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Identifying potential areas for biofuel production and evaluating the environmental effects: a case study of the James River Basin in the Midwestern United States

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Abstract

Biofuels are now an important resource in the United States because of the Energy Independence and Security Act of 2007. Both increased corn growth for ethanol production and perennial dedicated energy crop growth for cellulosic feedstocks are potential sources to meet the rising demand for biofuels. However, these measures may cause adverse environmental consequences that are not yet fully understood. This study 1) evaluates the long-term impacts of increased frequency of corn in the crop rotation system on water quantity and quality as well as soil fertility in the James River Basin and 2) identifies potential grasslands for cultivating bioenergy crops (e.g. switchgrass), estimating the water quality impacts. We selected the soil and water assessment tool, a physically based multidisciplinary model, as the modeling approach to simulate a series of biofuel production scenarios involving crop rotation and land cover changes. The model simulations with different crop rotation scenarios indicate that decreases in water yield and soil nitrate nitrogen (NO_3-N) concentration along with an increase in NO_3-N load to stream water could justify serious concerns regarding increased corn rotations in this basin. Simulations with land cover change scenarios helped us spatially classify the grasslands in terms of biomass productivity and nitrogen loads, and we further derived the relationship of biomass production targets and the resulting nitrogen loads against switchgrass planting acreages. The suggested economically efficient (planting acreage) and environmentally friendly (water quality) planting locations and acreages can be a valuable guide for cultivating switchgrass in this basin. This information, along with the projected environmental costs (i.e. reduced water yield and increased nitrogen load), can contribute to decision support tools for land managers to seek the sustainability of biofuel development in this region.

Keywords: biofuels, land management, nitrogen, SWAT, switchgrass, water

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Introduction

The Energy Independence and Security Act (EISA) of 2007, which aims to increase energy efficiency and the availability of renewable energy, requires an increase in the production of renewable fuels to 36 billion gallons by 2022 (U.S. Congress, 2007). Ethanol was expected to be the primary fuel to reduce US dependence on foreign oil (Thomas *et al.*, 2009). Subsidized corn ethanol may provide a competitively priced transportation fuel, but expanded corn ethanol will increase and intensify corn production (Simpson *et al.*, 2008), which may cause an increase in the corn market price and acreage use, and a decrease in crop rotation for soybeans (CWIBP, 2008; Simpson *et al.*, 2008; Thomas *et al.*, 2009; Zhang *et al.*, 2010). Further, increased corn cultivation may cause adverse environmental impacts due to its greater water requirement (http://aggie-horticulture.tamu.edu/publications/guides/vegetable-crops/waterrequirements.html) and higher fertilizer application rates (Simpson *et al.*, 2008; Welch *et al.*, 2010) when compared to those for soybeans and cotton. Therefore, water availability and water quality remain big concerns under the projected changes in the crop rotation systems (CWIBP, 2008; Thomas *et al.*, 2009; Welch *et al.*, 2010).

Although corn is the primary feedstock for US ethanol production, the competition in feed and food demands on grain supplies and prices will eventually limit expansion of grain-ethanol capacity (Schmer *et al.*, 2008). Thus, perennial dedicated energy crops such as switchgrass (Schmer *et al.*, 2008), crop residues, and

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forestry biomass are being considered as major cellulosic ethanol sources, especially when the thermo-chemical conversion offers the potential for feedstock versatility (Stone *et al.*, 2010). Among them, switchgrass demonstrated relative reliability for high productivity across a wide geographical range, suitability for marginal quality land, low water requirements, and high nutrient use efficiency (Tolbert & Wright, 1998; Stone *et al.*, 2010; Wright & Turhollow, 2010). Therefore, growing switchgrass on current rangelands, pasture lands, and even marginal croplands may present a viable alternative for meeting the increasing demand for biofuels. However, the potential changes of land cover and management practices may influence water availability and quality.

In brief, both increased corn growth frequency and land cover change for dedicated energy crops (e.g. switchgrass) may create unintended environmental consequences (Simpson *et al.*, 2008; Welch *et al.*, 2010). Therefore, it is important to quantify the long-term environmental effects of the above two trends at the watershed scale using numerical models. Furthermore, by examining the biomass and nitrogen yields for cultivating switchgrass, we can identify two area types: 1) those with high productivity, and 2) those with low nitrogen loads. This could help land managers develop bioenergy in an economically efficient (in terms of planting acreage) and environmentally friendly (in terms of water quality) way.

Driven by the above motivations, we further reviewed the related literature involving evaluation of biomass productivity and water quality impacts of biofuel production. For assessing potential biofuel production, Srinivasan *et al.* (2010) examined the biomass yield of switchgrass on all agricultural lands in the Upper Mississippi River Basin using the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998). Baskaran *et al.* (2010) also used this model to predict switchgrass yields for the eastern United States and evaluated the bioenergy-related changes on water quantity for the Arkansas-White-Red River Basin. Wu & Liu (2012) evaluated the potential effects of increased corn stover removal rates on water quality and soil fertility in the Iowa River Basin using a modified SWAT. By developing a Spatially Explicit Integrative Modeling Framework based on the Erosion Productivity Impact Calculator (EPIC), Zhang *et al.* (2010) evaluated the productivity and sustainability of the biofuel crop production systems in southwestern Michigan. Using the Integrated Biosphere Simulator – agricultural version (Kucharik & Brye, 2003), Vanloocke *et al.* (2010) investigated the impacts of miscanthus (*miscanthus* × *giganteus*) production on the Midwest US hydrologic cycle. To assess water quality impacts of expanded corn production, Thomas *et al.* (2009) used the Groundwater Loading Effects of Agricultural Management Systems (Leonard *et al.*, 1987) in northeastern Indiana. Using SWAT, Love & Nejadhashemi (2011) examined the water quality impacts in southern Michigan with a group of crop rotations involving corn, soybean, rye, canola, and native grasses. By compiling the growth parameters of miscanthus for SWAT, Ng *et al.* (2010) projected the nitrogen loads of cultivating this perennial bioenergy crop in the Salt Creek watershed in Illinois. From the description above, the SWAT model can be a useful tool for evaluating the bioenergy development at the regional scale.

In this study, we selected the modified SWAT (Wu & Liu, 2012), which can facilitate the implementation of land cover change scenarios, as a basic tool to accomplish our objectives: 1) to evaluate the long-term impacts of increasing corn rotations (i.e. less rotation with soybeans) by comparing different crop rotation scenarios on water yield, nitrate nitrogen (NO_3-N) load, and soil NO_3-N concentration in the James River Basin of the Midwestern United States; 2) to identify the potential areas with higher switchgrass productivity and areas with lower nitrogen loads on the rangelands and pasture lands which are most likely for cultivation as dedicated energy crops; and 3) to estimate the relationships of biomass production and the resulting water quality status against switchgrass planting acreage and locations under two priorities: the preferential cultivation on higher productivity areas or lower nitrogen load areas.

Materials and methods

Study area

The James River (USGS Hydrologic Unit Code 101600) is a tributary of the Missouri River in the United Sates (http://water.usgs.gov/GIS/regions.html). The James River is approximately 1143 km long; it begins in North Dakota and flows south into South Dakota (Fig. 1) and into the Missouri River. The streamflow and water quality gage near Scotland (USGS gage number: 6478500), South Dakota, is located close to the mouth of the James River; this gage controls a drainage area of about 53 490 km^2 (Fig. 1). Based on the National Land Cover Database (NLCD 2001), the primary land covers in the basin include agriculture land (44.9%), pasture land (25.2%), rangeland (18.4%), wetland (3.9%), residential areas (3.8%), water (3.5%), and other uses (0.3%). The annual average precipitation at the basin scale is about 576 mm yr^{-1} based on the 48-year (1961–2008) daily precipitation data from the weather stations shown in Fig. 1; these data can be accessed from the National Climatic Data Center (http://www.ncdc.noaa.gov). The annual average discharge at the basin outlet (see Fig. 1) is around 23 m^3 s^{-1} near Scotland for the same 48-year period based on the daily discharge records from the National Water Information System (http://waterdata.usgs.gov/nwis/sw).

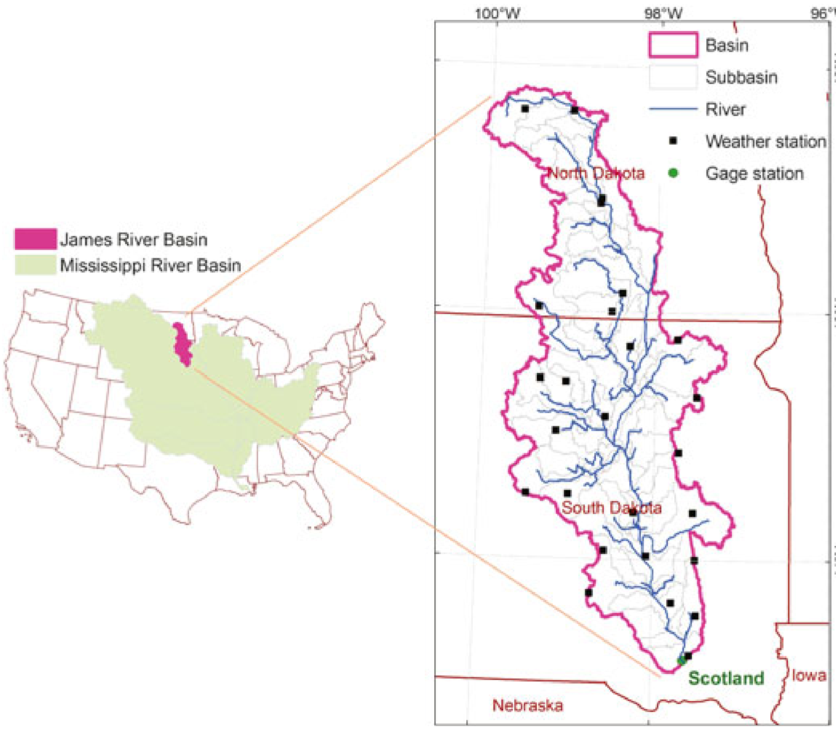


Fig. 1 Locations of the James River Basin, weather stations, and the gage station.

Model description

The SWAT model was developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (Arnold *et al.*, 1998; Neitsch *et al.*, 2005b) to evaluate the impacts of climate and land management practices on water, sediment, and agricultural chemical yields. This physically based watershed scale model simulates the hydrological cycle, plant growth, sediment transport, and nutrients on a daily time step (Arnold *et al.*, 1998). The hydrological part of the model is based on the water balance equation in the soil profile with processes, including precipitation, surface runoff, infiltration, evapotranspiration, lateral flow, percolation, and groundwater flow (Arnold *et al.*, 1998; Neitsch *et al.*, 2005b). Surface runoff volume is predicted from daily rainfall using the Soil Conservation Service (SCS) curve number equation (Arnold *et al.*, 1998; Bouraoui *et al.*, 2004; Neitsch *et al.*, 2005b). For the present study, the Penman-Monteith method (Monteith, 1965) was selected for estimating potential evapotranspiration (PET). The daily value of the leaf area index is used to partition the PET into potential soil evaporation and potential plant transpiration (Bouraoui *et al.*, 2004). The EPIC (Sharpley & Williams, 1990; Williams, 1995) was incorporated into SWAT to simulate the crop growth that influences the hydrological cycle intimately, and temperature, water, and nitrogen stresses were considered to predict the actual plant growth (Neitsch *et al.*, 2005b). SWAT simulates the organic and mineral nitrogen and phosphorus fractions by separating each nutrient into component pools, which can increase or decrease depending on the transformation and/or the additions/losses occurring within each pool (Green & van Griensven, 2008). Details of the nutrient process equations can be found in the model's theoretical documentation (Neitsch *et al.*, 2005b).

Our literature review indicates that the SWAT model has been widely applied to address numerous watershed issues involving water, sediment, nutrients, and pesticides at watershed scales (Gassman *et al.*, 2007; Schilling *et al.*, 2008; Douglas-Mankin *et al.*, 2010; Tuppad *et al.*, 2010).

Model input

A Geographic Information System (GIS) interface, ArcSWAT, was used to automate the development of model input parameters. In this study, the 10-m National Elevation Dataset was resampled to create 90-m resolution digital elevation model data for delineating subbasins. This discretization resulted in the definition of 83 subbasins for the James River Basin (Fig. 1). The 30-m resolution (NLCD 2001) and Soil Survey Geographic Database (SSURGO) were used to parameterize the SWAT model. The original SSURGO data were pre-processed into a format compatible with ArcSWAT using a conversion tool developed by Sheshuko *et al.* (2009). Since the NLCD data do not provide detailed crop species, agricultural land was replaced by the 56-m USDA National Agricultural Statistics Service (NASS) crop data. Thus, the combined NLCD and NASS data were used as the land cover input for the model's parameterization. The multiple Hydrological Response Unit (HRU) option was used to represent the land uses and soil types as separate HRUs within a subbasin, and a single HRU represents a unique combination of land cover and soil type. As a result, the study area was discretized into 1372 HRUs. In

this study, the daily precipitation and air temperatures at 26 weather stations (Fig. 1) were selected from the National Climatic Data Center (http://www.ncdc.noaa.gov), and daily values of solar radiation, wind speed, and relative humidity were generated using the weather generator based on the multiyear average monthly statistics database in the SWAT model.

Cropping rotations can be determined using the annual Cropland Data Layer map from USDA NASS (http://www.nass.usda.gov/research/Cropland/metadata/meta.htm) (Green *et al*., 2006; USDA-NASS, 2010; Secchi *et al*., 2011). In this study, 4 years of NASS cropland maps (2006–2009) were overlaid to identify dominant crop rotations occurring on agricultural lands (NLCD 2001) in the basin. Nitrogen fertilizers are typically applied to enhance corn production at a total rate of 109 kg N ha^{-1} (i.e. 98 lb ac^{-1}), which is the multiyear average application rate for the period from 1991 to 2007; these data are based on the fertilization survey data for North Dakota and South Dakota (http://www.ers.usda.gov/Data/FertilizerUse/). The planting and harvesting dates for corn and soybean were from the published literature (Thomas *et al*., 2009; Jha *et al*., 2010). In our hypothetical scenario analyses (switchgrass cultivation), the heat unit schedule algorithm was used to find the probable beginning and end of the growing season (Arnold *et al*., 2000). The 'auto-application of nitrogen fertilizer' built-in the SWAT model was used for switchgrass cultivation; this algorithm can automatically apply sufficient fertilizer once the nitrogen stress is below the threshold value during the crop growth stage (Arnold *et al*., 2000; Neitsch *et al*., 2005b). Using this algorithm with higher threshold value is consistent with our purpose of estimating the potential biomass production of switchgrass. However, insufficient or limited application of fertilizer in the real world will make plants experience nitrogen stress to some degree and hinder reaching their optimal biomass production (Neitsch *et al*., 2005b; Williams *et al*., 2006).

Model calibration and validation

Hydrological models usually contain parameters that cannot be determined by using field measurements directly, and these parameters need to be estimated through calibration for reaching agreement between observation and simulation (Beven, 2001; Zhang *et al*., 2009). In this study, the SWAT model was calibrated with a 10-year (1991–2000) record of the monthly streamflow and NO_3-N load collected from the gage near Scotland (Fig. 1), and then validated using data collected for the subsequent 8 years (2001–2008). A 3-year (1988–1990) warm-up period was used to minimize the impacts of uncertain initial conditions (e.g. soil water storage) in the model simulation.

Through a review of literature related to the SWAT model calibration (Santhi *et al*., 2001; Muleta & Nicklow, 2005; Arabi *et al*., 2008), as well as testing of sensitive parameters reported therein, eight parameters were selected for model calibration in this basin (Table 1). In SWAT2005, an auto-calibration procedure (van Griensven *et al*., 2006; Green & van Griensven, 2008) is available, which incorporates the Shuffled Complex Evolution-University of Arizona algorithm (Duan *et al*., 1992). This procedure was used to optimize the parameters across the basin until an acceptable fit between the observations and the simulations was obtained. The criteria to assess model performance, including Percentage Bias (PB), Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970), R^2, and the corresponding equations, can be found in the Appendix.

Modeling scenarios

To evaluate the potential impacts of an increasing crop rotation with corn, we selected a series of scenarios with different crop rotations: Soybean-Soybean (SS), Corn-Soybean (CS), Corn-Corn-Soybean (CCS), and Corn-Corn (CC) (see the first four scenarios in Table 2). These scenarios, representing increased frequency of corn in the crop rotation system, were simulated using SWAT during the 18-year (1991–2008) study period (see results in Section 3.2).

Cultivating dedicated energy crops on rangelands or pasture lands may be highly practical because it will not affect food production. However, the potential environmental impacts of such land cover changes still deserve investigation. From the Plant Materials Program of the USDA Natural Resources Conservation Service (NRCS), the cultivars of switchgrass such as 'Alamo', 'Kanlow', and 'Cave-In-Rock' are being utilized as biofuel crops in the Northern Great Plains and southeastern United States (USDA-NRCS, Report-b). Among them, Cave-In-Rock is recommended for Iowa, Illinois, Missouri, and most of the states in the Midwest (USDA-NRCS, Report-a). Based on field-sized plantings of Cave-In-Rock in South Dakota, this cultivar can produce biomass approximately as high as 9 t ha^{-1}

Table 1 Calibrated parameter values for the James River Basin

Parameter	Description	Range	Calibrated value/change
CN2	SCS curve number for moisture condition II	−15 ± 15%	−11%*
SURLAG	Surface runoff lag coefficient	0.1–3	0.8
ESCO	Soil evaporation compensation factor	0.1–1	0.655
EPCO	Plant uptake compensation factor	0.1–1	0.75
ALPHA_BF	Baseflow alpha factor (day)	0.001–0.1	0.08
CH_N2	Manning's n for main channel	0.014–0.16	0.152
NPERCO	Nitrogen percolation factor	0–1	0.221
CMN	Rate factor for humus mineralization of active organic nitrogen	–	0.00003

Note: *CN2 changed –11% relative to the default values.

(Lee & Boe, 2005). Therefore, we selected the Cave-In-Rock switchgrass as the modeling bioenergy crop species to classify our study area in terms of biomass productivity and nitrogen load (see results in Section 3.3). Through a literature review, we collected several major growth parameters for this cultivar: 2 m of the maximum height (Bransby, 2008; USDA-NRCS, Report-a) and 3 m of the maximum root depth (Bransby, 2008); 10 °C of the base temperature and 5 m^2 m^{-2} of the maximum Leaf Area Index (Jain *et al*., 2010); and 0.0046 kg N kg^{-1} Biomass of N fraction in plant at maturity (Elbersen, 2001). Other parameters were referenced from the Alamo switchgrass built-in the SWAT model's crop database (Neitsch *et al*., 2005a; Parrish & Fike, 2005; Baskaran *et al*., 2010).

Modeling scenarios A, B, and C in Table 2 represent different biomass production levels (three, six, and nine million tons) with preferential cultivation of switchgrass on higher productivity areas (denoted as 'productivity priority'); scenarios D, E, and F refer to the preferential cultivation on lower nitrogen load areas (denoted as 'water quality priority') (see results in Section 3.4).

Results and discussion

Model examination

The graphical comparisons of monthly and annual simulated streamflow against those observed during the 10-year (1991–2000) calibration and the 8-year (2001–2008) validation periods are shown in Fig. 2. The monthly

Table 2 Definition of scenarios with different crop rotations and land cover changes

No.	Scenario	Description
1	SS	Soybean-Soybean (Continuous Soybean)
2	CS	Corn-Soybean
3	CCS	Corn-Corn-Soybean
4	CC	Corn-Corn (Continuous Corn)
5	A	Producing two million tons of biomass with productivity priority*
6	B	Producing four million tons of biomass with productivity priority
7	C	Producing six million tons of biomass with productivity priority
8	D	Producing two million tons of biomass with water quality priority†
9	E	Producing four million tons of biomass with water quality priority
10	F	Producing six million tons of biomass with water quality priority

Note: Scenarios A through F refers to cultivating switchgrass on current rangelands and pasture lands.
*Productivity priority refers to the preferential cultivation of switchgrass on higher productivity areas.
†Water quality priority refers to the preferential cultivation of switchgrass on lower nitrogen load areas.

streamflow simulations matched well with the observations, but two peak flows were underestimated during extreme high-water years (1995 and 1997). The 1997 underestimation may be explained by intensified rainfall that year causing high streamflow despite an overall moderate amount of precipitation (Fig. 2b) (see also Zhou *et al*. (2011)). Three numeric criteria, PB, NSE, and R^2 (Table 3 and Appendix), were also used to evaluate the model performance. From Table 3, it can be seen that the NSE and R^2 for monthly streamflow simulation ranged from 0.59 to 0.80, and annual results ranged from 0.68 to 0.86. Based on the performance ratings of Moriasi *et al*. (2007) which is assuming typical uncertainty in observations, the monthly streamflow simulations can be evaluated as 'satisfactory' (NSE > 0.5 and $|PB| \leq 25\%$) for both calibration and validation periods. Figure 3 shows the overall agreement between simulated NO_3-N and those observed, except for the underestimation in extreme high-water years (e.g. 1995 and 1997) and overestimation in extreme low-water years (e.g. 2004 and 2005). As listed in Table 3, the NSE and R^2 for monthly NO_3-N simulation ranged between 0.53 and 0.72, and the annual results ranged from 0.61 to 0.76. Similarly, the model performance in simulating NO_3-N load can be rated as 'satisfactory' (NSE > 0.5 and $|PB| \leq 70\%$) for the calibration period and 'good' (NSE > 0.65 and $|PB| \leq 40\%$) for the validation period. From the above description, the model performance in streamflow and NO_3-N simulations for the James River can be considered satisfactory for this study's purpose: evaluating long-term environmental impacts based on multi-year averaged simulation results.

The modeling units of SWAT (HRU and subbasin) are not consistent with the county boundaries on which the USDA-NASS reported yields are based. For testing the crop (corn and soybean) yields simulation, therefore, we selected several counties which are situated in the James River Basin for obtaining the NASS-observed yields. As shown in Fig. 4, there are nine such counties: Stutsman, La Moure, Dickey, Brown, Spink, Beadle, Sanborn, Davison, and Hutchinson (sequentially listed from upstream to downstream). To obtain the corresponding simulated yields for each county, we selected one subbasin which is located in that county to get the simulation values. The comparison of the multi-year (1991–2008) average NASS-observed and simulated crop yields is then shown in Fig. 4 (a for corn and b for soybean). The corn yield simulation for the first (i.e. Stutsman) and the last two (i.e. Davison and Hutchinson) counties were slightly overestimated, whereas the underestimation was predicted for the other counties with a mean PB of −5.7% (negative sign refers to underestimation). The simulation of soybean yield is quite close to the observation with a PB of −4.1%. Overall,

Table 3 Evaluation of model performance in streamflow and NO_3-N simulations at the basin outlet during calibration (1991–2000) and validation (2001–2008) periods

Period	Time scale	Mean* Observed	Mean* Simulated	PB (%)	NSE	R^2
Streamflow						
Calibration	Monthly	46.9	35.1	−25.0	0.59	0.61
	Annual				0.68	0.86
Validation	Monthly	25.9	32.4	24.8	0.74	0.80
	Annual				0.70	0.82
NO_3-N						
Calibration	Monthly	830.6	693.7	−16.5	0.53	0.60
	Annual				0.61	0.76
Validation	Monthly	438.8	572.7	30.5	0.69	0.72
	Annual				0.63	0.70

Note: *The unit for streamflow is $m^3 s^{-1}$, and the unit for NO_3-N is kg d^{-1}. Please see Appendix for details of PB (Percentage Bias), NSE (Nash-Sutcliffe Efficiency), and R^2.

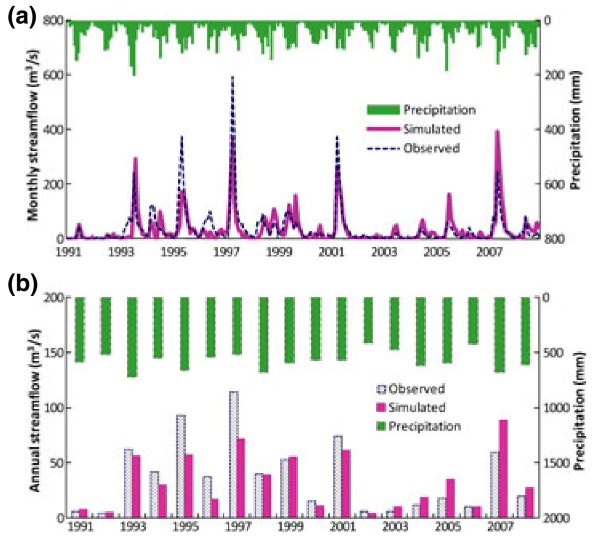


Fig. 2 Monthly (a) and annual (b) time-series comparison of simulated vs. observed streamflow at the gage near Scotland during the 10-year (1991–2000) calibration and 8-year (2001–2008) validation periods.

the simulation of corn and soybean yields can be considered acceptable for the study area.

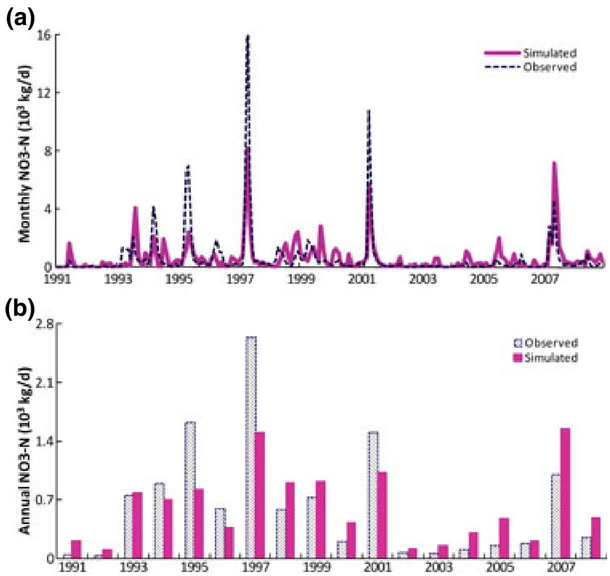


Fig. 3 Monthly (a) and annual (b) time-series comparison of simulated vs. observed NO_3-N at the gage near Scotland during the 10-year (1991–2000) calibration and 8-year (2001–2008) validation periods.

Impacts of crop rotations

Using a series of scenarios with rising corn rotations (Table 2), we examined the long-term environmental consequences in the James River Basin. Figure 5 shows annual average water yield, NO_3-N load, and soil NO_3-N concentration during the 18-year (1991–2008) simulation period. From Fig. 5a, the annual average water yield demonstrates a decreasing trend as the corn growth frequency increases; this is caused by the higher water requirement for corn production compared to soybean production. For example, CS, CCS, and CC resulted in a slight decrease of 1.3%, 1.4%, and 3.4% in water yield, respectively, compared to the SS rotation. For NO_3-N load comparison under these rotation scenarios, we found that CS, CCS, and CC lead to a dramatic increase of 281%, 338%, and 436%, respectively, compared to the SS rotation. If we take CS as the reference scenario, CCS and CC would lead to the NO_3-N increase of 15% and 41%, respectively. In addition, in terms of soil NO_3-N concentration, a significant

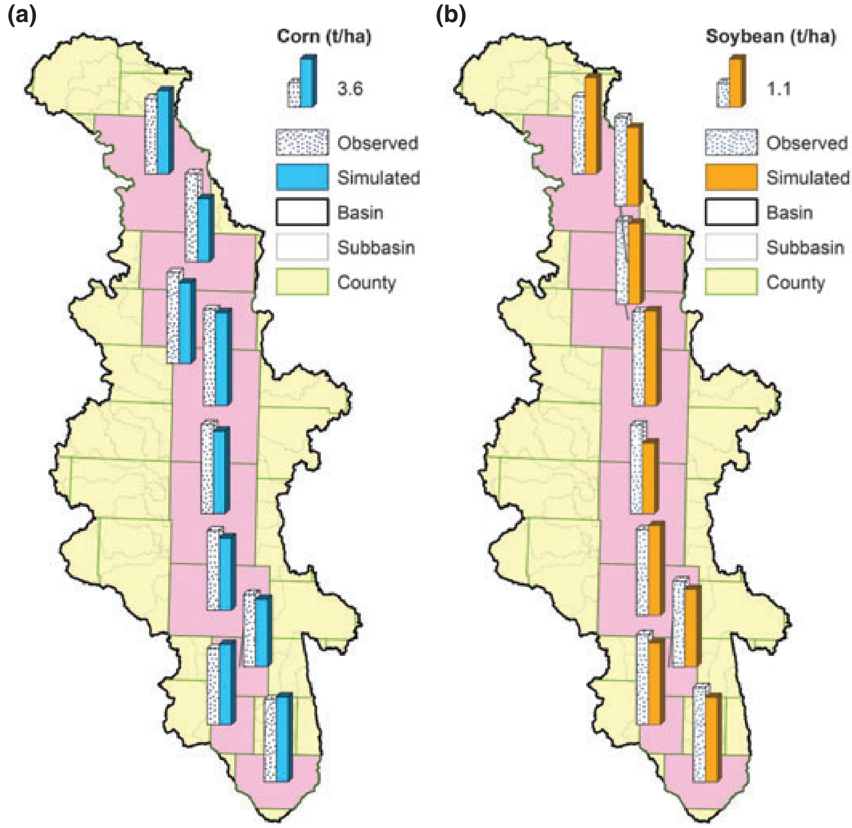


Fig. 4 Annual average NASS-observed and simulated (a) corn and (b) soybean yields for the selected nine counties (light purple shaded) in the James River Basin during the 18-year (1991–2008) simulation period. These selected counties include Stutsman, La Moure, Dickey, Brown, Spink, Beadle, Sanborn, Davison, and Hutchinson (sequentially listed from upstream to downstream).

decrease of 13%, 32%, and 59% was predicted when comparing CS, CCS, and CC with the SS rotation (Fig. 5c). Similarly, CCS and CC would reduce the soil NO_3-N concentration by 22% and 53%, respectively, when compared to the CS rotation. In brief, the rising crop rotation of corn could cause a slight decrease in water yield, a significant increase in NO_3-N load to stream water, and a substantial reduction of soil NO_3-N concentration.

Assessment of switchgrass productivity and nitrogen load

From the study of Baskaran *et al.* (2010), the SWAT model can be used to explore switchgrass productivity at regional scales because the model can simulate the plant growth process and represent the geographic and climatic conditions. In this study, we used the SWAT model to assess switchgrass biomass productivity on the rangelands and pasture lands by simulating its cultivation under sufficient fertilization. For a detailed model representation, the rangelands and pasture lands were further discretized into 3481 HRUs to assess switchgrass cultivation scenarios. The multi-year (1991–2008) average simulated biomass production of switchgrass at the HRU level is shown in Fig. 6 (a for rangelands and b for pasture lands). This figure indicates that the switchgrass productivity ranged from less than 1 to over 10 t ha^{-1} (tons per hectare) on these lands, and the classification of productivity magnitude demonstrates that the relatively higher productivity areas are located in the middle to downstream area of the basin. These results can be used to identify potential areas with higher biomass production levels for switchgrass cultivation.

With the above scenarios for cultivating switchgrass on rangelands and pasture lands, the SWAT model can also be used to predict the spatial pattern of the NO_3-N load. The 18-year average simulated NO_3-N loads are shown in Fig. 7 (a for rangelands and b for pasture lands). The projected NO_3-N load ranged from less than 0.1 kg ha^{-1} to over 9.6 kg ha^{-1} with most HRUs being below 1 kg ha^{-1}; the classification of NO_3-N load demonstrates that higher NO_3-N load areas are located in the middle-stream areas. These results can be used to identify potential areas with lower NO_3-N load levels for switchgrass cultivation.

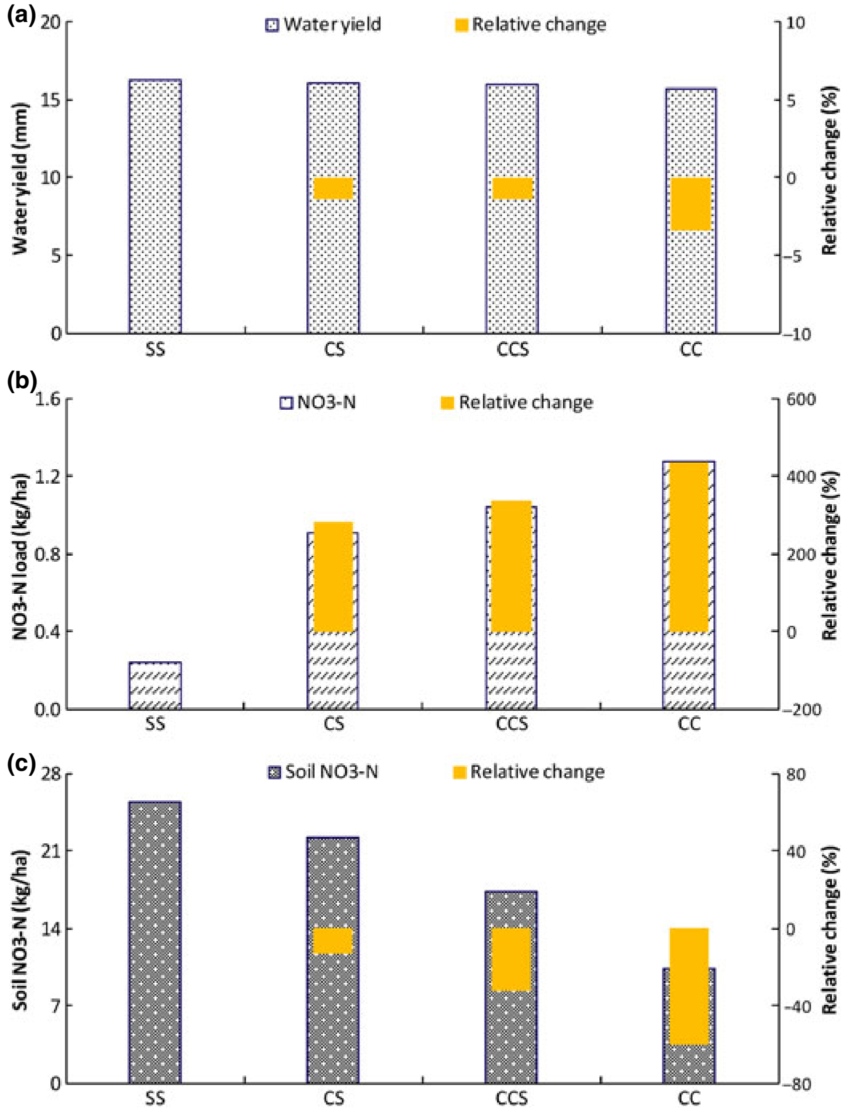


Fig. 5 Projected annual average water yield (a) NO_3-N load (b) and soil NO_3-N concentration (c) during the 18-year simulation period (1991–2008) under different crop rotations. Relative change refers to change relative to SS (i.e. Continuous Soybean).

Biomass production and water quality

The classifications of productivity (Fig. 6) and NO_3-N load (Fig. 7) can be useful for land managers because they can provide information about which plots are most suitable for biofuel development in terms of productivity and water quality protection, respectively. Clearly, the preferential cultivation of switchgrass on higher productivity areas could result in the maximum production with low cost (in terms of acreage); whereas the preferential cultivation on lower NO_3-N load areas could cause minimum impairment of water quality. The first preferential cultivation is denoted as the productivity priority, and the second is denoted as the water quality priority. Under each priority, we can derive the relationships of biomass production and the resulting increased NO_3-N load against the switchgrass planting acreage (Fig. 8). The acreage (horizontal axis) is the required area of rangelands and pasture lands converted to switchgrass, and the increased NO_3-N load (secondary vertical axis) refers to the net increase in projected NO_3-N load due to the conversion. As shown in Fig. 8a, the biomass production accumulation rate becomes a little slower as more areas with lower productivity were used for cultivating switchgrass. However, Fig. 8b shows that the accumulation rate of net increase in NO_3-N load becomes a little higher as more areas with higher nitrogen loads were used for cultivating switchgrass. Figure 8 also demonstrates that the biomass production capacity would be around 11.8 million

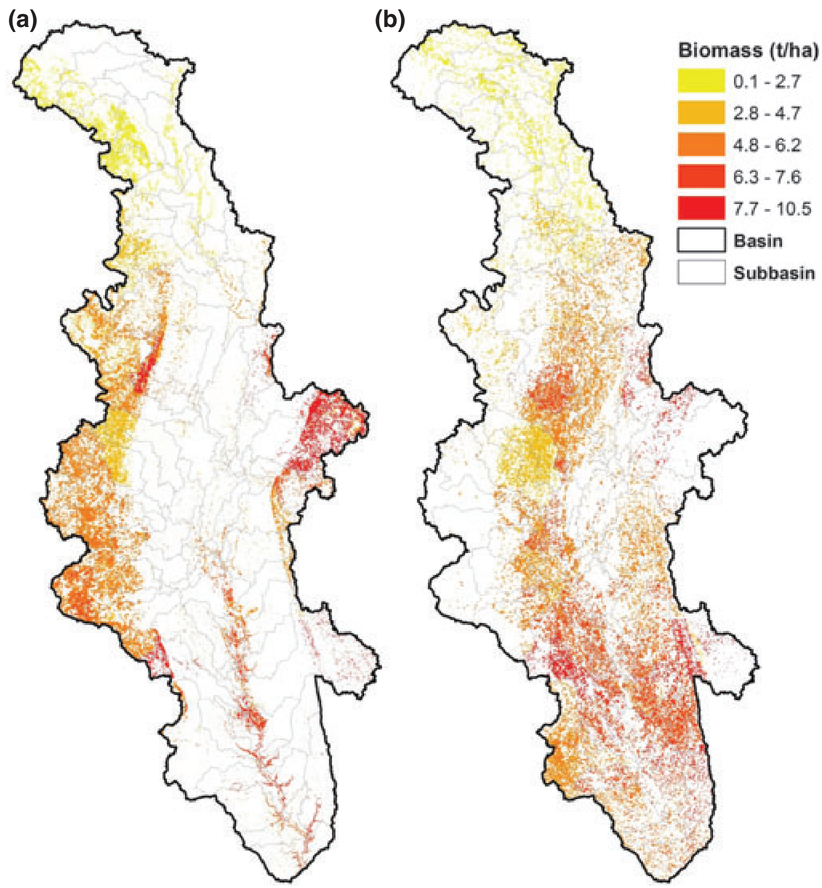


Fig. 6 Projected annual mean biomass yield with cultivating switchgrass on all rangelands (a) and pasture lands (b).

tons if all the rangeland and pasture lands (23740 km^2) were developed for the cultivation of switchgrass. Under the productivity priority, for example, the biomass production targets of three, six, and nine million tons require 3900, 8600, and 14 300 km^2 of planting acreage, respectively; and they are marked as A, B, and C in Fig. 8a, which also shows the corresponding increased NO_3-N loads. Under the water quality priority, however, the planting acreage requirement can be 7100, 12 500, and 17 600 km^2 for producing the same amounts of biomass; and they are marked as D, E, and F in Fig. 8b, which also shows the corresponding increased NO_3-N loads. Points A through F are associated with Scenarios A through F in Table 2. As an example, Fig. 9 shows the spatial planting locations and acreages for accomplishing the above three biomass production targets (three, six, and nine million tons) under the productivity priority (Fig. 9a–c) and the water quality priority (Fig. 9d–f).

In terms of NO_3-N load, three, six, and nine million tons of biomass can result in 32.6, 61.3, and 93.1 tons of increase in NO_3-N under the productivity priority; and this nitrogen load increase can be 3.2, 12.2, and 33.5 tons under the water quality priority (see the right panel of Fig. 8). Consequently, the comparison of Fig. 8a and b indicates that the productivity priority can be economically preferable as it requires less planting acreage, but causes a higher NO_3-N load. Instead, the water quality priority can be more environmentally friendly as it causes a lower NO_3-N load, but requires a larger planting acreage (i.e. a larger cost).

Certainly, we admit that the projected planting acreages using the potential biomass production in the case study may be underestimated because of the climate variation and insufficiency of fertilizer in the real world in the future. Therefore, the required planting acreages and the resulting nitrogen loads may be larger than projected values in our study. However, the study method we used can be reasonable and helpful for others.

In addition, to demonstrate the two conflicting objectives—biomass production and water quality protection—when developing biofuels in this region, we projected the relationships between biomass production and water quality index (see Fig. 10). Liou *et al.* (2004) published a generalized water quality index for each major species such as ammonia nitrogen, turbidity, and

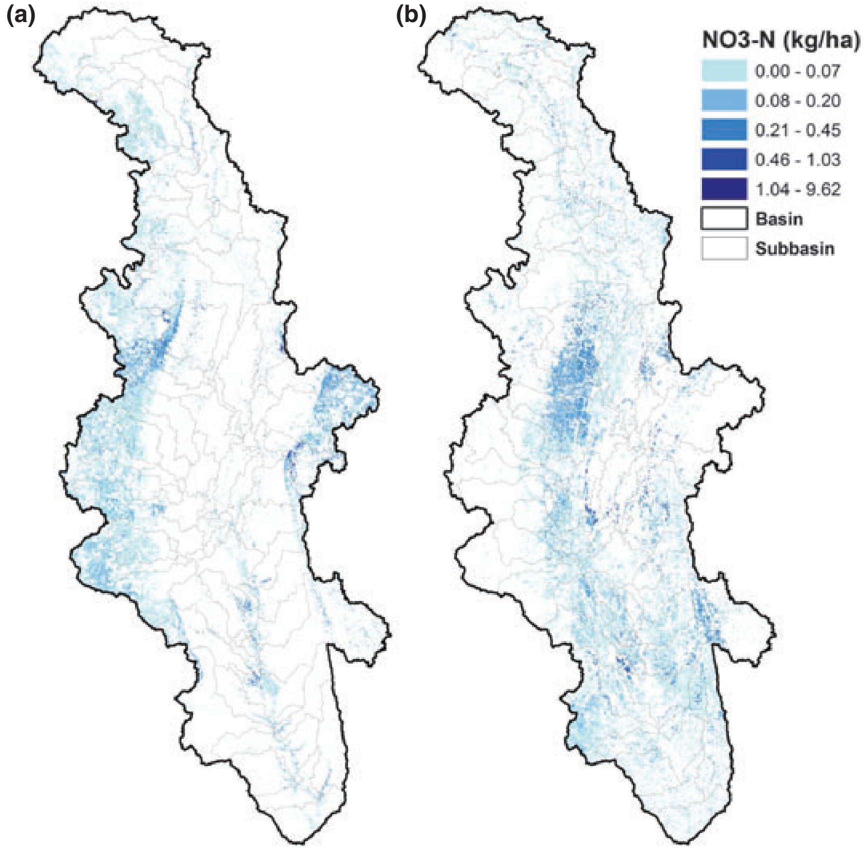


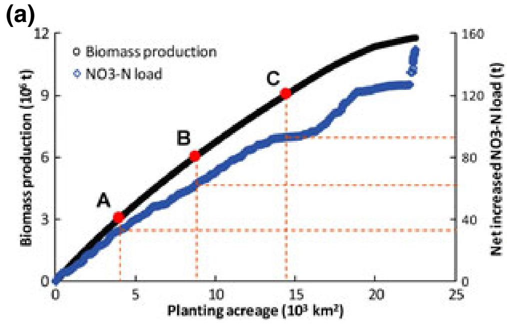
Fig. 7 Projected annual mean NO_3-N load with cultivating switchgrass on all rangelands (a) and pasture lands (b).

dissolved oxygen. By referencing their study and extending the range of pollutant concentration, we compute the water quality index as a function of NO_3-N concentration with the following equation:

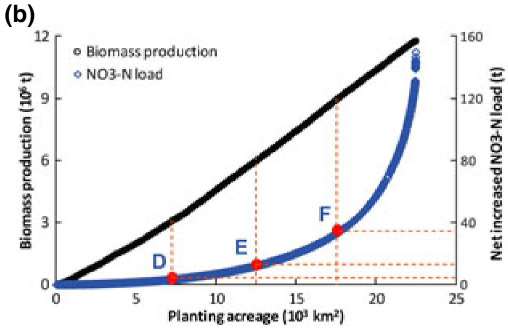
$$\text{Water quality index} = \frac{300 - 100 \times \text{conc}_{NO_3-N}}{3} \qquad (1)$$

where conc_{NO_3-N} is the NO_3-N concentration in the stream water with a unit of mg L^{-1}; and it is calculated by dividing the projected total NO_3-N load (sum of the current NO_3-N load and increased NO_3-N due to the land cover change) by annual average total discharge at the basin outlet. This water quality index, with the maximum value of 100 for water without NO_3-N, can be used to classify the water quality status in terms of NO_3-N: the larger the index, the better the water quality. To clarify, the only purpose of using the index is to reflect this kind of monotonic decreasing relationship between water quality status and NO_3-N concentration; and the absolute values do not support additional implications.

Using simulated productivity (Fig. 6) and NO_3-N load (Fig. 7) values for each HRU, we can derive the relationship between biomass production and water quality index under the productivity priority and the water quality priority, respectively (Fig. 10). This projected relationship clearly demonstrates the two conflicting objectives: the larger the biomass production, the worse the water quality. Because of the large number of HRUs composing the rangelands and pasture lands (3481 HRUs) in the model simulation, the possible combinations of these HRUs can result in such large samples that we cannot enumerate all of them. Nevertheless, the curve derived under the water quality priority can be deemed as the 'pareto optimal frontier': improvement to one component (e.g. biomass production) cannot be made without making the other (e.g. water quality) worse (http://en.wikipedia.org/wiki/Pareto_efficiency). The reason is because this curve represents the lowest water quality cost (i.e. the highest water quality index) for any given biomass production target under the water quality priority rule. As shown in Fig. 10, the green shaded area (i.e. the area between the two curves) represents the potential range of water quality degradation for a given biomass production target when land managers consider a balance between productivity and water quality preferences. Therefore, this figure can be a useful and informative guide for balancing between biomass production and water quality protection. In reality, decision making is



Point	Acreage (10^3 km^2)	Biomass (10^6 t)	Increased NO3-N (t)
A	3.9	3	32.6
B	8.6	6	61.3
C	14.3	9	93.1



Point	Acreage (10^3 km^2)	Biomass (10^6 t)	Increased NO3-N (t)
D	7.1	3	3.2
E	12.5	6	12.2
F	17.6	9	33.5

Fig. 8 Projected relationships of biomass production and NO_3-N load against switchgrass planting acreage with (a) the productivity priority (preferential cultivation of switchgrass on higher productivity areas (see Fig. 6)) and (b) the water quality priority (preferential cultivation of switchgrass on lower NO_3-N load areas (Fig. 7)). The secondary vertical axis (net increased NO_3-N load) refers to the net increase in projected NO_3-N load due to the conversion from current land cover types (rangeland or pasture land) to switchgrass. The additional tables on the right indicate the corresponding values of points A through F.

much more complicated because it is also dependent on other socioeconomic factors (transportation cost, biorefinery plant location, etc.) that are beyond the scope of this article. Nevertheless, this study can provide land managers with useful information on two aspects—biomass production and water quality—when developing biofuels in this region.

Implications

This study may suggest the importance of water resources protection as we seek for biofuel development: increased corn production in the crop rotation system and land cover conversion from native grassland to dedicated energy crops like switchgrass. The increased corn growth frequency can be an alternative to meet the rising ethanol demand since it may not lead to the expansion of agricultural land. However, this shift in crop rotation may cause a slight reduction in water yield, a significant increase in nitrogen load to stream water, and a decrease in soil fertility (in terms of NO_3-N) (Fig. 5). In addition, a decrease in soybean production can be expected due to the expanding corn production (CWIBP, 2008; Simpson *et al*., 2008; Thomas *et al*., 2009), and this may influence the soybean supply and price in grain markets (CEEIIBP, NRC, 2011) and soybean-based biodiesel production (CWIBP, 2008). On the other hand, although the land cover change—using the potential non-agricultural lands (e.g. rangelands and pasture lands) to cultivate switchgrass—is promising, since it will not affect food production, the decrease in water yield and increase in nitrogen load are still a challenge (Figs 8 and 10). Therefore, this study demonstrates that the potential land management changes for biofuel production could cause reduced water yield and increased nutrient load, which may further contribute to hypoxic (low dissolved oxygen) conditions in the Gulf of Mexico.

The simulated environmental impacts of the case study are generally consistent with other published studies (CWIBP, 2008; Simpson *et al*., 2008; Thomas *et al*., 2009; Baskaran *et al*., 2010; Ng *et al*., 2010; Vanloocke *et al*., 2010; Welch *et al*., 2010; Love & Nejadhashemi, 2011). However, this study further addresses the connections between biofuel production and environmental cost (in terms of water quality) by elaborating on the relationship of biomass production and the resulting nitrogen load against switchgrass planting acreage and locations (Figs 8–10). The projected water yield reduction and water quality degradation can affect both terrestrial and aquatic ecosystems: drought in the upland, lower discharge in the channel, hypoxia of the

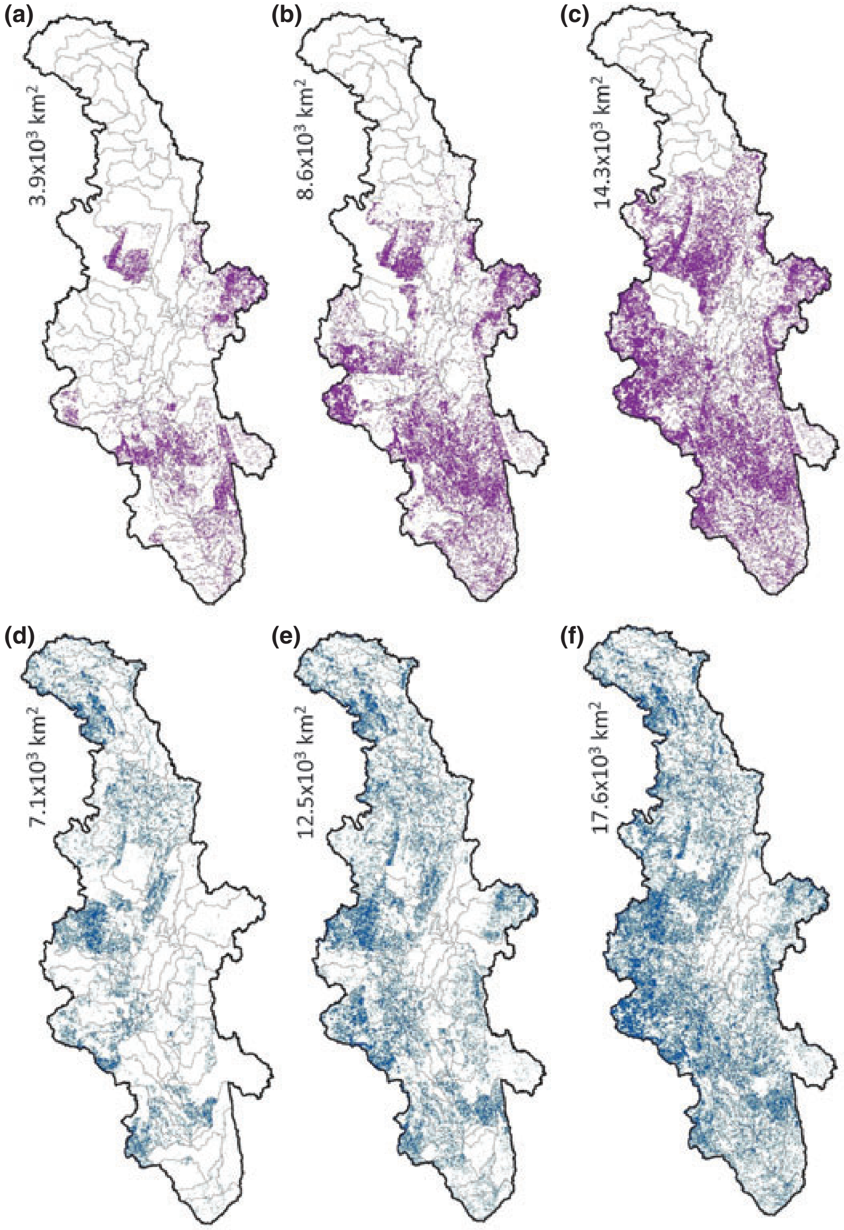


Fig. 9 Indication of planting locations and acreages for producing three, six, and nine million tons of biomass with (a–c) the productivity priority (preferential cultivation of switchgrass on higher productivity areas) and (d–f) the water quality priority (preferential cultivation of switchgrass on lower NO_3-N load areas). Panels (a) through (f) correspond to points A through F in Fig. 8.

stream water, and the resulting loss of habitats and species, etc. In turn, these adverse consequences may have significant effects on socioeconomic well-being (such as reduced crop yield and compromised environment) in this region. Quantifying the long-term effects of land management changes is critical for developing adaptive strategies for water resource and ecosystem sustainability. Thus, this study emphasizes that biofuels development, especially the large-scale implementation, to consider taking into account the potential adverse environmental effects on water resource and ecosystems to ensure sustainability of energy and environment. Moreover, various ecological, economic, and social impacts of the potential biofuel production also deserve additional investigation.

To mitigate the potential negative environmental impacts of farming, Best Management Practices (BMPs) such as conservation tillage, filter strips, etc. are a set of established methods in practice. Thus, BMPs application could be considered as part of the sustainable bioenergy

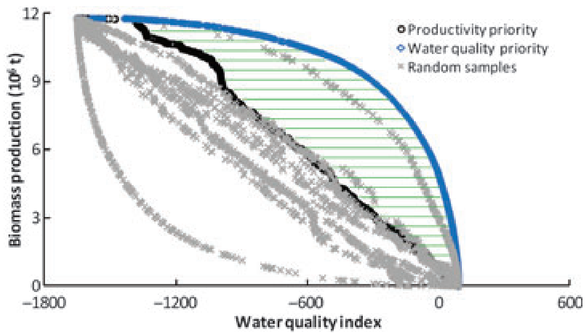


Fig. 10 Projected relationship between two conflicting objectives (biomass production and water quality protection) with (a) the productivity priority (preferential cultivation of switchgrass on higher productivity areas) and (b) the water quality priority (preferential cultivation of switchgrass on lower NO_3-N load areas). Random samples refer to planting switchgrass randomly (in terms of locations and acreages), and this could result in substantially huge samples with 'gray x' indicating part of them. Green shaded area (i.e. area between the two curves) represent the potential range of water quality degradation for a certain biomass production target when considering a balance between productivity and water quality protection. Water quality index is a monotonic decreasing function of NO_3-N concentration, and it is used to classify the water quality status in terms of NO_3-N: a larger index indicates a better water quality.

development for this region; the evaluation of their effects can be a subject for additional study.

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Supporting Information

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

Appendix S1. Criteria to assess model performance.

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