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Assessing the impacts of climate change and tillage practices on stream flow, crop and sediment yields from the Mississippi River Basin

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ABSTRACT

This study evaluated climate change impacts on stream flow, crop and sediment yields from three different tillage systems (conventional, reduced 1–close to conservation, and reduced 2–close to no-till), in the Big Sunflower River Watershed (BSRW) in Mississippi. The Soil and Water Assessment Tool (SWAT) model was applied to the BSRW using observed stream flow and crop yields data. The model was calibrated and validated successfully using monthly stream flow data (2001–2011).

The model performances showed the regression coefficient (R^2) from 0.72 to 0.82 and Nash–Sutcliffe efficiency index (NSE) from 0.70 to 0.81 for streamflow; R^2 from 0.40 to 0.50 and NSE from 0.72 to 0.86 for corn yields; and R^2 from 0.43 to 0.59 and NSE from 0.48 to 0.57 for soybeans yields. The Long Ashton Research Station Weather Generator (LARS-WG), was used to generate future climate scenarios. The SRES (Special Report on Emissions Scenarios) A1B, A2, and B1 climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC) were simulated for the mid (2046–2065) and late (2080–2099) century. Model outputs showed slight differences among tillage practices for corn and soybean yields. However, model simulated sediment yield results indicated a large difference among the tillage practices from the corn and soybean crop fields. The simulated future average maximum temperature showed as high as 4.8 °C increase in the BSRW. Monthly precipitation patterns will remain un-changed based on simulated future climate scenarios except for an increase in the frequency of extreme rainfall events occurring in the watershed. On average, the effect of climate change and tillage practice together did not show notable changes to the future crop yields. The reduced tillage 2 practices showed the highest responses of erosion control to climate change followed by the reduced tillage 1 and conventional tillage in this study.

1. Introduction

An increase in the world crop production is essential to feed the anticipated increase in world population. Several challenges including soil erosion and the anticipated impact of climatic change on crop yield must be addressed. Soil erosion can convert productive agricultural lands into unproductive barren lands, and climate change can aggravate the problem. Consequences of the climate change on crop production are already visible, and future climatic change will have a major effect on changing crop production at regional and global scale (Abraha and Savage, 2006). For example, the damage to future corn yields due to climate change will be $3 billion per year in the U.S. (Rosenzweig et al., 2002). Elevated carbon dioxide (CO_2) concentration in the atmosphere, changing precipitation, and temperature fluctuations are some of the anticipated climatic changes that will affect future crop production and erosion in multiple ways.

Global warming occurs because of CO_2 increases in the atmosphere, which could have many consequences on hydrological systems (Zhang et al., 2007). There is sufficient scientific evidence that temperature has increased over the last 15–20 years in both air and water (Barnett et al., 2005; IPCC, 2007). These temperature changes may have significant effects on future crop production. Based on IPCC (2007) findings, future crop production may increase with an increase of average temperature range from 1 to 3 °C but beyond that, yield is expected to decline. Moreover, most of the crops are currently near to their climatic thresholds; shifts away from these thresholds will impair the quantity and quality of the

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crop yields due to unfavorable climatic conditions (White et al., 2006). These effects may be positive or negative depending on the crop type and locations. For example, the moderate climate change in the North American region may have positive impacts on crop yields (Reilly, 2002). Future rainfall patterns may change and modify runoff and erosion processes, which lead to a change of the transport and deposition process of contaminants (Macdonald et al., 2005; Doris et al., 2007). These changes will have an effect on non-point sources pollutant transport from agricultural landuses. Currently agricultural pollutants such as sediment, generated by crop management activities, have caused visible degradation of surface water resources (Zalidis et al., 2002; Thorburn et al., 2003; Howarth et al., 2011; Thorburn et al., 2013). Soil erosion related to crop management practices can vary spatially indicating a need to identify critical areas for implementation of remedial measures (Marshall and Randhir 2008; Howarth et al., 2011).

Several studies have been conducted to evaluate the effects of climate change on crop production (Boxall et al., 2009; Biggs et al., 2013; Challinor, 2009; Webster et al., 2009; Crane et al., 2011; Jeppesen et al., 2011; Lobell et al., 2006), and account for the spatial variability of these effects. A climate change study on maize yield in South Africa found that increasing rainfall and temperature under future climate change positively influenced maize yield. The results indicated that precipitation is a more important factor than temperature in determining crop yield (Akpalu et al., 2008). Changes to precipitation amounts directly affect crop yield if precipitation cannot fulfill the demand of evapotranspiration (Mera et al., 2006), especially for non-irrigated crops. A detailed review of the effects of precipitation and temperature on crop yield is available in the work of Yinhong et al. (2009). Precipitation and temperature are not the only climatic variables that impact crop performance; the elevated CO_2 levels predicted in climate models will have positive effects on future crop production by increasing the growth of future crops (Kimball et al., 2002). A detailed review of the effects of elevated CO_2 on crop growth is available from Tubiello and Ewert (2002).

Implementation of adaptation and mitigation measures prior to the consequences of future climate changes is essential to improve crop production and water quality. Crop simulation models are useful tools for predicting the impact of climate change on crop growth and production. Moreover, these models can investigate the environmental effects on crop physiology in the future climate (Southworth et al., 2000). Despite the interest of international audiences, most of the previous climate change studies focused on conditions in the western U. S. (Stone et al., 2001; Rosenberg et al., 2003; Payne et al., 2003; Christensen et al., 2004; Villarini and Strong, 2014). Climate change studies on crop and sediment yields are limited in the south-eastern U.S., especially in Mississippi where climatic conditions are different from other regions of the U.S. Although beneficial for crop production, the abundant water resources and high rainfall levels common to the southern U.S. states such as Mississippi have high runoff related pollution problems. Some studies in the U.S. have reported anticipated soil erosion and crop productivity levels under future climate conditions. O'Neal et al. (2005) have investigated crop management and erosion rate under climate change in the Midwestern U.S. Mehta et al. (2012) has carried out a crop simulation study in the Missouri River Basin. However, the effects of climate change on crop production vary between locations (Southworth et al., 2000).

The Mississippi River is one of the world's major river systems in size, habitat diversity and biological productivity. The Mississippi River watershed is the largest watershed of all other rivers discharging into U.S. Gulf waters combined, which drains 40% of continental U.S. including parts of 31 states and 2 Canadian provinces (Kemp et al., 2011). The Mississippi River outlet dominates ecosystem processes in northern Gulf of Mexico. These ecosystem processes include freshwater inflow as the Mississippi River provides 80–90% of freshwater entering the northen Gulf of Mexico from rivers, creating critically important freshwater (Kemp et al., 2011). The Mississippi River contributes about 95% of all sediment entering the northern Gulf of Mexico with an average of 436,000 tons of sediment each day and up to 550 million tons of sediment during a major flood year (MRR, 2015). The U.S. Geological Survey identified the watersheds that are the largest contributors of nutrient loading to the Gulf of Mexico, which includes the Yazoo River Basin (Robertson et al., 2009). The BSRW in this study is the largest portion of the Yazoo River Basin in Mississippi (Parajuli et al., 2013), which contributes pollutants to the Gulf of Mexico via The Mississippi River.

To address the internationally important discharge of agricultural pollutants from the Mississippi River into the Gulf of Mexico, the current study evaluated the effects of three tillage practices on corn and soybean production and their potential for soil erosion in the humid mid-south. Further, the effects of climate change on crop and sediment yields in future climates scenarios were evaluated for the BSRW using a modeling approach.

2. Material and methods

2.1. Study area and model description

This study was conducted in the Big Sunflower River Watershed (BSRW), which extends over 7660 km^2 and is a major sub-watershed of the Yazoo River Basin in Mississippi (Fig. 1). The BSRW encompasses eleven counties in Mississippi (Coahoma, Bolivar, Tallahatchie, Sunflower, Leflore, Washington, Humphreys, Sharkey, Issaquena, Yazoo and Warren), which is a majority of the land area in Mississippi River Alluvial Flood Plain, colloquially known as the Mississippi Delta. Agriculture is the main land use (>80%) in the watershed. Soybean and corn are major crops in the watershed. The BSRW drains into the Mississippi River near Vicksburg via the Sunflower and Yazoo Rivers.

The SWAT model was chosen for this study as it has been used for modeling climate change (Lirong and Jianyun, 2012; Shrestha et al., 2012), water quality (Pisinaras et al., 2010; Cho et al., 2012), and crop growth and development (Masih et al., 2011; Kim et al., 2013) in various geographical regions around the world. The SWAT model is a semi distributed physically based, continuous, daily time-step model and it allows for predicting surface runoff, sediment and nutrient yields, pesticide, bacteria, and crop yields (Arnold et al., 1998; Neitsch et al., 2005). The SWAT model divides a watershed into a number of sub-watersheds, which are further divided into small spatial units called hydrological response units (HRUs). The HRUs are lumped land areas within the sub-watershed and consist of unique land cover, soil and management combinations (Neitsch et al., 2005).

The SWAT computes on a daily basis, for each HRU in every sub-watershed, the soil water balance, lateral flow and channel routing (main and tributary), groundwater flow, evapotranspiration, crop growth and nutrient uptake, soil pesticide degradation, and in-stream transformation of water quality parameters. Irrigation, fertilization, tillage, and drainage are subroutines within SWAT and applied based on the user settings. The SWAT calculates daily surface runoff using either curve number (CN) or Green Ampt method when the sub-daily precipitation data are available. The Erosion Productivity Impact Calculator (EPIC) model within the SWAT simulates the crop growth functions and heat units above the base temperature used for crop growth and development. The SWAT model determines crop yield as a function of Harvest Index (HI) and the biomass above the ground. The daily HI is calculated based on an optimal HI and a fraction of potential heat units (Neitsch et al., 2002). The crop-growth module in the SWAT model