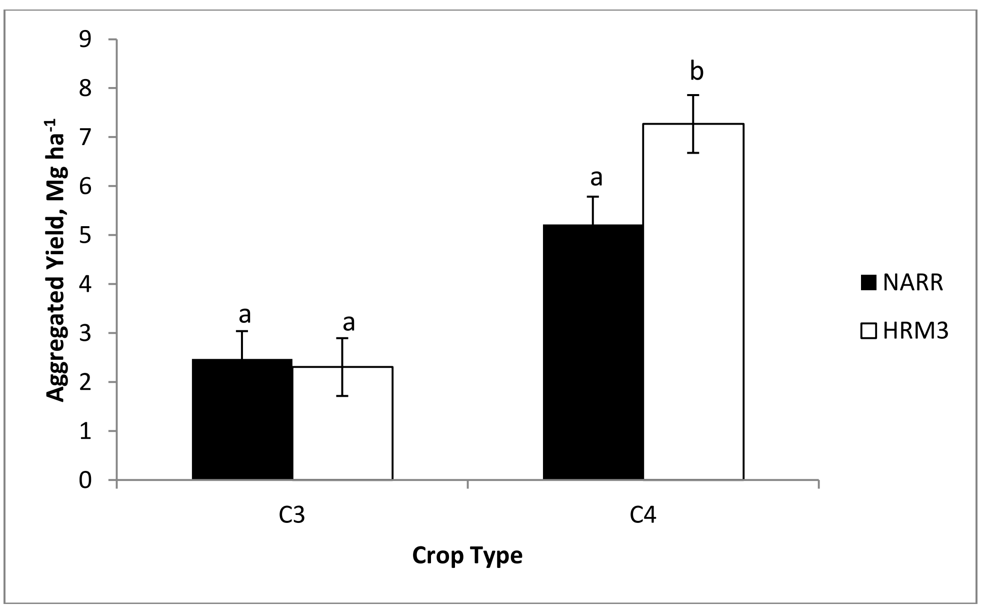


Fig. 4.6 Comparison of aggregated yields for C_3 and C_4 crops using the NARR (historical baseline climate scenario) and future climate predicted by the HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3) regional climate model. Letters indicate LSD (Least significant differences) mean differences at P < 0.05.

Climate and Adaptation Effects on Future Predicted Corn Yields

There were statistically significant region x RCM interactions for all RCM models requiring that the data be analyzed separately by each region and model. By the end of the final year of the future simulation period (2068), corn yields for all RCMs displayed significant declines of 3-15% for all models across all regions (Table 4.6) in comparison with the beginning year of the future simulation period (2038). Yield decreases were primarily associated with increased number of days with temperature stress, as future climate progressed toward the end of the final year of simulation. These results support findings of Tsvetsinskaya et al. (2003) who investigated regional impacts of climate change on corn yields in the Southeastern US. According to their findings, projected declines in corn yields due to climate change ranged between 0 to 40%, depending on the region within the Southeastern US. Similarly, Easterling et al. (2003) found reductions of corn yields between 10 to 30% for the North region of the Southeastern US in the case when no adaptation measures were taken to alleviate climate change impacts.

Irrigation had significant impacts on corn yields for the North and South regions using the RCM3C and RCM3G models with yield increases up to 33% (Table 4.6). For all other RCMs across all other regions, data suggested a trend in increased corn yields due to irrigation, but the patterns of increased corn yields were not statistically significant (Table 4.6). The reasons for the weaker than expected response to irrigation was observed is because all RCMs used in this simulation study are stochastic models that do not predict extreme events like droughts and occurrence of very intense rainfalls. Instead, these models operate with weather patterns on average basis, i.e. they envisage 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. It is also important to note that all four regional climate models predicted increases in average annual precipitation rates and this may also help explain the lack of a statistically significant uniform positive response to irrigation (Table 4.1). The effects of biochar application on future corn yield was not significant in cases of the North region across all RCMs, the West region for the HRM3 and the RCM3G model, and the South region for the RCM3C and the RCM3G models (Table 4.6).

The period x biochar interaction was significant for the CRCM model's predictions for the South region and displayed a significant 12% decline in corn yields during the last ten years of annual biochar applications (Table 4.7). In the West region, the CRCM and RCM3C models predicted significant declines of 16% and 20%, respectively, in corn yields during the last five years of annual biochar applications. In the South region using the HRM3 regional climate model, the period x biochar interaction was significant indicating that biochar applications do not result in a uniform response for corn yields across all time periods. However, when the biochar simple effects were examined across all future climate periods using the HRM3 model, there were no significant differences in yield responses attributable to biochar applications (Table 4.7).

Table 4.6 Climate adaptation effects on predicted corn yields (Mg ha^{-1}) for four regional climate models. Letters within the same column for each effect indicate LSD mean differences at $P < 0.05$.

Effect		Regional Climate Model*											
		CRCM			HRM3			RCM3C			RCM3G		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Period (years)	2038-2042	11.14a	-	-	10.73a	-	9.76a	8.53b	11.84a	-	8.36abc	11.26ab	11.07a
	2043-2047	10.9ab	-	-	10.33ab	-	9.12b	9.07a	11.22b	-	7.91bc	10.72bc	9.24cd
	2048-2052	10.31cd	-	-	10.33ab	-	9.72a	7.82c	11.3b	-	8.4ab	11.6a	10.28b
	2053-2057	10.15cd	-	-	10.2b	-	9.92a	8.38b	10.51c	-	8.45ab	11.25ab	9.3cd
	2058-2062	10.48bc	-	-	10.4ab	-	8.72c	8.46b	10.98bc	-	8.66a	10.58cd	8.74d
	2063-2068	9.82d	-	-	9.59c	-	9.25b	7.89c	11.05b	-	7.78c	10.1d	9.74bc
Irrigation	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
Biochar	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

*(NARR – Historical baseline climate scenario; CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - The Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD - Least significant differences)

Table 4.7 The effects of biochar applications on corn yields ($Mgha^{-1}$) for different interval periods under each different regional climate model. Letters within the same column for each period indicate LSD mean differences at $P < 0.05$.

Effect		Biochar	Model*			
			CRCM		HRM3	RCM3C
			Region			
			South	West	South	West
Period x Biochar	2038-2042	No	12.45a	12.54a	11.50a	14.03a
		Yes	12.42a	12.54a	11.49a	14.02a
	2043-2047	No	12.18a	12.40a	11.27a	13.82a
		Yes	12.03a	12.41a	11.26a	13.81a
	2048-2052	No	12.36a	12.75a	11.71a	13.89a
		Yes	11.87a	12.72a	11.37a	13.58a
	2053-2057	No	12.30a	12.70a	11.62a	13.69a
		Yes	11.59a	12.43a	11.05a	13.18a
	2058-2062	No	12.16a	12.40a	11.18a	13.31a
		Yes	11.11b	11.73a	10.31a	12.36a
	2063-2068	No	12.19a	12.65a	11.49a	13.17a
		Yes	11.26b	11.06b	10.44a	11.16b

*(NARR – Historical baseline climate scenario; CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - The Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD - Least significant differences)

Climate and Adaptation Effects on Future Predicted Soybean Yields

There were significant region x model interactions across all regions that required the data to be analyzed separately for each region and model (Table 4.8).

Soybean yields displayed significant declines of 3% to 15% in comparison with the beginning year of the future simulation period (2038) for the CRCM and the HRM3 model's North region, the RCM3C model's South region, and the RCM3G model's South and West regions. As in the case with declines in corn yields, future declines in soybean yields were associated with an increased number of days with temperature stress, as future climate progressed toward the end of the final year of simulation. For all other RCMs and regions, there were declining trends in soybean yields although no statistical differences were observed (Table 4.8). Our findings on soybean yields seem to be in agreement with the results obtained by Carbone et al. (2003) who simulated effects of climate change on soybean yields in the Southeastern US. They found 10-30% decreases in soybean yields in the region due to climate change.

Irrigation and biochar applications displayed no effects on soybean yields for any RCM across all regions. There were general positive trends in the data indicating a positive response of irrigation on soybean yields, but these trends were not statistically significant (Table 4.8). This lack of statistical significance for irrigation effects on soybean yields is attributed to the increases in the average annual precipitation rate inherent in all the RCMs that created soil conditions such that the soybean crops were not subjected to water stress and irrigation was not required.

Table 4.8 Climate and adaptation effects on predicted soybean yields (Mg ha^{-1}) for each regional climate model. Letters within the same column for each effect indicate LSD mean differences at P < 0.05.

Effect		Model*											
		CRCM			HRM3			RCM3C			RCM3G		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Period (years)	2038-2042	1.01a	0.95a	1.01ab	0.91a	0.91a	0.75ab	0.81bc	0.96a	1.14a	0.84ab	0.87a	1.00a
	2043-2047	0.98ab	0.95a	0.99c	0.86c	0.92a	0.71c	0.88a	0.85d	1.13bc	0.78c	0.88a	0.81cd
	2048-2052	0.95b	0.90b	1.01ab	0.89ab	0.87b	0.76ab	0.76d	0.90bc	1.12c	0.87a	0.88a	0.90b
	2053-2057	0.97ab	0.93ab	1.02a	0.88b	0.91a	0.79a	0.78cd	0.84d	1.15a	0.82bc	0.87a	0.82cd
	2058-2062	0.96b	0.96a	1.00b	0.90ab	0.91a	0.68d	0.83b	0.93ab	1.14ab	0.82bc	0.86a	0.77d
	2063-2068	0.95b	0.94a	1.01ab	0.88bc	0.92a	0.73bc	0.78cd	0.88cd	1.14ab	0.80bc	0.78b	0.87bc
Irrigation	No	0.96a	0.94a	1.00a	0.89a	0.91a	0.73a	0.78a	0.86a	1.14a	0.82a	0.83a	0.83a
	Yes	0.98a	0.94a	1.00a	0.89a	0.91a	0.74a	0.84a	0.92a	1.14a	0.82a	0.88a	0.89a
Biochar	No	0.97a	0.94a	1.01a	0.89a	0.91a	0.74a	0.80a	0.89a	1.14a	0.82a	0.86a	0.86a
	Yes	0.97a	0.94a	1.00a	0.88a	0.91a	0.74a	0.81a	0.89a	1.14a	0.82a	0.86a	0.86a

*(NARR – Historical baseline climate scenario; CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - The Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD - Least significant differences)

Future Aggregated Yield Comparisons for C_3 and C_4 Crop Types

There were significant region x model interactions for all RCMs which required that the data be analyzed separately for each region and model. Comparisons of the aggregated yields between C_3 and C_4 crops revealed that there was a significant period x crop type interaction for all models, except for the HRM3 regional model, with C_4 crops displaying significantly higher yields for all climate scenarios across all regions (Table 4.9). As noted above, the C_4 crops seem to be better adapted to climate change than the C_3 crops due to a lesser degree of photorespiration for the C_4 crops under conditions of high light intensities and increased temperatures when compared to the C_3 crops. Aggregated yields for the HRM3 model's South region were the exception as the period x crop interaction was not significant. In this case, the crop type main effect was significant indicating that overall aggregated yield differences existed between the C_3 and C_4 crops with the C_4 crops exhibiting increased yields that was attributable to climate (Fig. 4.7).

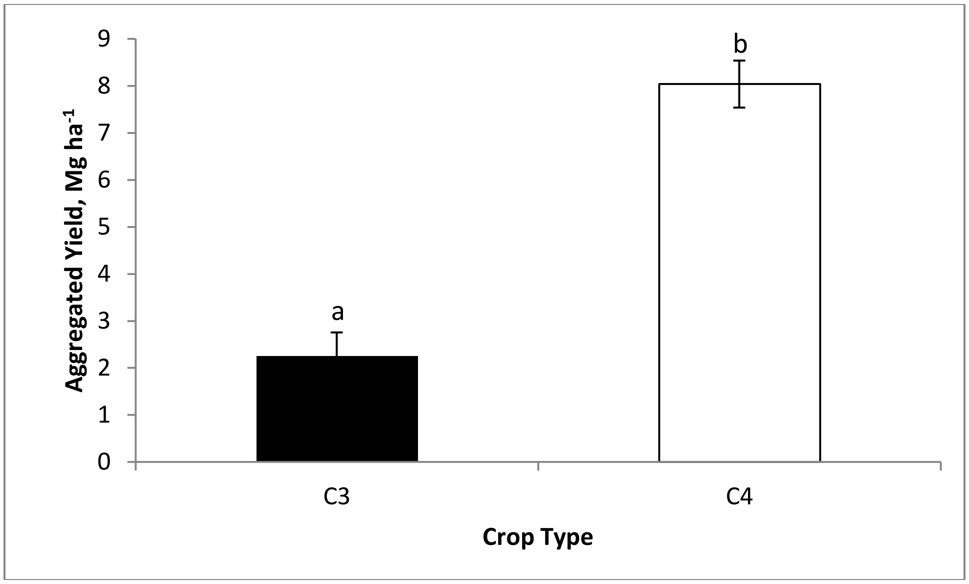


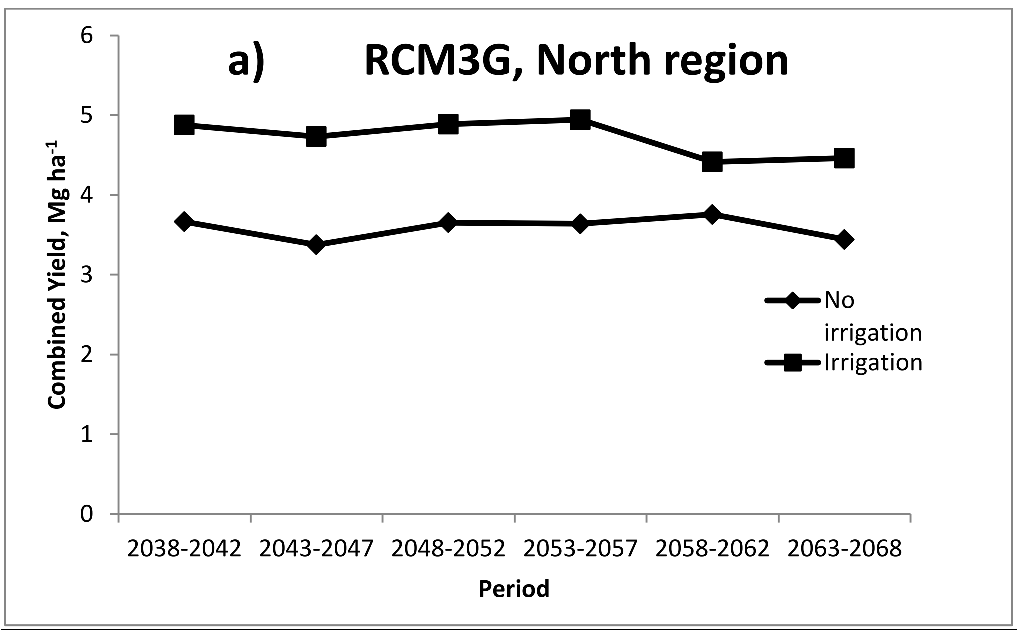
Fig. 4.7 Comparison of the C_3 and C_4 crop aggregated yields for the HRM3 (The Hadley Regional Model and the Hadley Coupled Model version 3) regional model South region. Letters indicate Least significant differences (LSD) in means comparison at $P < 0.05$.

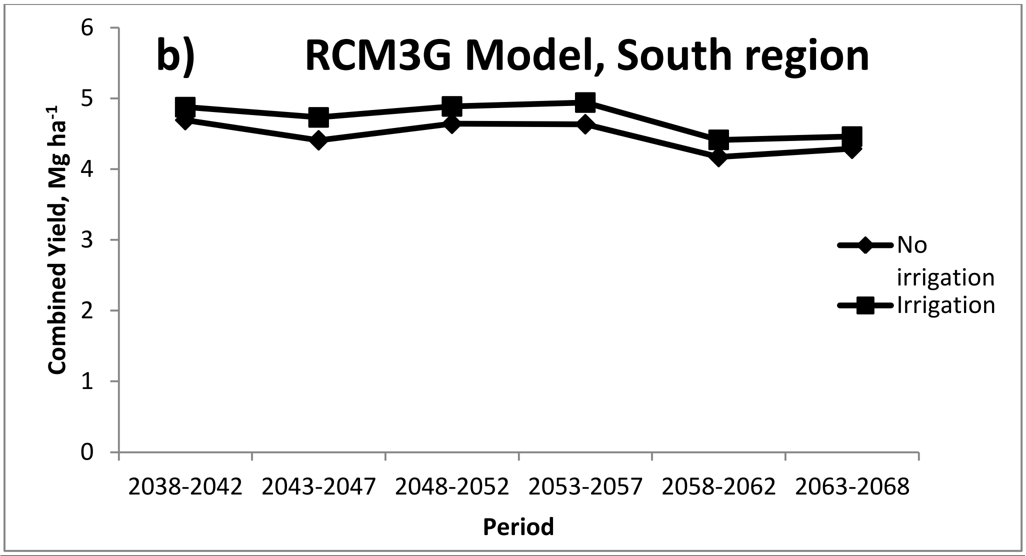
Table 4.9 Comparison of aggregated yields for C_3 and C_4 crops (Mg ha^{-1}) for different time periods under each regional climate model. Letters within the same column for each period indicate LSD mean differences at $P < 0.05$.

Effect		Crop Type	Model*											
			CRCM			HRM3			RCM3C			RCM3G		
			Region											
			North	South	West	North	South	West	North	South	West	North	South	West
Period x Crop Type	2038-2042	C3	2.33a	2.59a	2.74a	2.21a	-	2.61a	2.59a	2.74a	2.80a	2.30a	2.67a	2.94a
		C4	7.47b	8.62b	8.71b	7.41b	-	6.96b	5.58b	7.89b	9.37b	5.27b	7.35b	7.41b
	2043-2047	C3	2.41a	2.60a	2.76a	2.22a	-	2.64a	2.50a	2.74a	2.79a	2.26a	2.59a	2.86a
		C4	7.43b	8.47b	8.69b	7.25b	-	6.50b	5.96b	7.45b	9.33b	5.11b	7.09b	6.26b
	2048-2052	C3	2.32a	2.46a	2.75a	2.14a	-	2.58a	2.39a	2.58a	2.74a	2.22a	2.46a	2.77a
		C4	6.96b	8.36b	8.79b	7.18b	-	6.95b	5.21b	7.60b	9.15b	5.34b	7.60b	6.83b
	2053-2057	C3	2.27a	2.38a	2.59a	2.12a	-	2.47a	2.33a	2.41a	2.58a	2.16a	2.36a	2.77a
		C4	6.83b	8.17b	8.75b	6.95b	-	7.11b	5.50b	7.05b	8.89b	5.27b	7.30b	6.27b
	2058-2062	C3	2.16a	2.26a	2.37a	1.98a	-	2.28a	2.18a	2.29a	2.41a	2.15a	2.31a	2.51a
		C4	7.22b	8.21b	8.43b	7.32b	-	6.31b	5.68b	7.57b	8.87b	5.69b	7.14b	5.95b
	2063-2068	C3	2.13a	2.26a	2.30a	2.01a	-	2.17a	2.02a	2.33a	2.29a	1.96a	2.33a	2.41a
		C4	6.65b	8.12b	8.22b	6.71b	-	6.58b	5.31b	7.28b	8.41b	5.04b	6.77b	6.69b

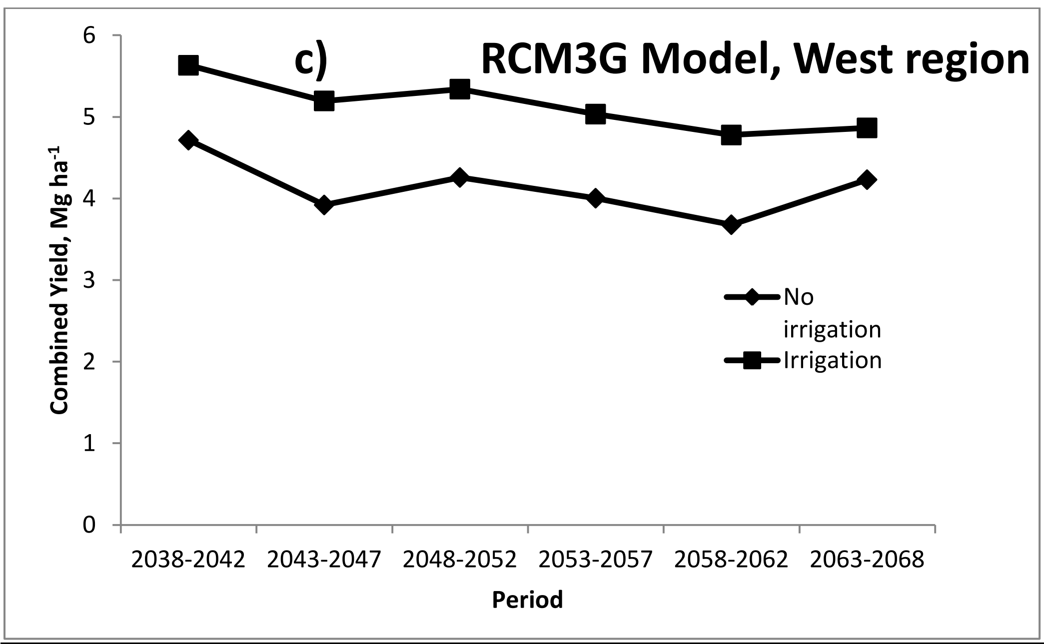
*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD - Least significant differences)

The irrigation treatment displayed a significant period x irrigation interaction with significantly higher combined C_3 and C_4 aggregated yields for irrigation treatments for all three regions using the RCM3G model, the South region using the RCM3C model, and the West region using the HRM3 model (Fig. 4.8). Yield increases that were attributable to irrigation ranged from 2% to 35%. For all other regions and models, the combined C_3 and C_4 aggregated yields displayed trends in the data that suggested irrigation caused increases in the combined aggregated yields, however, no statistically significance differences were detected.

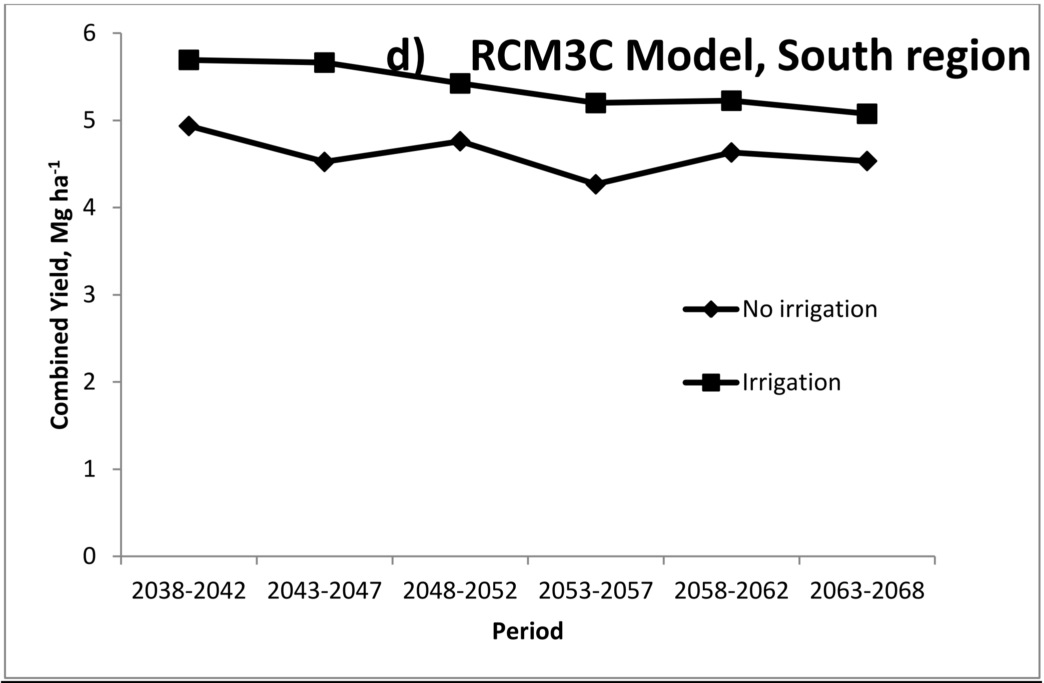




b) RCM3G Model, South region
Combined Yield, Mg ha-1
0
1
2
3
4
5
6
No irrigation
Irrigation
2038-2042
2043-2047
2048-2052
2053-2057
2058-2062
2063-2068
Period



c) RCM3G Model, West region
Combined Yield, Mg ha-1
0
1
2
3
4
5
6
No irrigation
Irrigation
2038-2042
2043-2047
2048-2052
2053-2057
2058-2062
2063-2068
Period



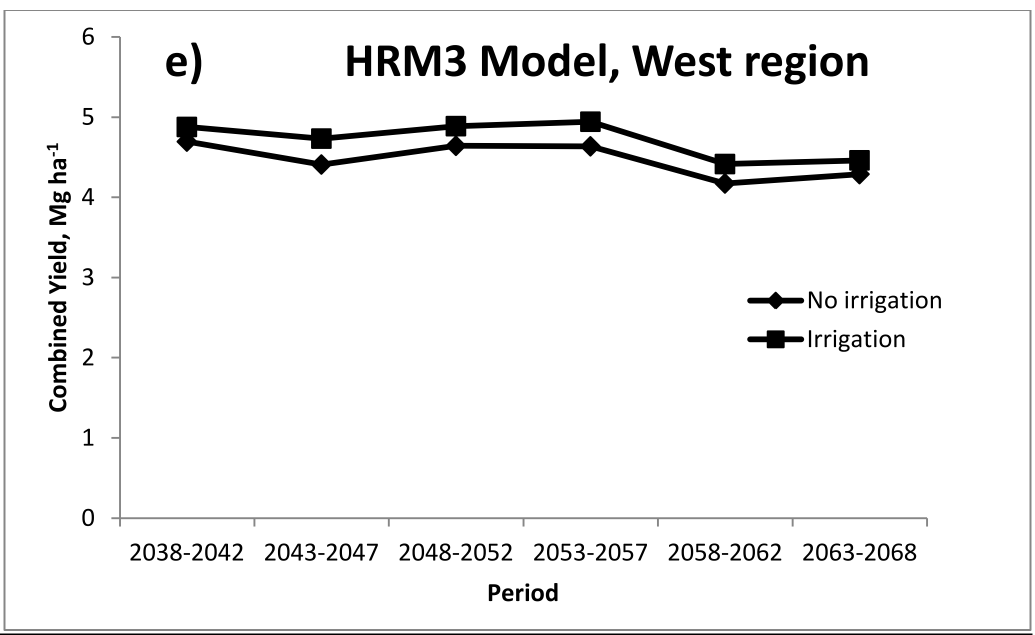
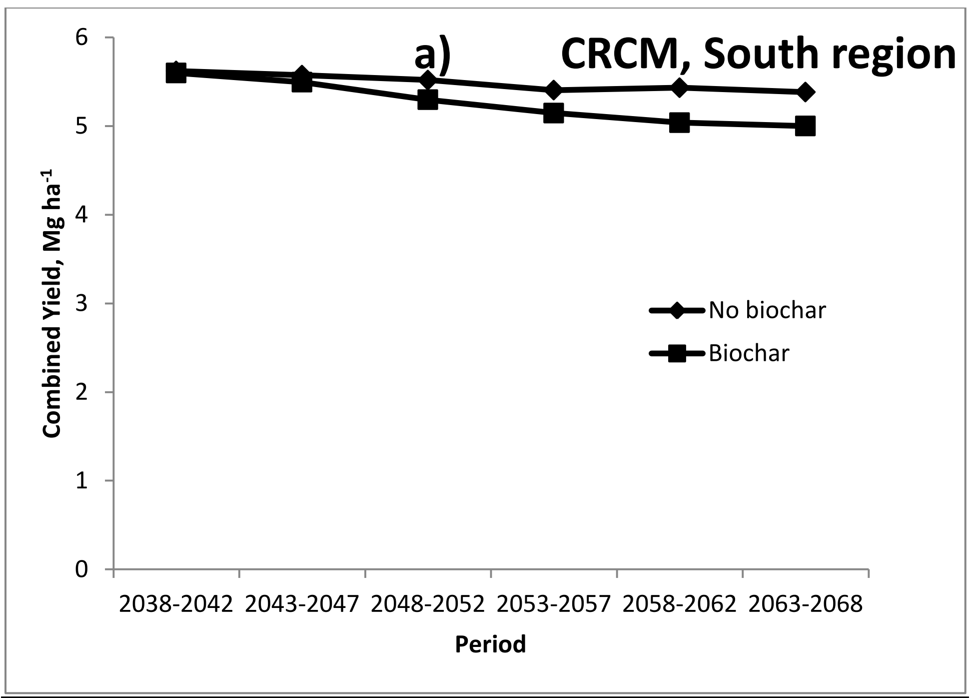
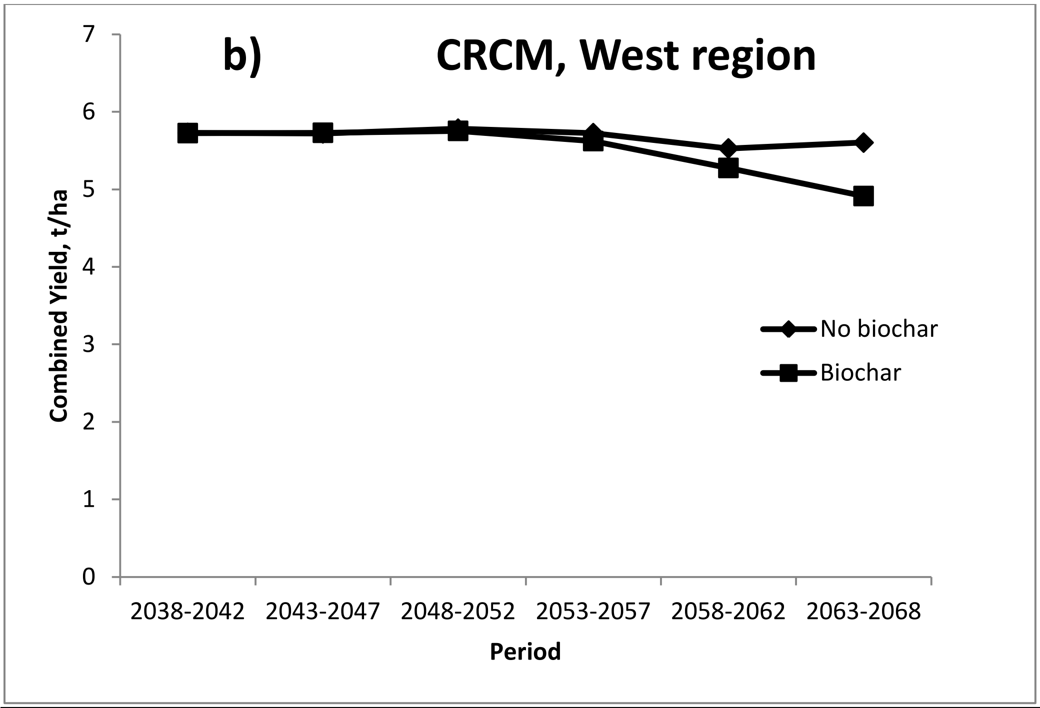
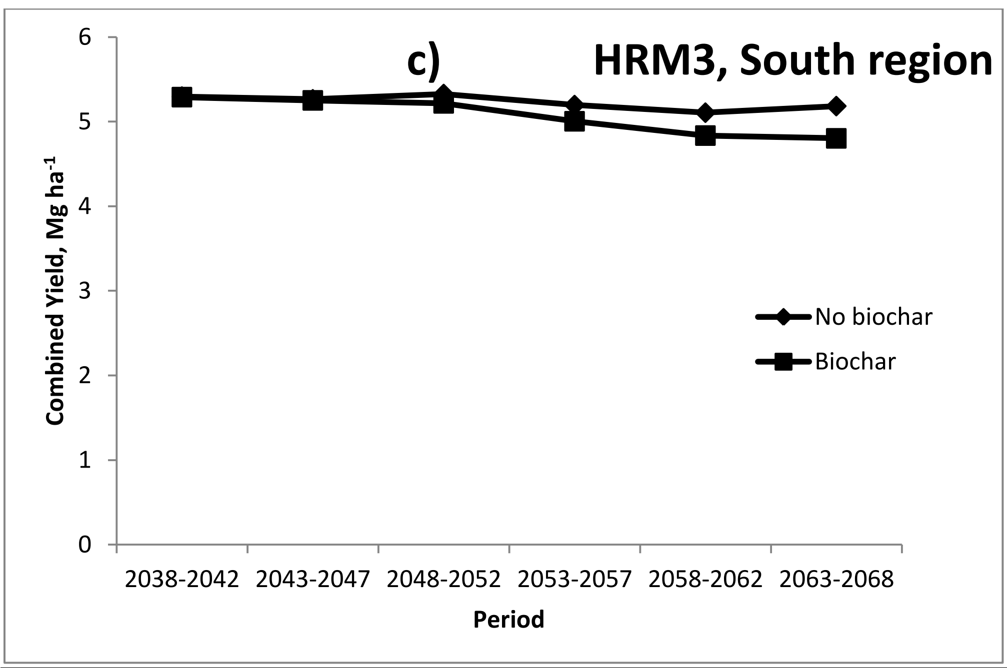


Fig. 4.8 Effects of irrigation on the combined C_3 and C_4 aggregated yields during different time interval periods for the 2038 to 2068 period for different regions and climate change scenario models identified as RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) for the (a) North, (b) South, and (c) West regions, RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) for the (d) South region and the HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3) for the (e) West region

Analyses of the aggregated yields of C_3 and C_4 crops over time intervals that had received biochar treatments displayed significant period x biochar interactions for the South and West regions under the CRCM model, the South region under the HRM3 model, and the West region under the RCM3C model. For the above stated regions and models, biochar treatments significantly reduced yields by 1% to 20% (Fig. 4.9). For all the other regions and models, the yields displayed trends in the data that suggested biochar applications caused decreased yields, however, no statistically significance differences were detected.




b)
CRCM, West region
Combined Yield, t/ha
7
6
5
4
3
2
1
0
No biochar
Biochar
2038-2042
2043-2047
2048-2052
2053-2057
2058-2062
2063-2068
Period


c)
HRM3, South region
Combined Yield, Mg ha-1
6
5
4
3
2
1
0
No biochar
Biochar
2038-2042
2043-2047
2048-2052
2053-2057
2058-2062
2063-2068
Period

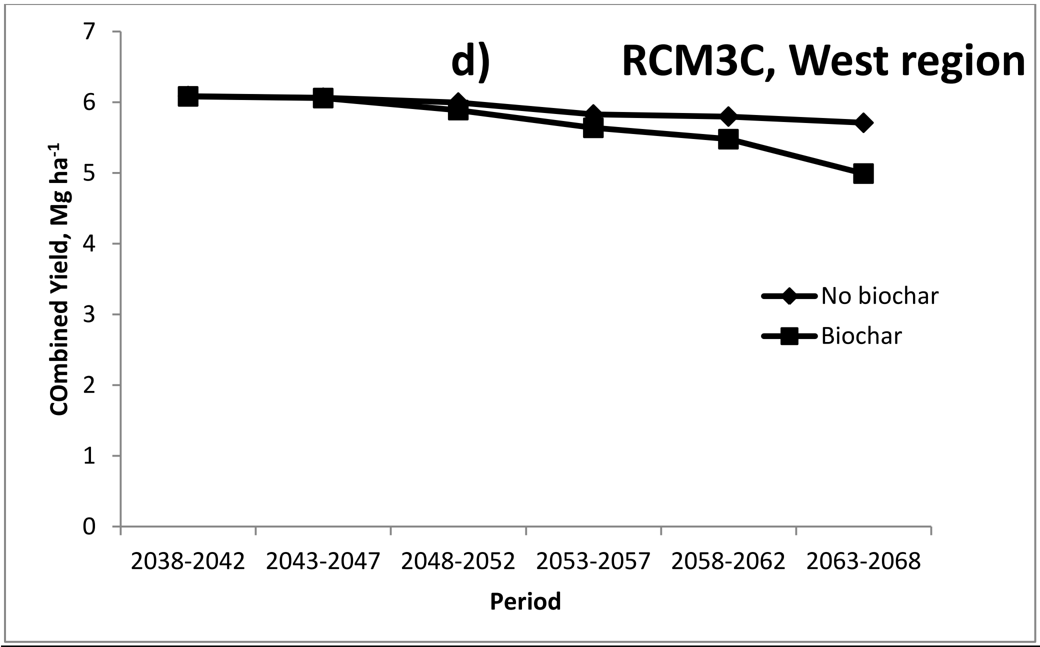


Fig. 4.9 Effects of biochar applications on the combined C_3 and C_4 aggregated yields during different time interval periods for the 2038 to 2068 period for different regions and climate change scenario models identified as the CRCM (the Canadian Regional Climate Model with the Third Generation Coupled Climate Model) for the (a) South and (b) West region, HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3) for the (c) South region, and the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) for the (d) West region.

Summary and Conclusions

The four regional climate models used in this study showed a wide range of differences in maximum and minimum air temperatures, as well as differences in precipitation for the regions of interest. Generally, the CRCM and HRM3 models predicted increased maximum daily air temperatures, while the RCM3C and the RCM3G models predicted decreased maximum daily air temperatures. All models except for the HRM3 model predicted decreased minimum daily air temperatures. Models generally predicted increased precipitation for the Southeastern US which partially explains a weaker than expected crop response to the irrigation for some of the models.

Differences in corn and soybean yields were indicated in response to climate change for different regions of the Southeastern US. Compared to the historical baseline, corn yields increased; however, predictions also indicated corn yields decreased by 12% due to the continually increased temperature and moisture stress by the end of the 2038 – 2068 simulation period if adaptation measures were not implemented. Irrigation resulted in an increase of up to 33% in corn yields that was statistically significant for the RCM3C and RCM3G regional climate models. There was a positive corn yield response to irrigation for the CRCM and HRM3 models, but the positive response was not statistically significant. The stochastic models used in this simulation study do not directly predict extreme events like droughts and partially helps explain why a weak response to irrigation was observed. Contrary to the expectations, biochar applications resulted in decreased corn yield for the CRCM, RCM3C and HRM3 regional models, but not for the RCM3G regional climate model.

A decreasing trend was generally observed for soybean yields when compared with the historical baseline yields, although the differences in soybean yields were not statistically significant. Soybeans had statistically significant decreased yields by up to 15% by the end of the simulation period in 2068 for the South and North regions of the Southeastern US when the climate scenarios presented by the CRCM, HRM3 and RCM3G models were used in the simulations. Yield decreases in soybean were associated with a greater number of days with temperature stress toward the end of the final year of future simulation period (2068). Even though a trend in the data suggested positive soybean yield responses to irrigation, irrigation and/or annual biochar applications had no significant effects on soybean yields for any of the regions using any of the regional climate models. This lack of statistical response is primarily attributed to increased annual precipitation predicted by all four regional models such that the soybean crops were not subjected to water stress.

The models varied in their predictions for the historical baseline and future comparisons of the aggregated yields of the grouped C_3 and C_4 crops. No statistically significant differences were found between C_3 and C_4 aggregated crop yields for the historical baseline and future climate comparisons for the North and South regions when using the RCM3C model and all regions when using the RCM3G model. In the simulation for the West region when using the RCM3C model, the C_4 crops produced increases in aggregated yields that were generally twice the quantities of increases observed for the C_3 aggregated crop yields. When comparisons were made between historical baseline and CRCM and HRM3 regional climate models, significant RCM x crop type interactions were observed. It was determined that the C_4 crops generally produced higher aggregated yields when compared to the C_4 historical baseline aggregated yields. The historical baseline aggregated yields of the C_3 crops do not differ compared to the C_3 aggregated yields predicted when using either the CRCM or the HRM3 regional climate models. Comparisons of the future (2038 – 2068) aggregated yields between the C_3 and C_4 crops revealed that the C_4 crops displayed significantly higher yields for all climate scenarios across all regions, with the exception of the HRM3 regional model. We concluded that the C_4 crops, which had greater yields, seemed to be better adapted to climate change than C_3 crops due to a lesser degree of photorespiration for the C_4 crops under conditions of high light intensities and increased temperatures when compared to C_3 crops.

With the exception of the South region when using the HRM3 model, the C_4 crops produced significantly higher aggregated yields compared to the aggregated yields of the C_3 crops for the 2038 to 2068 interval periods when using any of the regional climate models. Irrigation resulted in statistically significant increased aggregated yields of up to 35% for the combined crop yields within all regions when using the RCM3G model with similar results presented for several regions when using the RCM3C and HRM3 models. Corn and soybean crops both exhibited decreased crop yields when annual biochar applications were used. Similarly, there were decreased aggregated yields observed for the combined C_3 and C_4 crops after annual biochar applications. The regional combined yields were significantly lower towards the end of the 2038 to 2068 simulation period when using the CRCM, HRM3, or RCM3C models.

The results of this study demonstrated that climate change can be expected to affect the regions of the Southeastern US differently. The C_4 crops seemed to be generally more adaptive to the increased temperature and water stress associated with the future climate and demonstrated that adaptability by producing greater aggregated yields in comparison to the C_3 crops. Annual biochar applications were not effective in increasing crop yields and in several scenarios caused significant yield losses. There were indications that irrigation may be an effective adaptation technique for alleviating climate change effects on crop yields in the Southeastern US. The effect of irrigation will be more or less pronounced based on the regional climate model used for making the future weather predictions. Further research is needed to identify other adaptation practices for agriculture in the Southeastern US and to quantify the effectiveness of these adaptation practices in alleviating climate change impacts on crop yields.

Acknowledgements

This project was jointly supported by Climate Modeling (SFA), the Climate Mitigation (CSiTE) Projects within the Joint Global Change Research Institute (sponsored by the Battelle Memorial Institute Pacific Northwest National Laboratory and the University of Maryland, College Park), the University of Maryland Department of Environmental Science and Technology, and the US Fulbright Commission.

We also wish to thank the North American Regional Climate Change Assessment Program (NARCCAP) for providing the data used in this paper. NARCCAP is funded by the National Science Foundation (NSF), the US Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), and the US Environmental Protection Agency Office of Research and Development (EPA).

References

Allen, L.H., Valle, R.R., Jones, J.W. and Jones, P.H., 1998. Soybean leaf water potential responses to carbon dioxide and drought. Agronomy Journal, 90(3): 375-383.

Apezteguia, H.P., Izaurralde, R.C. and Sereno, R., 2009. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Cordoba, Argentina. Soil & Tillage Research, 102(1): 101-108.

ASA, SSSA, 2011. Climate Change Position Statement Working Group. Position Statement on Climate Change. Working Group Rep. ASA, CSSA, and SSSA, Madison, WI, USA.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil, 337(1-2): 1-18.

Bowes, G., 1993. Facing the inevitable - plants and increasing atmospheric CO_2. Annual Review of Plant Physiology and Plant Molecular Biology, 44: 309-332.

Carbone, G.J. et al., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. Climatic Change, 60(1-2): 73-98.

Chavas, D.R., Izaurralde, R.C., Thomson, A.M. and Gao, X.J., 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agricultural and Forest Meteorology, 149(6-7): 1118-1128.

Costantini, E.A.C., Castelli, F. and L'Abate, G., 2005. Use of the EPIC model to estimate soil moisture and temperature regimes for desertification risk in Italy. Advances in Geoecology, 36: 251-263.

Diaz, R.A., Magrin, G.O., Travasso, M.I. and Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean Rolling Pampas. Climate Research, 9(1-2): 25-30.

Easterling, W.E., 1996. Adapting North American agriculture to climate change in review. Agricultural and Forest Meteorology, 80(1): 1-53.

Easterling, W.E., Chhetri, N. and Niu, X.Z., 2003. Improving the realism of modeling agronomic adaptation to climate change: Simulating technological substitution. Climatic Change, 60(1-2): 149-173.

Easterling, W.E. et al., 1993. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. Climatic Change, 24(1-2): 23-61.

Edmonds, J.A. and Rosenberg, N.J., 2005. Climate change impacts for the conterminous USA: An integrated assessment summary. Climatic Change, 69(1): 151-162.

FAO, 2002a. World agriculture: towards 2015/2030.

FAO, 2002b. World agriculture: towards 2015/2030. Long-term perspectives. The outlook for agriculture.

Gassman, P.W. et al., 2004. Historical Development and Applications of the EPIC and APEX Models.

Gates, W.L., 1985. The use of general-circulation models in the analysis of the ecosystem impacts of climatic-change. Climatic Change, 7(3): 267-284.
International Biochar Initiative, 2014. http://www.biochar-international.org/biochar/soils.
IPCC, 1996. Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge.
IPCC, 2000. Special Report on Emission Scenarios.
IPCC, 2001a. Impacts, Adaptation, and Vulnerability - Contribution of Working Group II to the IPCC Third Assessment Report, Cambridge, United Kingdom.
IPCC, 2001b. Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the IPCC Third Assessment Report, Cambridge, United Kingdom.
IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.
Izaurralde, R.C., Rosenberg, N.J., Brown, R.A. and Thomson, A.M., 2003. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States - Part II. Regional agricultural production in 2030 and 2095. Agricultural and Forest Meteorology, 117(1-2): 97-122.
Izaurralde, R.C., Thomson, A.M., Rosenberg, N.J. and Brown, R.A., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 6. Distribution and productivity of unmanaged ecosystems. Climatic Change, 69(1): 107-126.
Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J. and Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192(3-4): 362-384.
Jeffery, S., Verheijen, F., van der Velde, M. and Bastos, A., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture Ecosystems & Environment, 144(1): 175-187.
Kuzyakov, Y., Subbotina, I., Chen, H.Q., Bogomolova, I. and Xu, X.L., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biology & Biochemistry, 41(2): 210-219.
Laird, D.A. et al., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma, 158(3-4): 443-449.
Lehmann, J., Gaunt, J. and Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitigation and Adaptation Strategies for Global Change, 11: 403- 427.
Luo, Q.Y. and Lin, E., 1999. Agricultural vulnerability and adaptation in developing countries: The Asia-Pacific region. Climatic Change, 43(4): 729-743.
Lychuk, T., Izaurralde, R., Hill, R., McGill, W. and WIlliams, J., 2014. Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated

Climate (EPIC) model. Mitigation and Adaptation Strategies for Global Change. DOI 10.1007/s11027-014-9554-7
Makino, A. and Mae, T., 1999. Photosynthesis and plant growth at elevated levels of CO2. Plant and Cell Physiology, 40(10): 999-1006.
Maroco, J.P., Edwards, G.E. and Ku, M.S.B., 1999. Photosynthetic acclimation of maize to growth under elevated levels of carbon dioxide. Planta, 210(1): 115-125.
Mearns, L.O.e.a., 2007, updated 2012. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal. Data downloaded 2013-05-25., Boulder, CO.
Mesinger, F., 2004. North American Regional Reanalysis.
Nesbitt, H.J., 1997. Rice production in Cambodia. International Rice Research Institute, Manilla, Philippines, pp. 15 - 29.
Novak, J. et al., 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science, 3: 195 - 206.
Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change-Human and Policy Dimensions, 9: S51-S67.
Reilly, J. et al., 2003. US agriculture and climate change: New results. Climatic Change, 57(1-2): 43-69.
Reilly, J.M. and Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Climatic Change, 43(4): 745-788.
Rosenberg, N.J., 1992. Adaptation of agriculture to climate change. Climatic Change, 21(4): 385-405.
Rosenberg, N.J., Brown, R.A., Izaurralde, R.C. and Thomson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States - I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agricultural and Forest Meteorology, 117(1-2): 73-96.
Smith, S.J. et al., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 1. Scenarios and context. Climatic Change, 69(1): 7-25.
Spokas, K. et al., 2012. Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. Journal of Environmental Quality, 41(4): 973-989.
Stockle, C.O., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992. Estimation of the effects of CO_2 induced climate change on growth and yield of crops. Part I. Modification of the EPIC model for climate change analysis. Agricultural Systems, 38: 225-238.
Thomson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C. and Benson, V., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 3. Dryland production of grain and forage crops. Climatic Change, 69(1): 43-65.

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J. and He, X.X., 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China. Agriculture Ecosystems & Environment, 114(2-4): 195-209.
Tsvetsinskaya, E.A. et al., 2003. The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climatic Change, 60(1-2): 37-71.
Tubiello, F.N., Donatelli, M., Rosenzweig, C. and Stockle, C.O., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy, 13(2-3): 179-189.
Williams, J.R., 1995. The EPIC model. In: V.P. Singh (Editor), Computer Models of Watershed Hydrology. Water Resources Public, Highland Ranch, CO, USA, pp. 909 - 1000.

Chapter 5: Evaluation of Climate Change Impacts and Effectiveness of Adaptation Options on Nitrate Losses, Microbial Respiration, and Carbon Sequestration in the Southeastern United States

Abstract

Changes in temperature, CO_2, and precipitation patterns associated with climate change present a challenge for agriculture in the Southeastern United States. The EPIC (Environmental Policy Integrated Climate) model was used to evaluate the potential impacts of climate change and adaptations on nitrate leaching and runoff losses, microbial respiration, and soil carbon content for representative farms growing C_3 and C_4 crops in Alabama, Arkansas, Missouri, Mississippi, Florida, Kentucky, Louisiana, Texas, Georgia, and Tennessee that were grouped into North, West, and East regions for analysis. In this modeling study, three C_3 crops were represented by combined yields of soybean (*Glycine max* L.), alfalfa (*Medicago sativa* L.), and winter wheat (*Triticum aestivum* L.), whereas C_4 crops were represented by combined corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and pearl millet yields (*Pennisetum glaucum* L.). Adaptations included annual biochar applications and irrigation occurring prior to plant stress. Historical baseline (1979 – 2009) and future (2038 – 2068) climate scenarios were used for simulations with baseline and future CO_2 concentrations of 360 ppmv and 500 ppmv, respectively. Climatic data for

baseline scenarios used NOAA's North American Regional Reanalysis (NARR) database. Climatic data for the future scenarios used the North American Regional Climate Change Assessment Program (NARCCAP) database. Four regional climate models (RCMs) were used for the future simulations to project different patterns of changes in air temperatures, precipitation, and solar radiation that are expected to occur over time. 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 periods of regional models. Results of this study indicated that climate change will increase nitrate leaching and runoff losses by 40 to 90% compared to a historical baseline scenario because of future increased annual precipitation as predicted by the four RCMs. Under C_4 crops, nitrate leaching losses were significantly lower than under C_3 crops by 50 to 85%, but crop type had no significant effects on nitrate losses in runoff. Although not universally significant, data trends suggest decreased nitrate leaching losses in response to biochar application and increased nitrate leaching in response to irrigation. Future climate caused significantly increased microbial respiration rates by as much as 20% for C_4 crops in comparison with historical rates. Comparison between individual future 5 year periods within the 2038 – 2068 simulation period revealed that biochar applications and C_4 crops caused microbial respiration rates to increase by 20 to 45%. Soil carbon rates were significantly affected by crop type and biochar application. Soil carbon accumulation was significantly greater under biochar application by as much as 40%, and under C_4 crops by about 5%. The results of this modeling study indicated that during 2038 –

2068 there will be increased nitrate losses attributable to climate change in the Southeastern US in comparison with the historic baseline scenario of 1979 - 2009. Similarly, there will be increased microbial respiration in response to C_4 crops and biochar applications. Overall, C_4 crops and biochar applications resulted in significantly greater soil carbon sequestration and, although not universally significant, reductions in nitrate losses. Irrigation resulted in greater losses of nitrate in leachate and runoff, however, no significance was detected.

Introduction

Climate change

Global climate change is perceived by some as the greatest environmental challenge the world is facing at the present time (Alig et al., 2002). Increasing atmospheric CO_2 is thought to be a driving force leading to climate change. A large portion of increased atmospheric CO_2 concentrations is the direct result of human activities, primarily the burning of fossil fuels, cement production, and modified land-use patterns (IPCC, 1996). Climate change is expected to impact crop production, hydrologic balances, livestock management, and other components of the agricultural sector (Adams et al., 1998). In addition to its direct effects on weather, climate change will also influence the severity of abiotic stresses such as drought, biotic stresses, and pest pressures on agricultural systems. It is anticipated that climate change will not only change the mean values of many climatic properties, but it will also change the distribution and frequencies of weather patterns that will lead to increases in the occurrence of extreme events such as droughts and floods. To gain an understanding of climate change impacts on agricultural systems requires a holistic perspective to understand the implications of the interactions of changing temperature, CO_2, and precipitation on crop growth and development processes. The likelihood that additional changes in the climate will occur over this century is almost certain; however, the magnitude and the scale of climate change impacts are uncertain.

Climate change impacts on agriculture

World demand for agricultural products in 2030 is predicted to increase by one third of what it was in 2010 (FAO, 2002a). To meet future needs for agricultural products, an additional 120 million ha of land will need to be converted to cropland by 2030 (FAO, 2002b). During this time period the need for urban land will continue to grow and it is thought that the additional land for crop production will come from forest land that will be cleared (FAO, 2002b). At the same time, the agricultural sector is likely to be significantly affected by regional changes in temperature and precipitation, so there is no certainty that agriculture will be able to satisfy increased food demands from the ever growing population. Crops may initially benefit from a CO_2 fertilization effect caused by higher atmospheric CO_2 concentrations, but high temperatures, drought, and other environmental stressors associated with climate change may outweigh the positive CO_2 fertilization effects on crops and result in yield reductions. The response of agricultural systems to future changes in climate depends strongly on management practices and the development of new practices to address the climate change impacts.

Climate change impacts on agricultural nitrate losses into the Gulf of Mexico

Agriculture and water resources are closely interconnected so climate change through its impact on agriculture will also impact the quality of US freshwater and coastal ecosystems by altering precipitation, temperature, and runoff patterns (Baron et al., 2013). Nitrogen (N) is one of the most important nutrients used in crop production and its loss from agricultural lands greatly influences freshwater quality. Excessive N in surficial waters is primarily responsible for algal blooms that lead to decreased aquatic biodiversity. Presently, two-thirds of US estuaries are degraded from N pollution (Baron et al., 2013; Bricker et al., 2008). Nitrogen is a highly mobile element, moving freely in a cycle through the atmosphere, water, soil, and plants in its many chemical forms. The nitrogen cycle is affected by climate change more easily and severely than the carbon cycle and, therefore, nitrogen plays an important role when the impacts, mitigation, and adaptation strategies of climate change are being addressed (Suddick et al., 2013).

Nitrogen and phosphorus fertilizer applications used in broad-based agriculture have been tied to increased stream nutrient loads (Hatfield et al., 2013) that eventually make their way to the Mississippi River and the Gulf of Mexico. These pollutants have caused the formation of a vast hypoxic zone in the northern part of the Gulf of

Mexico. Nitrogen and phosphorus, after reaching surface waters, result in the increased growth of algae whose decomposition deplete oxygen from water and form hypoxic and anoxic surface water conditions. Nitrogen transport mechanisms, in the form of nitrate-N, are dominated by leaching and tile drainage of water from agricultural lands (Jaynes et al., 2001; Singer et al., 2011). Since more than 70% of the N delivered to the Gulf of Mexico comes from the agricultural fields within the Mississippi River basin (Alexander et al., 2008; Baron et al., 2013; Brown and Power, 2011; Smith et al., 1997), it is expected that increased precipitation associated with climate change will increase the quantities of N runoff and leaching and will result in further declines of freshwater quality if timely adaptation measures are not implemented (Hatfield et al., 2013). In addition to the surface water inputs, enriched N groundwater with residence times from ten to hundreds of years can add to the pollution problem by strongly influencing stream and estuarine water quality for decades (Baron et al., 2013)

Regional modeling and adaptations

Modeling driven by historical and future climate scenarios has been an essential tool for testing hypotheses concerning the impacts of climate change on the agricultural sector (Rosenberg, 1992). Utilizing general circulation models (GCMs), previous researchers routinely used global and national contexts to evaluate the possible changes caused by climate change on agriculture (Parry et al., 1999; Reilly et al., 2003; Rosenberg, 1992). However, the resolution scale at which national and global scale simulations have been performed was seen as too coarse for detailed interpretations of climate change impacts (Gates, 1985; Thomson et al.2005). The main concern with using GCMs for regional predictions of climate change impacts arises due to the fact that regional impacts of climate change may not be fully embraced by a resolution of the100 kilometers resolution that is typical of most GCMs. This low resolution becomes a problem when trying to make climate change interpretations on a regional level. Therefore, regional climate change modeling is currently widely utilized and incorporates a higher resolution scale of 100 meters allowing climate change interpretations to be made on the local level.

Climate change will likely force farmers to take steps to minimize yield losses from its deleterious impacts and to maximize yield gains from its beneficial impacts. Farmers will be faced to utilize either mitigation and/or adaptations to help alleviate the climate change impacts. *Mitigation* is the use of current or future technologies to counteract emissions of greenhouse gases and thus contribute to their stabilization in the atmosphere. *Adaptation* is the use of current or future technologies which are designed to lessen adverse impacts of climate change on human and natural systems. The main goal of adaptation is to reduce the vulnerability of agriculture to the detrimental impacts of climate change. Early regional modeling studies that considered the use of adaptations to help alleviate the impacts of climate change were done by Easterling et al. (1992a; 1992b). In these studies, the MINK region (Missouri, Iowa, Nebraska, Kansas) was used to model the impacts of 1930's historic climatic data on agriculture and the effectiveness of possible adaptations to counteract the climate impacts that occurred during the Dust Bowl period (i.e. the area was known as the Dust Bowl for its persistent drought and erosion). It was found that some adaptations as suggested by the authors of these studies, such as early planting, long-season-cultivars, planting density, and use of cultivars in simulations with improved radiation use efficiency and stress tolerance were able to partly alleviate yield losses induced by climate change during the Dust Bowl period.

Biochar as climate change adaptation tool

Biochar application to soil has recently received widespread attention as a potential climate change adaptation tool. There were about a dozen articles on biochar published in 2000. In 2012, 3000-plus articles were published that addressed a wide range of topics (Maddox, 2013). However, no modeling studies have been implemented so far to evaluate biochar as an adaptation tool to test its ability in reducing nitrate losses and its effect on microbial respiration and soil carbon. The International Biochar Initiative (International Biochar Initiative, 2014) defines biochar as fine-grained charcoal high in organic carbon and largely resistant to decomposition. Although biochar is typically derived from plant and waste feedstocks in which the carbon may have been readily available, after pyrolysis the resultant biochar may consist of up to 90% recalcitrant carbon. When applied to soil as an amendment, biochar creates a recalcitrant soil carbon pool, which is carbon-negative in nature. This net withdrawal of atmospheric CO_2 is stored in the soil carbon stocks and is very resistant to decomposition. Kuzyakov et al. (2009) concluded that the half-life of biochar under natural soil conditions is about 1400 years. Carbon pools in biochar typically possess an approximately 2% fraction of readily bioavailable C, approximately a 60% fraction of C that is slowly available over decades, and approximately a 38% fraction that is considered to be a passive pool that will be available over centuries (Joseph et al. 2009; Lehmann et al. 2009; Zimmerman 2010; Lychuk et al., 2014). Biochar typically possesses a number of distinctive beneficial characteristics which include a high cation exchange capacity (CEC) of 40 to 190 $cmol_c\ kg^{-1}$, a high porosity in comparison to soil, polyaromatic complex chemistry compounds, and a high surface area and reactivity (Atkinson et al., 2010; Laird et al., 2010b; Lehmann et al., 2006).

Biochar application has been found to decrease nutrient leaching of various forms of N and P from agricultural soils (Laird et al., 2010a; Lehmann et al., 2003). It is thought that due to its high surface charge density, it enables the retention of cations by cation exchange (Liang et al., 2006). Other mechanisms of nutrient retention includes biochar's ability to adsorb organic molecules and associated nutrients because of its high surface area, its internal porosity, and the presence of both polar and non-polar surface sites (Laird et al., 2010a). It has also been shown that biochar application increases soil microbial respiration rates, soil microbial biomass, and nutrient cycling (Rogovska et al., 2011; Steiner et al., 2008; Warnock et al., 2007). These effects on soil microbiology affect the quantities of soil carbon and influence either the carbon sequestration or loss of carbon from the soil profile. The feedstock material used for biochar production and the type of pyrolysis used play key roles in biochar's properties that impact microbial respiration processes in soil. These suppositions were confirmed by Kuzyakov et al. (2009) who found that the presence of easily metabolized organic carbon accelerated biochar decomposition. Similarly, Spokas et al. (2009) observed both increases and decreases in CO_2 rates exuded from biochar amended soils suggesting that biochar quality plays an important role in influencing soil microbial processes. Other researchers (Baldock and Smernik, 2002; Hamer et al., 2004; Shneour, 1966) have reported that biochar can be metabolized by microorganisms and that heterotrophic decomposition is the most important mechanism of biochar decay. Nguyen and Lehmann (2009) observed that carbon loss from biochar under unsaturated conditions was significantly higher than under saturated conditions suggesting that soil water regimes may play an important role in biochar's behavior in the soil and it is likely that biochar's oxidation is a major mechanism that controls its stability in the soil.

Research objectives

There have been no previous regional modeling studies that have evaluated the climate change impacts and the use of adaptations to influence nitrate loads from agriculture in the Southeastern United States. Lychuk et al. (2014) tested a biochar-enhanced version of the Environmental Policy Integrated Climate (EPIC) model to simulate biochar behavior in an Oxisol soil using the experimental data reported by Major et al. (2010). In this modeling study, the same enhanced version of the EPIC model discussed in Lychuk et al. (2014) has been used. In addition, we coupled the EPIC model with four regional climate models fitted within global climate models to evaluate the effects of future climate change and the effectiveness of the proposed adaptation practices of biochar application and irrigation on nitrate leaching and runoff losses, microbial respiration, and changes in soil carbon contents from representative farms growing C_3 and C_4 crops in Alabama, Arkansas, Missouri, Mississippi, Florida, Kentucky, Louisiana, Texas, Georgia, and Tennessee. The funder of this project, the US Department of Energy, selected the ten Southeastern US states, in which representative farms were located and for which simulations were performed.

The specific objectives of this modeling study were:

1. Compare differences in historical baseline and future predicted values of nitrate losses, microbial respiration and soil carbon content trends, as well as the influence of the aggregated impacts of C_3 and C_4 crops on these parameters in the past and in the future.
2. Compare the predicted nitrate losses, microbial respiration, and soil carbon content trends for the four RCMs during the 2038 – 2068 period.
3. Evaluate the effectiveness of biochar applications, irrigation, and the influence of C_3 and C_4 crops on nitrate losses, microbial respiration and soil carbon content trends for the four RCMs.

A companion paper looking at the effects of climate change and adaptation strategies on crop yields in the Southeastern US was presented in the previous chapter of this dissertation.

Materials and Methods

Description of the simulation model

The Environmental Policy Integrated Climate (EPIC) model (Williams, 1995) was used for simulating impacts of climate change and proposed adaptations on nitrate losses, microbial respiration, and soil carbon content within the Southeastern US. EPIC is a widely tested model originally built to quantify the effects of soil erosion and agricultural productivity. EPIC operates on a daily time step and can perform long-term simulations (hundreds of years) on watersheds up to 100 ha in size. Since its inception, the EPIC model has evolved into a comprehensive agro-ecosystem model. 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 used for simulations inputs. EPIC can simultaneously model the growth of about 100 plant species including crops, native grasses, and trees; inter-crop, cover-crop mixtures, and/or similar scenarios can be simulated. Crops can be grown in complex rotations and 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; residue and nutrients mixing in the surface layer; water and wind erosion; soil hydrology; soil temperature and heat flow; C, N, and P cycling; effects of fertilizer and irrigation on crop growth; fate of pesticides; and economics. Stockle et al. (1992) modified EPIC to account for the CO_2 fertilization effect on growth of C_3 and C_4 crops. A comprehensive description of the EPIC model application and development was presented by Gassman et al. (2004).

EPIC has undergone many improvements and intensive testing under diverse climate, soil, and management environments. Recently, several improvements have been made in EPIC. These include implementation of a coupled carbon-nitrogen submodel to simulate terrestrial carbon dynamics as affected by environmental and management factors. A detailed description of the new C and N algorithms can be found in Izaurralde et al. (2006).

Among a variety of available simulation models, EPIC has proven to be one of the most reliable in its accuracy to predict crop/biomass production based on climatic, soil, operational management, and other relevant data. Long-term field experiments have verified reasonable precision in representing these interactions in the US and Canada (Izaurralde et al., 2005; Izaurralde et al., 2006). EPIC 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, and other countries (Apezteguia et al., 2009;

Chavas et al., 2009; Costantini et al., 2005; Diaz et al., 1997; Edmonds and Rosenberg, 2005; Thomson et al., 2006). For more detailed information on EPIC algorithms and more in-depth model description refer to Izaurralde et al. (2006).

We previously updated the EPIC model with algorithms describing the influence of biochar amendments on crop yields and important soil properties, and verified EPIC's performance as described in Lychuk et al. (2014). For this modeling study, this newly updated biochar enhanced version of the EPIC model was used.

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 data from 1979 to 2009 was obtained from NOAA's North America Regional Reanalysis (NARR) database (Mesinger, 2004). NARR is a long-term, consistent high-resolution (on a scale of about 100 meters) climate dataset for the North American continent and is a major improvement in both resolution and accuracy in comparison to the earlier global reanalysis datasets. Climatic data for the future scenario runs of 2038 to 2068 was obtained from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP provides high resolution future climate scenario data for most of the North America continent using regional climate models, coupled global climate models, and time-slice experiments

(Mearns, 2007, updated 2012). The year 2038 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, 2007a). 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 and 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 ppm. The future weather simulations were conducted under a CO_2 concentration of 500 ppm. This concentration was selected based on the projections reported in the IPCC reports (IPCC 2014; IPCC 2007; IPCC 2001) and available literature investigating future impacts of climate change on agriculture in the US (Izaurralde et al., 2003; Parry et. al., 1999; Carbone et al., 2003) The adaptation practices evaluated were annual additions of biochar in the amount of 5 Mg ha^{-1} and irrigation occurring prior to plant stress (plant available water deficit in the root zone). The biochar was incorporated in the soil with a single pass of a disc harrow to a depth of 5 cm one month prior to planting. The biochar used 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% and 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. Plant available water deficit in the root zone (-65 mm) was used as a parameter to trigger irrigation. Depending on the severity of the crop available water deficit in the root zone, the amount of water applied varied between 25 and 75 mm each time irrigation occurred. Three C_3 and three C_4 crops were used for simulations in this study. The C_3 crops were represented by combined yields of soybean (*Glycine max* L.), alfalfa (*Medicago sativa* L.), and winter wheat (*Triticum aestivum* L.), whereas the C_4 crops were represented by combined corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and pearl millet yields (*Pennisetum glaucum* L.).

For future weather simulations, four regional climate models (RCMs) were used that had boundary weather conditions defined by global models. The RCMs used in this study were:

- The Canadian Regional Climate Model with the Third Generation Coupled Climate Model (CRCM CGCM3)
- The Hadley Regional Model and the Hadley Coupled Model version 3 (HRM3 HADCM3)
- The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model (RCM3 CGCM3)
- The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory GCM (RCM3 GFDL).

Table 5.1 summarizes regional distribution of air temperatures and precipitation under baseline (NARR) conditions and deviations from the historical baseline predicted by the four RCMs.

Table 5.1 Regional distribution of air temperatures and precipitation under historical baseline North America Regional Reanalysis (NARR, 1979 - 2009) conditions and deviations from the baseline predicted by the four regional climate models* (RCMs) over the future 30-year simulation period (2038 – 2068).

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	2.3	3.3	1.6	1.9	2.4	2.6	3.3	3.2	3.0	2.6
HRM3	0.2	2.6	1.0	1.4	2.9	2.2	2.6	4.1	3.1	1.8
RCM3C	0.5	0.4	-1.6	-1.4	0.4	-0.9	-0.3	1.7	0.7	-1.2
RCM3G	-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	-1.5	-0.5	-1.6	-1.1	-1.0	-0.1	-0.4	-0.1	-0.5	-2.0
HRM3	-1.3	1.96	0.2	0.6	0.9	1.5	1.8	2.9	2.1	1.5
RCM3C	-1.0	-0.8	-2.1	-1.2	-1.1	-1.2	-1.1	0.1	-0.6	-2.2
RCM3G	-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	-87	-80	107	-141	211	-432	-199	-15	-66	-194
HRM3	51	69	262	67	254	-360	-59	97	-7	4
RCM3C	42	68	631	265	126	-186	-99	232	40	25
RCM3G	-48	-28	494	204	105	-188	-157	81	-60	101

*(NARR – Historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

For simplicity, we will refer to these regional climate models as CRCM, HRM3, RCM3C, and RCM3G. Regional climate models are used to project different patterns of changes in air temperatures, precipitation, and solar radiation that are expected to occur over time. All future weather simulations were part of the A2 scenario from the Special Report on Emissions Scenarios (SRES) (IPCC, 2000). The A2 scenario assumes a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in some other scenarios.

The representative farms approach, as proposed by Easterling et al. (1993), 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. Soil types and their properties used in the simulations are shown in table 5.2.

Table 5.2 Soil types and their properties used in Environmental Policy Integrated Climate model simulations.

Representative farms located in the following 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

Simulations were performed on farms using typical existing technologies and management practices. The EPIC model was updated with crop varieties used in simulations according to the region in which they were grown. All representative farms in the Southeastern US drain to the Mississippi River or directly to the Gulf of Mexico. 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 soil profile in 10 cm increments based on the model partitioning of the soil profile. 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 nitrogen, 50 kg ha^{-1} of phosphorus, and best favorable planting and harvesting days were used for model simulations. Application of potassium and sulfur fertilizer as well as micronutrients was not included in the simulations. The simulated land area at each farm was 10 hectares.

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 the comparisons between the 5 year periods within the regional models. Experimental units consisted of the10 farms being placed into one of three regional groupings to allow regional comparisons to be made. The number of farms in each grouping 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 the regions were used as blocks (Izaurralde et al., 2003) within which the main plots were assigned to 2 x 2 factorial combinations of biochar and irrigation. 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 (2038 - 2068) predicted by the four RCMs. Periods for the future scenarios were averaged for 5 year intervals and were treated as repeated measures. Future scenarios were not statistically compared across RCMs because of excessive interaction effects. Comparisons were made (1) between baseline and future scenarios and (2) between the 5 year periods within each future climate scenario.

All statistical analyses were performed using the MIXED Procedure in SAS v. 9.3 (SAS Institute, 2013). Response variables were nitrate leaching and runoff losses, microbial respiration, and soil carbon content. The LSD-adjusted significant differences (following a significant F test) were used for multiple mean comparisons.

Results and Discussion

In total, there were eight groups of comparisons made in this study.

1. Comparison between past (baseline) and future nitrate leachate losses predicted by the four regional climate models/scenarios.
2. Comparisons of future nitrate leachate losses between 5 year periods within each regional climate model.
3. Comparison between past (baseline) and future nitrate runoff losses predicted by the four regional climate models/scenarios.
4. Comparisons of future nitrate runoff losses between 5 year periods within each regional climate model.
5. Comparison between past (baseline) and future microbial respiration predicted by the four regional climate models/scenarios.
6. Comparisons of future microbial respiration between 5 year periods within each regional climate model.
7. Comparison between past (baseline) and future dynamics of soil carbon predicted by the four regional climate models/scenarios.
8. Comparisons of future dynamics of soil carbon between 5 year periods within each regional climate model.

Nitrate leaching losses (past vs. future comparison)

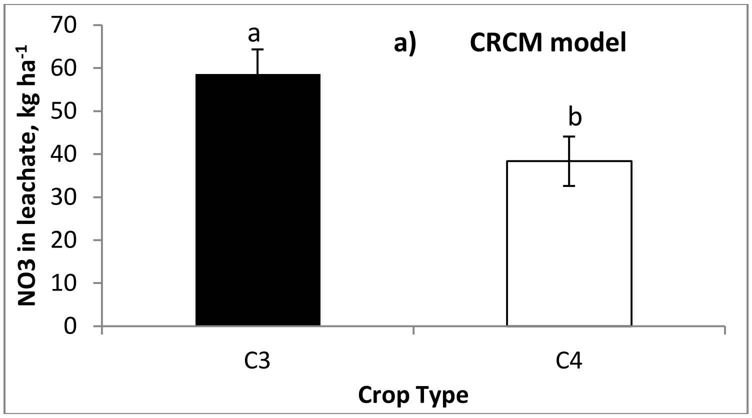
The climate model main effect was statistically significant for the CRCM, RCM3C, and RCM3G regional climate models in comparison to the historical baseline climate. The future climate predicted by these regional climate models resulted in increased nitrate leachate losses when compared to the historical baseline period if no adaptations were implemented (Table 5.3). As previously noted, the four regional models used in this study generally predicted increased precipitation for the Southeastern US. Consequently, increased nitrate leachate losses ranged from 40 to 90% depending on the regional model used. These findings are consistent with the results of Tian et al. (2012) who determined that the future nitrogen deposition rates under the new climate conditions in the Southeastern US will almost double compared to the historical baseline scenario. In China, similar findings were reported by Xu et al. (2013) who stated that nitrate concentrations in the soil and nitrate leaching were partially controlled by the rainfall depth, intensity, and distribution. In case of the HRM3 regional model, there was a significant region x HRM3 model interaction, indicating that there were variations in the manner the climate change impacted the regions (Fig. 5.2).

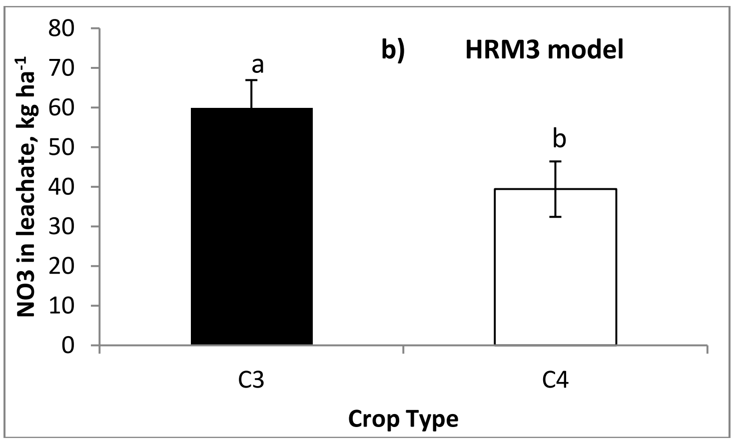
Table 5.3 Comparisons between historical baseline and future nitrate leachate losses. Letters within the same column indicate LSD mean differences at $P < 0.05$

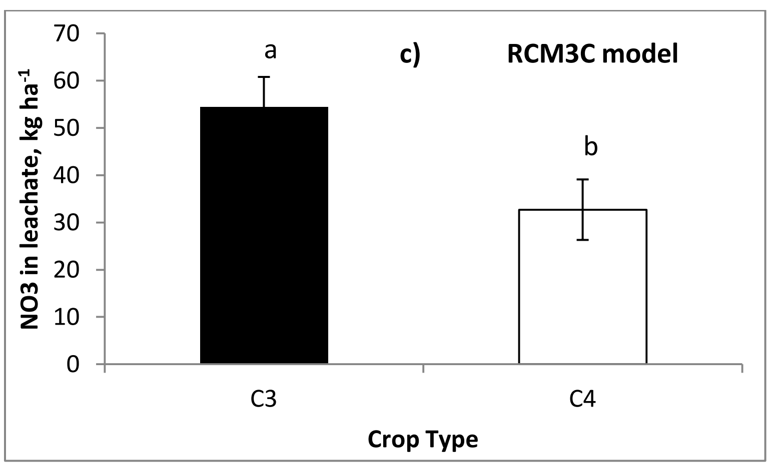
Model*	NO_3, kg ha^{-1}
NARR (baseline)	34.54a
CRCM	62.42b
RCM3C	52.61b
RCM3G	48.17b

*(NARR – Historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

The crop type effects were significant for all the regional climate models and predicted significantly lower rates of nitrate leachate losses for C_4 crops compared to C_3 crops (Fig. 5.1). The reductions in leachate nitrate losses for C_4 crops were in the range of 50 to 85% compared to nitrate leachate losses under C_3 crops and reflects the higher nitrogen crop uptake that is typical for C_4 crops in comparison to C_3 crops (Fig. 5.1). The C_4 crops also responded better to impacts of climate change in comparison to the C_3 crops and had disproportionately higher yields (Chapter 4 in dissertation).


a) CRCM model
NO3 in leachate, kg ha-1
70
60
50
40
30
20
10
0
a
b
C3
C4
Crop Type


b) HRM3 model
NO3 in leachate, kg ha-1
80
70
60
50
40
30
20
10
0
a
b
C3
C4
Crop Type


c) RCM3C model
NO3 in leachate, kg ha-1
70
60
50
40
30
20
10
0
a
b
C3
C4
Crop Type

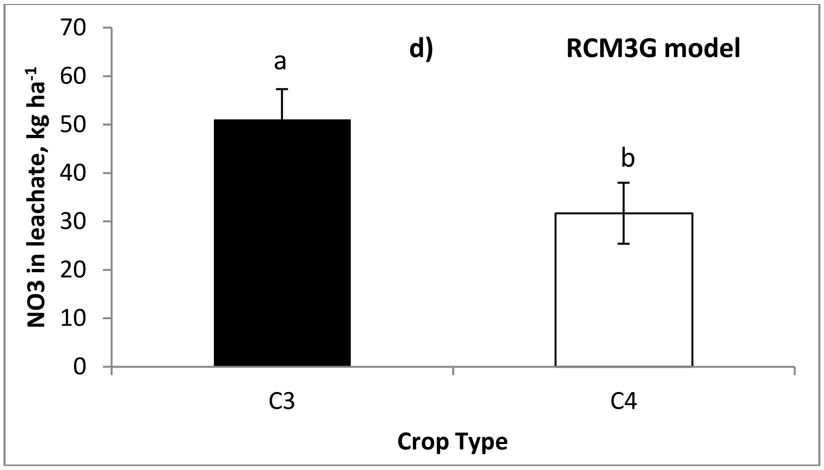


Fig. 5.1 Comparisons of nitrate leachate losses for the C_3 and C_4 crops as predicted by the four regional climate models*. Letters indicate LSD mean differences at $P < 0.05$. * (a) CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; (b) HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; (c) RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; (d) RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

The regional effect was significant when using the CRCM, RCM3C, and RCM3G regional climate models for the West region indicating that the regions differed in their nitrate leachate losses. The West region has a nitrate leachate loss that was twice the loss experienced in the other regions (Table 5.4). Although increased precipitation occurred in all RCMs, it is thought the distribution of that precipitation pattern in the West region was such that crops could not obtain optimal benefits of the precipitation which, coupled with very low soil carbon content, resulted in greater nitrate losses.

Table 5.4 Regional effects on nitrate leachate losses (kgha^{-1}) for the CRCM, RCM3C, and RCM3G regional climate models. Letters within the same column indicate LSD mean differences at P < 0.05.

Region	Model*		
	CRCM	RCM3C	RCM3G
North	36.89a	31.92a	35.03a
South	39.07a	30.38a	31.15a
West	69.47b	68.41b	57.88b

*(CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences).

Additionally, there was a significant region x RCMs interaction in case of the HRM3 model for nitrate leachate losses with statistically significant increased nitrate loss for all three regions indicating that there were variations in the manner the climate change impacted these regions (Fig. 5.2).

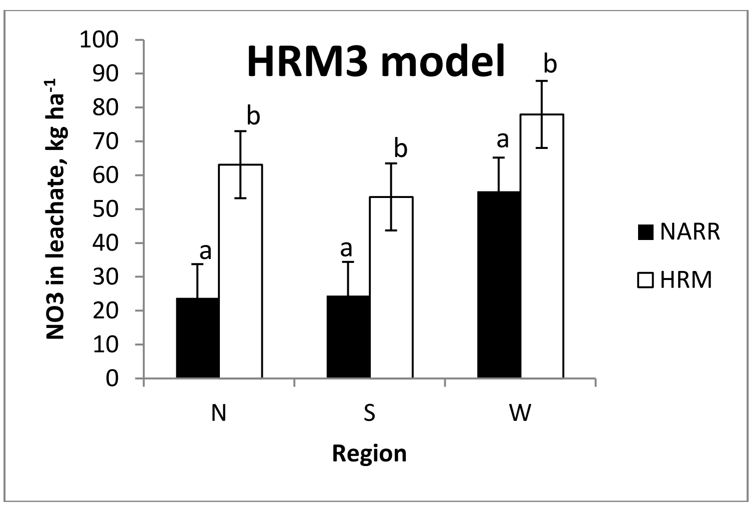


Fig. 5.2 Comparison of nitrate leachate losses for the North (N), South (S), and West (W) regions using the 1979 – 2009 NARR (historical baseline climate scenario) and the HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3) regional climate model. Letters indicate LSD (Least significant differences) mean comparisons at P < 0.05.

Climate effects on future nitrate leachate losses

There were significant region x RCM interactions indicating that the future nitrate leachate losses needed to be analyzed separately by each region and each model. Irrigation and biochar main effects were not significant, although the data trends suggested evidence for a constant increase in nitrate leachate losses under irrigation and reduction in nitrate losses following biochar application (Table 5.5). These findings were consistent with Laird et al. (2010a) who observed significantly lower nitrate leachate losses under biochar amended soils.   There was a significant period x crop type interaction for all models except for the RCM3G model's West region (Table 5.6). In case of the West region and the RCM3G model, the C_4 crops resulted in significantly lower rates of nitrate losses compared to the C_3 crops with reductions up to 25% (data not shown). We concluded that the differences in nitrate leachate losses between the two crop types were due to the higher nitrogen crop uptake that is typical for C_4 crops in comparison to C_3 crops. Similarly, for all other regions and models, the C_4 crops resulted in significantly lower nitrate leachate losses of 10 to 50% compared to the C_3 crops, mostly in the first two decades of the future 2038 – 2068 simulation period. There was a strong decreasing trend in nitrate leachate losses toward the end of the final year of the future simulation period, which was associated with the greater rates of denitrification losses resulting from higher temperatures and greater precipitation associated with the future climates as predicted by the four RCMs.

Much of the findings can be explained by an examination of the differences in growth between the C_3 and C_4 crops and the nitrogen requirements for the respective crop types. The C_4 crops seem to be generally more adaptive to increases in temperature and water stress associated with the future climate and demonstrated adaptability by producing greater aggregated yields in comparison to the C_3 crops (Chapter 4 of this dissertation) particularly during the earlier portions of the future simulation period. The regional aggregated yields for the C_3 and C_4 crops were significantly lower towards the end of the 2038-2068 simulation period for 3 out of 4 RCMs. The reduced nitrate leachate losses for the C_4 crops during the earlier portions of the future simulation period would mirror the increased growth of the C_4 crops and greater nitrogen utilization requirements of the C_4 crops. The reduction in yields during the later portion of the simulation period would have decreased nitrogen utilization requirements and increased nitrate leachate losses would occur. It is also possible that the increases or decreases in nitrate leachate losses may be affected due to the differences in the root systems of C_4 and C_3 crops or so called "biological loosing effect" that can change infiltration and leaching. While quantifying this impact was beyond the scope of this study, this issue will likely be addressed in future research.

Table 5.5. Irrigation and biochar main effects on predicted nitrate leaching losses (kg ha^{-1}) for the 2063 – 2068 simulation period. Letters within the same column for each effect indicate LSD mean differences at $P < 0.05$.

Effect		Regional Climate Model*											
		CRCM			HRM3			RCM3C			RCM3G		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Irrigation	No	45.57a	49.50a	77.25a	58.03a	48.90a	70.56a	35.90a	31.84a	75.16a	-	33.18a	-
	Yes	50.50a	51.31a	80.05a	58.77a	52.89a	80.54a	41.26a	37.71a	75.28a	-	41.50a	-
Biochar	No	52.32a	54.70a	85.12a	63.67a	55.36a	83.38a	43.16a	38.87a	-	49.50a	41.80a	66.19a
	Yes	43.75a	46.11a	72.19a	53.13a	46.43a	67.71a	34.00a	30.69a	-	39.99a	32.88a	55.16a

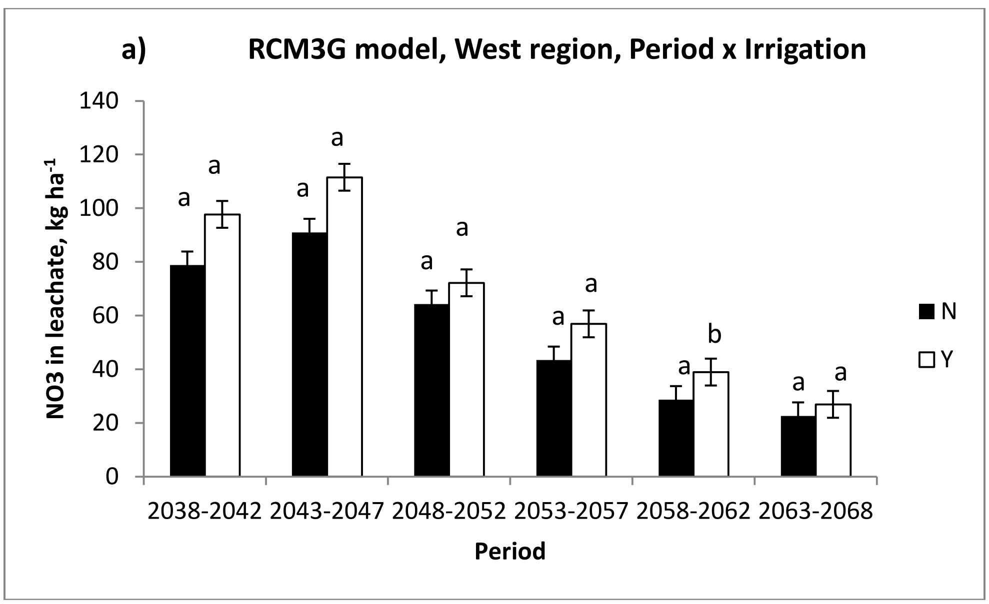
*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

Table 5.6. Effects of crop type on nitrate leachate losses (kg ha^{-1}) for 5 year future climate periods for each model and region. Letters within the same column for each period indicate LSD mean comparisons at $P < 0.05$.

Effect		Crop Type	Regional Climate Model*											
			CRCM			HRM3			RCM3C			RCM3G		
			Region											
			North	South	West	North	South	West	North	South	West	North	South	West
Period x Crop Type	2038-2042	C_3	95.00a	105.51a	169.54a	103.00a	105.73a	142.15a	55.53a	67.90a	160.37a	61.56a	60.88a	-
		C_4	62.87b	66.56b	112.82b	73.26b	64.71b	101.22b	42.10a	35.72b	110.94b	51.56a	37.44b	-
	2043-2047	C_3	89.04a	93.72a	143.56a	96.78a	97.39a	149.94a	71.49a	53.62a	150.60a	67.44a	71.94a	-
		C_4	63.88b	61.91b	108.64b	67.85b	62.50b	107.35b	41.37b	36.58b	98.31b	53.00a	47.89b	-
	2048-2052	C_3	51.04a	59.01a	90.33a	66.71a	60.12a	88.91a	51.22a	54.22a	91.03a	56.46a	47.06a	-
		C_4	42.87a	40.49b	64.76b	51.50a	40.35b	69.52b	35.27a	33.90a	53.57b	43.80a	34.89a	-
	2053-2057	C_3	31.27a	40.38a	61.44a	46.30a	40.46a	60.40a	38.06a	32.48a	64.91a	43.26a	35.98a	-
		C_4	39.64a	35.12a	47.21a	52.65a	34.57a	51.90a	30.45a	29.55a	39.19b	41.63a	30.73a	-
	2058-2062	C_3	24.30a	26.33a	43.27a	33.79a	27.53a	36.39a	26.76a	21.80a	44.49a	30.00a	21.49a	-
		C_4	30.50a	28.52a	38.69a	43.92a	29.85a	35.09a	28.21a	18.16a	31.66b	35.32a	23.40a	-
	2063-2068	C_3	17.06a	20.07a	29.47a	24.67a	20.21a	30.19a	19.40a	15.59a	30.66a	24.07a	16.33a	-
		C_4	28.95b	27.26a	34.03a	40.35b	27.27a	33.51a	23.11a	17.79a	26.88a	28.83a	20.05a	-

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

There were significant period x irrigation interactions for the individual 5 year future climate periods, with increased nitrate leachate losses ranging between 10 to 15% for the RCM3G model's North and West regions (Fig. 5.3). Similarly, there were significant period x biochar interactions for the RCM3C model's West region resulting in a significant 5% reduction in nitrate leachate losses during the last 5 year period of the future 2038 - 2068 simulation range (Fig. 5.4). As noted above, the overall decreasing trend in nitrate leachate losses toward the end of the final year of the future simulation period was associated with the greater rates of denitrification losses resulting from higher temperatures and greater precipitation associated with the future climate.



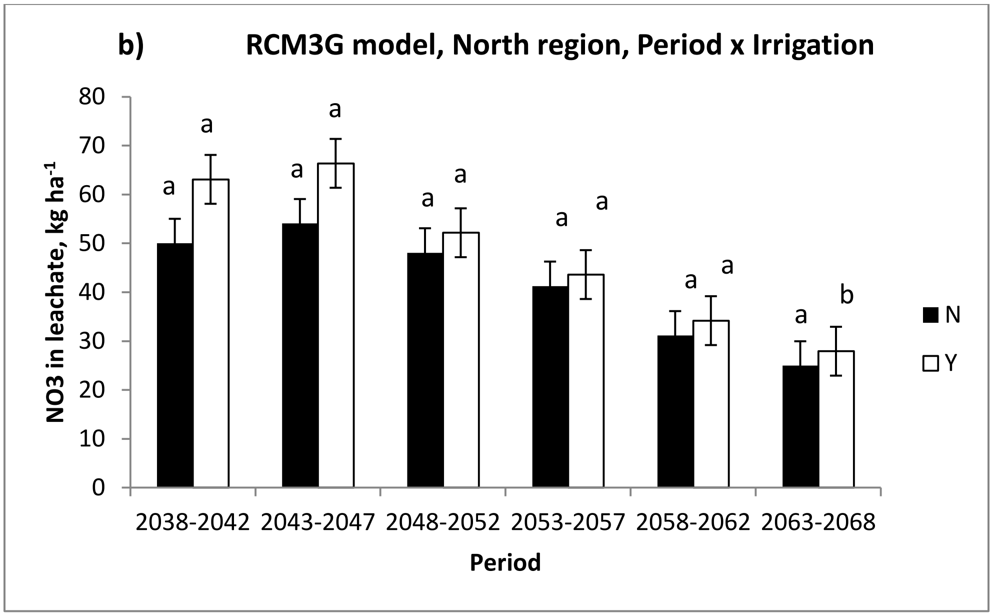


Fig. 5.3 Effects of irrigation on nitrate leachate losses across individual 5 year future period levels for the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) model's (a) West and (b) North regions. Letters indicate LSD (Least significant differences) mean comparisons at $P < 0.05$.

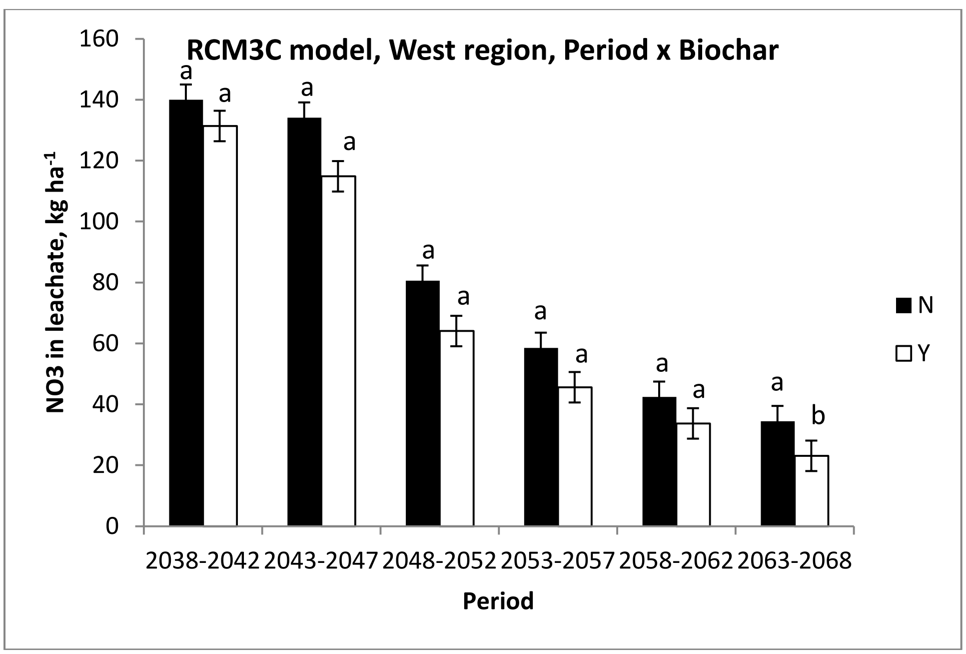


Fig. 5.4 Effects of biochar application across individual period levels for the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) model's West region. Letters indicate LSD (Least Significant Differences) mean comparisons at $P < 0.05$.

Nitrate losses in runoff (past vs. future comparison)

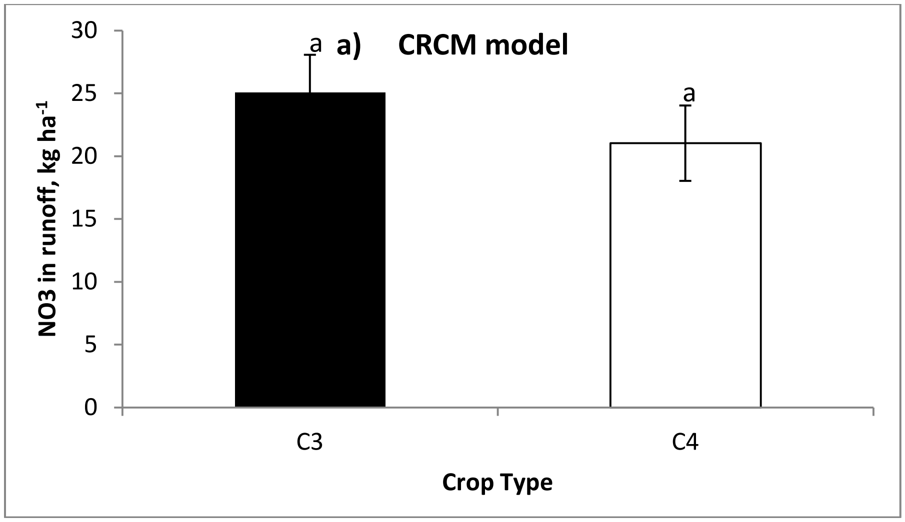
Nitrate losses in runoff for the CRCM and RCM3C models were significantly greater than the nitrate losses for the NARR historical baseline data with the nitrate losses in runoff being between 40 and 90% greater, depending on the model (Table 5.7). Nitrate losses in runoff were higher compared to the baseline for the RCM3G model, but were not statistically significant. Since the regional climate models used in this study generally predicted increased precipitation for the Southeastern US, the results were in agreement with the findings of Moriasi et al. (2013) who reported increased nitrate losses in runoff due to increased precipitation based on a study using the Soil and Water Assessment Tool (SWAT) model.

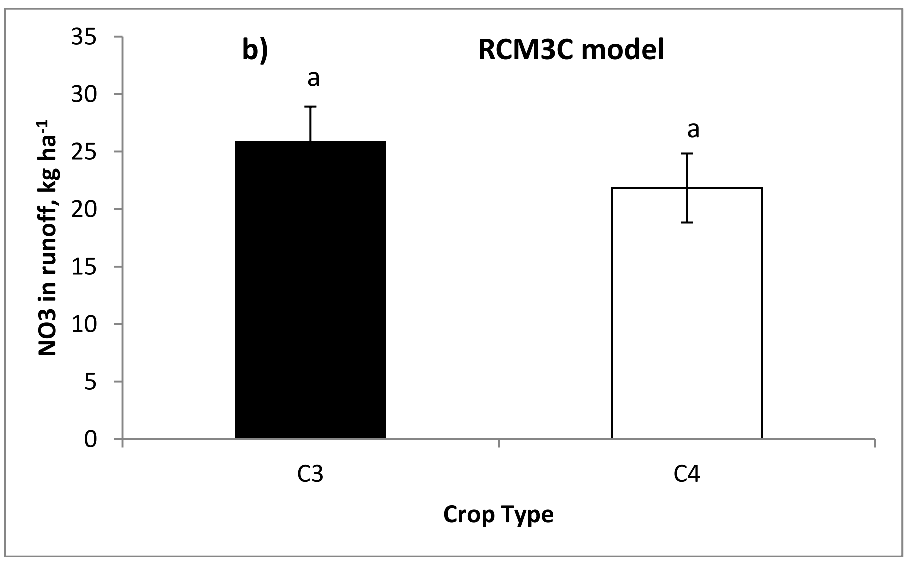
Table 5.7. Comparisons between historical baseline (NARR) and future nitrate losses in runoff for different regional climate models. Letters within the same column indicate LSD mean differences at $P < 0.05$.

Model*	NO_3, kg ha^{-1}
NARR (baseline)	19.06a
CRCM	27.04b
HRM3	-
RCM3C	28.72b
RCM3G	21.96a

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model; LSD – Least significant differences)

Although C_3 crop types consistently displayed larger nitrate losses in runoff than the C_4 crop types when using the CRCM, RCM3C and RCM3G regional climate models, these differences were not statistically significant (Fig. 5.5).


a) CRCM model
NO3 in runoff, kg ha-1
0
5
10
15
20
25
30
a
a
C3
C4
Crop Type


b) RCM3C model
NO3 in runoff, kg ha-1
0
5
10
15
20
25
30
35
a
a
C3
C4
Crop Type

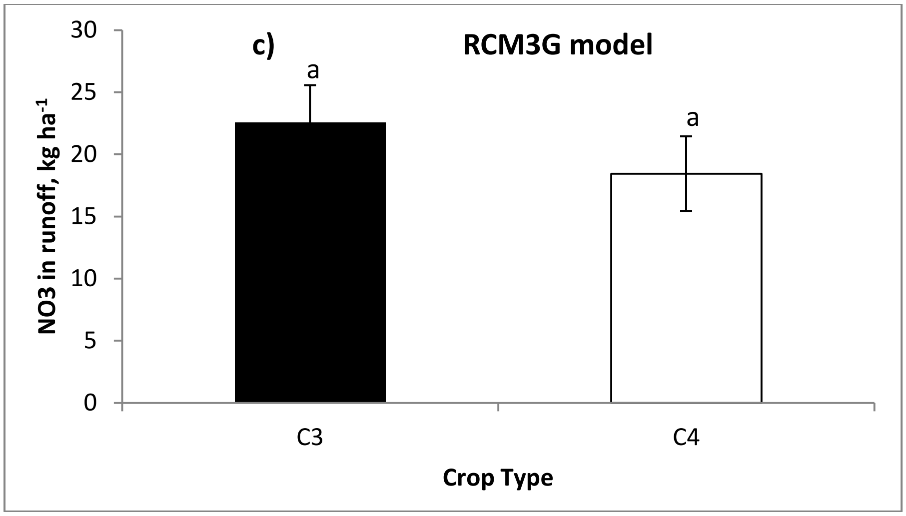


Fig. 5.5 Nitrate losses in runoff for C_3 and C_4 crop types as predicted by the (a) CRCM (The Canadian Regional Climate Model with the Third Generation Coupled Climate Model), (b) the RCM3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model), and (c) the RCM3G (The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) regional climate models. Letters indicate Least Significant Difference (LSD) mean comparisons at $P < 0.05$

Further, there was significant model x crop type interaction, with significantly higher nitrate losses under C_3 plants for the comparison between the future climate predicted by the HRM3 regional climate model and NARR historical baseline scenario. For the C_4 plants, future nitrate losses in runoff were higher, but not statistically significant in comparison with the historical baseline (Fig. 5.6). Since C_4 plants are known for greater biomass yield, our finding was in agreement with Asada et al. (2013) who estimated nitrate losses with the LEACHM model and concluded that there is an increased nitrate loss following crops that provide less crop residue input to the soil .

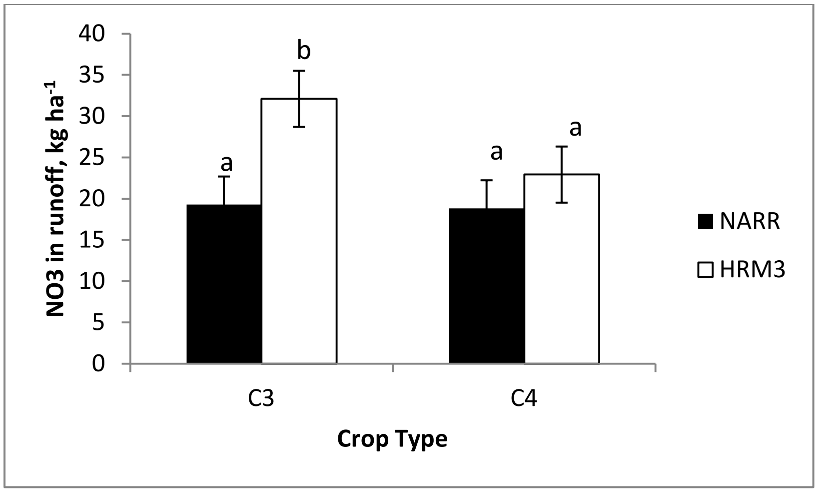


Fig. 5.6 Nitrate losses in runoff for C_3 and C_4 crop types using the historical baseline (NARR) and the HRM3 (The Hadley Regional Model and the Hadley Coupled Model version 3) regional climate model. Letters indicate Least significant differences (LSD) mean comparisons at $P < 0.05$

There were no statistically significant differences in the nitrate losses in runoff for any of the regions (Table 5.8), which suggested that regions were not responding differently to nitrate losses in runoff due to climate effects simulated by the four regional climate models.

Table 5.8. Nitrate losses in runoff ($kgha^{-1}$) for the North, South, and West region evaluated using the CRCM (The Canadian Regional Climate Model with the Third Generation Coupled Climate Model) model, the HRM3 (The Hadley Regional Model and the Hadley Coupled Model version 3) model, the RCM3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) model, and the RCM3G (The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) model. Letters within the same column indicate Least Significant Difference mean comparisons at $P < 0.05$.

Region	Model			
	CRCM	HRM3	RCM3C	RCM3G
North	21.22a	23.53a	21.18a	19.46a
South	23.62a	23.07a	23.76a	21.71a
West	24.29a	23.24a	26.73a	20.36a

Climate effects on future nitrate losses in runoff

There were significant region x RCM interactions indicating that the future nitrate losses in runoff needed to be analyzed separately by each region and model. Irrigation and biochar application displayed no significant impacts on nitrate losses in runoff although the data trends suggested evidence for increased nitrate runoff losses with irrigation and biochar treatments (Table 5.9). Crop types when considered over future time intervals behaved in a statistically significant different manner for all regional climate models except for the RCM3G model's South region (Table 5.10). The C_4 crop type displayed significantly lower nitrate losses in runoff with values that were 40 to 60% lower when compared to the C_3 crop types for some individual periods of the CRCM model's North region; HRM3 model's West region; RCM3C model's North, South and West regions; and RCM3G model's North region. Overall data trends suggested that nitrate losses in runoff were lower when a C_4 crop was being grown. Since C_4 plants are known for greater biomass yields and, therefore, larger quantities of residue being left in the field, this finding was in agreement with results obtained by Gowda et al. (2011) who reported that nitrate losses were lower from crop land covered with more residue than cropland that had less residue cover.

Table 5.9. Irrigation and biochar application effects on predicted nitrate losses (kg ha^{-1}) in runoff for the 2038 – 2068 simulation period when different regional climate models were used. Letters within the same column for each effect indicate Least Significant Difference mean comparisons at $P < 0.05$.

Effect		Regional Climate Model*											
		CRCM			HRM3			RCM3C			RCM3G		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Irrigation	No	24.76a	30.57a	29.58a	30.17a	29.71a	26.73a	24.97a	30.13a	33.26a	21.69a	25.85a	20.09a
	Yes	26.30a	33.25a	32.27a	32.21a	33.25a	33.08a	28.28a	32.73a	34.76a	23.49a	27.74a	23.40a
Biochar	No	25.05a	30.49a	29.23a	29.85a	29.59a	28.92a	25.96a	30.45a	33.20a	21.84a	25.98a	20.95a
	Yes	26.01a	33.33a	32.62a	32.53a	33.37a	30.89a	27.29a	32.41a	34.82a	23.33a	27.61a	22.54a

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

Table 5.10. The effects of C3 and C4 crop types on nitrate losses in runoff (kg ha^{-1}) across 5 year future climate periods for each region and regional climate model. Letters within the same column for each period indicate Least significant differences mean comparisons at $P < 0.05$.

Effect		Crop Type	Regional Climate Model*											
			CRCM			HRM3			RCM3C			RCM3G		
			Region											
			North	South	West	North	South	West	North	South	West	North	South	West
Period x Crop Type	2038-2042	C_3	29.12a	29.13a	24.43a	25.96a	25.14a	24.00a	26.88a	31.93a	26.99a	22.26a	-	19.55a
		C_4	23.62a	33.04a	31.28a	30.49a	28.34a	20.74a	16.38b	27.35a	17.05b	15.99a	-	22.19a
	2043-2047	C_3	34.82a	34.71a	36.20a	35.82a	34.62a	33.27a	30.59a	32.86a	33.87a	25.33a	-	24.30a
		C_4	23.92b	29.45a	27.52a	26.30a	32.03a	21.21b	23.88a	19.94b	37.91a	13.77b	-	17.19a
	2048-2052	C_3	30.99a	35.48a	33.70a	38.49a	31.11a	35.93a	30.88a	35.49a	35.52a	31.58a	-	24.75a
		C_4	25.06a	32.52a	30.03a	28.62a	30.88a	26.69a	20.67b	32.33a	35.18a	17.57b	-	23.60a
	2053-2057	C_3	29.00a	34.80a	34.32a	34.84a	37.30a	38.41a	30.34a	35.82a	38.85a	27.22a	-	23.43a
		C_4	18.16b	29.87a	27.46a	26.29a	29.08a	32.65a	24.97a	29.78a	30.49a	17.76b	-	25.07a
	2058-2062	C_3	27.99a	28.84a	34.51a	33.34a	32.53a	31.19a	32.50a	36.66a	32.93a	27.67a	-	22.02a
		C_4	20.09a	32.69a	27.72a	30.42a	31.91a	28.67a	22.64a	27.86a	28.35a	24.14a	-	17.82a
	2063-2068	C_3	25.21a	33.39a	33.58a	31.74a	32.67a	33.30a	31.27a	34.19a	30.60a	27.98a	-	19.52a
		C_4	18.40a	28.99a	30.35a	31.96a	32.17a	32.82a	28.50a	32.98a	30.39a	19.80a	-	21.47a

*(NARR – Historical baseline climate scenario; CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - The Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

Nitrate losses in runoff displayed statistical significance for different periods in the RCM3G model's South region and caused approximately 20% greater losses of nitrate in runoff for the middle part of the 2038 – 2068 simulation period (Fig. 5.7) and may be attributed to the increased annual precipitation associated with future climate. This finding is similar to the results reported by Chiang et al. (2012) who reported increased nitrate losses with climate change from experimental plots in Northern Arkansas and Eastern Oklahoma. Another study reported nitrate losses rates to be about 1.2 – 1.9 times greater under future climate conditions for two watersheds in Nebraska (Van Liew et al., 2012).

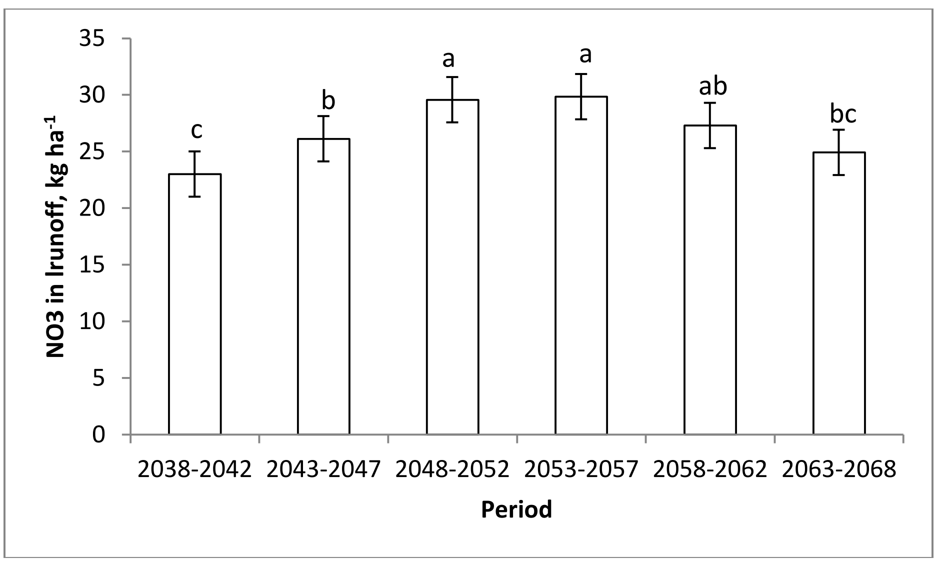


Figure 5.7. Nitrate losses in runoff for different periods in the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) model's South region. Letters indicate Least significant differences mean comparisons at $P < 0.05$.

Although C_3 crop types displayed greater nitrate losses in runoff when compared to the C_4 crop types in the RCM3G model's South region and suggest lower rates of nitrate losses in runoff under C_4 plants, these observed differences were not statistically significant (Fig. 5.8)

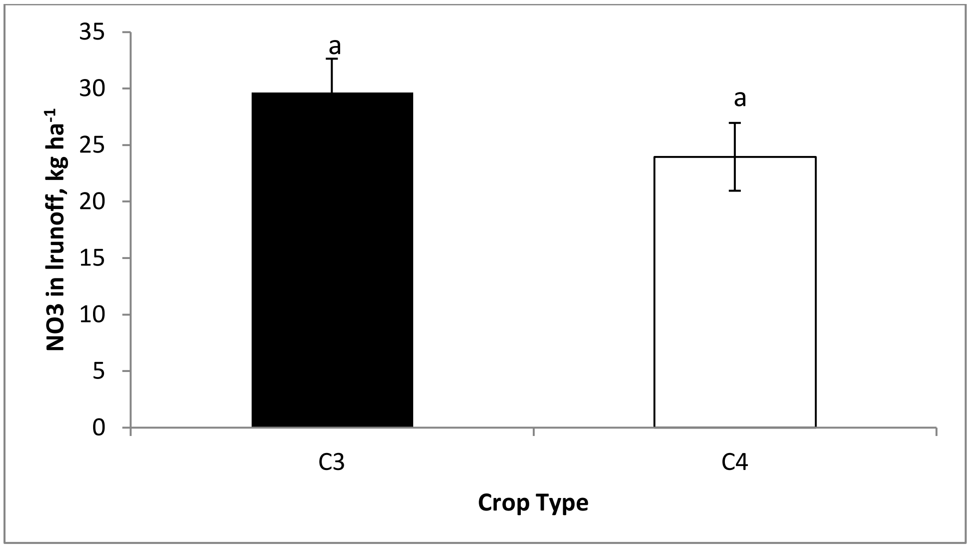
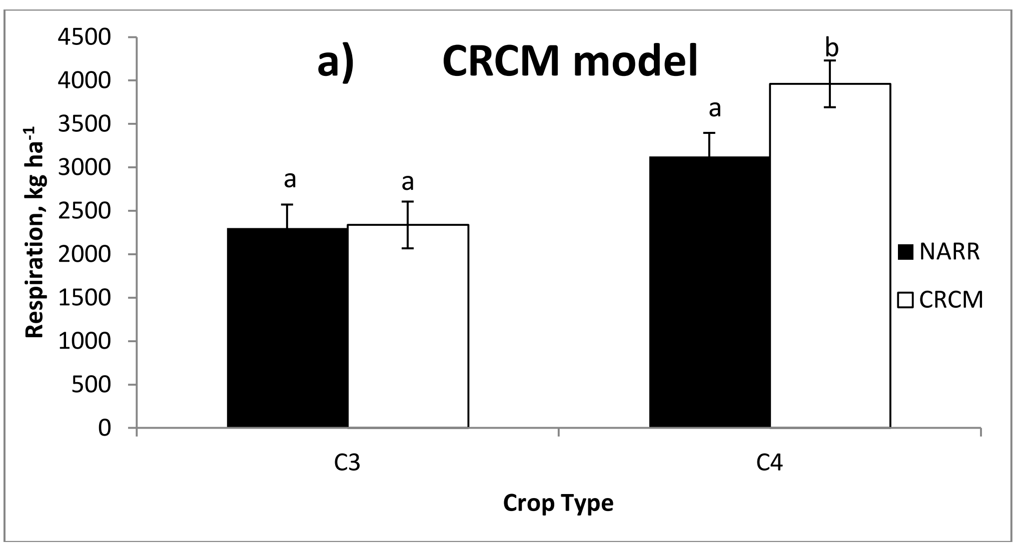
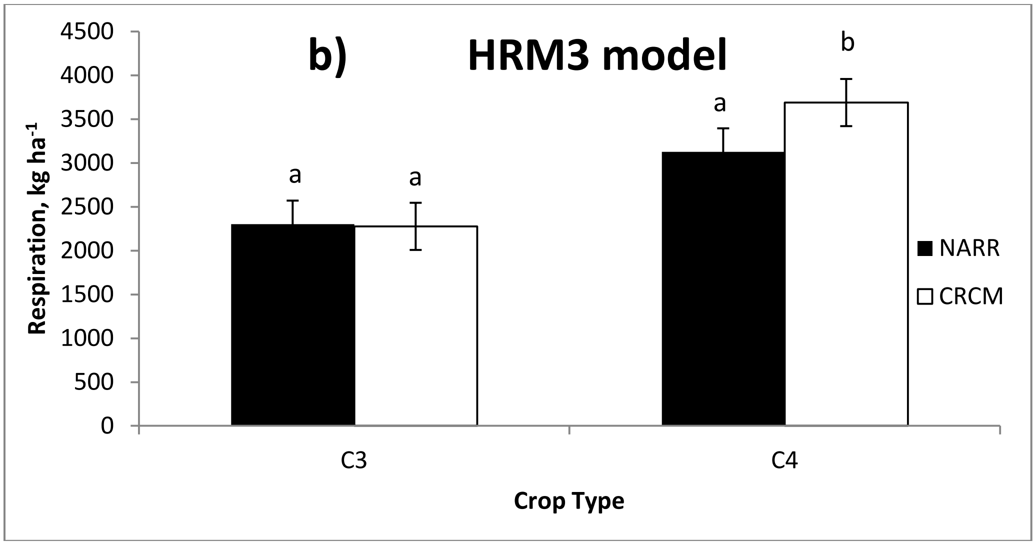


Figure 5.8. The effects of C_3 and C_4 crop types on nitrate losses in runoff for the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) model's South region. Letters indicate Least significant differences mean comparisons at $P < 0.05$.

Microbial respiration (past vs. future comparison)

Microbial respiration displayed significant crop type x RCM interactions for the CRCM, HRM3, and RCM3G models indicating differences in microbial respiration existed between C_3 and C_4 crops for three RCMs. Based on the statistically significant means comparisons, it appears that in the future microbial respiration under C_4 crops will be as much as 20% higher than the previous microbial respiration under C_4 crops during the historical baseline period (Fig. 5.9). No significant changes in microbial respiration were detected under C_3 crops when comparing the historical baseline periods and future climate as predicted by the CRCM, HRM3, and RCM3G regional climate models (Fig. 5.9). This finding seems logical as the C_4 crops used in this modeling study produce higher biomass yields and, therefore, more residue is left on the field, resulting in higher microbial respiration. Franzluebbers (2005) found the same results in his study investigating soil organic carbon sequestration and agricultural greenhouse gas emissions in the Southeastern US. He concluded that microbial respiration was, among other factors, related to primary inputs of crop residue. Shao et al. (2013) came to a similar conclusion that microbial respiration will increase in the future compared to historical baseline periods based on similar simulations performed by the eight Earth system models.





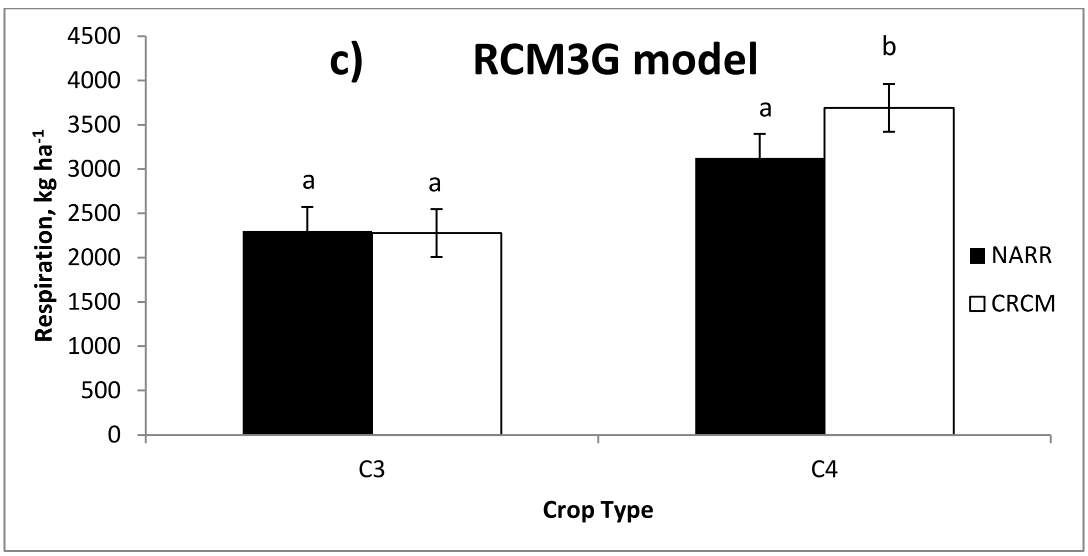


Fig. 5.9 The effects of C_3 and C_4 crop types on microbial respiration using historical baseline and future climate data as predicted by the (a) CRCM (the Canadian Regional Climate Model with the Third Generation Coupled Climate Model), (b) the HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3), and (c) the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) regional climate models. Letters indicate Least significant differences means comparisons at $P < 0.05$.

The different regions did not appear to have any impacts on microbial respiration as no statistically significant differences were found (Table 5.11).

Table 5.11. Microbial respiration (kg ha^{-1}) for different regions when using the CRCM (the Canadian Regional Climate Model with the Third Generation Coupled Climate Model), the HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3), and the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) regional climate models. Letters within the same column indicate Least significant differences means comparisons at $P < 0.05$.

Region	Model		
	CRCM	HRM3	RCM3G
North	2667a	2659a	2659a
South	2856a	2790a	2790a
West	3271a	3099a	3099a

There were significant region x RCM interactions for the RCM3C model although no statistically significant differences in microbial respiration were displayed when comparing the North and South regions for the historical baseline and future climate scenarios (Table 5.12).

Table 5.12. Comparison of regional mean values of microbial respiration ($kgha^{-1}$) for the North and South region using the NARR (historical baseline scenario) and the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate models. Letters within the same column indicate Least significant differences means comparisons at $P < 0.05$.

Model	Region	
	North	South
NARR (baseline)	2514a	2667a
RCM3C	2470a	2818a

The C_4 crops displayed statistically significant microbial respiration that was as much as 50% greater than the microbial respiration displayed by the C_3 crops for the RCM3C model's North and South regions simulations (Table 5.13).

Table 5.13. The effects of C_3 and C_4 crop types on microbial respiration ($kgha^{-1}$) using the RCM3C (The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional model for the North and South regions. Letters within the same column indicate Least significant differences mean comparisons at P < 0.05

Crop Type	Region	
	North	South
C_3	2060a	2194a
C_4	2924b	3291b

Similarly, for the same RCM3C model, there was a significant RCM x crop type interaction for the West region with significant increases in microbial respiration for the C_4 crops by as much as 45% compared to the historical baseline scenario. However, under the C_3 crops, no significant differences were detected in microbial respiration when comparing historical baseline and future climates (Fig. 5.10).

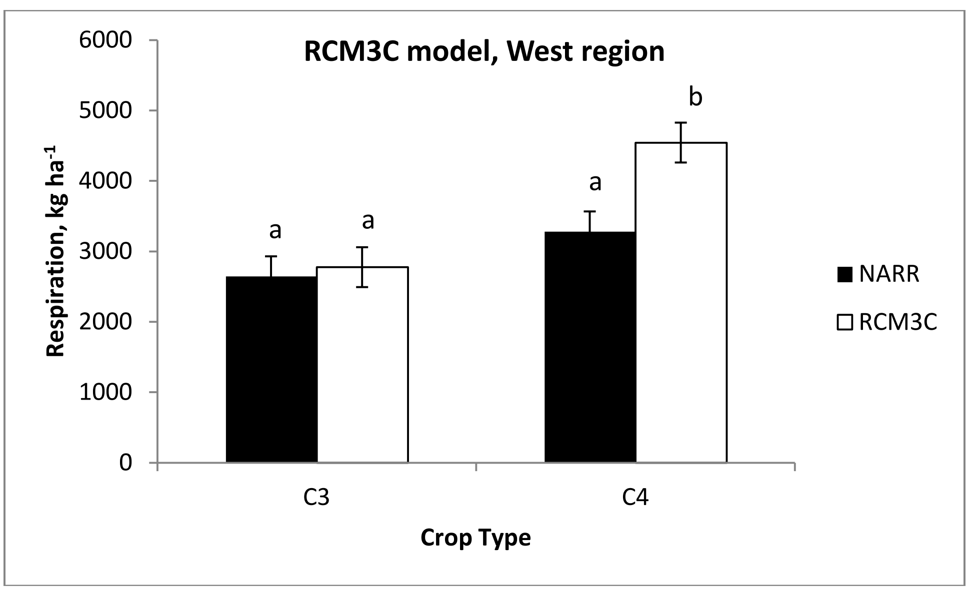


Fig. 5.10 The effects of C_3 and C_4 crop types on microbial respiration for NARR (historical baseline scenario) and future climate using the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) regional climate model. Letters indicate Least significant differences means comparisons at P < 0.05.

Climate effects on future microbial respiration

Irrigation did not have a statistically significant impact on microbial respiration for the majority of regions and regional models. Although not statistically significant, trends in the data suggested that a slight increase in microbial respiration might have occurred in response to irrigation (Table 5.14). There were significant period x irrigation, period x biochar, and period x crop type interactions in quantifying climate effects on future microbial respiration for many regional climate models and regions (Table 5.15). In all cases of significant period x biochar and period x crop type interactions, microbial respiration under the C_4 crop types and biochar were significantly greater if compared to the C_3 crop types and treatments with no biochar application. The differences in microbial respiration between the C_4 and C_3 crops ranged from 20 to 45%. The differences in microbial respiration between biochar application and no biochar treatment ranged from 15 to 55% (Table 5.15). The results were not surprising because C_4 crops leave more residue on the ground upon harvesting, which results in higher microbial respiration. In the case of biochar application, the increase in microbial respiration is associated with the active carbon pool in biochar which, upon application, is immediately available for microbial decomposition. Our determinations of increased microbial respiration under C_4 crops for future climate scenarios are supported by the results of Wieder et al. (2013) who compared predictions in microbial respiration between the Community Land Model and the Earth system models. They concluded that larger microbial biomass pools, similar to the increased residue input from C_4 plants, would result in increased rates of heterotrophic respiration. Since the four regional climate models used in this study predict raises in average annual temperatures, increased microbial respiration is not surprising. Bond-Lamberty and Thomson, (2010) came to similar conclusions and reported that future microbial respiration rates were positively correlated with increases in temperature associated with future climate.

There were significant period x irrigation interactions for the RCM3C model's North and South regions and all regions for RCM3G model. Although data patterns indicated higher rates of microbial respiration under irrigation as compared to the no irrigation treatment, the effects of irrigation on microbial respiration across individual future periods were not significantly different (Table 5.14).

Table 5.14. The effects of irrigation on microbial respiration (kg ha^{-1}) for the 2038 – 2068 simulation period using all regional climate models. Letters within the same column indicate Least significant differences means comparisons at $P < 0.05$.

Effect		Regional Climate Model*											
		CRCM			HRM3			RCM3C			RCM3G		
		Region											
		North	South	West	North	South	West	North	South	West	North	South	West
Irrigation	No	3542a	3847a	4385a	3560a	3728a	4045a	-	-	4454a	-	-	-
	Yes	3624a	3851a	4400a	3565a	3769a	4143a	-	-	4454a	-	-	-

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

Table 5.15 The effects of C_3 and C_4 crop types, biochar application, and irrigation on microbial respiration (kg ha^{-1}) across individual future climate periods. Letters within the same column for each period indicate Least significant differences means comparisons at $P < 0.05$.

Effect		Crop Type	Model*											
			CRCM			HRM3			RCM3C			RCM3G		
			Region											
			North	South	West	North	South	West	North	South	West	North	South	West
Period x Crop Type	2038-2042	C_3	3069a	3525a	4874a	3148a	3479a	4853a	3024a	3479a	4790a	2707a	3359a	4555a
		C_4	4370b	4904b	6173b	4341b	4814b	5750b	3712b	4590b	6147b	3732b	4442b	5328b
	2043-2047	C_3	2962a	3264a	4067a	2957a	3186a	4037a	2953a	3226a	4028a	2655a	3125a	3841a
		C_4	4577b	4859b	5526b	4423b	4715b	4972b	4011b	4574b	5710b	3952b	4546b	4795b
	2048-2052	C_3	2813a	2973a	3516a	2780a	2911a	3447a	2798a	3028a	3516a	2710a	2938a	3486a
		C_4	4402b	4723b	5193b	4378b	4628b	4626b	3793b	4471b	5324b	4060b	4571b	4588b
	2053-2057	C_3	2673a	2807a	3200a	2637a	2738a	3156a	2698a	2833a	3193a	2605a	2796a	3244a
		C_4	4246b	4574b	4876b	4301b	4456b	4399b	3800b	4367b	5033b	4149b	4505b	4223b
	2058-2062	C_3	2612a	2701a	2968a	2543a	2623a	2909a	2635a	2741a	2979a	2580a	2703a	3006a
		C_4	4364b	4609b	4781b	4325b	4411b	4091b	4022b	4418b	4959b	4179b	4371b	4015b
	2063-2068	C_3	2585a	2656a	2883a	2517a	2594a	2821a	2550a	2678a	2906a	2540a	2693a	2961a
		C_4	4323b	4592b	4654b	4393b	4420b	4071b	3809b	4372b	4857b	4185b	4341b	4133b
Period x Biochar	2038-2042	N	3470a	3908a	5216a	3478a	3889a	4998a	3122a	3743a	5168a	2991a	3621a	4665a
		Y	3970b	4521b	5823b	4011b	4455b	5604b	3614b	4326b	5769b	3448b	4180b	5218b
	2043-2047	N	3229a	3421a	4161a	3120a	3297a	3867a	2956a	3285a	4249a	2830a	3246a	3764a
		Y	4310b	4703b	5432b	4260b	4604b	5142b	4008b	4515b	5489b	3777b	4425b	4872b
	2048-2052	N	2867a	3002a	3499a	2796a	2908a	3178a	2580a	2921a	3587a	2685a	2946a	3254a
		Y	4348b	4694b	5210b	4362b	4632b	4895b	4011b	4578b	5253b	4086b	4563b	4820b
	2053-2057	N	2606a	2746a	3074a	2580a	2635a	2796a	2397a	2663a	3167a	2550a	2726a	2812a
		Y	4312b	4636b	5002b	4358b	4560b	4758b	4102b	4537b	5058b	4204b	4575b	4655b

	2058-2062	N	2538a	2654a	2855a	2461a	2499a	2464a	2370a	2552a	2967a	2442a	2538a	2534a
		Y	4438b	4656b	4894b	4407b	4536b	4536b	4286b	4607b	4971b	4316b	4536b	4487b
	2063-2068	N	2413a	2552a	2709a	2403a	2424a	2354a	2182a	2471a	2808a	2340a	2436a	2485a
		Y	4496b	4697b	4828b	4507b	4590b	4538b	4177b	4579b	4955b	4385b	4598b	4609b
Period x Irrigation	2038-2042	N	-	-	-	-	-	-	3245a	3914a	-	3117a	3747a	4795a
		Y	-	-	-	-	-	-	3491a	4154a	-	3322a	4054a	5089a
	2043-2047	N	-	-	-	-	-	-	3359a	3724a	-	3152a	3677a	4107a
		Y	-	-	-	-	-	-	3605a	4076a	-	3455a	3994a	4529a
	2048-2052	N	-	-	-	-	-	-	3109a	3635a	-	3299a	3677a	3872a
		Y	-	-	-	-	-	-	3482a	3864a	-	3472a	3833a	4202a
	2053-2057	N	-	-	-	-	-	-	3114a	3480a	-	3321a	3577a	3599a
		Y	-	-	-	-	-	-	3384a	3720a	-	3433a	3724a	3868a
	2058-2062	N	-	-	-	-	-	-	3196a	3486a	-	3310a	3423a	3360a
		Y	-	-	-	-	-	-	3460a	3674a	-	3448a	3651a	3661a
	2063-2068	N	-	-	-	-	-	-	3057a	3441a	-	3289a	3416a	3456a
		Y	-	-	-	-	-	-	3302a	3609a	-	3436a	3619a	3638a

*(NARR – historical baseline climate scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

Soil carbon content (past vs. future comparison)

There were no significant regional impacts on soil carbon contents (Table 5.16), suggesting that soil carbon stocks were not influenced differently in the different regions.

Table 5.16. Regional impacts on soil carbon content (kg ha^{-1}). Letters within the same column indicate Least significant differences means comparisons at P < 0.05.

Region	Regional Climate Model*			
	CRCM	HRM3	RCM3C	RCM3G
	Kg C ha^{-1}			
North	9450a	9214a	9424a	9495a
South	8875a	8645a	8738a	8753a
West	12067a	11959a	12137a	12162a

*(CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

No significant differences existed in soil carbon contents when evaluated using the NARR historical baseline scenario and future climate scenario as predicted by the CRCM model. Although there were no significant differences, the data suggested that approximately a slight amount of 130 kg of C per hectare would exist in future climate scenarios (Fig.5. 11). This finding was in agreement with Tian et al. (2012) who found an increase in soil carbon stocks in a modeling study which looked at the effects of climate change on soil carbon dynamics in the Southeastern US. The results were also in agreement with Causarano et al. (2008) and Franzluebbers (2010) who conducted a literature review of about 150 available studies on carbon sequestration in the Southeastern US, performed controlled experiments, and concluded that conservation agricultural systems will sequester a significant amount of organic carbon.

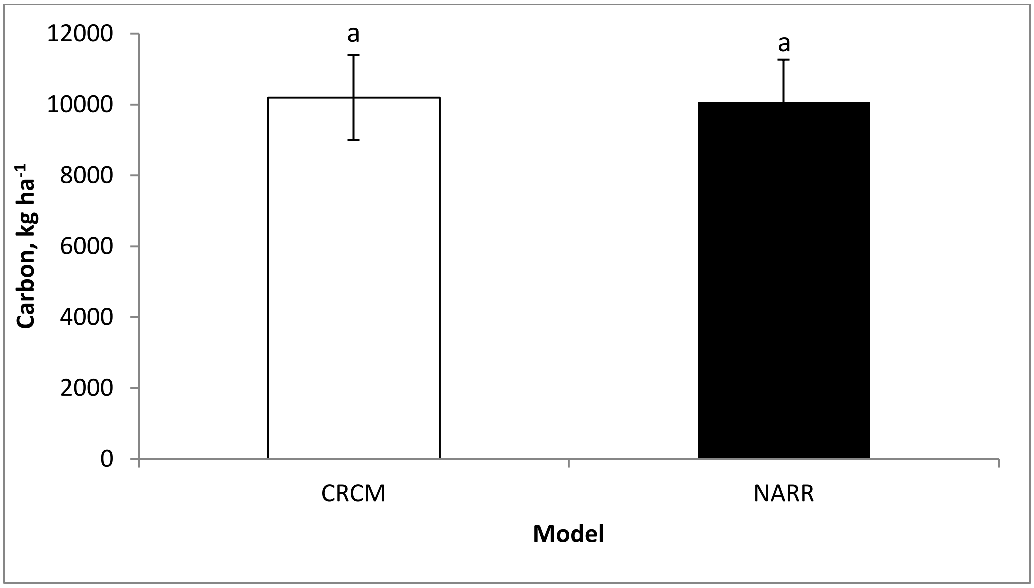


Fig. 5.11 The effects of climate on soil carbon content when comparing the NARR (historical Baseline Scenario) and the CRCM (Canadian Regional Climate Model with the Third Generation Coupled Climate Model) regional climate model scenario. Letters indicate Least significant differences means comparisons at $P < 0.05$.

Significant differences existed for different quantities of soil carbon under the C_3 and C_4 crop types using the CRCM regional climate model (Fig. 5.12). Soil carbon content was significantly higher under the C_4 crops by as much as 6% compared to the C_3 crops and was primarily due to the greater biomass yield and root mass associated with the C_4 crops. These results are supported by Abrahamson et al. (2009) who reported that no-till management and crop rotations that included C_4 crops significantly increases soil organic carbon stocks in the Southeastern US.

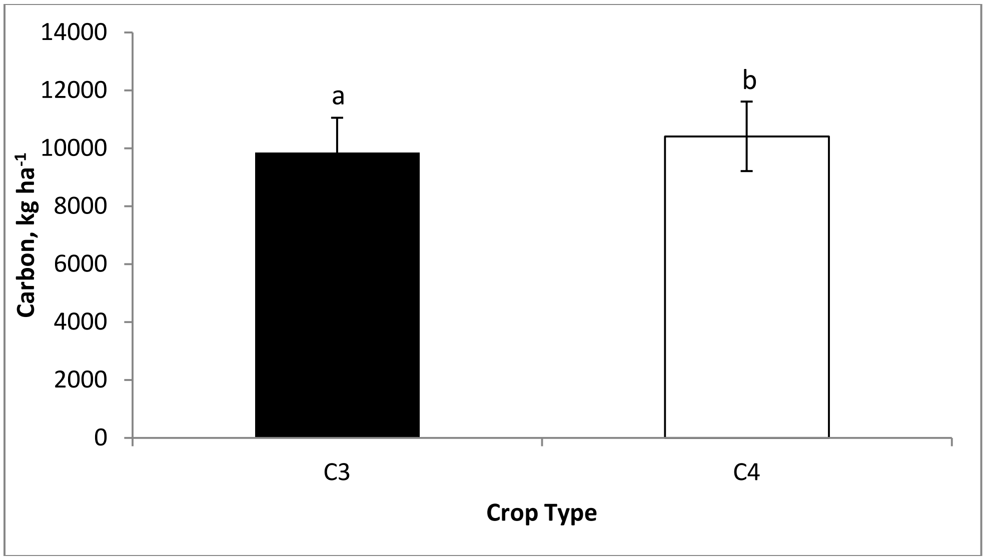
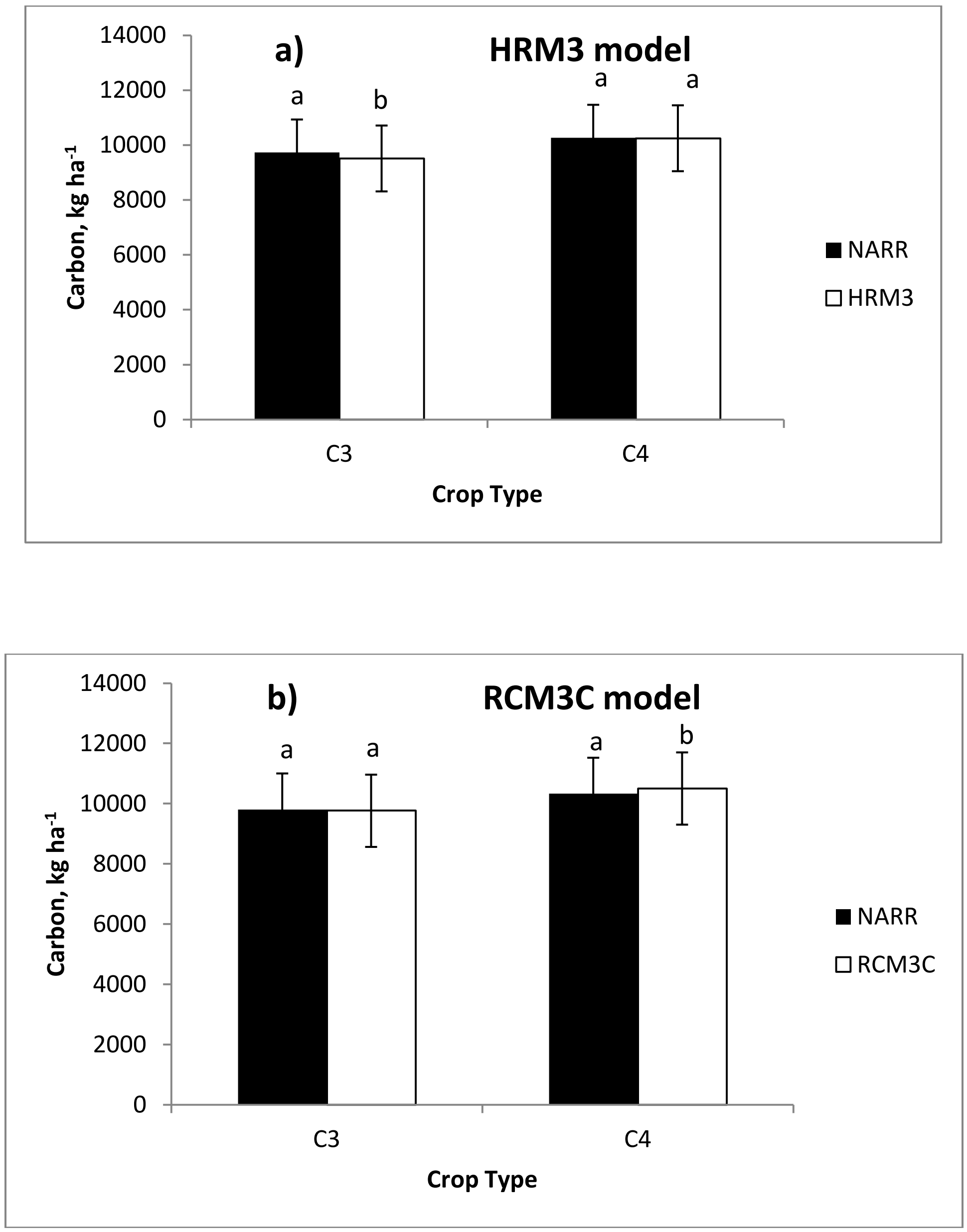


Fig. 5.12 The effects of C_3 and C_4 crop types on soil carbon content as predicted when using the CRCM (Canadian Regional Climate Model with the Third Generation Coupled Climate Model) regional climate model. Letters indicate Least significant differences means comparisons at $P < 0.05$.

There were significant crop type x RCM interactions when the HRM3, RCM3C and RCM3G climate models were used. The effects of climate change on the soil carbon content were highly variable depending on the RCM. It appears that in cases using the RCM3C and RCM3G models, the predicted soil carbon contents under the C_4 crops were significantly higher by 1.7% and 3.5%, respectively, when compared to soil carbon contents under the C_4 crops during the historical baseline period (Fig. 5.13). No significant changes in soil carbon contents were detected under the C_3 crops using the historical baseline climate scenarios and the future climate scenarios as predicted by the RCM3C model. However, soil carbon contents under the C_3 crops were significantly lower by 3% when comparing the historical baseline climate scenario and the future climate scenario predicted by the HRM3 model. Soil carbon contents under the C_3 crops were significantly higher by 2% when comparing historical baseline climate scenarios and future climate scenarios predicted by the RCM3G model (Fig. 5.13).



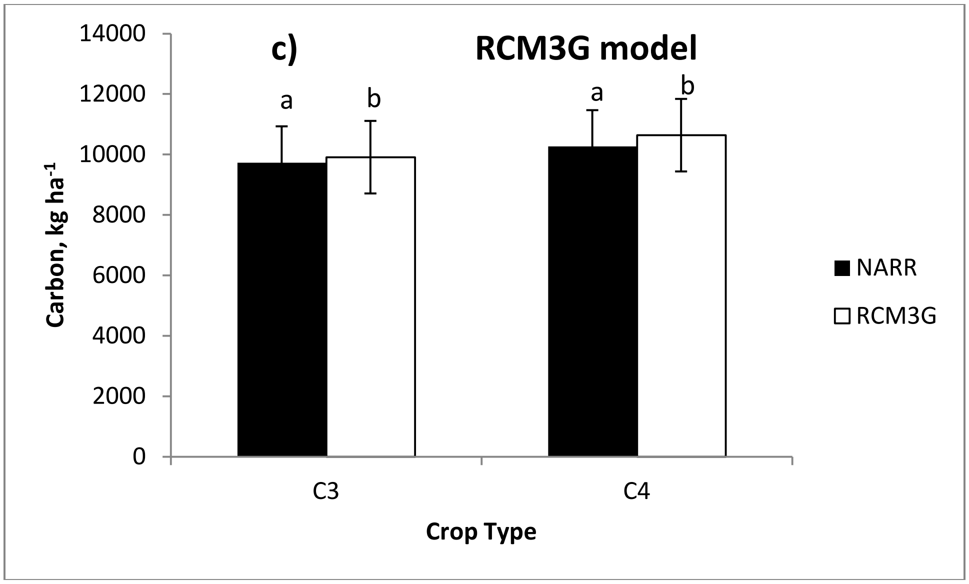


Fig. 5.13 The effects of the C_3 and C_4 crop types on soil carbon contents using the historical baseline climate scenarios and the future climate scenarios as predicted by the (a) HRM3 (the Hadley Regional Model and the Hadley Coupled Model version 3), (b) the RCM3C (the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model) and (c) the RCM3G (the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model) regional climate models. Letters indicate Least significant differences means comparisons at $P < 0.05$.

Climate effects on future soil carbon contents

There were significant region x RCM interactions requiring that data on future soil carbon dynamics be analyzed separately by each region and model (Appendix A). Biochar applications displayed significant impacts on future soil carbon contents for all regional climate models across all regions and individual periods. Biochar applications resulted in significantly greater soil carbon contents by as much as 40% compared to the no biochar treatment. These results are in agreement with several previous researchers (Joseph et al., 2009; Lehmann et al., 2009; Major et al., 2010;

Nguyen and Lehmann, 2009; Rogovska et al., 2011; Laird et al. 2010b) who concluded that increased carbon sequestration rates existed in soil treated with biochar but the result in greater carbon content was not due to the simple addition effect of biochar application. Crop type was significant in cases of the West region for all regional climate models across all regions and individual periods, with C_4 plants resulting in significantly higher values approximating 5% of soil carbon compared to C_3 plants (Appendix A). As previously stated, the greater biomass yield in C_4 crops resulted in greater carbon content under this crop type. For all other regions and models, data suggest greater carbon sequestration under C_4 crops compared to C_3 crops, but no significant differences were detected. These findings are supportive of conclusions reached by previous researchers (Franzluebbers, 2005; Han et al., 2007) who concluded that the Southeastern US has a high potential for soil organic carbon sequestration to the amount of up to 130 Tg C year $^{-1}$ that would offset the region's total 22.3% greenhouse gas emission. Irrigation did not have significant impacts on soil carbon contents for all regional climate models across all regions.

Summary and Conclusions

The four future regional climate models used in this study showed variability in changes of maximum and minimum air temperatures, as well as changes in annual precipitation for the regions of interest within the Southeastern US. Generally, the CRCM and HRM3 models predicted increased maximum daily air temperatures, while the RCM3C and RCM3G models predicted decreased maximum daily air temperatures. All models, except for the HRM3 model, predict decreased minimum daily temperatures. All RCMs generally predicted increased annual precipitation for the Southeastern US.

The regional climate models generally predicted increased nitrate leachate losses due to future climate scenarios. Compared to the historic baseline scenario, nitrate leachate losses increased by as much as 85% primarily due to increased average annual precipitation in the future assuming that no adaptations are implemented to help alleviate climate change impacts. Nitrate leachate losses under the C_4 crops were significantly lower than under the C_3 crops with differences ranging between 50 to 85% under historical baseline and future climate simulation periods. We concluded that differences in nitrate leachate losses between the two crop types were due to the higher nitrogen crop uptake that is typical for C_4 crops in comparison to C_3 crops. For the 2038-2068 simulation period, differences in nitrate leachate losses were significantly lower under C_4 crops primarily for the first three 5-yr periods within each regional climate model. Irrigation did not cause significant differences in nitrate leachate losses compared to non-irrigated treatments, except for the case of the RCM3G model's West and North regions. Although irrigation did not cause statistically significant increased nitrate leachate losses for the majority of RCMs, the data trended towards increased nitrate leachate losses under irrigation. With the exception of several individual 5 year simulation periods, biochar applications did not cause significant differences in nitrate leachate losses compared to areas not receiving biochar applications. Although biochar applications did not cause statistically significant reductions in nitrate leachate losses for the majority of the RCMs, the data again trended towards decreased nitrate leachate losses following biochar applications for all models across all regions.

The future climate simulations displayed increased nitrate losses in runoff compared to the historical baseline scenario, with increased nitrate runoff losses ranging between 40 to 90% in the case of no adaptations. The increases in future nitrate runoff losses were associated with greater annual precipitation associated with future climates. Crop type did not have a significant impact in the simulation between historical baseline and future climate, even though data suggested decreasing trends in nitrate runoff losses under C_4 crops. Regions within the Southeastern US did not differ significantly in terms of nitrate losses in runoff, suggesting that there is no impact on nitrate losses due to differences between regions used in this simulation study. For the 2038 – 2068 simulation period, the C_4 crops displayed significantly lower rates of nitrate runoff losses for some individual 5 year period when compared to nitrate losses for C_3 crops. The differences were attributed to the increased nitrate demands for growing C_4 crops in comparison to C_3 crops. For the majority of periods, the difference in nitrate losses in runoff under C_4 and C_3 plants was not significant; however the data trended towards lower values of nitrate runoff losses for C_4 crops. Irrigation and biochar applications did not have statistically significant effects on nitrate runoff losses compared to areas that received no biochar and no irrigation, however, the data indicated increasing trends in nitrate runoff losses with irrigation and biochar applications.

Mean values for crop types indicated significantly greater rates of microbial respiration in the future compared to historical baseline with values for C_4 crops being as much as 20% higher than values for the C_3 crops. At the same time, microbial respiration under C_3 crops were not statistically different in the future compared to microbial respiration under C_3 crops during the historical baseline scenario. For the future 2038 – 2068 simulation period, the differences in microbial respiration between C_4 and C_3 plants ranged from 20 to 45%, primarily due to the differences between the amount of biomass and reside between these two crop types. The differences in microbial respiration between biochar application and no biochar treatment ranged from 15 to 55%, primarily due to the active/metabolic carbon pool in biochar which is immediately available for microbial decomposition upon application of biochar. Regions within the Southeastern US did not differ significantly among themselves in terms of microbial respiration. For the 2038 – 2068 simulation period for the majority of the regional climate models and regions, irrigation did not result in significantly greater values of microbial respiration.

Finally, for the soil carbon contents, we observed a great variability in soil carbon contents for comparisons between the historical baseline scenario and the future climate predicted by the four regional climate models. Significantly greater rates of soil carbon sequestration were observed with values up to 3.5% greater under C_4 crops in the future compared to the historical baseline scenario. The C_3 crop type impacts on soil carbon contents were significantly higher by as much as 2% between the historical baseline period and the future climate when using the RCM3G regional climate model. In case of the HRM3 regional climate model, soil carbon contents were significantly lower under C_3 crops by as much as 3% between the historical baseline period and the future climate. Regions within the Southeastern US did not have a significant impact on soil carbon contents. For the 2038 – 2068 simulation period, biochar applications resulted in significantly higher soil carbon sequestration values for all regional climate models across all the regions and periods by as much as 40%. The C_4 crops resulted in significantly higher soil carbon contents up to 5% in the case of the West region for all regional climate models across all periods. Irrigation did not have a significant impact on soil carbon contents for all regional climate models across all regions.

The results of this modeling study indicated that nitrate losses will increase during the 2038 – 2068 future climate in the Southeastern United States in comparison to the historic baseline scenario of 1979 - 2009. Similarly, microbial respiration will be increased under the C_4 crop types and when biochar is applied to soil. In general, the C_4 crop type and biochar applications resulted in significantly greater soil carbon sequestration rates and, although not significant, strong evidence of reduction in nitrate losses. Overall, irrigation resulted in greater losses of nitrate in leachate and runoff, however, no significant impacts were detected.

Acknowledgements

This project was jointly supported by Climate Modeling (SFA), the Climate Mitigation (CSiTE) Projects within the Joint Global Change Research Institute (sponsored by the Battelle Memorial Institute Pacific Northwest National Laboratory and the University of Maryland, College Park), the University of Maryland Department of Environmental Science and Technology, and the US Fulbright Commission.

We also wish to thank the North American Regional Climate Change Assessment Program (NARCCAP) for providing the data used in this paper. NARCCAP is funded by the National Science Foundation (NSF), the US Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), and the US Environmental Protection Agency Office of Research and Development (EPA).

References

Abrahamson, D., Causarano, H., Williams, J., Norfleet, M. and Franzluebbers, A., 2009. Predicting soil organic carbon sequestration in the southeastern United States with EPIC and the soil conditioning index. Journal of Soil and Water Conservation, 64(2): 134-144.

Adams, R.M., Hurd, B.H., Lenhart, S. and Leary, N., 1998. Effects of global climate change on agriculture: an interpretative review. Climate Research, 11(1): 19-30.

Alexander, R.B. et al., 2008. Differences in phosphorus and nitrogen delivery to the gulf of Mexico from the Mississippi river basin. Environmental Science & Technology, 42(3): 822-830.

Alig, R.J., Adams, D.M. and McCarl, B.A., 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. Forest Ecology and Management, 169(1-2): 3-14.

Allen, L.H., Valle, R.R., Jones, J.W. and Jones, P.H., 1998. Soybean leaf water potential responses to carbon dioxide and drought. Agronomy Journal, 90(3): 375-383.

Apezteguia, H.P., Izaurralde, R.C. and Sereno, R., 2009. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Cordoba, Argentina. Soil & Tillage Research, 102(1): 101-108.

ASA, C., SSSA, 2011. Climate Change Position Statement Working Group. Position Statement on Climate Change. Working Group Rep. ASA, CSSA, and SSSA, Madison, WI, USA.

Asada, K. et al., 2013. Modifying the LEACHM model for process-based prediction of nitrate leaching from cropped Andosols. Plant and Soil, 373(1-2): 609-625.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil, 337(1-2): 1-18.

Backlund, P., Janetos, A. and Schimel, D., 2008. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. Report by the U.S. Climate Change Science Program and the Subcommittee on global change research.

Baldock, J.A. and Smernik, R.J., 2002. Chemical composition and bioavailability of thermally, altered Pinus resinosa (Red Pine) wood. Organic Geochemistry, 33(9): 1093-1109.

Baron, J.S. et al., 2013. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. Biogeochemistry, 114(1-3): 71-92.

Bond-Lamberty, B. and Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature, 464(7288): 579-U132.

Bowes, G., 1993. Facing the inevitable - plants and increasing atmospheric CO_2. Annual Review of Plant Physiology and Plant Molecular Biology, 44: 309-332.

Bricker, S.B. et al., 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. Harmful Algae, 8(1): 21-32.

Brown, C.A. and Power, J.H., 2011. Historic and recent patterns of dissolved oxygen in the Yaquina Estuary (Oregon, USA): Importance of anthropogenic activities and oceanic conditions. Estuarine Coastal and Shelf Science, 92(3): 446-455.

Carbone, G.J. et al., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. Climatic Change, 60(1-2): 73-98.

Causarano, H. et al., 2008. Soil organic carbon fractions and aggregation in the Southern Piedmont and Coastal Plain. Soil Science Society of America Journal, 72(1): 221-230.

Chavas, D.R., Izaurralde, R.C., Thomson, A.M. and Gao, X.J., 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agricultural and Forest Meteorology, 149(6-7): 1118-1128.

Chiang, L., Chaubey, I., Hong, N., Lin, Y. and Huang, T., 2012. Implementation of BMP Strategies for Adaptation to Climate Change and Land Use Change in a Pasture-Dominated Watershed. International Journal of Environmental Research and Public Health, 9(10): 3654-3684.

Costantini, E.A.C., Castelli, F. and L'Abate, G., 2005. Use of the EPIC model to estimate soil moisture and temperature regimes for desertification risk in Italy. Advances in Geoecology, 36: 251-263.

DeLuca, T., MacKenzie, M.D. and Gundale, M.J., 2009. Biochar effects on soil nutrient transformations. In: J. Lehmann and S. Joseph (Editors), Biochar environmental management: Science and technology. Earthscan, Sterling, VA, pp. 251-268.

Diaz, R.A., Magrin, G.O., Travasso, M.I. and Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean Rolling Pampas. Climate Research, 9(1-2): 25-30.

Easterling, W.E., 1996. Adapting North American agriculture to climate change in review. Agricultural and Forest Meteorology, 80(1): 1-53.

Easterling, W.E., Chhetri, N. and Niu, X.Z., 2003. Improving the realism of modeling agronomic adaptation to climate change: Simulating technological substitution. Climatic Change, 60(1-2): 149-173.

Easterling, W.E. et al., 1993. Agricultural impacts of and responses to climate-change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. Climatic Change, 24(1-2): 23-61.

Easterling, W.E., McKenney, M.S., Rosenberg, N.J. and Lemon, K.M., 1992a. Simulations of crop response to climate change - effects with present technology and no adjustments (the dumb farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 53-73.

Easterling, W.E., Rosenberg, N.J., Lemon, K.M. and McKenney, M.S., 1992b. Simulations of crop responses to climate change - effects with present technology and currently available adjustments (the smart farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 75-102.

Edmonds, J.A. and Rosenberg, N.J., 2005. Climate change impacts for the conterminous USA: An integrated assessment summary. Climatic Change, 69(1): 151-162.

FAO, 2002a. World agriculture: towards 2015/2030.

FAO, 2002b. World agriculture: towards 2015/2030. Long-term perspectives. The outlook for agriculture.

Franzluebbers, A., 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil & Tillage Research, 83(1): 120-147.

Franzluebbers, A., 2010. Achieving Soil Organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States. Soil Science Society of America Journal, 74(2): 347-357.

Gaskin, J.W. et al., 2010. Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield. Agronomy Journal, 102(2): 623-633.

Gassman, P.W. et al., 2004. Historical Development and Applications of the EPIC and APEX Models, American Society of Agricultural and Biological Engineers.

Gates, W.L., 1985. The use of general-circulation models in the analysis of the ecosystem impacts of climatic-change. Climatic Change, 7(3): 267-284.

Glaser, B., Lehmann, J. and Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils, 35(4): 219-230.

Gowda, P.H., Westra, J.V., Petrolia, D.R., Mulla, D.J. and Dalzell, B.J., 2011. Impact of targeted removal of residue cover on water quality in the Sand Creek watershed. Journal of Environmental Hydrology, 19 (25): 1-12.

Hamer, U., Marschner, B., Brodowski, S. and Amelung, W., 2004. Interactive priming of black carbon and glucose mineralisation. Organic Geochemistry, 35(7): 823-830.

Han, F., Plodinec, M., Su, Y., Monts, D. and Li, Z., 2007. Terrestrial carbon pools in southeast and south-central United States. Climatic Change, 84(2): 191-202.

Hatfield, J.L., Cruse, R.M. and Tomer, M.D., 2013. Convergence of agricultural intensification and climate change in the Midwestern United States: implications for soil and water conservation. Marine and Freshwater Research, 64(5): 423-435.

Herath, H.M.S.K., Camps-Arbestain, M. and Hedley, M., 2013. Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. Geoderma, 209: 188-197.

International Biochar Initiative, 2014a. http://www.biochar-international.org/biochar.

International Biochar Initiative, 2014b. http://www.biochar-international.org/biochar/soils.

IPCC, 1996. Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge.

IPCC, 2000. Special Report on Emission Scenarios.

IPCC, 2001a. Impacts, Adaptation, and Vulnerability - Contribution of Working Group II to the IPCC Third Assessment Report, Cambridge, United Kingdom.
IPCC, 2001b. Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the IPCC Third Assessment Report, Cambridge, United Kingdom.
IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2007b. IPCC Fourth Assessment Report. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.
Izaurralde, R., McGill, W. and Williams, J., 2012. Development and application of the EPIC model for carbon cycle, greenhouse-gas mitigation, and biofuel studies. In: M.A. Liebig, A.J. Franzluebbers and R.F. Follett (Editors), Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate. Elsevier, Amsterdam, pp. 409-429.
Izaurralde, R.C., Rosenberg, N.J., Brown, R.A. and Thomson, A.M., 2003. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States - Part II. Regional agricultural production in 2030 and 2095. Agricultural and Forest Meteorology, 117(1-2): 97-122.
Izaurralde, R.C., Thomson, A.M., Rosenberg, N.J. and Brown, R.A., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 6. Distribution and productivity of unmanaged ecosystems. Climatic Change, 69(1): 107-126.
Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J. and Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192(3-4): 362-384.
Jaynes, D.B., Colvin, T.S., Karlen, D.L., Cambardella, C.A. and Meek, D.W., 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. Journal of Environmental Quality, 30(4): 1305-1314.
Jeffery, S., Verheijen, F., van der Velde, M. and Bastos, A., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture Ecosystems & Environment, 144(1): 175-187.
Joseph, S., Peacocke, C., Lehmann, J. and Munroe, P., 2009. Developing a biochar classification and test methods. In: J. Lehmann and S. Joseph (Editors), Biochar for environmental management: science and technology. Earthscan, London, pp. 107-125.
Joseph, S.D. et al., 2010. An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48(6-7): 501-515.
Kimball, B. et al., 1995. Productivity and water use of wheat under free-air CO2 enrichment. Global Change Biology, 1(6): 429-442.

Kuzyakov, Y., Subbotina, I., Chen, H.Q., Bogomolova, I. and Xu, X.L., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biology & Biochemistry, 41(2): 210-219.

Laird, D., Fleming, P., Wang, B., Horton, R. and Karlen, D., 2010a. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158(3-4): 436-442.

Laird, D.A. et al., 2010b. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma, 158(3-4): 443-449.

Leakey, A., Bernacchi, C., Dohleman, F., Ort, D. and Long, S., 2004. Will photosynthesis of maize (Zea mays) in the US Corn Belt increase in future [CO2] rich atmospheres? An analysis of diurnal courses of CO2 uptake under free-air concentration enrichment (FACE). Global Change Biology, 10(6): 951-962.

Lee, J.W., Hawkins, B., Day, D.M. and Reicosky, D.C., 2010. Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy & Environmental Science, 3(11): 1695-1705.

Lehmann, J., 2007. A handful of carbon. Nature, 447(7141): 143-144.

Lehmann, J., Czimczik, C., Laird, D. and Sohi, S., 2009. Stability of biochar in the soil. In: J. Lehmann and S. Joseph (Editors), Biochar for environmental management: science and technology. Earthscan, London, pp. 183-203.

Lehmann, J. et al., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, 249(2): 343-357.

Lehmann, J., Gaunt, J. and Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitigation and Adaptation Strategies for Global Change, 11: 403- 427.

Liang, B. et al., 2006. Black Carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70(5): 1719-1730.

Luo, Q.Y. and Lin, E., 1999. Agricultural vulnerability and adaptation in developing countries: The Asia-Pacific region. Climatic Change, 43(4): 729-743.

Lychuk, T., Izaurralde, R., Hill, R., McGill, W. and WIlliams, J., 2014. Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated Climate (EPIC) model. Mitigation and Adaptation Strategies for Global Change.

Maddox, N., 2013. The promise and uncertainties of Biochar. CSA News Magazine, 58: 4 - 9.

Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil, 333(1-2): 117-128.

Makino, A. and Mae, T., 1999. Photosynthesis and plant growth at elevated levels of CO2. Plant and Cell Physiology, 40(10): 999-1006.

Maroco, J.P., Edwards, G.E. and Ku, M.S.B., 1999. Photosynthetic acclimation of maize to growth under elevated levels of carbon dioxide. Planta, 210(1): 115-125.

Mearns, L.O.e.a., 2007, updated 2012. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal. Data downloaded 2013-05-25., Boulder, CO.

Mesinger, F., 2004. North American Regional Reanalysis.

Moriasi, D. et al., 2013. Modeling the impact of nitrogen fertilizer application and tile drain configuration on nitrate leaching using SWAT. Agricultural Water Management, 130: 36-43.

Mukherjee, A., Zimmerman, A.R. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. Geoderma, 163(3-4): 247-255.

Nesbitt, H.J., 1997. Rice production in Cambodia. International Rice Research Institute, Manilla, Philippines, pp. 15 - 29.

Nguyen, B.T. and Lehmann, J., 2009. Black carbon decomposition under varying water regimes. Organic Geochemistry, 40(8): 846-853.

Novak, J. et al., 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science, 3: 195 - 206.

Nowak, R. et al., 2001. Leaf conductance decreased under free-air CO2 enrichment (FACE) for three perennials in the Nevada desert. New Phytologist, 150(2): 449-458.

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change-Human and Policy Dimensions, 9: S51-S67.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic-matter levels in great-plains grasslands. Soil Science Society of America Journal, 51(5): 1173-1179.

Reilly, J. et al., 2003. US agriculture and climate change: New results. Climatic Change, 57(1-2): 43-69.

Reilly, J.M. and Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Climatic Change, 43(4): 745-788.

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R. and Lehmann, J., 2010. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. Environmental Science & Technology, 44(2): 827-833.

Rogers, A. et al., 2004. Leaf photosynthesis and carbohydrate dynamics of soybeans grown throughout their life-cycle under Free-Air Carbon dioxide Enrichment. Plant Cell and Environment, 27(4): 449-458.

Rogovska, N. et al., 2011. Impact of Biochar on Manure Carbon Stabilization and Greenhouse Gas Emissions. Soil Science Society of America Journal, 75(3): 871-879.

Rondon, M., Ramirez, J. and Lehmann, J., 2005. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere, 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore.

Rosenberg, N.J., 1992. Adaptation of agriculture to climate change. Climatic Change, 21(4): 385-405.

Rosenberg, N.J., Brown, R.A., Izaurralde, R.C. and Thomson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States - I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agricultural and Forest Meteorology, 117(1-2): 73-96.

Shao, P., Zeng, X., Moore, D. and Zeng, X., 2013. Soil microbial respiration from observations and Earth System Models. Environmental Research Letters, 8(3).

Shneour, E.A., 1966. Oxidation of graphitic carbon in certain soils. Science, 151(3713): 991-&.

Singer, J.W., Malone, R.W., Jaynes, D.B. and Ma, L., 2011. Cover crop effects on nitrogen load in tile drainage from Walnut Creek Iowa using root zone water quality (RZWQ) model. Agricultural Water Management, 98(10): 1622-1628.

Smith, R.A., Schwarz, G.E. and Alexander, R.B., 1997. Regional interpretation of water-quality monitoring data. Water Resources Research, 33(12): 2781-2798.

Smith, S.J. et al., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 1. Scenarios and context. Climatic Change, 69(1): 7-25.

Sohi, S., Lopez-Capel, E., Krull, E. and Bol, R., 2009. Biochar's roles in soil and climate
change: A review of research needs. CSIRO Land and Water Science Report.

Spokas, K. et al., 2012. Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. Journal of Environmental Quality, 41(4): 973-989.

Spokas, K.A., Koskinen, W.C., Baker, J.M. and Reicosky, D.C., 2009. Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere, 77(4): 574-581.

Steiner, C. et al., 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 171(6): 893-899.

Stockle, C.O., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992. Estimation of the effects of CO_2 induced climate change on growth and yield of crops. Part I. Modification of the EPIC model for climate change analysis. Agricultural Systems, 38: 225-238.

Suddick, E.C., Whitney, P., Townsend, A.R. and Davidson, E.A., 2013. The role of nitrogen in climate change and the impacts of nitrogen-climate interactions in the United States: foreword to thematic issue. Biogeochemistry, 114(1-3): 1-10.

Thomson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C. and Benson, V., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 3. Dryland production of grain and forage crops. Climatic Change, 69(1): 43-65.

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J. and He, X.X., 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the

Huang-Hai Plain of China. Agriculture Ecosystems & Environment, 114(2-4): 195-209.
Tian, H. et al., 2012. Century-Scale Responses of Ecosystem Carbon Storage and Flux to Multiple Environmental Changes in the Southern United States. Ecosystems, 15(4): 674-694.
Tsvetsinskaya, E.A. et al., 2003. The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climatic Change, 60(1-2): 37-71.
Tubiello, F.N., Donatelli, M., Rosenzweig, C. and Stockle, C.O., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy, 13(2-3): 179-189.
United Nations, 2004. World Population to 2300, United Nations, New York, USA.
Van Liew, M.W., Feng, S. and Pathak, T.B., 2012. Climate change impacts on streamflow, water quality, and best management practices for the shell and logan creek watersheds in Nebraska. International Journal of Agricultural and Biological Engineering, 5: 13-34.
Walthall, C.L. et al., 2013. Climate Change and U.S. Agriculture: an Assessment of Effects and Adaptation Responses, U.S. Department of Agriculture.
Warnock, D.D., Lehmann, J., Kuyper, T.W. and Rillig, M.C., 2007. Mycorrhizal responses to biochar in soil - concepts and mechanisms. Plant and Soil, 300(1-2): 9-20.
Webster, M. et al., 2003. Uncertainty analysis of climate change and policy response. Climatic Change, 61(3): 295-320.
Wieder, W., Bonan, G. and Allison, S., 2013. Global soil carbon projections are improved by modelling microbial processes. Nature Climate Change, 3(10): 909-912.
Williams, J.R., 1995. The EPIC model. In: V.P. Singh (Editor), Computer Models of Watershed Hydrology. Water Resources Public, Highland Ranch, CO, USA, pp. 909 - 1000.
Winsley, P., 2007. Biochar and bioenergy production for climate change mitigation. *New Zealand Science Review*, 64: 5-10.
Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nature Communications, 1.
Xu, L., Niu, H., Xu, J. and Wang, X., 2013. Nitrate-Nitrogen Leaching and Modeling in Intensive Agriculture Farmland in China. Scientific World Journal.
Zheng, J., Stewart, C.E. and Cotrufo, M.F., 2012. Biochar and Nitrogen Fertilizer Alters Soil Nitrogen Dynamics and Greenhouse Gas Fluxes from Two Temperate Soils. Journal of Environmental Quality, 41(5): 1361-1370.
Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory-produced clack carbon (biochar). Environmental Science and Technology, 44:1295-1301

Chapter 6: General Summary

The Environmental Policy Integrated Climate (EPIC) model was updated with algorithms to determine the impacts of using biochar soil amendments on corn yields and selected soil properties. The EPIC model was initially validated using the results of a 4-yr field experiment performed on an Amazonian Oxisol that had been amended with two rates of biochar. Observed results in the field and simulation results of the four year study both confirmed increases in short term corn yields after biochar application, as well as increases in soil CEC and pH. Soil bulk density decreased while soil carbon content increased. Long term 20-yr future simulations predicted further increases in the soil CEC, pH, soil carbon content, and decreases in the soil bulk density values after biochar applications once every five years. The EPIC model performed well in both short term and long term simulations.

The EPIC model was then used in a regional modeling approach to evaluate the climate change impacts and the effectiveness of selected adaptation options on corn and soybean yields, as well as the aggregated yields of three C_3 (soybean, alfalfa, and winter wheat) and three C_4 (corn, sorghum, and pearl millet) crops from representative farms in 10 Southeastern US states. Annual applications of biochar and the use of irrigation prior to crop stress were the adaptation practices evaluated for all crops. The Southeastern US was divided into North, South, and West regions for the simulations and analyses. Comparisons were made (1) using the 1979-2009 historical baseline climate data and four regional climate models to predict crop yields, and (2) using the four regional climate models to predict future crop yields for the 2038-2068 period. Results and observations obtained during this series of studies are detailed in the following bullets.

- The four regional climate models (RCMs) used in this study displayed a wide range of differences in maximum and minimum air temperatures as well as differences in quantities of average annual precipitation.
- All models generally predicted increased precipitation for the Southeastern US.
- All RCM models predicted statistically significant differences between the baseline and future corn yields with yield increases from 36 to 84% when compared to the baseline scenario. The observed increases were primarily associated with greater availability of soil moisture resulting from greater average annual precipitation in the future predicted by the four RCMs.
- Long term predictions indicate that corn yields will decrease by 12% due to the continually increasing temperature stress by the end of 2068 in comparison with the 2038 beginning year of the future simulation period, if adaptation measures are not implemented.
- Irrigation resulted in an increase of up to 33% in corn yields that was statistically significant for two of the four RCMs.
- Contrary to expectations, biochar applications resulted in decreased corn yields for 3 of the 4 RCMs.
- A decreasing trend was generally observed for soybean yields when compared to the historical baseline yields, but the differences were not statistically different.
- Soybean yields had statistically significant decreased yields by up to 15% by the end of the simulation period in 2068 compared to the 2038 beginning year of the future

simulations for the South and North regions for 3 of the 4 RCMs. As in case with declines in corn yields, future declines in soybean were associated with an increased number of days during which the crop might have experienced temperature stress.

- Neither irrigation and/or biochar applications had any significant effects on soybean yields for any of the regions using any of the RCMs. This lack of statistical response was primarily attributed to increased annual precipitation predicted by all four RCMs such that the soybean crop was not subjected to water stress.
- The RCMs varied in their predictions for the historical baseline and future comparisons of the aggregated yields of the grouped C_3 and C_4 crops.
- Irrigation resulted in statistically significant increased aggregated yields of up to 35% for combined yields of the C_3 and C_4 crops.
- Annual biochar applications resulted in decreased combined yields for the C_3 and C_4 crops.
- The C_4 crops seem to be generally more adaptive to increases in temperature and water stress associated with the future climate and demonstrated adaptability by producing greater aggregated yields in comparison to the C_3 crops.
- Climate change will increase nitrate leaching and runoff losses by 40 to 90% compared to a historical baseline scenario if adaptation measures are not implemented to alleviate climate change impacts.
- Under C_4 crops, nitrate leachate losses were significantly lower than under C_3 crops by 50 to 85%, so crop type had significant effects on nitrate leachate losses. These differences in nitrate loss reflects the higher nitrogen crop uptake that is typical for C_4 crops in comparison to C_3 crops.

- Although not universally significant, data trends suggest decreased nitrate leachate losses under biochar applications and increased nitrate leachate losses in response to irrigation.
- Future climate will cause significant increases in microbial respiration rates by as much as 20% for C_4 crops in comparison with historical rates.
- Comparison between individual future 5 year periods within a 2038 – 2068 simulation period revealed that biochar applications and C_4 crops caused microbial respiration to increase by 20 to 45% in comparison to C_3 crops. The C_4 crops used in this modeling study produce higher biomass yields and, therefore, more residue is left on the field, resulting in increased microbial respiration.
- Soil carbon contents were significantly affected by crop type and biochar applications. Soil carbon accumulation was significantly greater under biochar application by as much as 40%, and under C_4 plants by about 5%.
- The results of this modeling study indicated that during the 2038 – 2068 period there will be an increase in nitrate losses caused by climate change in the Southeastern United States in comparison with the historic baseline scenario of 1979 - 2009.
- Similarly, there will be an increase in microbial respiration under C_4 crop types and under biochar applications.
- Overall, C_4 crop type and biochar applications resulted in significantly greater soil carbon sequestration and, although not significant, reductions in nitrate losses.
- Irrigation resulted in trends of greater losses of nitrate in leachate and runoff, however, no statistically significant differences were detected.

Results of this dissertation further confirmed that climate change is affecting different regions of the United States differently. For the Southeastern US, it was concluded that under some weather scenarios, regional modeling results suggest that irrigation and biochar applications may be considered as promising potential adaptation strategies for agriculture. Modeling can be a useful tool in evaluating the long term impacts of climate change on ecosystems, including agriculture. Modeling also allows the testing of potential adaptation strategies to evaluate their efficiency in coping with climate change impacts. We consider the ongoing development of the new adaptation strategies to climate change and their subsequent testing in regional simulation models to be one of the avenues for successful policy to adapt agriculture in the US to ever increasing threats from changing climate. Regional modeling will help test effectiveness and optimize time, resources and planning strategies for specific adaptation techniques prior to their practical implementation in the real world.

Glossary

CRCM - The Canadian Regional Climate Model with the Third Generation Coupled Climate Model

EPIC – Environmental Policy Integrated Climate Model

GCM – Global Climate Model

HRM3 – The Hadley Regional Model and the Hadley Coupled Model version 3

NARR – North American Regional Reanalysis

NARCCAP – North American Regional Reanalysis Climate Change Assessment Program

RCM – Regional Climate Model

RCM3C – The Regional Climate Model Version 3 and the Third Generation Coupled Climate Model

RCM3G - The Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model

Appendices

Appendix A. The effects of biochar application, C_3 and C_4 crop types, and irrigation on soil carbon content (kg ha^{-1}) across individual 5 year future climate periods predicted by the four regional climate models. Comparisons are made within the same column for each effect
* Significant at $P < 0.05$; NS – Non-significant at $P < 0.05$)

Period	Effect		Regional Climate Model^											
			CRCM			HRM3			RCM3C			RCM3G		
			Region											
			North	South	West	North	South	West	North	South	West	North	South	West
2038 - 2042	Biochar	No	9443*	8884*	12065*	9279*	8640*	11903*	9399*	8762*	12215*	9951*	8865*	12301*
		Yes	15769*	14613*	17986*	15493*	14528*	17868*	15864*	14789*	18180*	16420*	15016*	18572*
	Crop type	C_3	12162NS	14494NS	14861*	11972NS	11269NS	14640*	12291NS	11437NS	14808*	12838NS	11589NS	15162*
		C_4	13050NS	12003NS	15369*	12800NS	11898NS	15131*	12973NS	12114NS	15586*	13533NS	12293NS	15711*
	Irrigation	No	12640NS	11838NS	15038NS	12391NS	11590NS	14926NS	12670NS	11795NS	15200NS	13027NS	11965NS	15507NS
		Yes	12572NS	11660NS	15013NS	12381NS	11578NS	14844NS	12594NS	11756NS	15194NS	13345NS	11917NS	15366NS
2043 - 2047	Biochar	No	9415*	8886*	12058*	9251*	8637*	11898*	9371*	8772*	12209*	9721*	8859*	12297*
		Yes	15796*	14665*	18077*	15519*	14569*	17952*	15891*	14844*	18262*	16448*	15076*	18666*
	Crop type	C_3	13047NS	11527NS	14718*	11976NS	11288NS	14676*	12293NS	11482NS	14843*	12642NS	11620NS	15202*
		C_4	12165NS	12024NS	15416*	12795NS	11919NS	15174*	12970NS	12135NS	15628*	13528NS	12315NS	15761*
	Irrigation	No	12623NS	11690NS	15080NS	12373NS	11604NS	14964NS	12609NS	11830NS	15239NS	13127NS	11988NS	15547NS
		Yes	12588NS	11862NS	15056NS	12397NS	11602NS	14866NS	12653NS	11787NS	15232NS	13043NS	11947NS	15416NS
2048 - 2052	Biochar	No	9386*	8888*	12050*	9224*	8635*	11893*	9344*	8769*	12203*	9693*	8853*	12293*
		Yes	15823*	14717*	18169*	15544*	14610*	18036*	15918*	14900*	18349*	16476*	15135NS	18760*
	Crop type	C_3	12167NS	11560NS	14754*	11980NS	11307NS	14712*	12296NS	11513NS	14877*	12648NS	11652NS	15243*

		C_4	13043NS	12045NS	15465*	12788NS	11939NS	15218*	12966NS	12156NS	15675*	13522NS	12337NS	15847*
	Irrigation	No	12606NS	11886NS	15120NS	12355NS	11619NS	15002NS	12625NS	11850NS	15278NS	13060NS	12010NS	15587NS
		Yes	12604NS	11720NS	15099NS	12412NS	11627NS	14928NS	12637NS	11818NS	15273NS	13110NS	11979NS	15466NS
2053-2057	Biochar	No	9358*	8890*	12042*	9196*	8633*	11888*	9316*	8765*	12197*	9665*	8847*	12289*
		Yes	15851*	14769*	18260*	15569*	14652*	18120*	15944*	14955*	18436*	16504*	15194*	18854*
	Crop type	C_3	12170NS	11593NS	14790*	11983NS	11325NS	14747*	12298NS	11543NS	14911*	12653NS	11683NS	15283*
		C_4	13039NS	12066NS	15512*	12782NS	11960NS	15261*	12963NS	12177NS	15726*	13516NS	12359NS	15860*
	Irrigation	No	12588NS	11910NS	15160NS	12338NS	11634NS	15039NS	12620NS	11849NS	15318NS	13093NS	12032NS	15627NS
		Yes	12621NS	11749NS	15141NS	12427NS	11651NS	14969NS	12640NS	11871NS	15315NS	13076NS	12010NS	15516NS
2058-2062	Biochar	No	9330*	8692*	12034*	9168*	8630*	11883*	9288*	8762*	12191*	9637*	8842*	12286*
		Yes	15878*	14821*	18351*	15594*	14693*	18205*	15971*	15010*	18523*	16532*	15253*	18448*
	Crop type	C_3	12173NS	12087NS	14826*	11987NS	11344NS	14783*	12300NS	11574NS	14845*	12659NS	11714NS	15323*
		C_4	13035NS	11980NS	15588*	12776NS	11980NS	15305*	12459NS	12147NS	15786*	13511NS	12382NS	15910*
	Irrigation	No	12571NS	11934NS	15200NS	12443NS	11648NS	15077NS	12604NS	11891NS	15357NS	13077NS	12055NS	15668NS
		Yes	12637NS	11179NS	15184NS	12320NS	11676NS	15011NS	12656NS	11880NS	15357NS	13093NS	12041NS	15566NS
2063 – 2068	Biochar	No	9312*	8894*	12025*	9141*	8628*	11878*	9260*	8758*	12185*	9619*	8839*	12282*
		Yes	15903*	14873*	18442*	15620*	14735*	18284*	15988*	15065*	18610*	16560*	15313*	19042*

	Crop type	C_3	12175NS	11659NS	14826*	11991NS	11363NS	14819*	12302NS	11605NS	14975*	12665NS	11748NS	15364*
		C_4	13041NS	12108NS	15605*	12770NS	12000NS	15348*	12956NS	12218NS	15815*	13515NS	12404NS	15960*
	Irrigation	No	12565NS	11958NS	15241NS	12303NS	11663NS	15115NS	12587NS	11912NS	15396NS	13071NS	12080NS	15708NS
		Yes	12651NS	11809NS	15227NS	12458NS	11700NS	15052NS	12671NS	11912NS	15398NS	13109NS	12072NS	15616NS

^(NARR – historical Baseline Scenario; CRCM - the Canadian Regional Climate Model with the Third Generation Coupled Climate Model; HRM3 - the Hadley Regional Model and the Hadley Coupled Model version 3; RCM3C - the Regional Climate Model Version 3 and the Third Generation Coupled Climate Model; RCM3G - the Regional Climate Model Version 3 and the Geophysical Fluid Dynamics Laboratory Global Climate Model)

Bibliography

Abrahamson, D., Causarano, H., Williams, J., Norfleet, M. and Franzluebbers, A., 2009. Predicting soil organic carbon sequestration in the southeastern United States with EPIC and the soil conditioning index. Journal of Soil and Water Conservation, 64(2): 134-144.

Adams, R.M., Hurd, B.H., Lenhart, S. and Leary, N., 1998. Effects of global climate change on agriculture: an interpretative review. Climate Research, 11(1): 19-30.

Adams, R.M., McCarl, B.A., Sergeson, K. and Rosenzweig, C., 1998. Climate change and U.S. agriculture: Some further evidence. Electric Power Research Institute, Corvallis, OR USA.

Adams, W.A., 1973. Effect of organic matter on bulk and true densities of some uncultivated podzolic soils. Journal of Soil Science, 24: 10-17.

Alexander, R.B. et al., 2008. Differences in phosphorus and nitrogen delivery to the gulf of Mexico from the Mississippi river basin. Environmental Science & Technology, 42(3): 822-830.

Alig, R.J., Adams, D.M. and McCarl, B.A., 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. Forest Ecology and Management, 169(1-2): 3-14.

Antal, M.J. and Grønli, M., 2003. The art, science, and technology of charcoal production. Industrial Engineering and Chemistry, 42: 1619-1640.

Apezteguia, H.P., Izaurralde, R.C. and Sereno, R., 2009. Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Cordoba, Argentina. Soil & Tillage Research, 102(1): 101-108.

Asada, K. et al., 2013. Modifying the LEACHM model for process-based prediction of nitrate leaching from cropped Andosols. Plant and Soil, 373(1-2): 609-625.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil, 337(1-2): 1-18.

Backlund, P., Janetos, A. and Schimel, D., 2008. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. Report by the U.S. Climate Change Science Program and the Subcommittee on global change research.

Baldock, J.A. and Smernik, R.J., 2002. Chemical composition and bioavailability of thermally, altered Pinus resinosa (Red Pine) wood. Organic Geochemistry, 33(9): 1093-1109.

Baron, J.S. et al., 2013. The interactive effects of excess reactive nitrogen and climate change on aquatic ecosystems and water resources of the United States. Biogeochemistry, 114(1-3): 71-92.

Bond-Lamberty, B. and Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature, 464(7288): 579-U132.

Bowes, G., 1993. Facing the inevitable - plants and increasing atmospheric CO_2. Annual Review of Plant Physiology and Plant Molecular Biology, 44: 309-332.

Bricker, S.B. et al., 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. Harmful Algae, 8(1): 21-32.

Brown, C.A. and Power, J.H., 2011. Historic and recent patterns of dissolved oxygen in the Yaquina Estuary (Oregon, USA): Importance of anthropogenic activities and oceanic conditions. Estuarine Coastal and Shelf Science, 92(3): 446-455.

Carbone, G.J. et al., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. Climatic Change, 60(1-2): 73-98.

Carbone, G.J., Kiechle, W., Locke, C., Mearns, L.O., McDaniel, L. and Downton, M.W., 2003. Response of soybean and sorghum to varying spatial scales of climate change scenarios in the Southeastern United States. Climatic Change 60: 73-98

Causarano, H. et al., 2008. Soil organic carbon fractions and aggregation in the Southern Piedmont and Coastal Plain. Soil Science Society of America Journal, 72(1): 221-230.

Chavas, D.R., Izaurralde, R.C., Thomson, A.M. and Gao, X.J., 2009. Long-term climate change impacts on agricultural productivity in eastern China. Agricultural and Forest Meteorology, 149(6-7): 1118-1128.

Chiang, L., Chaubey, I., Hong, N., Lin, Y. and Huang, T., 2012. Implementation of BMP Strategies for Adaptation to Climate Change and Land Use Change in a Pasture-Dominated Watershed. International Journal of Environmental Research and Public Health, 9(10): 3654-3684.

Costantini, E.A.C., Castelli, F. and L'Abate, G., 2005. Use of the EPIC model to estimate soil moisture and temperature regimes for desertification risk in Italy. Advances in Geoecology, 36: 251-263.

DeLuca, T., MacKenzie, M.D. and Gundale, M.J., 2009. Biochar effects on soil nutrient transformations. In: J. Lehmann and S. Joseph (Editors) Biochar environmental management: science and technology. Earthscan. Sterling, VA, p. 251-268.

Department of Climate Change and Energy Efficiency, 2012. An overview of the Carbon Farming Initiative. Available via http://www.climatechange.gov.au/reducing-carbon/carbon-farming-initiative Cited 14 Jan 2014

Diaz, R.A., Magrin, G.O., Travasso, M.I. and Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean Rolling Pampas. Climate Research, 9(1-2): 25-30.

Easterling, W.E. et al., 1992c. Preparing the Erosion Productivity Impact Calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO_2. Agricultural and Forest Meteorology, 59(1-2): 17-34.

Easterling, W.E. et al., 1993. Agricultural impacts of and responses to climate-change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. Climatic Change, 24(1-2): 23-61.

Easterling, W.E., 1996 Adapting North American agriculture to climate change in review. Agriculture and Forest Meteorology, 80: 1-53.

Easterling, W.E., Chhetri, N. and Niu, X.Z., 2003. Improving the realism of modeling agronomic adaptation to climate change: Simulating technological substitution. Climatic Change, 60(1-2): 149-173.

Easterling, W.E., McKenney, M.S., Rosenberg, N.J. and Lemon, K.M., 1992a. Simulations of crop response to climate change - effects with present technology and no adjustments (the dumb farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 53-73.

Easterling, W.E., Rosenberg, N.J., Lemon, K.M. and McKenney, M.S., 1992b. Simulations of crop responses to climate change - effects with present technology and currently available adjustments (the smart farmer scenario). Agricultural and Forest Meteorology, 59(1-2): 75-102.

Edmonds, J.A. and Rosenberg, N.J., 2005. Climate change impacts for the conterminous USA: An integrated assessment summary. Climatic Change, 69(1): 151-162.

FAO, 2002a. World agriculture: towards 2015/2030.

FAO, 2002b. World agriculture: towards 2015/2030. Long-term perspectives. The outlook for agriculture.

Franzluebbers, A., 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil & Tillage Research, 83(1): 120-147.

Franzluebbers, A., 2010. Achieving Soil Organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States. Soil Science Society of America Journal, 74(2): 347-357.

Galinato, S.P., Yoder, J.K. and Granatstein, D., 2011. The economic value of biochar in crop production and carbon sequestration. Energy Policy, 39: 6344 – 6350

Gaskin, J.W., Speir, R.A., Keith, H., Das, K.C., Lee, R.D., Morris, L.A. and Fisher, D.S., 2010. Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agronomy Journal, 102: 623-633.

Gassman, P.W. et al., 2004. Historical Development and Applications of the EPIC and APEX Models, American Society of Agricultural and Biological Engineers.

Gates, W.L., 1985. The use of general-circulation models in the analysis of the ecosystem impacts of climatic-change. Climatic Change, 7(3): 267-284.

Gauch, H.G., Hwang, J.T.G. and Fick, G.W., 2003. Model evaluation by comparison of the model-based predictions and measured values. Agronomy Journal 95:1442-1446

Gaunt, J.L. and Lehmann, J., 2008. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environmental Science and Technology, 42: 4152 - 4158.

Glaser, B., Lehmann, J. and Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils, 35(4): 219-230.

Gowda, P.H., Westra, J.V., Petrolia, D.R., Mulla, D.J. and Dalzell, B.J., 2011. Impact of targeted removal of residue cover on water quality in the Sand Creek watershed. Journal of Environmental Hydrology, 19 (25): 1-12.

Hamer, U., Marschner, B., Brodowski, S. and Amelung, W., 2004. Interactive priming of black carbon and glucose mineralisation. Organic Geochemistry, 35(7): 823-830.

Han, F., Plodinec, M., Su, Y., Monts, D. and Li, Z., 2007. Terrestrial carbon pools in southeast and south-central United States. Climatic Change, 84(2): 191-202.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A. and Wolfe, D.W., 2011. Climate impacts on agriculture: Implications for crop production. Agronomy Journal, 103:351-370.

Hatfield, J.L., Cruse, R.M. and Tomer, M.D., 2013. Convergence of agricultural intensification and climate change in the Midwestern United States: implications for soil and water conservation. Marine and Freshwater Research, 64(5): 423-435.

Herath, H.M.S.K., Camps-Arbestain, M. and Hedley, M., 2013. Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. Geoderma, 209-210: 188-197.

IPCC, 1996. Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge.

International Biochar Initiative, 2014. http://www.biochar-international.org/biochar/soils.

IPCC, 2000. Special Report on Emission Scenarios.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (Editors) Cambridge University Press, Cambridge, UK, and New York

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (Editors) Cambridge University Press, Cambridge, United Kingdom and New York, NY

IPCC, 2014. Intergovernmental Panel on Climate Change Working Group II Assessment Report 5 Summary for Policy Makers: Climate Change 2014: Impacts, Adaptation, and Vulnerability, Available online at http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-TS_FGDall.pdf Retrieved April 11, 2014.

Izaurralde, R.C., McGill, W.B. and Williams, J.R., 2012. Development and application of the EPIC model for carbon cycle, greenhouse-gas mitigation, and biofuel studies. In: M.A. Liebig, A.J. Franzluebbers, R.F. Follett (Editors)

Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate. Elsevier, Amsterdam, p. 409-429

Izaurralde, R.C., Thomson, A.M., Rosenberg, N.J. and Brown, R.A., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 6. Distribution and productivity of unmanaged ecosystems. Climatic Change, 69(1): 107-126.

Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J. and Jakas, M.C.Q., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, 192(3-4): 362-384.

Jaynes, D.B., Colvin, T.S., Karlen, D.L., Cambardella, C.A. and Meek, D.W., 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. Journal of Environmental Quality, 30(4): 1305-1314.

Joseph, S., Peacocke, C., Lehmann, J. and Munroe, P., 2009. Developing a biochar classification and test methods. In: J. Lehmann and S. Joseph (Editors), Biochar for environmental management: science and technology. Earthscan, London, pp. 107-125.

Joseph, S.D. et al., 2010. An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48(6-7): 501-515.

Kuzyakov, Y., Subbotina, I., Chen, H.Q., Bogomolova, I. and Xu, X.L., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biology & Biochemistry, 41(2): 210-219.

Laird, D., Fleming, P., Wang, B., Horton, R. and Karlen, D., 2010a. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158(3-4): 436-442.

Laird, D.A. et al., 2010b. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma, 158(3-4): 443-449.

Lee, J.W., Hawkins, B., Day, D.M. and Reicosky, D.C., 2010. Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy and Environmental Science, 3: 1695 – 1705

Lehmann, J. et al., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, 249(2): 343-357.

Lehmann, J., 2007. A handful of carbon. Nature. 447:143-144

Lehmann, J., Czimczik, C., Laird, D., Sohi, S., 2009. Stability of biochar in the soil. In: J. Lehmann and S. Joseph (Editors) Biochar for environmental management: science and technology. Earthscan, London, p. 183-203

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitigation and Adaptation Strategies for Global Change, 11: 403-427.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B. and Skjemstad, J.O., 2006. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70: 1719-1730.

Lychuk, T., Izaurralde, R., Hill, R., McGill, W. and WIlliams, J., 2014. Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated Climate (EPIC) model. Mitigation and Adaptation Strategies for Global Change. DOI 10.1007/s11027-014-9554-7

Luo, Q.Y. and Lin, E., 1999. Agricultural vulnerability and adaptation in developing countries: The Asia-Pacific region. Climatic Change, 43(4): 729-743.

Maddox, N., 2013. The promise and uncertainties of Biochar. CSA News Magazine, 58: 4 - 9.

Magdoff, F.R. and Bartlett, R.J., 1985. Soil pH buffering revisited. Soil Science Society of America Journal, 49: 145-148.

Major, J., Rondon, V., Molina, D., Riha, S.J. and Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil, 333: 117-128.

Makino, A. and Mae, T., 1999. Photosynthesis and plant growth at elevated levels of CO2. Plant and Cell Physiology, 40(10): 999-1006.

McCarl, B.A., Peacocke, C., Chrisman, R., Kung, C. and Sands, R.D., 2009. Economics of biochar production, utilization and greenhouse gas offsets. In: J. Lehmann and S. Joseph (Editors) Biochar for environmental management. Earthscan, London, p. 341 – 358

Mearns, L.O.e.a., 2007, updated 2012. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal. Data downloaded 2013-05-25., Boulder, CO.

Mesinger, F., 2004. North American Regional Reanalysis.

Moriasi, D. et al., 2013. Modeling the impact of nitrogen fertilizer application and tile drain configuration on nitrate leaching using SWAT. Agricultural Water Management, 130: 36-43.

Mukherjee, A., Zimmerman, A.R. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. Geoderma, 163:247–255

Nguyen, B.T. and Lehmann, J., 2009. Black carbon decomposition under varying water regimes. Organic Geochemistry, 40(8): 846-853.

NOAA National Centers for Environmental Prediction (NCEP). Cited January 14, 2014. http://globalweather.tamu.edu/

Novak, J., Lima, I., Xing, B., Gaskin, J., Steiner, C., Das, K.C. and Ahmedna, M., 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science, 3:195 – 206

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G. and Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change-Human and Policy Dimensions, 9: S51-S67.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S. and Kirchner, T., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biochemistry Cycles, 7: 785-809.

Parton,W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal, 51:1173–1179.

Reilly, J. et al., 2003. US agriculture and climate change: New results. Climatic Change, 57(1-2): 43-69.

Reilly, J.M. and Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Climatic Change, 43(4): 745-788.

Rippstein, G., Amezquita, E., Escobar, G. and Grollier, C., 2001. Condiciones naturales de la sabana. In: G. Rippstein et al (Editors) Agroecologia y Biodiversidad de las Sabanas en los Llanos Orientales de Colombia. Centro Internacional de Agricultura Tropical (CIAT), Cali, 1–21

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R. and Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environmental Science and Technology, 44: 827 – 833

Rogovska, N. et al., 2011. Impact of Biochar on Manure Carbon Stabilization and Greenhouse Gas Emissions. Soil Science Society of America Journal, 75(3): 871-879.

Rondon, M., Ramirez, J. and Lehmann, J., 2005. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In: Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, 21 - 24 March 2005

Rosenberg, N.J., 1992. Adaptation of agriculture to climate change. Climatic Change, 21(4): 385-405.

Rosenberg, N.J., Brown, R.A., Izaurralde, R.C. and Thomson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States - I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agricultural and Forest Meteorology, 117(1-2): 73-96.

Shao, P., Zeng, X., Moore, D. and Zeng, X., 2013. Soil microbial respiration from observations and Earth System Models. Environmental Research Letters, 8(3).

Shneour, E.A., 1966. Oxidation of graphitic carbon in certain soils. Science, 151(3713): 991-&.

Singer, J.W., Malone, R.W., Jaynes, D.B. and Ma, L., 2011. Cover crop effects on nitrogen load in tile drainage from Walnut Creek Iowa using root zone water quality (RZWQ) model. Agricultural Water Management, 98(10): 1622-1628.

Smith, B., Burton, I., Klein, R. and Wandel, J., 2000. An anatomy of adaptation to climate change and variability. Climatic Change, 45: 223-251.

Smith, J., Smith, P. and Addiscott, T., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: D.S. Powlson, P. Smith, J.U. Smith (Editors) Evaluation of soil organic matter models using existing long-term datasets. Spinger-Verlag. Heidelberg, Germany, p.181-199

Smith, R.A., Schwarz, G.E. and Alexander, R.B., 1997. Regional interpretation of water-quality monitoring data. Water Resources Research, 33(12): 2781-2798.

Sohi, S., Lopez-Capel, E., Krull, E., and Bol, R., 2009. Biochar's roles in soil and climate change: A review of research needs. CSIRO Land and Water Science Report

Soil Survey Staff, 1994. Keys to Soil Taxonomy. Pocahontas Press, Blacksburg VA USA

Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H.P., Boateng, A.A., Lima, I.M., Lamb, M.C., McAloon, A.J., Lentz, R.D. and Nichols, K.A., 2011. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality, 41: 973-989

Spokas, K.A., Koskinen, W.C., Baker, J.M. and Reicosky, D.C., 2009. Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere, 77(4): 574-581.

Stavi, I. and Lal, R., 2013. Agroforestry and biochar to offset climate change: a review Agronomy and Sustainable Development, 33:81-96

Steiner, C. et al., 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 171(6): 893-899.

Stockle, C.O., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992. Estimation of the effects of CO_2 induced climate change on growth and yield of crops. Part I. Modification of the EPIC model for climate change analysis. Agricultural Systems, 38: 225-238.

Suddick, E.C., Whitney, P., Townsend, A.R. and Davidson, E.A., 2013. The role of nitrogen in climate change and the impacts of nitrogen-climate interactions in the United States: foreword to thematic issue. Biogeochemistry, 114(1-3): 1-10.

Tejada, M., Gonzalez, J.L., 2007. Influence of organic amendments on soil structure and soil loss under simulated rain. Soil and Tillage Research, 93: 197-205

Thomson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C. and Benson, V., 2005. Climate change impacts for the conterminous USA: An integrated assessment - Part 3. Dryland production of grain and forage crops. Climatic Change, 69(1): 43-65.

Thomson, A.M., Izaurralde, R.C., Rosenberg, N.J. and He, X.X., 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China. Agriculture Ecosystems & Environment, 114(2-4): 195-209.

Tian, H. et al., 2012. Century-Scale Responses of Ecosystem Carbon Storage and Flux to Multiple Environmental Changes in the Southern United States. Ecosystems, 15(4): 674-694.

Tsvetsinskaya, E.A. et al., 2003. The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climatic Change, 60(1-2): 37-71.

Tubiello, F.N., Donatelli, M., Rosenzweig, C. and Stockle, C.O., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy, 13(2-3): 179-189.

Van Liew, M.W., Feng, S. and Pathak, T.B., 2012. Climate change impacts on streamflow, water quality, and best management practices for the shell and logan creek watersheds in Nebraska. International Journal of Agricultural and Biological Engineering, 5: 13-34.

Walthall, C.L. et al., 2013. Climate Change and U.S. Agriculture: an Assessment of Effects and Adaptation Responses, U.S. Department of Agriculture.

Warnock, D.D., Lehmann, J., Kuyper, T.W. and Rillig, M.C., 2007. Mycorrhizal responses to biochar in soil - concepts and mechanisms. Plant and Soil, 300(1-2): 9-20.

Webster, M. et al., 2003. Uncertainty analysis of climate change and policy response. Climatic Change, 61(3): 295-320.

Wieder, W., Bonan, G. and Allison, S., 2013. Global soil carbon projections are improved by modelling microbial processes. Nature Climate Change, 3(10): 909-912.

Williams, J.R., 1995. The EPIC Model. In: V.P. Singh (Editors) Computer models of watershed hydrology. Water Resource Publications. Highlands Ranch, CO, p. 909–1000

Winsley, P., 2007. Biochar and bioenergy production for climate change mitigation. New Zealand Science Review, 64: 5-10.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nature Communications, 1:56

Xu, L., Niu, H., Xu, J. and Wang, X., 2013. Nitrate-Nitrogen Leaching and Modeling in Intensive Agriculture Farmland in China. Scientific World Journal.

Zheng, J., Stewart, C.E. and Cotrufo, M.F., 2012. Biochar and Nitrogen Fertilizer Alters Soil Nitrogen Dynamics and Greenhouse Gas Fluxes from Two Temperate Soils. Journal of Environmental Quality, 41(5): 1361 – 1370

Zimmerman, A.R., 2010, Abiotic and microbial oxidation of laboratory-produced clack carbon (biochar). Environmental Science and Technology, 44:1295-1301