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Development and evaluation of targeted marginal land mapping approach in SWAT model for simulating water quality impacts of selected second generation biofeedstock

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ABSTRACT

Information about location of marginal lands in a watershed is of interest to those who view these areas as potential land for producing biofuel crops. However, representing marginal lands into a distributed model such as the Soil and Water Assessment Tool (SWAT) is a challenge due to a rigid framework used for watershed sub-division. In this study, we developed a Geographic Information System (GIS) based approach for implementing targeted land use i.e. marginal lands into the SWAT model and evaluated the applicability of the approach on a 8-digit Hydrologic Unit Code (HUC) watershed scale. Comparative results showed that conventional targeting approach overestimates the benefit of targeting marginal lands for Alamo switchgrass (*Panicum virgatum*, L) and giant miscanthus (Miscanthus × giganteus) production due to simulation of larger area under marginal land category. Compared to baseline condition, which corresponds to no biofuel crop production on marginal lands, the pollutant losses under new targeting approach with simulation of Alamo switchgrass and giant miscanthus on marginal lands were substantially lower. The new targeting approach advances the science behind landscape representation in the SWAT model – that has potential to be used in future targeting studies.

1. Introduction

The Renewable Fuel Standard (RFS) program under the Energy Policy Act (EPAct) of 2005 mandated 28 billion liters (7.5 billion gallons) of renewable fuel to be blended into gasoline by 2012 (EPA, 2012). The Energy Independence and Security Act (EISA) of 2007 expanded the RFS program by increasing the volume of renewable fuel required to be blended into transportation fuel to 136 billion liters (36 billion gallons) by 2022 (EISA, 2007). Under the EISA (2007) Act, corn starch and cellulosic biofuels were identified as major renewable fuel sources. Corn starch falls under the category of first generation biofuel crops along with soybean [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum*), and some other row crops. Studies have reported eutrophication problems relating with the first generation biofuel crop productions (Babcock et al., 2007; Donner and Kucharik, 2008; Powers, 2007). Increased uses of corn (*Zea mays* L.) and soybeans have been reported to worsen eutrophication problems in Midwest US and Gulf of Mexico (Powers, 2007). As per the EISA (2007) Act, fuel requirement from corn starch ethanol is not expected to increase beyond 56 billion liters (15 billion gallons) in 2015. Because of the fact that increasing area under first generation biofuel crops has the potential to exacerbate eutrophication problems as reported by other researchers and oil requirement from corn starch is projected to plateau in 2015, the research community has focused attention on second generation biofuel crops.

Second-generation biofuel crops also known as cellulosic biofuels include dedicated energy crops (e.g. switchgrass and miscanthus) that are grown exclusively for fuel production. The EISA (2007) Act mandated a target volume of 60 billion liters (16 billion gallons) for second-generation biofuel crops. To meet targeted volume, three production strategies are recognized: displacement, intensification and expansion/targeting approach (Kloverpris et al., 2008). Displacement involves cultivation of field for biofuel production on current land uses. However, this strategy might result in the food vs. fuel debate. The second strategy, intensification, involves increase in biofuel crop yield with increase in inputs like fertilizer application, pesticide application, irrigation

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level, and the cropping intensity. However, the increase in yield per unit of input is often subjected to diminishing returns (Kloverpris et al., 2008). The third strategy, expansion/targeting, involves the conversion of targeted area (e.g. marginal or degraded land) to biofuel crop production.

It is pertinent to note that a report suggested an annual production of 30 billion liters (8 billion gallons) of advanced biofuels i.e. half of targeted production under EISA Act of 2007, might result from dedicating 10% of marginal lands along the Missouri and Mississippi rivers to energy crop production (Geiver, 2012). However, the definition of marginal land is not constant and it varies widely as per country, local conditions and the organizations studying the issue (Dale et al., 2010). The same attributes that qualify a land as marginal in one place or for one purpose might regard it productive in another place or for another purpose (Dale et al., 2010). Similarly, marginal lands could be defined using a single (Strijker, 2005) or multiple biophysical variables (Gopalakrishnan et al., 2011). Strijker (2005) defined marginal land as land with marginal economic viability whereas Gopalakrishnan et al. (2011) defined it based on soil health, current land use, and environmental degradation. Irrespective of the definition, marginal or degraded land has been reported as an environmentally friendly and sustainable approach for producing second-generation biofuel crops production (Campbell et al., 2008; Kort et al., 1998).

Estimating environmental benefits of biofuel crop production has frequently relied on the use of hydrologic and water quality (H/WQ) watershed models. These models help in predicting sediment and nutrient loss under various land uses, management, and climate conditions (Singh and Frevert, 2006). Among several H/WQ models, the SWAT model has been used by numerous studies for simulating biofuel crop production. For example, SWAT was used for assessing regional water quality implication of biofuel feedstock production in Upper Mississippi River Basin (Demissie et al., 2014). Sarkar and Miller (2014) used SWAT to model nitrogen losses from simulated switchgrass at the watershed scale. Apart from bioenergy crops simulation, the SWAT model has also been applied to identify critical source areas (CSA) for effective targeting of areas. Niraula et al. (2012a) identified sediment and nutrient CSAs and concluded that the calibration process should not affect the CSAs. Panagopoulos et al. (2011) parametrized SWAT for identifying CSAs under data limitations and concluded that the CSAs of sediments and nutrients can be identified with the current data limitations. Winchell et al. (2014) identified phosphorus CSAs by adjusting SCS curve numbers based on local compound topographic index and reported that 20% of the watershed produced 74% of the total phosphorus (TP) load.

Our group has been active in researching issues related to identifying CSAs. CSAs can be identified at the subwatershed (Pai et al., 2011) and hydrological response unit (HRU) (Pai et al., 2012) level. Targeting work at the HRU level resulted in the development of tools such as SWAT2009_LUC and FIELD_SWAT (Pai and Saraswat, 2011; Pai et al., 2012). The SWAT2009_LUC tool updates land uses over the modeling period by redistributing HRU fractions in subwatersheds. Updating land use represents a more realistic temporal land use variation in models for heterogeneous watersheds. Moreover, the updated version of SWAT2009_LUC tool includes a feature to analyze the impact of land use categorical uncertainty on SWAT hydrologic modeling (Pai and Saraswat, 2013). The FIELD_SWAT tool converts HRU level outputs to the field boundaries defined by the user. The present study advances our group's targeting related work at the HRU level. Apart from our group, White et al. (2009) used SWAT to identify and quantify sediment and TP loads originating from CSAs. White et al. (2009) considered six Oklahoma priority watersheds from 2001 to 2007. Sediment and TP loads were obtained from each HRU. The HRUs were ranked as per the predicted sediment and TP loadings, and the highest 2.5 and 5% fractions were defined as CSAs. Ghebremichael et al. (2010) conducted a similar study identifying CSAs for phosphorus loss in the Rock River watershed, Vermont. They selected SWAT predictions on an HRU level in determining CSAs of phosphorus loss. Currently, there is a growing interest among researchers in conducting SWAT related HRU level studies (Huang et al., 2015; Her et al., 2015).

HRUs are the lowest simulation level in SWAT with specific identification numbers (IDs). However, HRUs are discontinuous landmasses in a subwatershed (Gassman et al., 2007; Pai et al., 2012), thereby posing a challenge in simulating targeted crop production in a spatially distributed manner. For example, assume that there is a typical model setup containing a rectangular subwatershed with four quadrants that represents the arrangement of HRUs (Fig. 1a). Further, assume that the marginal land (or the targeted area) is located in the first quadrant (Fig. 1b). Therefore, quadrant no. 1 should only be the focus of simulation in order to simulate crop production on marginal lands. However, as per the conventional model setup, crops simulated on HRU no. 1 will also be simulated in the fourth quadrant (along with the first quadrant) because of the presence of the same HRU in the fourth quadrant of the subwatershed. Thus, spatial discontinuity among HRUs hinders the simulation of crop production on spatially delineated marginal lands. As a result, there is a need to develop a new approach for simulating crops on those HRUs only that represents marginal lands for their accurate spatial representation in the watershed.

The objective of this study was to develop a new targeted land use simulation approach in SWAT model and assess comparative performance of conventional and new targeting approach for evaluating water quality impacts of second generation biofeedstocks produced on marginal lands. The tasks associated to accomplish study objective were: (1) development of a new simulation approach for incorporating marginal land in the SWAT model developed for L'Anguille River watershed (LRW), (2) setting up a conventional SWAT model and new targeted approach based model and its calibration and validation, (3) comparison of the model outputs between the conventional and new targeting approach, and (4) application of the new targeting approach to simulate second-generation biofuel crops, namely Alamo switchgrass (hereafter referred to as “switchgrass”) and giant miscanthus (hereafter referred to as “miscanthus”) on marginal lands in the LRW for analyzing their impacts on water quality.

2. Materials and methods

2.1. Study area

The LRW is located in the Mississippi Delta ecoregion of east central Arkansas and designated by the hydrological unit code (HUC) 08020205 (Seaber et al., 1994) (Fig. 2). The total drainage area for this watershed is 2474 square kilometers that covers a portion of Craighead, Cross, Lee, Poinsett, St. Francis, and Woodruff counties. Various land uses and land covers in the LRW watershed are soybean [*G. max* (L.) Merr.] (43.6%), forest (18.9%), rice (*Oriza sativa*) (14.9%), cotton (*Gossypium hirsutum)* (6.9%), pasture (5.1%), corn (*Z. mays* L.) (4.5%), urban (3.5%), water (1.4%), and generic agriculture (mixed land uses that are not statistically significant: tomatoes, watermelon, etc.) (1.2%) (CAST, 2007). The Arkansas Department of Environmental Quality (ADEQ) has included the L'Anguille River in the list of impaired water bodies for dissolved oxygen, chlorides, total dissolved solids, and sulfates (ADEQ, 2012). Moreover, the Arkansas Natural Resources Commission (ANRC) has designated the LRW as a priority watershed for the 2011–2016 NPS Pollution Management Plan for nutrients (ANRC, 2012).