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Research article

Spatial optimization of cropping pattern for sustainable food and biofuel production with minimal downstream pollution

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A B S T R A C T

Biofuel has emerged as a substantial source of energy in many countries. In order to avoid the 'food versus fuel competition', arising from grain-based ethanol production, the United States has passed regulations that require second generation or cellulosic biofeedstocks to be used for majority of the biofuel production by 2022. Agricultural residue, such as corn stover, is currently the largest source of cellulosic feedstock. However, increased harvesting of crops residue may lead to increased application of fertilizers in order to recover the soil nutrients lost from the residue removal. Alternatively, introduction of less-fertilizer intensive perennial grasses such as switchgrass (*Panicum virgatum* L.) and *Miscanthus (Miscanthus x giganteus Greef et Deu.)* can be a viable source for biofuel production. Even though these grasses are shown to reduce nutrient loads to a great extent, high production cost have constrained their wide adoptability to be used as a viable feedstock. Nonetheless, there is an opportunity to optimize feedstock production to meet bioenergy demand while improving water quality. This study presents a multi-objective simulation optimization framework using Soil and Water Assessment Tool (SWAT) and Multi Algorithm Genetically Adaptive Method (AMALGAM) to develop optimal cropping pattern with minimum nutrient delivery and minimum biomass production cost. Computational time required for optimization was significantly reduced by loose coupling SWAT with an external in-stream solute transport model. Optimization was constrained by food security and biofuel production targets that ensured not more than 10% reduction in grain yield and at least 100 million gallons of ethanol production. A case study was carried out in St. Joseph River Watershed that covers 280,000 ha area in the Midwest U.S. Results of the study indicated that introduction of corn stover removal and perennial grass production reduce nitrate and total phosphorus loads without compromising on food and biofuel production. Optimization runs yielded an optimal cropping pattern with 32% of watershed area in stover removal, 15% in switchgrass and 2% in *Miscanthus*. The optimal scenario resulted in 14% reduction in nitrate and 22% reduction in total phosphorus from the baseline. This framework can be used as an effective tool to take decisions regarding environmentally and economically sustainable strategies to minimize the nutrient delivery at minimal biomass production cost, while simultaneously meeting food and biofuel production targets.

1. Introduction

Bioenergy has emerged as the single largest energy source, providing 10% of world's primary energy supply (IEA, 2012). In the United States, biomass accounts for the largest share of renewable energy consumption (EIA, 2011). Furthermore, the U.S Department of Energy (DOE) and the United States Department of Agriculture (USDA) are committed to expand the role of biofuels as an important energy source (USDA, 2016). The Energy Independence and Security Act (EISA) of 2007 in the United States has envisaged a targeted production of 36 billion gallons (136.2 billion liters) of biofuel by 2022 in order to reduce the dependence on fossil fuels. The USDA estimated that approximately 11 million hectares of

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cropland would be required to achieve this EISA biofuel target (USDA Biofuel Strategic Production Report, 2010).

Currently, biofuel in the U.S. is primarily produced from grain-based crops such as corn, and can create an unhealthy competition amongst food, feed and fuel. Consequently, there have been regulations to limit the ethanol production from grains, and to use cellulosic crops (e.g. crop residues such as corn stover, wheat straw etc. and dedicated bioenergy crops such as switchgrass and *Miscanthus*) as raw material for biofuel production. Removal of corn stover from the fields and concomitant increased use of fertilizers lead to soil erosion and reduced downstream water quality (Cibin et al., 2012). The U.S.-Canada binational great Lakes Water Quality Agreement (GWLQA) set goals to address excess algal growth in Lake Erie by reducing phosphorus loads by 40% from a 2008 baseline (USEPA, 2016). In this context, use of perennial grasses such as switchgrass and *Miscanthus,* which require relatively lesser amounts of fertilizers has emerged as a better alternative with minimal negative impacts on water quality compared to the row-cropped systems (Cibin et al., 2016). Appropriate selection of energy crops and its allocation at suitable locations in the watershed can minimize the negative impacts on water quality (Robertson et al., 2008; Parish et al., 2012). However, introduction of these crops in commercial agriculture comes with a high production cost (Khanna et al., 2008). Further, it becomes inevitable to assess the long-term impacts of the changes associated with such new cropping practices. Considering the tradeoff between economic viability and environmental sustainability, an optimal land use scenario with mixed cropping of grain crops and cellulosic crops has to be developed in order to meet the demand for food and biofuel without compromising on water quality and energy production (Muth, 2014; Brandes et al., 2017).

Land use optimization is a complex process and requires the incorporation of an efficient optimization platform along with a simulation model to assess the impacts of choice of various land use and land management options on hydrology, water quality, and biomass production. The Soil and Water Assessment Tool (SWAT) model is one of the most widely used simulation models in this context (Arnold et al., 2012; Srinivasan et al., 2010; Zhang et al., 2008; Gassman et al., 2007; among many others). Previous studies have used SWAT-based optimization methods to evaluate impacts of cellulosic feedstock production on water quality. Gramig et al. (2013) used multi-objective watershed level optimization with corn stover removal scenarios for pollutant cost minimization based on economic cost of cropping practices and the effect on nitrate, total phosphorus (TP), sediment, or global warming potential. In a similar study, Song et al. (2017), examined the tradeoff between cost of biofeedstock production and environmental outcomes by considering cost of transporting feedstock to a hypothetical biorefinery in the watershed. Another study conducted by Herman et al. (2016) used SWAT and evolutionary algorithm to optimize selection and placement of bioenergy crops to achieve improved stream health. One of the major limitations of using SWAT model for optimization studies is its high computational time requirement for optimizing land use/land management choices (Cibin and Chaubey, 2015). An effective way to reduce the number of simulations of SWAT within an optimization framework while taking decisions on best management practices (BMP) was proposed by Maringanti et al. (2009, 2011). In their study, look up tables were developed using annual average nutrient loads at source level without considering nutrient routing in streams. However, for watershed scale studies concerning water quality, it is appropriate to run the model at a daily scale and to include in-stream nutrient fate and transport processes. In order to utilize the lookup table approach at daily scale, present study proposes to couple an existing in-stream first order nutrient decay model (Smith, 1993; Smith et al., 2007) with SWAT to estimate the nutrient loads at watershed outlet. The loosely coupled SWAT model would act as a 'pseudo-SWAT model' and work similar to the original SWAT model except for the inclusion of the external in-stream model to simulate in-stream nutrient routing. Overall, the objectives of this study were to (1) reduce SWAT model optimization time by loosely coupling an existing exponential decay based in-stream model with SWAT, and (2) use a simulation-optimization framework to develop optimal cropping pattern for sustainable bio-energy production considering economic and water quality attributes, and food security constraints. It is anticipated that the resulting outcomes would inform policy makers and farmers to adopt sustainable agricultural practices. Even though large-scale shift in cropping practice is challenging and infeasible in many parts of the world, the methods and framework proposed in this study may be applied globally for optimization-related studies by carefully altering the given objective functions and constraints.

2. Methodology

SWAT model (version 615) used was an improved version that better represents perennial bioenergy crops and was calibrated and validated using measured data from the watershed (Trybula et al., 2015). The landscape simulation from the watershed model was loosely coupled with a first order decay model for instream routing and subsequently linked with an optimization algorithm to develop optimal cropping pattern for sustainable biofuel production. Corn stover, switchgrass and *Miscanthus* were considered as potential cellulosic bioenergy feedstock options for the optimization. AMALGAM (A Multi Algorithm Genetically Adaptive Method, Vrugt and Robinson (2007)) was used as optimization algorithm. Using effective time-reducing techniques that avoid multiple model runs, an optimal cropping pattern was obtained for the watershed considering economic as well as environmental constraints and objective functions. Formulation of the optimization problem is discussed in detail in section 2.4.

2.1. Study area and data

St. Joseph River watershed (Fig. 1) encompasses an area of approximately 280,000 hectares of land in northeast Indiana, northwest Ohio and south-central Michigan. It is a major tributary of Maumee River which flows into Lake Erie. The major land use in the watershed is agriculture dominated by corn/soybean (39%), followed by pasture (25%). Remaining area is composed of forest (12%), urban areas (10%), wetlands (7%) and other smaller agricultural fields (6%) (USDA-NASS, 2013). For the model calibration, observed daily stream flow data at 3 stations (Fig. 1) were obtained from the United States Geological Survey (USGS) for 1990–2012. Measured sediment data was obtained at seven water quality gauging sites from Indiana Department of Environmental Management (IDEM) and nutrient data (nitrate and total phosphorus (TP)) was obtained at 49 stations from St. Joseph River Watershed Initiative (SJRWI) program, respectively. All the water quality data (sediment, nitrate and TP) were in the form of discrete weekly/biweekly data, with no measurements being made in the winter season (November–March). Sediment data were available for 1995–2009, nitrate data for 2008–2012 and phosphorus data for 2003–2012.

2.2. SWAT model: calibration and validation

SWAT is a widely used ecohydrologic model to predict the effect of different management practices on water, sediment and nutrient yields (Arnold et al., 1993; Neitsch et al., 2005). Based on the