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Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT

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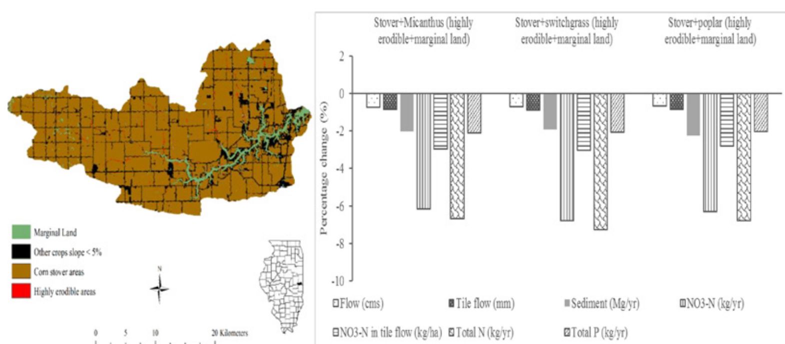
HIGHLIGHTS

- Calibrated parameter sets for bioenergy crop growth and tile drainage were used.
- Corn stover removal (38%) did not result in significant water quality impacts.
- Bioenergy crops can offset adverse water quality impacts of corn stover removal.
- Small bioenergy crop areas provided limited ability to improve water quality.
- Results provide guidance for evaluation of bioenergy scenarios in tile-drained areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Large quantities of biofuel production are expected from bioenergy crops at a national scale to meet US biofuel goals. It is important to study biomass production of bioenergy crops and the impacts of these crops on water quantity and quality to identify environment-friendly and productive biofeedstock systems. SWAT2012 with a new tile drainage routine and improved perennial grass and tree growth simulation was used to model long-term annual biomass yields, streamflow, tile flow, sediment load, and nutrient losses under various bioenergy scenarios in an extensively agricultural watershed in the Midwestern US. Simulated results from bioenergy crop scenarios were compared with those from the baseline. The results showed that simulated annual crop yields were similar to observed county level values for corn and soybeans, and were reasonable for *Miscanthus*, switchgrass and hybrid poplar. Removal of 38% of corn stover (3.74 Mg/ha/yr) with *Miscanthus* production on highly erodible areas and marginal land (17.49 Mg/ha/yr) provided the highest biofeedstock production (279,000 Mg/yr). Streamflow, tile flow, erosion and nutrient losses were reduced under bioenergy crop scenarios of bioenergy crops on highly erodible areas and marginal land. Corn stover removal did not result in significant water quality changes. The increase in sediment and nutrient losses under corn stover removal could be offset with the combination of other bioenergy crops. Potential areas for bioenergy crop production when meeting

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the criteria above were small (10.88 km^2), thus the ability to produce biomass and improve water quality was not substantial. The study showed that corn stover removal with bioenergy crops both on highly erodible areas and marginal land could provide more biofuel production relative to the baseline, and was beneficial to water quality at the watershed scale, providing guidance for further research on evaluation of bioenergy crop scenarios in a typical extensively tile-drained watershed in the Midwestern U.S.

1. Introduction

One of the grand challenges in meeting the US biofuel goal is supplying large quantities of cellulosic materials for biofuel production at a national scale (Cibin et al., 2016). Based on productivity and adaptability in different regions, the selection of biofeedstocks will vary geographically. It is necessary to evaluate potential environmental impacts before considering implementation of bioenergy crops on a large scale (Love and Nejadhashemi, 2011). Land cover change, management practices and climate change have impacts on water quantity, sediment and nutrient losses. Thus, it is challenging to take advantage of the opportunity bioenergy crops offer, while safeguarding against their potential environmental disadvantages.

Bioenergy crops, such as corn (*Zea mays* L.), corn stover, switchgrass (*Panicum virgatum* L.), *Miscanthus* (*Miscanthus* × *giganteus*) and *Populus* 'Tristis #1' (*Populus balsamifera* L. × *P. tristis* Fisch), are biofeedstock sources for biofuel production in U.S. (Cibin et al., 2016; Gamalero et al., 2012; Guo et al., 2015; Kiniry et al., 2012; McIsaac et al., 2010; Parajuli et al., 2017; Thomas et al., 2014). Using marginal land to grow non-grain bioenergy crops helps minimize impacts on food security while reducing ecological restoration costs (He et al., 2017; Zhuang et al., 2010).

Bioenergy crops have different yields estimated by simulation models under different scenarios. For example, simulated biofeedstock production from the same bioenergy crop, such as *Miscanthus*, switchgrass or corn stover, differed when growing on pasture, agricultural marginal land or highly erodible areas (Cibin et al., 2016). Additionally, simulated biomass yields of five forest scenarios (clear cutting at 10%, 20%, 30%, 55% and 75% of the total forest area) increased as the forest area clearcut increased (Khanal and Parajuli, 2013). Simulated annual average biomass yields for corn stover with 38%, 52% and 70% removal rates were 4.1 Mg/ha, 6 Mg/ha and 7.5 Mg/ha (Cibin et al., 2012).

Bioenergy crop planting in large areas can affect hydrology and water quality (Guo et al., 2012a; Guo et al., 2012b; He and Guo, 2012; Liu et al., 2015; Ng et al., 2010; Srinivasan et al., 2010; Yan et al., 2015). For example, simulated streamflow was reduced, and nitrate and mineral phosphorus loading were reduced at the watershed outlet with 38%, 52% and 70% corn stover removed in watersheds in Indiana (Cibin et al., 2012; Thomas et al., 2011). Additionally, corn stover removal can reduce soil cover (Delgado, 2010), reduce organic carbon and total nitrogen and increase soil erosion, and additional fertilizer was recommended to compensate for nutrient reduction by corn stover removal. However, 30 to 50% of corn stover could be removed without significantly impacting soil erosion and crop production (Brechbill and Tyner, 2008; Graham et al., 2007; Hoskinson et al., 2007; Kim and Dale, 2004; Lindstrom, 1986). Moreover, Hickman et al. (2010) predicted that switchgrass could increase evapotranspiration by 25% during the growing season compared with corn. Switchgrass and *Miscanthus* scenarios could reduce sediment and nutrient loadings at the watershed outlet simulated by SWAT (Boles, 2013; Love and Nejadhashemi, 2011; Parajuli and Duffy, 2013). Additionally, measured sediment loss and nutrient movement from a *Populus* tree plot was lower than that from a conventional cotton plot in Mississippi (Thornton et al., 1998; Tolbert et al., 1997). Moreover, fast growing hybrid poplar trees were also predicted to decrease total nitrogen and phosphorus loading (Sood and Ritter, 2010).

Tile drainage of agricultural fields in the Midwestern U.S. provides the majority of the nitrate that enters the Mississippi River and contributes to hypoxia in the northern Gulf of Mexico (Jaynes and James, 2007; Kalita et al., 2007). Models that link Mississippi River discharge with Gulf of Mexico hypoxia have shown that a decrease of nutrient loading can alleviate hypoxia in the Gulf of Mexico (Rabalais et al., 1999). The Little Vermilion River (LVR) watershed is a typical tile-drained watershed with altered hydrology from subsurface drainage systems in east central Illinois, USA (Kladivko et al., 2001). Surface runoff rarely occurs in the LVR, and the removal of water from soils was mainly by subsurface drainage systems (Kalita et al., 2006).

Subsurface drainage systems can increase hydrological connectivity to the channels (Basu et al., 2010; Evans et al., 1999; Kuzmanovski et al., 2015), enhance water transport through soils and serve as major transport pathways for soluble chemicals such as nitrate-N and atrazine and affect plant growth (Buhler et al., 1993; Kalita et al., 1998; Randall and Iragavarapu, 1995). Plant growth also influences nutrient transport in the tile drainage system. For example, nitrate-N concentrations in tile drains were higher from fields with more N fertilization, particularly when fertilization occurred prior to planting (Borah et al., 2003; Mitchell et al., 2000). Thus, it is important to take tile drainage system into consideration for examination of hydrologic and water quality impacts of bioenergy crop scenarios in watersheds in the Midwest.

Some researchers have simulated bioenergy crop growth and its impacts on water quantity and quality at a watershed scale using SWAT globally (Boles, 2013; Cibin et al., 2012; Cibin et al., 2016; Gush, 2010; Liu et al., 2014; Love and Nejadhashemi, 2011; Valcu-Lisman et al., 2016; Yasarer et al., 2016), but few of them incorporated woody bioenergy crops, such as *Populus* into bioenergy crop scenarios, or under tile drainage systems. The objective of this study was to quantify biomass yields of bioenergy crops scenarios, including woody bioenergy crops, and their impacts on streamflow, tile drain flow and nutrient losses under consideration of tile drainage systems in a typical tile drained watershed. The results of this study can help determine optimal bioenergy scenarios with high biomass yields, and water quality benefits in the LVR watershed and even the Mississippi River system and Gulf of Mexico.

2. Materials and methods

2.1. Study area

The LVR watershed is a typical flat upland watershed in east-central Illinois and drains approximately 518 km^2, at the boundary of Champaign and Vermilion counties. The LVR watershed has an average slope about 1%, with elevation ranging from approximately 235 m in the headwaters to 174 m at the outlet of the watershed (Zanardo et al., 2012). About 90% of the LVR watershed is agricultural land used for corn and soybean production, and the remainder consists of grassland, forest land, roadways and farmsteads (Kalita et al., 2006). Based on agricultural statistical data for the LVR watershed, the cropland was equally subdivided between corn and soybeans (Algoazany et al., 2007). The dominant soil associations are Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) and Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) (Keefer, 2003; Zanardo et al., 2012). Annual average precipitation at the watershed