Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model

RAJ CIBIN¹, ELIZABETH TRYBULA², INDRAJEET CHAUBEY³, SYLVIE M. BROUDER² and JEFFREY J. VOLENEC²
¹Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, 47907 IN, USA, ²Department of Agronomy, Purdue University, West Lafayette, 47907 IN, USA, ³Department of Earth, Atmospheric, and Planetary Sciences, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, 47907 IN, USA

Abstract

Cellulosic bioenergy feedstock such as perennial grasses and crop residues are expected to play a significant role in meeting US biofuel production targets. We used an improved version of the Soil and Water Assessment Tool (SWAT) to forecast impacts on watershed hydrology and water quality by implementing an array of plausible land-use changes associated with commercial bioenergy crop production for two watersheds in the Midwest USA. Watershed-scale impacts were estimated for 13 bioenergy crop production scenarios, including: production of Miscanthus × giganteus and upland Shawnee switchgrass on highly erodible landscape positions, agricultural marginal land areas and pastures, removal of corn stover and combinations of these options. Water quality, measured as erosion and sediment loading, was forecasted to improve compared to baseline when perennial grasses were used for bioenergy production, but not with stover removal scenarios. Erosion reduction with perennial energy crop production scenarios ranged between 0.2% and 59%. Stream flow at the watershed outlet was reduced between 0 and 8% across these bioenergy crop production scenarios compared to baseline across the study watersheds. Results indicate that bioenergy production scenarios that incorporate perennial grasses reduced the nonpoint source pollutant load at the watershed outlet compared to the baseline conditions (0–20% for nitrate-nitrogen and 3–56% for mineral phosphorus); however, the reduction rates were specific to site characteristics and management practices.

Keywords: bioenergy production, corn stover, environmental impacts of bioenergy, impacts of bioenergy, Miscanthus, SWAT Model, Switchgrass

Introduction

Bioenergy crop production has been discussed globally as an alternative fuel source with the concurrent benefits to reduce greenhouse gas emissions and improve water quality, specifically with cellulosic feedstock sources including perennial grasses. However, these discussions also include concerns over increased water use (Vanloocke et al., 2010; Phong et al., 2011) and reduced soil productivity potential due to intensive agricultural practices and removal of crop residues (Costello et al., 2009; Thomas et al., 2011; Cibin et al., 2012; Demissie et al., 2012). In the United States (US), the Energy Independence and Security Act (EISA-2007) mandates production of 136 billion liters of ethanol per year by 2022, but deployment of bioenergy cropping systems at this scale can have unknown environmental impacts. In 2010, the US Department of Agriculture (USDA) estimated that approximately 11 million hectares of cropland are needed to achieve the EISA biofuel target (USDA – 2010) and has suggested perennial grasses such as Miscanthus (Miscanthus × giganteus) and switchgrass (Panicum virgatum L.) as future energy crops capable of meeting production targets. Changes in land use and management practices associated with biofuel production scenarios, such as removal of crop residues and insertion of dedicated energy crops into farming systems, can potentially affect both the quality and quantity of water resources. For this reason, management decisions need to be carefully evaluated to quantify the environmental impact of various biofuel production practices.

Using mathematical models is ideal for analyzing impacts of future scenarios provided underlying processes are well represented in the model. The Soil and
Water Assessment Tool (SWAT) (Arnold et al., 1998) is an established watershed model that has been identified as a potential tool for evaluating impacts of biofuel-related scenarios (Engel et al., 2010). However, many bioenergy crops including Miscanthus and switchgrass have yet to be widely implemented in commercial agriculture and are not well represented in SWAT and other similar watershed models. Accurate representation of bioenergy crop phenology in SWAT requires specific crop growth parameters for perennial grasses and revision of model algorithms for crop growth and management. Recent efforts to represent energy crops in SWAT, with exception to Trybula et al. (2014), used either calibrated crop growth parameters (Ng et al., 2010) derived from other crop model simulations, such as BioCro (Miguez et al., 2012), or used parameters from other crops available in the crop database of the model (Love & Nejadhashemi, 2011; Parajuli, 2012). However, as in any complex hydrologic/water-quality model, when a process representation is taken from one model and put in another, the results obtained may be considerably different due to interactions among many parameters and processes. Therefore, it is important to (re)validate the model parameters and underlying algorithms. We believe that the evidence-based parameter values directly validated in the revised SWAT model improves our confidence in the model results. Currently, limited information on crop growth validation for SWAT model exists in the literature, especially for perennial bioenergy crops, such as switchgrass and Miscanthus. A lack of such validation may lead to potential misrepresentation of these crops in model without considering the processes affecting perennial grass growth, such as nutrient translocation, storage of nutrients in belowground biomass during dormancy and extended evapotranspiration periods due to indeterminate growth of perennial grasses. These factors can have significant impacts on crop water and nutrient uptake processes and subsequently on hydrology and water quality.

The SWAT model simulation comparison (Fig. 1) of Miscanthus using the parameters from Ng et al. (2010) and the improved SWAT model from Trybula et al. (2014) indicates that changes in the model code and field data based parameterization significantly improved the biophysical representation of perennial bioenergy crops in the model. The improved model represented the belowground biomass and nutrient storage during dormancy better than the default model used thus far. These factors affected plant nutrient uptake simulation and had significant impacts on the biomass yield, hydrology and water-quality simulation (Fig. 1). A detailed comparison of perennial bioenergy crop simulations from different SWAT model representations of perennial grasses (Ng et al., 2010; Love & Nejadhashemi, 2011; Parajuli, 2012; Trybula et al., 2014) is included in supplementary information (SI). This study used the improved SWAT model (Trybula et al., 2014) which had better biophysical representation of perennial grasses and was parameterized and validated for bioenergy crop growth with measured data collected from nearby research plots representative of watershed conditions. Our objective was to estimate potential impacts of plausible bioenergy scenarios on watershed hydrology and water quality. The specific objectives of the research were to (1) develop plausible bioenergy scenarios for Midwest US watersheds and (2) evaluate potential environmental impacts of the plausible bioenergy crop scenarios using the improved SWAT model.

![Fig. 1](image_url)  
Comparison of Miscanthus simulation using improved SWAT model (Trybula et al., 2014) with other published SWAT model representation (Ng et al., 2010). The table in figure shows the annual average water, sediment, total nitrogen, total phosphorus and biomass yield with the two representations. A detailed comparison is provided in Appendix S2.
Materials and methods

The SWAT model (Arnold et al., 1998) was used to quantify the impacts of biofuel scenarios on hydrology and water quality at the watershed scale for two watersheds located in the Midwest USA; (1) Wildcat Creek watershed (drainage area of 2,083 km²) located in northcentral Indiana and (2) St. Joseph River watershed (drainage area of 2,809 km²) located in Indiana, Ohio and Michigan (Fig. 2). The two watersheds were selected to contrast the impacts of bioenergy production on a flat heavily row cropped watershed (Wildcat Creek) and flat to hilly terrain mixed land-use watershed (St. Joseph River). SWAT is a process-based, semidistributed, watershed-scale model. The model divides a watershed into hydrologic response units (HRUs) within subwatersheds. HRUs, SWAT’s smallest spatial unit for simulation, are areas with unique combinations of land use, soil type and slope. A detailed description of SWAT can be obtained from Neitsch et al. (2005).

Thirteen biofuel crop production scenarios were formulated (Table 1) considering bioenergy crop production (1) on highly erodible soils (Scenarios 1 and 2); (2) on agriculturally marginal lands (Scenarios 3 and 4); (3) with stover removal from low-slope areas (Scenario 5); (4) with bioenergy crops planted on current pasture areas (Scenario 6 and 7); and their combinations (Scenarios 8–13). Miscanthus (Miscanthus × giganteus) and Shawnee, an upland switchgrass (Panicum virgatum L.) variety, were included as dedicated bioenergy crops and corn (Zea mays L.) stover as crop residue for biofuel production (70% mass removal rate, Cibin et al., 2012). The corn and soybean (Glycine max L. Merril) areas with >2% slope were considered as potential highly erodible areas. Agricultural marginal lands were defined as areas where simulated corn productivity compared to the 14-year baseline simulated average for the watershed was less than the 5th percentile. The 70% stover removal represents potential stover that can be collected from shredding, raking and baling (Brechbill & Tyner, 2008).

A calibrated and validated SWAT model [SWAT version 615 which includes improved perennial crop simulation (Trybula et al. (2014))] for the two watersheds were used to quantify impacts of 13 biofuel scenarios described above. The calibrated/validated model representing current agricultural land use is considered as the baseline scenario. Weather data for 14 years (1996–2009) was used to predict long-term hydrology and water-quality impacts of the thirteen bioenergy scenarios.

Study area description and SWAT model representation

Wildcat Creek watershed (WCC) is a relatively flat terrain (88% area <2% slope) and is predominantly agricultural with 70% of the total land in corn/soybean rotation and 5% in pasture (United States Department of Agriculture-National Agricultural Statistics Services, 2009). St. Joseph River (SJR) watershed is flat to hilly terrain (40% area >2% slope) and is mixed land use with 37% corn/soybean rotation, 25% pasture, 12% forest, 10% developed area and 8% forested wetlands. The SWAT model for both study watersheds were developed as methodology discussed in Cibin et al. (2012) and was calibrated/validated for crop growth, stream flow and water quality (sediment, nitrate-nitrogen and total phosphorus) using basin-level model
parameters as discussed in Cibin & Chaubey (2015) (SI Table S3). A detailed description of SWAT model development, calibration and validation is provided in supplementary information. The SWAT model calibration/validation evaluation indices for daily stream flow and water-quality simulations for the both watersheds (Appendix S1) were well above acceptable ranges recommended by many researchers (Engel et al., 2007; Moriasi et al., 2007).

**Biofuel scenarios representation in the SWAT model**

The SWAT model requires about 25 crop growth parameters to represent plant emergence, biomass production and partitioning, leaf area and canopy development, water and nutrient uptake, and maturity definitions. This study used crop growth parameters (SI Table S7) derived by Trybula et al. (2014) from field measurements for Miscanthus and Shawnee switchgrass at the Purdue Water Quality Field Station (WQFS) located in northcentral Indiana near WCC. Trybula et al. (2014) also improved SWAT crop model algorithms to better represent bioenergy production of perennial grasses. The evidence-based parameterization and model code improvements enhanced the physical representation of perennial grass growth for biomass production, nutrient uptake and nutrient translocation/storage in model simulations, which improved hydrologic and water-quality outputs. The model improvements are included in release version of SWAT model (version 615 and beyond). Additional detailed information about model parameterization and improvements are provided in Trybula et al. (2014).

*Miscanthus, switchgrass and pasture grasses were represented in the model as multiyear crop rotations, with planting in the first year of simulation only. Tall fescue (Schedonorus arundinaceus (Schreb.) Dumort) was selected in this study for pasture management with rotational grazing and hay cut. A detailed discussion of pasture and other crop management practices is provided in Appendix S1. Miscanthus and switchgrass were planted on April 1, and tall fescue was planted on March 1. Perennial crop emergence after dormancy was triggered in subsequent years by average daily air temperature above the crop base temperature. Crop management practices were the same for Miscanthus and switchgrass, including fertilizer application of 56 kg-N ha⁻¹ in the form of urea and an October 31 harvest date, as practiced at the WQFS (Trybula et al., 2014). The first 4 years of model simulation were considered in the model warm-up period to stabilize initial conditions in the model. Perennial energy crops have a recognized period of establishment in the first 3–4 years of grass development; at present, the SWAT model is not capable to represent the establishment phase for perennial grasses. SWAT model for this study was designed to include this establishment period of perennial grasses during the model warm-up; in effect, the study results discussed for perennial grasses are with fully established stands of Miscanthus, switchgrass and tall fescue. Corn stover removal was represented in SWAT as 70% stover biomass removal after corn grain harvest. Stover removal scenarios included additional fertilizer application at the rate of 7.95 kg anhydrous ammonia and 2.85 kg P₂O₅ per tonne or Mg of stover removed to account for nutrient replacement (Brechbill & Tyner, 2008).
Results and discussion

Simulated yields of bioenergy crops on erodible (>2% slope) nontilled corn/soybean areas averaged 20.6 and 18.3 Mg ha$^{-1}$ for Miscanthus and switchgrass, respectively, for WCC and SJR watersheds. Simulated yields were similar to measured yields of 25 and 10 Mg ha$^{-1}$ for Miscanthus and switchgrass, respectively, at the WQFS (Burks, 2013), considering the climate variability across simulation period, differences in soil and slope at WQFS and the WCC watershed. SJR watershed further north of WCC crop yields were generally lower compared to WCC due to relatively lower temperature, growing period and land quality. SJR has more highly erodible and agricultural marginal lands compared to WCC (Table 1). The corn stover harvested yield was estimated to be 7.3 and 5.9 Mg ha$^{-1}$ with 70% stover removal rate from low-slope tiled areas in WCC and SJR, respectively. The 5th percentile corn yield for identifying agricultural marginal land was estimated as 8 Mg ha$^{-1}$ (5.5 Mg ha$^{-1}$ for SJR) for the WCC watershed from SWAT model simulations; HRUs with <5 percentile corn yield were considered as agriculturally marginal land for Scenarios 3, 4, 12 and 13. The average biomass yield from agricultural marginal land (18.6 and 9.8 Mg ha$^{-1}$ for Miscanthus and switchgrass, respectively, for WCC) was less than yield from highly erodible soils. Table 2 shows the ethanol production potential for the scenarios, considering ethanol potential as 473 l per Mg for corn stover and 403 l per Mg for energy crop feedstock obtained from a theoretical ethanol yield (http://www.afdc.energy.gov/fuels/ethanol_feedstocks.html). Biofuel production potentials for the WCC watershed with Miscanthus were estimated as 83, 97 and 45 million liters when placed in pasture, highly erodible and agriculturally marginal areas, respectively. The two watersheds combined could produce approximately 1.4 billion liters of ethanol with Scenario 12 which represents stover removal from low erodible soil and Miscanthus grown in pasture, highly erodible and agriculturally marginal lands.

**Impacts of biofuel crop production scenarios**

**Impacts on hydrology.** Stream flow at the watershed outlet was slightly reduced under biofuel production scenarios (Table 2). The percentage reduction in stream flow ranged from 0.2% (Scenario 7) to 4.5% (Scenario 12) for WCC and 0.3% (Scenario 3) to 7.9% (Scenario 12) for SJR watershed (Fig. 3). In general, the reduction in stream flow was slightly more for Miscanthus than switchgrass. In Scenario 13, 40% area land-use change and 25% area land-management change (stover removal) in SJR induced only 3% reduction in stream flow for SJR watershed, which indicates minimal impacts on blue water footprint with switchgrass and stover removal based scenarios. A detailed monthly analysis to better understand different hydrologic processes resulting from bioenergy-driven land-use changes (corn/soybean and pasture to energy crops) was performed for two sample HRUs in the WCC watershed, one corn/soybean and one pasture HRU.

### Table 2

| Wildcat Creek watershed | Flow (m$^3$ s$^{-1}$) | Sediment (Mg ha$^{-1}$) | Nitrate (kg ha$^{-1}$) | Min P (kg ha$^{-1}$) | Biofuel potential ($\times 10^6$ l) |
|-------------------------|-----------------------|-------------------------|-----------------------|-----------------------|-----------------------------------|
| Baseline                | 25.95                 | 1.04                    | 18.89                 | 0.37                  | 0                                 |
| Scenario 1              | 25.56                 | 0.69                    | 18.75                 | 0.31                  | 97                                |
| Scenario 2              | 25.82                 | 0.69                    | 18.77                 | 0.31                  | 52                                |
| Scenario 3              | 25.82                 | 1.01                    | 18.44                 | 0.34                  | 45                                |
| Scenario 4              | 25.92                 | 1.01                    | 18.60                 | 0.34                  | 24                                |
| Scenario 5              | 25.36                 | 1.13                    | 17.96                 | 0.36                  | 229                               |
| Scenario 6              | 25.73                 | 1.04                    | 18.86                 | 0.36                  | 83                                |
| Scenario 7              | 25.96                 | 1.04                    | 18.88                 | 0.36                  | 45                                |
| Scenario 8              | 25.35                 | 0.69                    | 18.72                 | 0.31                  | 180                               |
| Scenario 9              | 25.83                 | 0.69                    | 18.75                 | 0.31                  | 97                                |
| Scenario 10             | 24.76                 | 0.78                    | 17.79                 | 0.31                  | 409                               |
| Scenario 11             | 25.24                 | 0.78                    | 17.82                 | 0.30                  | 326                               |
| Scenario 12             | 24.68                 | 0.76                    | 17.42                 | 0.29                  | 433                               |
| Scenario 13             | 25.23                 | 0.76                    | 17.59                 | 0.29                  | 336                               |

| St Joseph River watershed | Flow (m$^3$ s$^{-1}$) | Sediment (Mg ha$^{-1}$) | Nitrate (kg ha$^{-1}$) | Min P (kg ha$^{-1}$) | Biofuel potential ($\times 10^6$ l) |
|---------------------------|-----------------------|-------------------------|-----------------------|-----------------------|-----------------------------------|
| Baseline                  | 31.27                 | 0.22                    | 7.42                  | 1.04                  | 0                                 |
| Scenario 1                | 30.28                 | 0.10                    | 7.13                  | 0.51                  | 256                               |
| Scenario 2                | 30.75                 | 0.10                    | 7.16                  | 0.51                  | 143                               |
| Scenario 3                | 31.02                 | 0.16                    | 7.17                  | 0.96                  | 86                                |
| Scenario 4                | 31.17                 | 0.16                    | 7.39                  | 0.96                  | 46                                |
| Scenario 5                | 31.01                 | 0.23                    | 6.54                  | 1.06                  | 98                                |
| Scenario 6                | 30.18                 | 0.22                    | 7.29                  | 1.01                  | 542                               |
| Scenario 7                | 31.15                 | 0.22                    | 7.35                  | 1.00                  | 295                               |
| Scenario 8                | 29.19                 | 0.10                    | 7.00                  | 0.48                  | 797                               |
| Scenario 9                | 30.62                 | 0.10                    | 7.09                  | 0.48                  | 438                               |
| Scenario 10               | 28.92                 | 0.11                    | 6.11                  | 0.50                  | 895                               |
| Scenario 11               | 30.36                 | 0.11                    | 6.21                  | 0.50                  | 536                               |
| Scenario 12               | 28.79                 | 0.09                    | 5.94                  | 0.46                  | 943                               |
| Scenario 13               | 30.33                 | 0.09                    | 6.25                  | 0.46                  | 557                               |
with the same climate region and soil type. The monthly analysis for both corn/soybean and pasture changing to energy crops shows more reduction in surface runoff with *Miscanthus* compared to switchgrass (Fig. 4a), possibly due to higher evapotranspiration and soil moisture reduction for *Miscanthus* when compared to switchgrass. The study used SCS curve number (SCS, 1972) method to estimate surface runoff from field units, and it should be noted that the same initial curve number (CN) was assumed for both energy crops. The model updates CN on a daily basis with soil moisture and residue cover. The simulated reduction in surface runoff was more with corn/soybean than pasture changing to a perennial grass energy crop (Fig. 4a). The reduction in surface runoff for perennial energy crops compared to annual crops was predominant in the months of June and July when the crops are fully mature and perennials have better soil cover compared to row cropped annuals. Surface runoff from pasture area was high in the months of June to August compared to perennial energy crops due to summer grazing of pasture area.

A prolonged growing season resulted in increased evapotranspiration from energy crops during the growing season (months 6 to 8; Fig. 4b) compared to corn/soybean, which could be attributed to pasture management representation such as hay harvest in May and energy crops. Nongrowing season (November–April) evapotranspiration dominated by soil evaporation for both energy crops was lower than corn/soybean and pasture (Fig. 4b), potentially due to a reduction in soil moisture with energy crops at the final stages of growth period (September–October) (Fig. 4c). Field trials from McIsaac *et al.* (2010) also reported similar reduced moisture content with *Miscanthus* in later stages of growing season compared to corn/soybean. The changes in soil moisture and evapotranspiration affect the subsurface flows (lateral, tile and ground water flow); thus, in general, reduction in water yield for *Miscanthus* was slightly more than switchgrass (Fig. 4d). Subsurface flow generally increased with perennial grasses compared to baseline corn/soybean rotation (Table S8), this reduces peak flows and improves low flow conditions and could be attributed toward increased infiltration and soil moisture content with perennials. Tile flow measured using undisturbed lysimeters at WQFS demonstrated reduction in drainage event volume with cropping system transition from corn/soybean to *Miscanthus* similar to current study results, while switchgrass response varied across replicates (Trybula, 2012). Residue removal scenarios also predicted reduced stream flow at the watershed.
outlet, which may be caused by increased evaporation from loss of soil cover (van Donk et al., 2010; Cibin et al., 2012) during the nongrowing season. Residue removal also tends to reduce the water-holding capacity of soil (van Donk et al., 2010).

**Impacts on erosion.** Sediment loading at watershed outlet decreased with biofuel scenarios, with the exception of the stover removal (Table 2). Erosion reduction was expected for land-use change from annual row crops to perennial bioenergy crops (Self-Davis et al., 2003; Parrish & Fike, 2005). Erosion rates predicted for both Miscanthus and switchgrass scenarios were nearly identical. This may be associated with same Modified Universal Soil Loss Equation (MUSLE) crop factor used for both energy crops. The percentage reduction in sediment loading with bioenergy crops ranged from 0.2% for scenario 7 in WCC to 59.4% for scenario 12 in SJR (Fig. 3). The 70% corn stover removal scenario showed an increase in erosion and sediment loading as compared to the baseline. This potential increase in soil erosion with residue removal is a major concern for biofuel production (Delgado, 2010; van Donk et al., 2010; Johnson et al., 2010; Cibin et al., 2012). Perennial energy crops in highly erodible area (5.8% and 12.3% of total WCC and SJR watershed area, respectively) reduced sediment loading at watershed outlet by 34% and 52% for WCC and SJR, respectively. The erosion reduction with energy crops in highly erodible areas for a relatively flat watershed such as WCC indicates the general opportunity of growing bioenergy crops as potential best management practice for reducing erosion. Monthly analysis (Fig. 5a) shows a consistent reduction in predicted soil erosion when corn/soybean cropping systems are changed to perennial energy crops, while predicted erosion rates for both pasture and perennial energy crops were similar. Another factor affecting soil erosion could be a lack of annual land preparation practices typically associated with many of the annual crops. The land-management practices such as tillage and fertilizer application in corn/soybean areas could change with stover removal implementation by farmers to minimize impacts; the current study accounted the possible increased fertilization with stover removal (SI Tables S1 and S5) while the tillage practices were represented same for with and without stover removal.

Fig. 4  Monthly analysis of energy crop impacts on various hydrology components in one corn/soybean and pasture HRU. Difference with corn/soybean changed to Miscanthus (MISC-CORN) and switchgrass (SWCH-CORN) and difference with pasture HRU changing to Miscanthus (MISC-PAST) and switchgrass (SWCH-PAST) for monthly surface runoff (a), evapotranspiration (b), soil moisture (c) and water yield (d). A positive value indicates the energy crop scenario values are higher than baseline scenario.
Impacts on nutrient losses. In general, the model simulations indicate that biofuel crop production will likely reduce nutrient losses compared to current cropping systems used in this watershed. The rate of reduction varies with the areal extent of deployment and type (perennial grass vs. stover) of bioenergy crop grown. The trend in nutrient loss reduction is highly correlated with sediment loading for adsorbed nutrients (organic N and P) and with stream flow for nutrients transported in dissolved form (nitrate and soluble P) (Fig. 3).

As expected, the reductions and trends in adsorbed nutrient losses were similar to that of sediment losses (Fig. 5). Organic N reduction ranged from 0.2% to 23% for WCC and 1.8% to 55% for SJR watershed, similarly, organic P reduction ranged from 0.4% to 26.4% and 2.2% to 59%, respectively, for both watersheds. Organic N and P loadings for pasture and energy crops were similar, and reductions were similar for Miscanthus and switchgrass for all other scenarios. The stover removal scenario showed 3.1% and 1.2% increase in organic N and 1.6% reduction and 4.5% increase in organic P loading for WCC and SJC, respectively.

Annual nitrate loading trend was very similar to the stream flow trend for bioenergy scenarios. The nitrate reduction from stover removal was found to be more prominent than reduction with the perennial grass scenarios. In general, Miscanthus scenarios showed slightly higher reduction in nitrate loading (Fig. 3) than switchgrass scenarios (Fig. S13) at the watershed outlet. This difference in nitrate loading from Miscanthus and switchgrass may be due to higher simulated nitrogen uptake by Miscanthus compared to switchgrass (Table S8), both crop scenarios received the same fertilizer application rates (56 kg-N ha$^{-1}$). Field studies also reported higher nitrogen uptake by Miscanthus compared to switchgrass (Heaton et al., 2009; Burks, 2013). In addition, this study considered a relatively high rate of mineralization of organic nutrients for all scenarios. Humus mineralization of organic nutrients rate coefficient (CMN) of 0.003 was recommended by Trybula et al. (2014) to increase mineralization rates for Miscanthus to better represent soil characteristics at the research plots, and this value was used for all scenarios including baseline scenario in this study. The rate of

© 2016 The Authors. Global Change Biology Bioenergy Published by John Wiley & Sons Ltd., 8, 837–848
humus mineralization could be land-use specific corresponding to their soil microclimate and associated crop-specific microorganisms (Orr, 2012; Chen et al., 2014). At present, the SWAT considers nonlimiting soil moisture, temperature and carbon-to-nitrogen ratio for mineralization, but the rate coefficient is a basin-level parameter uniform for all crop/soil types. Lack of measured data on mineralization rates also makes it difficult to estimate this parameter at field level leaving the option for a model user to calibrate the parameter using in-stream nitrate loading data. Further studies are required to better constrain crop-specific nutrient mineralization rates in SWAT representation and validation of mineralization.

Nitrate loading through surface runoff decreased when pasture and corn/soybean land use were converted to perennial grass energy crops (Fig. 6d). However, the impacts on subsurface nitrate losses such as nitrate leached (for nontiled areas) and tile nitrate loading varied across HRUs (Fig. S14), indicating the sensitivity of land area characteristics. The sample HRU selected for detailed analysis indicated increase in leached nitrate for both energy crops compared to baseline (Fig. 6c). Comparison of nitrate leached from all HRUs in Scenarios 1 and 2 indicates slightly over 50% of HRUs in WCC and 80% of HRUs in SJC trend toward reduction in nitrate leached with Miscanthus and almost 99% of WCC and 75% of SJC trend toward increased nitrate leached with switchgrass compared to baseline corn/soybean (Fig. S14). The major factors affecting nitrate leaching are the percolation rate, fertilization (application timing with precipitation and amount), soil nutrient dynamics and plant nutrient uptake. In general, percolation rate is increased with perennial grasses due to higher infiltration, while average fertilization rate, plant uptake and residue mineralization are low for energy crops comparing to annual corn/soybean rotation. The trend in leached nitrate depended on which of the above-mentioned factors are more dominant in specific HRU. The study scenarios considered only very limited tile drained area converting to bioenergy crops. The tile nitrate were generally reduced with both energy crops in WCC while simulation results from SJC indicated reduction in tile nitrate with Miscanthus and increase with switchgrass (Fig. S14). Field studies have reported reductions in subsurface nitrate loading with...
both perennial grass energy crops (McIsaac et al., 2010; Trybula, 2012). A lower total mineralization (including humus organic and fresh residue mineralization) for energy crops was predicted compared to corn/soybean and pasture (Fig. 6a). Field study conducted at side-by-side comparison of corn/soybean plots and energy crop plots also reported low net mineralization with energy crops comparing to corn/soybean (Orr, 2012). Relative to energy crops, pasture areas were simulated with high mineralization in growing season due to grazing as grazing adds extra manure and tramples grasses to soil. The literature on pasture area nutrient cycling reported increased mineralization with grazing through decomposition and excretion of plant nutrients (Bardgett et al., 1997; Bardgett & Wardle, 2003) along with stimulated soil microbial activity from animal excreta (Wang et al., 2006); however, the excreta is often heterogeneous and highest near shade and water sources (Iyyemperumal et al., 2007). At present, SWAT cannot represent the increased microbial activity and also considers excreta manure and trampling to be uniform in grazed HRU. Simulated average annual mineralization with corn/soybean and pasture was 97 and 72 kg-N ha$^{-1}$, respectively, for the selected HRU, while for Miscanthus and switchgrass, was 53 and 43 kg-N ha$^{-1}$, respectively. The major component of corn/soybean and pasture mineralization was from residue organic matter representing about 70 and 47 kg-N ha$^{-1}$, respectively. Aboveground residues after grain harvest and belowground biomass are incorporated to soil organic pool for corn/soybean and contribute to the residue organic N pool in the model. In pasture, the biomass trampled during grazing and manure contributes toward fresh organic nitrogen pool; this difference can be visualized in growing season (July–October, Fig. 6a). In perennial energy crops, the belowground biomass acts as nutrient storage organs during dormancy period and as aboveground biomass after harvest contributes to the fresh organic residue pool, resulting in low mineralization (Fig. 6a). Dormancy period of perennial grass root decay component is not considered in this study due to lack of data to represent root decay (Trybula et al., 2014). SWAT predicted nutrient uptake from soil by energy crops to be relatively low compared to corn/soybean and pasture crops. The nutrient stored in belowground biomass for perennial energy crops reduces the nutrient requirement at the early growing stages, and thus, the nutrient uptake was also simulated low for both Miscanthus (~100 kg-N ha$^{-1}$) and switchgrass (~80 kg-N ha$^{-1}$) compared to corn/soybean (~250 kg-N ha$^{-1}$) and pasture (115 kg-N ha$^{-1}$). Bioenergy field studies in Indiana (Barks, 2013) and Illinois (Heaton et al., 2009) also reported similar ranges of nitrogen uptake for both Miscanthus and switchgrass. Monthly analysis indicates reduction in surface runoff nitrate loading by about 0.16 kg ha$^{-1}$ month$^{-1}$ with corn/soybean and about 0.08 kg ha$^{-1}$ month$^{-1}$ with pasture area changing to energy crops. Reduction in surface flow nitrate and increased subsurface flow nitrate loading with energy crops will necessitate implementation of conservation practices (e.g., nitrate-reducing bioreactors) to reduce subsurface nitrate losses from perennial energy crops.

The stover removal in low-slope areas of SJC and WCC simulated a 4.9% and 11.9% nitrate load reduction at watershed outlet even with 8% and 24% increased fertilizer application, respectively. The reduced residue in field after stover harvest reduced the nutrient source for mineralization which reciprocated to reduced nitrate loading with stover removal. Previous research reveals that repeated stover removal can reduce net mineralization (Kapkiyai et al., 1999; Salinas-Garcia et al., 2001) and reduce organic N returning to soil (Dolan et al., 2006; Blanco-Canqui & Lal, 2009). A detailed discussion of stover removal impacts on hydrology and water quality with different stover removal rates for the WCC watershed can be obtained from Cibin et al. (2012).

Mineral P loading was reduced consistently across perennial grass scenarios (Table 2, Fig. 3), ranging from a reduction of 1.4% for scenario 6 in WCC to 56% for scenario 13 in SJC. Monthly analysis (Fig. 5c) for adsorbed P transport depicts same trend as sediment yield (Fig. 5a) for both pasture and corn/soybean changing to energy crops. Soluble P (Fig. 5d) had similar trend as that of surface runoff (Fig. 4a). Both dissolved and adsorbed P were reduced consistently across all months with energy crops.

Implications

Quantifying watershed-scale impacts of bioenergy production scenarios provides the opportunity to evaluate the potential commercial and environmental trade-offs associated with viable feedstock operations. As alternatives are considered across a variety of landscape scales, environmental managers, policymakers, industry leadership and farmers can utilize forecasted water-use needs and water-quality impacts of feedstock production scenarios in the process of decision making. In the broader context of comprehensive watershed management, this information may enable bioenergy crop production for ecosystem services restoration while reducing unintended negative consequences. Based on the results of this study, Miscanthus and switchgrass production may be a strong candidate for implementation in watersheds that would generally benefit from sediment and nutrient load reduction and can sustain base flows during drought conditions. Alternatively, integrated systems might harness the versatility of
stover production that can be buffered by manageable swatches of perennial grasses. A revised SWAT model with improved representation of energy crop systems was used to predict the direction and magnitude of environmental impacts associated with perennial bioenergy scenarios on hydrology and water quality. In general, the model predicted reduction in stream flow, sediment and nutrient loading at the watershed outlet with perennial bioenergy production scenarios. The results also indicated a need for priority-based, careful planning in bioenergy crop production considering the additional cobenefit of 114 million liters of ethanol. Corn yield reduction of 8% (food) at watershed level and the additional cobenefit of 114 million liters of ethanol. However, when corn stover is removed for feedstock, sediment and organic N losses increased compared to the baseline conditions under conventional tillage systems. These trade-offs must be carefully evaluated to meet production and environmental goals.

Acknowledgements

This material is based upon work supported by the Department of Energy under Award Number DE-EE0004396 and USDA-NIFA under Award Number 2009-51130-06029. The authors declare no competing financial interest.

References

Arnold JG, Srinivasan R, Muttiah RS, Williams JR Large area hydrologic modeling and assessment - Part 1: model development. Journal of the American Water Resources Association (1998) 34, 73-89.

Bardgett RD, Wardle DA (2003) Herbivore mediated linkages between above-ground and below-ground communities. Ecology, 84, 2258-2268.

Bardgett RD, Leemans DK, Cook R, Hobbs PJ (1997) Seasonality of the soil biota of grazed and ungrazed hill grasslands. Soil Biology and Biochemistry, 29, 1285-1294.

Blanco-Canqui H, Lal R (2009) Corn stover removal for expanded uses reduces soil fertility and structural stability. Soil Science Society of America Journal, 73, 418-426.

Brechbill SC, Tyner WE (2008) The economics of renewable energy: corn stover and switchgrass. BioEnergy: Fusing America Through Renewable Resources. Purdue Extension, ID-404-W.

Burks JL (2013) Eco-physiology of three perennial bioenergy systems. Ph.D. Dissertation, Purdue University, West Lafayette, IN. ProQuest Dissertations and Theses.

Chen B, Liu E, Tian Q, Yan C, Zhang Y (2014) Soil nitrogen dynamics and crop residues. A review. Agronomy for Sustainable Development, 34, 429-442.

Cibin R, Chaubey I (2015) A computationally efficient framework for watershed scale spatial optimization. Environmental Modelling & Software, 66, 1–11.

Cibin R, Chaubey I, Engel B (2012) Simulated watershed scale impacts of corn stover removal for biofuel on hydrology and water quality. Hydrological Processes, 26, 1629–1641.

Costella C, Griffin W, Landis A, Matthews H (2009) Impact of biofuel crop production on the formation of hypoxia in the Gulf of Mexico. Environmental Science & Technology, 43, 7985-7991.

Delgado JA (2010) Crop residue is a key for sustaining maximum food production and for conservation of our biosphere. Journal of Soil and Water Conservation, 65, 111-116.

Demissie Y, Yan E, Wu M (2012) Assessing regional hydrology and water quality implications of large-scale biofuel feedstock production in the upper Mississippi River basin. Environmental Science & Technology, 46, 9174-9182.

Dolan MS, Clapp CE, Allmaras RR, Baker JM, Molina JAE (2006) Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. Soil and Tillage Research, 89, 221–231.

van Donk SJ, Martin DL, Imnak M, Melvin SR, Petersen JL, Davison DR (2010) Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. Trans ASABE, 53, 1787-1797.

Energy Independence and Security Act 2007 (2007) Public Law 110-140. Available at: http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm (accessed 10 June 2015).

Engel B, Storm D, White M, Arnold JG, Arabi M (2007) A hydrologic/water quality model application protocol. Journal of the American Water Resources Association, 43, 1223-1236.

Engel BA, Chaubey I, Thomas MA, Saraswat D, Murphy P, Bhaduri B (2010) Biofuels and water quality: challenges and opportunities for simulation modeling. Future Science Group: Biofuels, 1, 463–477.

Heaton EA, Dohleman FG, Long SP (2009) Seasonal nitrogen dynamics of Miscanthus × giganteus and Panicum virgatum. Global Change Biology Bioenergy, 1, 297–307.

Hickman GC, Vanwookee D, Dohleman FG, Bernacki CJ (2010) A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. GCB Bioenergy, 2, 157–168.

Iyyemperumal K, Israel DW, Shi W (2007) Soil microbial biomass, activity and potential nitrogen mineralization in a pasture: impact of stock camping activity. Soil Biology and Biochemistry, 39, 149–157.

Johnson JMF, Karlen DL, Andrews SS (2010) Conservation considerations for sustainable bioenergy feedstock production: if, where, what, and how much? Journal of Soil and Water Conservation, 65, 88–91.

Kapkiyai JJ, Karanja NK, Qureshi JN, Smithson PC, Woomer PL (1999) Soil organic matter and nutrient dynamics in a Kenyan Nitisol under long-term fertilizer and organic input management. Soil Biology and Biochemistry, 31, 1773-1782.

Love BJ, Nejadhashemi AP (2011) Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan. Biomass and Bioenergy, 35, 2208-2216.

Mclaas GF, David MB, Mitchell CA (2010) Miscanthus and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching. Journal of Environmental Quality, 39, 1790-1799.

Miguez FE, Maughan M, Bolloren GA, Long SP (2012) Modeling spatial and dynamic variation in growth, yield, and yield stability of the bioenergy crops Miscanthus × giganteus and Panicum virgatum across the conterminous United States. GCB Bioenergy, 4, 509-520.

Mortasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE, 50, 885–900.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2005) Soil and Water Assessment Tool Theoretical Documentation, Version 2005. USDA Agricultural Research Service and Texas A&M Blackland Research Center, Temple, TX.

Ng TL, Elcarr EJ, Cal X, Miguez F (2010) Modelling Miscanthus in the soil and water assessment tool (SWAT) to simulate its water quality effects as a bioenergy crop. Environmental Science & Technology, 44, 7136-7144.

Orr MJN (2012) Comparative assessment of five cellulose biofuel management strategies: Implications to soil carbon and nitrogen dynamics. Ph.D. Dissertation, Purdue University, West Lafayette, IN. ProQuest Dissertations and Theses.

Parajuli PB (2012) Comparison of potential bio-energy feedstock production and water quality impacts using a modeling approach. Journal of Water Resource and Protection, 4, 763–771.

Parrish JD, Fike JH (2005) The biology and agronomy of switchgrass. Trans ASABE, 7, 459-468.

Phong VV, Kumar P, Drewry DT (2011) Implications for the hydrologic cycle under climate change due to the expansion of bioenergy crops in the Midwestern United States. Proceedings of the National Academy of Sciences of the United States of America, 108, 15085–15090.

Salinas-García JR, Baez-Gonzalez AD, Tiscareno-Lopez M, Rosales-Robles E (2001) Residue removal and tillage interaction effects on soil properties under rain-fed corn production in central Mexico. Soil and Tillage Research, 39, 67-79.

Sel-Davis ML, Moore PA, Daniel TD et al. (2003) Forage species and canopy cover effects on runoff from small plots. Journal of Soil and Water Conservation, 58, 349–358.
Soil Conservation Service (SCS) (1972) National Engineering Handbook, Section 4, Hydrology. U.S. Department of Agriculture, Washington, DC.

Thomas MA, Engel BA, Chaubey I (2011) Multiple corn stover removal rates for cellulosic biofuels and long-term water quality impacts. Journal of Soil and Water Conservation, 66, 431–444.

Trybula E (2012) Quantifying ecohydrologic impacts of perennial rhizomatous grasses on tile discharge: a plot level comparison of continuous corn, upland switchgrass, mixed prairie, and Miscanthus × giganteus. M.S. Dissertation, Purdue University, West Lafayette, IN. ProQuest Dissertations and Theses.

Trybula E, Cibin R, Burks J, Chaubey I, Brouder S, Volenec J (2014) Perennial rhizomatous grasses as bioenergy feedstock in SWAT: parameter development and model improvement. GCB Bioenergy, 7, 1185–1202.

United States Department of Agriculture-National Agricultural Statistics Services (2009) CropScape and Cropland Data Layer. Available at: http://www.nass.usda.gov/Data_and_Statistics/ (accessed 12 April 2011).

USDA Biofuels Strategic Production Report (2010) A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022. Available at: http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf (accessed 10 November 2010).

Vanloocke A, Bernacchi CJ, Twine TE (2010) The impacts of Miscanthus giganteus production on the Midwest US hydrologic cycle. GCB Bioenergy, 2, 180–191.

Wang KH, McSorley R, Bohlen P, Cathumbi SM (2006) Cattle grazing increases microbial biomass and alters soil nematode communities in subtropical pastures. Soil Biology and Biochemistry, 38, 1956–1965.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Location map of Wildcat Creek watershed and St Joseph River watershed. USGS station near watershed outlet is used for model calibration other stations were used for validation.

Appendix S1. SWAT model development, calibration/validation for the study watersheds

Figure S2. Comparison of tile flow with default CN and modified CN (hydrologic soil group one level down). X axis indicates cumulative tile drain area in the watershed.

Table S1. SWAT management inputs for Wildcat Creek watershed

Figure S3. Corn and soybean yield simulation comparison with measured data from NASS county level yield data.

Table S2. SWAT model parameters used for representing tall fescue in the study

Figure S4. Tall fescue simulations of total biomass, leaf area index (top), nitrogen and phosphorus uptake (bottom) for a sample pasture HRU in the watershed

Figure S5. Kentucky bluegrass simulations of total biomass and leaf area index for a sample urban HRU in the watershed.

Figure S6. Sample management file for an urban HRU

Figure S7. Forest simulations of total biomass and leaf area index for a sample HRU in the watershed.

Figure S8. Sample management file for a forest HRU

Table S3. Description of SWAT parameters calibrated in the study and calibrated parameter values

Table S4. Daily and monthly calibration and validation statistics for stream flow in Wildcat Creek watershed

Figure S9. (A-Top left) Scatter plot of observed and simulated daily stream flow.

Figure S10. Corn and soybean yield simulation comparison with measured data from NASS county level yield data.

Table S6. Daily and monthly calibration and validation statistics for stream flow in St Joseph River watershed

Figure S11. (A-Top left) Scatter plot of observed and simulated daily stream flow.

Appendix S2. SWAT model improvements comparison and energy crop parameters

Figure S12. Comparison of improved SWAT model (Trybula et al., 2014) with other published SWAT model representations (Blue line: Ng et al., 2010; Red line: default model with parameters from Trybula et al., 2014).

Table S7. SWAT model parameters used for representing Miscanthus (MISC) and switchgrass (SWCH) in the study (adapted from Trybula et al., 2014).

Figure S13. Average annual impact of switchgrass based biofuel scenarios on stream flow and water quality at the watershed outlet. (A) Wildcat Creek watershed (B) St Joseph River watershed. Positive value indicates increase in value with respect to baseline scenario.

Appendix S3. Bioenergy scenarios impacts-additional information.

Table S8. Comparison of hydrology and water quality simulation by different landuses in agricultural marginal lands (HRU level) in St Joseph River watershed (scenario 3).

Figure S14. Box plot comparison of difference in nitrate leach (Top: for Scenario1&2) and tile nitrate loading (Bottom: for Scenario 3&4) variability across HRU’s in the two study watersheds for perennial grasses compared to corn/soybean rotation.