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Evaluation of climate change impacts and effectiveness of adaptation options on crop yield in the Southeastern United States

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ABSTRACT

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

1. Introduction

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

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and nitrogen (N) become limiting (Bowes, 1993; Makino and Mae, 1999). In addition, research that has evaluated the effects of increased CO_2 concentrations on crop growth have shown that the accelerated rate of photosynthesis that accompanies higher CO_2 concentrations leads to reduced nutrient and protein contents in grain and forage crops (Thomson et al., 2005a).

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

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

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

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

2. Materials and methods

2.1. Description of the simulation model

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

The EPIC model has been successfully validated at the global scale with favorable results, as well as in many regions of the world under varying climates, soils, and management environments including China, Argentina, the United States, Italy, Canada, and other countries (Diaz et al., 1997; Costantini et al., 2005; Edmonds and Rosenberg, 2005; Thomson et al., 2006; Apezteguia et al., 2009; Chavas et al., 2009; Lychuk et al., 2017b,c). In a previous publication (Lychuk et al.,