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Hydrologic and water-quality impacts of agricultural land use changes incurred from bioenergy policies

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SUMMARY

The US Energy Independence and Security Act (EISA) of 2007 has contributed to widespread changes in agricultural land uses. The impact of these land use changes on regional water resources could also be significant. Agricultural land use changes were evaluated for the Red River of the North Basin, an international river basin shared by the US and Canada. The influence of the land use change on spring snowmelt flooding and downstream water quality was also assessed using watershed modeling. The planting areas for corn and soybean in the basin increased by 62% and 18%, while those for spring wheat, forest, and pasture decreased by 30%, 18%, and 50%, from 2006 to 2013. Although the magnitude of spring snowmelt peak flows in the Red River did not change from pre-EISA to post-EISA, our uncertainty analysis of the normalized hydrographs revealed that the downstream streamflows had a greater variability under the post-EISA land use scenario, which may lead to greater uncertainty in predicting spring snowmelt floods in the Red River. Hydrological simulation also showed that the sediment and nutrient loads at the basin's outlet in the US and Canada border increased under the post-EISA land use scenario, on average sediment increasing by 2.6%, TP by 14.1%, nitrate nitrogen by 5.9%, and TN by 9.1%.

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1. Introduction

In pursuit of greater energy independence and reduction of greenhouse gas (GHG) emissions to the atmosphere, the United States' Energy Independence and Security Act (EISA) was signed into law in December 2007. This landmark piece of US legislation mandated the annual use of 56.8 billion liters of conventional biofuels (e.g., corn-starch based ethanol) in transportation fuels by 2015 and a total annual use of 136 billion liters of biofuels (including 60.6 billion liters cellulosic biofuels and 4 billion liters of biomass-based diesels) by 2022 (U.S. Department of Energy, 2011). This mandate is sometimes referred to as the second Renewable Fuel Standard mandate (i.e., RFS2) as opposed to the first Renewable Fuel Standard mandate (i.e., RFS1) created under the Energy Policy Act (EPAct) of 2005. While RFS2 rendered great potential to ease the United States' dependence on foreign oils and to reduce its GHG emissions, its unintended impacts on water resources could also be significant (Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; Jager et al., 2014).

The impact of the bioenergy policies on water resources currently entails the conversion of agricultural land uses into bioenergy crops at large scales. The direction (i.e., positive or negative) and the magnitude of these impacts very much depend on local and regional factors such as the types of land use changes, topography, soils, climatic conditions, and the necessity of irrigation (Dominguez-Faus et al., 2009; Demissie et al., 2012; Valipour, 2013, 2014). Therefore, it is imperative to evaluate the agricultural land use changes resulting from these bioenergy policies and the benefits and costs derived from such land use changes on regional water resources, especially for the regions like the Red River of the North (hereafter referred to as "Red River") Basin where the land use is dominated by agriculture and the basin's water quantity and quality are already of a great concern to human and wildlife alike.

The Red River Basin is an international river basin, located near the geographic center of the North American continent. The river flows north and drains parts of the States of Minnesota (MN), North Dakota (ND), and South Dakota (SD), USA, as well as parts of the Provinces of Manitoba and Saskatchewan, Canada (see Fig. 1). The basin drains the Red River Valley (RRV), one of the most agriculturally productive regions in the world (Bagley et al., 2012). According to a 1998 study, approximately 80 percent of the basin area was agricultural, and 65 percent of the total area was cropland

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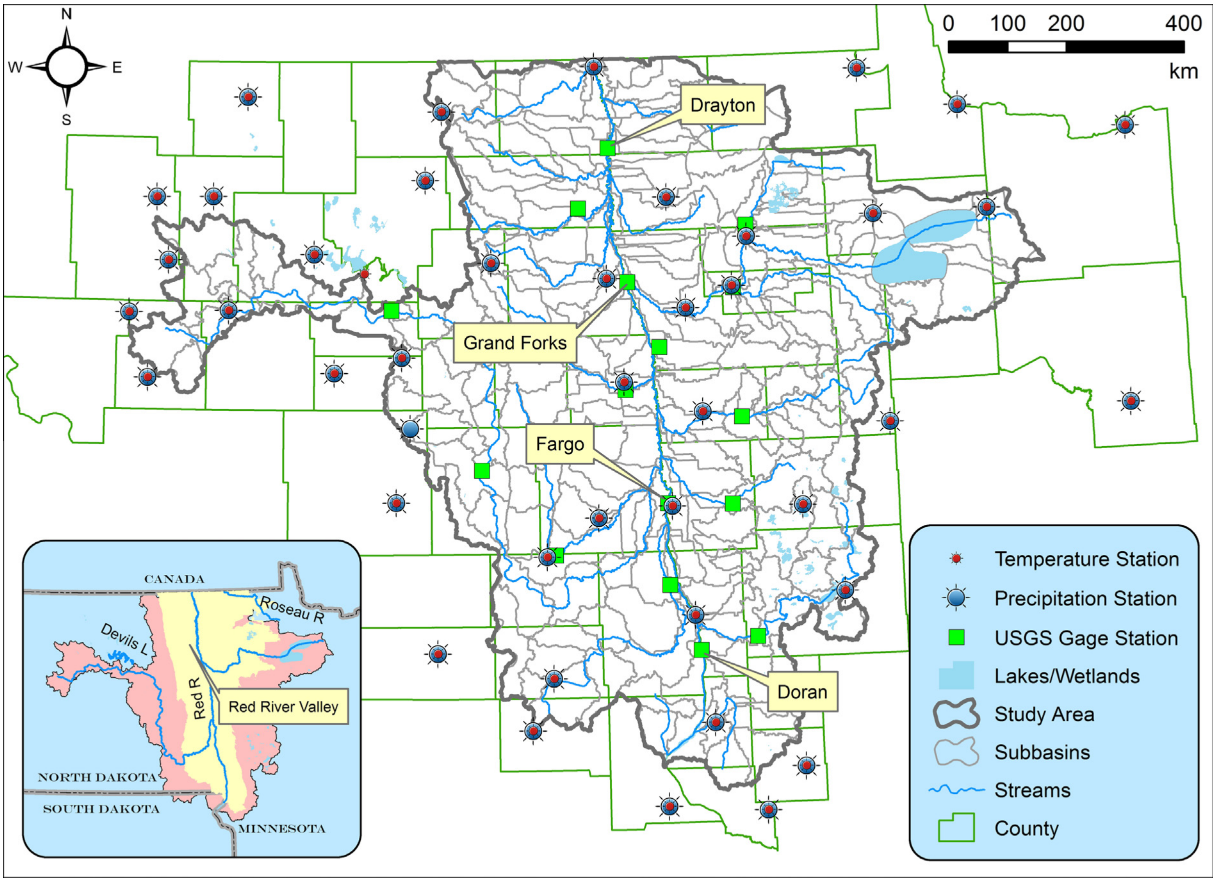

Fig. 1. The study area of the Red River of the North Basin.

(Stoner et al., 1998). Land use within the Red River Basin has recently been affected by the bioenergy policies, as with the whole Midwestern region (Mehaffey et al., 2012; Wright and Wimberly, 2013; Johnston, 2014). High commodity prices and other incentives provided by biofuel policies since 2006 (Tokgoz et al., 2007; Babcock and Fabiosa, 2011) have caused a significant regional shift in crops (more cultivated area of corn). Agriculture expansion into grasslands, including conservation lands, has occurred in order to meet the demands for biofuel feedstock (Campbell et al., 2008; Tilman et al., 2009).

The northward-flowing, meandering, gently-sloped (0.04–0.25 m/km) Red River is extremely prone to spring flooding. The flooding was exacerbated when the region received an equivalent of 2–3 years additional precipitation since 1993 (Jin et al., 2008; Rahman et al., 2014). The abnormally high precipitation increased the magnitude of spring flooding in the Red River Basin. During the century-long stream stage history at Fargo, ND (referring to Fig. 1), seven out of the fifteen highest peak flows in the Red River occurred in the past 20 years (Rahman et al., 2014). The Red River is also a main source of nutrient loads to Lake Winnipeg in Canada, despite the fact that it only accounts for about 16% of the total monthly average flow to Lake Winnipeg. The Red River contributed on average 5380 tonnes of phosphorous per year to Lake Winnipeg (or 68% of the annual total phosphorous load) during 1999 to 2007. In this same time frame it contributed 31476 tonnes of nitrogen per year (or 34% of the annual total nitrogen load) (Environment Canada and Manitoba Water Stewardship, 2011). The basin represents an international agricultural region where water is a valuable resource for the region's economy (Stoner et al., 1998).

Land use changes and the subsequent implications to water resources in the Red River Basin are also important to wildlife conservation. The central parts of the basin are straddled by the Prairie Pothole Region, a region encompasses the most productive waterfowl breeding habitats in North America, in addition to providing multiple ecosystem services including water storage, flood control, and filtering of pollutants (Ojima et al., 2002; Wright and Wimberly, 2013). Therefore, it is very important to understand the hydrologic and water quality impacts of the land use changes resulting from the bioenergy policies in the region. The objective of our study is twofold: (1) to evaluate the agricultural land use changes that occurred in the Red River Basin after the enactment of the EISA of 2007; and (2) to assess the implications of the bioenergy-related land use changes on the streamflows and water quality in the Red River Basin through hydrological and water quality modeling.

2. Materials and methods

2.1. Study area

The study area includes the surface drainage of the Red River within the US. The area almost coincides with the Red River Basin Study Unit assessed by the U.S. Geological Survey (USGS)'s National Water-Quality Assessment (NAWQA) Program (Stoner et al., 1998), except that ours does not include the Roseau River Basin that eventually drains to the Red River in Canada (see Fig. 1). Therefore, the Red River Basin under study drains approximately an area of 85000 square kilometers. The Red River Basin contains two distinct types of land forms – the flat plains and the rolling uplands. The center area, the Red River Valley, is remarkably flat and was the bottom of glacial Lake Agassiz (see Fig. 1). The lake deposits, consisting of sorted and stratified clay and silt,

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