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Biomass Production with Conservation Practices for Two Iowa Watersheds

Miae Ha, May Wu, Mark D. Tomer, Philip W. Gassman, Thomas M. Isenhart, Jeffrey G. Arnold, Michael J. White, Esther S. Parish, Kevin S. Comer, and Bill Belden

Research Impact Statement: A hydrologic model evaluates biomass production with conservation practices in two watersheds in Iowa and demonstrates the water quality benefits of bioenergy production based on landscape design.

ABSTRACT: Hydrologic modeling was used to estimate potential changes in nutrients, suspended sediment, and streamflow in various biomass production scenarios with conservation practices under different landscape designs. Two major corn and soybean croplands were selected for study: the South Fork of the Iowa River watershed and the headwater of the Raccoon River watershed. A physically based model, the Soil and Water Assessment Tool, was used to simulate hydrology and water quality under different scenarios with conservation practices and biomass production. Scenarios are based on conservation practices and biomass production; riparian buffer (RB), saturated buffer, and grassed waterways; various stover harvest rates of 30%, 45%, and 70% with and without winter cover crops; and conversion of marginal land to switchgrass. Conservation practices and landscape design with different biomass feedstocks were shown to significantly improve water quality while supporting sustainable biomass production. Model results for nitrogen, phosphorus, and suspended sediments were analyzed temporally at spatial scales that varied from hydrologic response units to the entire watershed. With conservation practices, water quality could potentially improve by reducing nitrogen loads by up to 20%–30% (stover harvest with cover crop), phosphorus loads by 20%–40% (RB), and sediment loads by 30%–70% (stover harvest with cover crop and RB).

(KEYWORDS: conservation practices; bioenergy; SWAT; hydrologic modeling; water quality; nutrients.)

INTRODUCTION

The United States (U.S.) “Corn Belt” region is a major area of agricultural productivity, especially corn, soybean, swine, and other livestock. However, this intensive production has resulted in considerable nutrient-related water quality problems, both for Corn Belt region stream systems and further downstream, primarily due to the use of inorganic fertilizer and livestock manure nutrients on cropland (Rabotyagov et al. 2012; Kling et al. 2017; Bouska et al. 2018; Christianson et al. 2018; Jones, Nielsen, et al. 2018; Turner and Rabalais 2019). The Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB) comprise much of the Corn Belt region and are major sources of exported nitrogen and phosphorus to the Mississippi River and the Gulf

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Argonne National Laboratory (Ha; Wu), Lemont, Illinois, USA; USDA-ARS (Tomer), Ames, Iowa, USA; Iowa State University (Gassman; Isenhart), Ames, Iowa, USA; USDA-ARS (Arnold; White), Temple, Texas, USA; Oak Ridge National Laboratory (Parish), Oak Ridge, Tennessee, USA; and Antares Inc. (Comer; Belden), Harrisonburg, Virginia, USA (Correspondence to Ha: mha@anl.gov).

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of Mexico (USEPA 2008; Demissie et al. 2012; Wu et al. 2012; Demissie et al. 2017; Kling et al. 2017; Panagopoulos et al. 2017; Ha et al. 2018). Monitoring data reported for the UMRB (Sprague et al. 2011) and major Iowa watersheds (Jones, Nielsen, et al. 2018) confirm continued high nitrate export to the Mississippi River. The discharge of nutrients from the outlet of the Mississippi River has been identified as the underlying cause of the seasonal oxygen-depleted hypoxic zone that forms annually in the northern Gulf of Mexico (Rabotyagov et al. 2014; Turner and Rabalais 2019).

Best management practices (BMPs) and cropping systems for mitigating agricultural nonpoint source nutrient pollution include cover crops, riparian buffers (RBs), saturated buffers, and grassed waterways (GRSW). These practices are generally noted for providing a range of environmental benefits, including reduced soil erosion, reduced nutrient losses, and increased organic carbon content (Fageria et al. 2005; Moore et al. 2014; Kalcic et al. 2015; Christianson et al. 2018).

Cellulosic bioenergy sources include perennial crops, such as switchgrass or *miscanthus*, and biomass harvested from row crops such as corn (Moore et al. 2014; Kling et al. 2017). Switchgrass, *miscanthus* and other perennial biofuel crops provide several potential benefits, such as reduced fertilizer input needs, reductions in nitrogen and phosphorus loss, reduced greenhouse gas emissions and soil erosion, and improved soil carbon sequestration and wildlife habitat (Cortese et al. 2010; Davis et al. 2012; Kiniry et al. 2012; Dale et al. 2013; Moore et al. 2014; Gassman et al. 2017; Kling et al. 2017; Panagopoulos et al. 2017; Christianson et al. 2018). However, harvesting corn residue can potentially negatively impact soil health and nutrient cycling, so sustainable management of crop residue (optimizing corn stover harvest rates) on the soil surface is essential to avoid soil erosion, degradation of soil fertility, nutrient depletion, and other negative impacts on the environment (Graham et al. 2007; Thomas et al. 2011; Dale et al. 2014). Various biofuel production initiatives could further result in increased production of bioenergy crops in agricultural fields or incentivize the removal of crop residues after harvest. For example, the EISA (2007) was designed to increase production of ethanol to 136 billion liters (about 36 billion gallons) per year by 2022 (although current production only slightly exceeds 16 billion gallons as reported at https://www.eia.gov/todayinenergy/detail.php?id=41393). In addition, a recent analysis by the U.S. Department of Energy reported that the U.S. has the potential to produce at least 1 billion dry tons of biomass resources annually by 2040 (USDOE 2016).

The potential negative impacts of stover removal could be mitigated by incorporating conservation practices, integrated landscape design, and management practices such as riparian or saturated buffers, cover crops, double cropping, or dedicated perennials like switchgrass and *miscanthus*. RBs are designed to reduce surface runoff, increase water infiltration, filter sediment, and trap and treat sediment-bound nutrients and pesticides transported from upland ecosystems. These buffers are commonly established between cropland and surface water to mitigate sediment, nutrient, and/or pesticide losses to streams, lakes, or other surface water bodies (NRC 2002; Lee et al. 2003; Mayer et al. 2007; Smith et al. 2008; Cho et al. 2010; Tomer and Locke 2011). However, extensive networks of subsurface drainage tiles have been installed in some parts of the UMRB and OTRB, which allow water, nitrate, and other soluble pollutants in the effluent to short-circuit RBs and directly enter surface water bodies (Demissie et al. 2012; Panagopoulos et al. 2017). To overcome this weakness, saturated buffers have been developed that use a control box to spread tile drainage effluent across RBs, which remove nitrates from the effluent through the process of denitrification, immobilization, and plant uptake (Jaynes and Isenhart 2018). The rate of nitrate removal relies on nitrate concentration, time to transport from the buffer to the stream, vegetation, and temperature (Jaynes and Isenhart 2011; Jaynes 2012). Saturated buffers have been found to reduce nitrates between 8% and 84%, based on 17 site-years across six sites in central and north-central Iowa (Jaynes and Isenhart 2018). GRSW are installed along ephemeral drainage ways to reduce surface runoff velocity and prevent gully erosion along the waterways, are implemented in areas where runoff concentrates, and convey water off the field (Fiener and Auerswald 2003; Arabi et al. 2008; Kaini et al. 2012; Kalcic et al. 2015). GRSW have been shown via field and simulation studies to be effective in removing sediment and sediment-bound nutrients (Fiener and Auerswald 2003; Kalcic et al. 2015). Used in combination with stover removal systems and/or other BMPs, they can help reduce the export of cropland pollutants to streams and other surface water bodies.

The impacts of implementing the vegetative-based BMPs described earlier on cropland landscapes can be assessed by combining elements of the U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) Agricultural Conservation Planning Framework (ACPF) Toolbox (Tomer, Boomer, et al. 2015; Tomer, Porter, et al. 2015) and the USDA-ARS Soil and Water Assessment Tool (SWAT) ecohydrological model (Gassman et al. 2007; Williams et al. 2008; Arnold et al. 2012). ACPF consists of a database and a GIS-based toolbox of practices that can be used in developing conservation plans, which are presented as a menu of practice placement options for agricultural watershed management. Sample scenarios describe the development of conservation plans that include cover crops, controlled drainage, GRSW, wetlands, saturated buffers, and RBs (Tomer, Boomer, et al. 2015; Tomer, Porter, et al. 2015). Establishing agricultural conservation practices in a watershed by incorporating ACPF practice placement results and conservation service guideline can improve water quality issues such as agricultural nonpoint source pollution.

SWAT is a physically based, spatially distributed parameter, watershed-scale model that simulates the long-term effects of various watershed management decisions on hydrology and water quality and quantifies the impacts of land management practices in complex watersheds with land use, soils, and management operations (Arnold et al. 2012). The model has been used worldwide to evaluate an extensive suite of alternative BMPs, climate change, land use change, and other water resource scenarios across a broad range of watershed scales and conditions, as described in several previous reviews (Gassman et al. 2007; Gassman et al. 2014; de Almeida Bressiani et al. 2015; Krysanova and White 2015; Tan et al. 2019). SWAT has been used to evaluate changes in hydrology, water quality, crop production, nutrient or pesticide cycling and loss, and sediment transport in response to vegetative-based, structural, and other BMPs that were simulated on cropland landscapes for protecting watershed environments (Gassman et al. 2007; Arabi et al. 2008; Kalcic et al. 2015). A variety of BMPs can be simulated in SWAT (Arabi et al. 2008; Waidler et al. 2011; Kalcic et al. 2015) including vegetative (perennial grasses, RBs, GRSW), structural (terraces, terraces and contouring, sediment basins, grade stabilization structures), and operational (contouring, cropping systems, tillage, irrigation, fertilizer, and manure applications) solutions. In the Corn Belt region, SWAT has also been used to predict impacts on watershed hydrology and water quality due to land cover changes to biofuel production alternatives such as corn stover, switchgrass, and *miscanthus* (Cibin et al. 2012; Demissie et al. 2012; Wu and Liu 2012; Ha and Wu 2015; Trybula et al. 2015; Cibin et al. 2016; Ha and Wu 2017; Guo et al. 2018; Wu and Ha 2018). These studies generally show reductions in streamflow and loadings of nitrate, phosphorus, and sediments when land use changes with biomass production scenarios were incorporated, although increases in phosphorus and sediment have been reported for corn stover removal scenarios (Wu and Liu 2012; Gassman et al. 2017; Kling et al. 2017; Panagopoulos et al. 2017; Song et al. 2017).

The focus of the study is the use of multifactor analyses in an ACPF-SWAT framework to evaluate the water quality implications of vegetation-based conservation practices and biomass production through landscape design at the watershed scale. “Landscape design” refers to a spatially explicit collaborative plan for integrated sustainable management of landscapes and supply chains. Two watersheds in Iowa, the South Fork of the Iowa River watershed (SFIR) and the headwater of Raccoon River watershed (HRRW), were selected to simulate and evaluate environmental impacts as well as the effectiveness of water resources and other vegetative-based practices such as RBs, GRSW, cover crops, and saturated buffers. Several studies report applications of SWAT for the entire RRW (Jha et al. 2007; Jha et al. 2010; Teshager et al. 2016; Teshager et al. 2017) but not for the HRRW subwatershed. The analysis included planting switchgrass on marginal lands, using a profitability indicator approach developed by the Oak Ridge National Laboratory that differs from the way that marginal or vulnerable land was accounted for in some previous studies (Valcu-Lisman et al. 2016; Gassman et al. 2017; Panagopoulos et al. 2017; Guo et al. 2018). The unique contribution of this work is as follows: (1) it presents a way to evaluate conservation practices incorporated into a landscape design in a modeling framework that contains the ACPF Toolbox, SWAT model, and decades of field monitoring data, and (2) it evaluates the water quality effects of landscape design scenarios that incorporate biomass into marginal or low productivity landscapes.

METHODS

Study Area

The two watersheds selected are part of the scope of a multi-institute, multiple-organization project that focuses on landscape design in these areas. The study areas focused on eight subwatersheds within the SFIR and four subwatersheds within the HRRW, which are defined at the 12-digit HUC level (USGS 2013) as shown in Figure 1. The hydrologic modeling (calibration and validation) for the HRRW was developed for the entire RRW (Figure 1), due to a lack of water quality and quantity monitoring gauging stations in the HRRW. The SFIR and the RRW are both located in the Des Moines Lobe landform region, which is characterized by relatively level landscapes and poorly drained soils (Schilling et al. 2014). The total drainage area of the SFIR is approximately

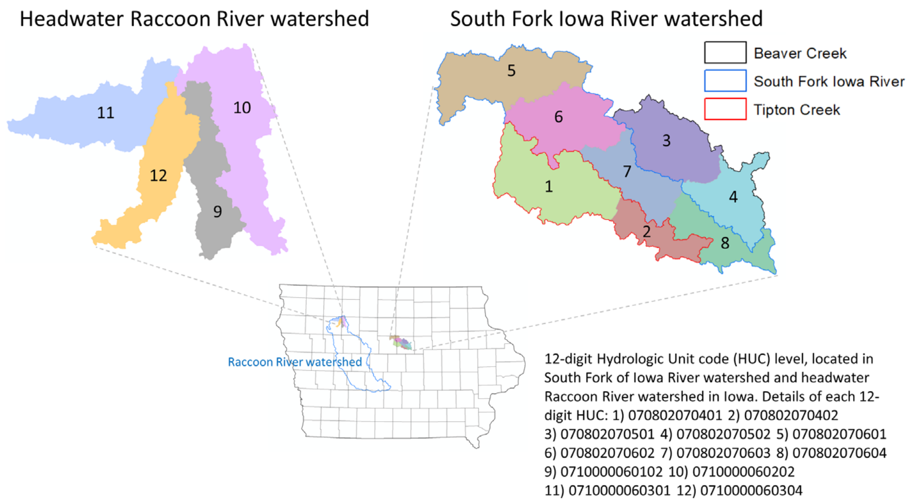

FIGURE 1. Study area at 12-digit hydrologic unit code (HUC) level, located in the headwater of Raccoon River watershed (HRRW) and the South Fork of the Iowa River (SFIR) watershed in Iowa. Details of each 12-digit HUC: (1) 070802070401; (2) 070802070402; (3) 070802070501; (4) 070802070502; (5) 070802070601; (6) 070802070602; (7) 070802070603; (8) 070802070604; (9) 0710000060102; (10) 0710000060202; (11) 0710000060301; and (12) 0710000060304.

797 km^2; the RRW's is 9,344 km^2, including the HRRW's 422 km^2. The SFIR drains portions of Hardin and Hamilton counties, and the HRRW is mainly located in Buena Vista and Pocahontas counties (the RRW drains parts of 17 counties in Iowa). The SFIR watershed includes the tributaries of Beaver Creek (HUC 0708020705), the SFIR (HUC 0708020706), and Tipton Creek (HUC 0708020704) at the 10-digit HUC level (USGS 2013). About 82.1% of the land in SFIR and 74.5% of the land in RRW (87.3% for HRRW) is used for agricultural purposes, mainly growing corn and soybeans (Figure 2). Other land uses include pasture (8.2%), urban lands (6.8%), forest (2.5%), and water or wetlands (0.4%) for SFIR, and pasture (4.4%), urban lands (6.8%), forest (0.1%), hay (0.1%), alfalfa (0.2%), and water or wetlands (1.1%) for HRRW.

Subsurface tile drainage was installed before 1900 in the Des Moines Lobe region to remove excess soil water from the poorly drained soils and support crop production. Intensive tile drainage networks now exist in both the SFIR (Green et al. 2006), and in the middle and northern parts of the RRW (which includes the HRRW) as noted by Schilling et al. (2014). These tile-drain systems have greatly altered the hydrologic landscape in the study watersheds and provided a foundation for consistent and high-yield crop production. However, the tile drain networks are also key sources of nitrate in stream systems throughout the Des Moines Lobe region, as documented in numerous previous studies (Schilling et al. 2014; Gassman et al. 2017; Schilling et al. 2019). Applications of inorganic fertilizer and livestock manure to row crops are major sources of nitrogen in both the SFIR and RRW/HRRW.

SWAT Model Setup

In SWAT, a watershed is delineated into smaller subbasins. These, in turn, are segmented into hydrologic response units (HRUs) to represent areas with unique land use, soil, and slope. A digital elevation model from the National Elevation Dataset (http://seamless.usgs.gov, 30-m resolution) was used to delineate the watersheds and to estimate topographic parameters. The subbasins were defined to coincide with HUC 12 subwatersheds. The watershed land use data were obtained from the cropland data layer (CDL) from the Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/). CDL data were used to analyze six-year rotations in SFIR and four-year rotations in RRW. The land use maps for SFIR and RRW are shown in Figure 2. Crop rotations for the SFIR were imported from the ACPF database, which is derived from CDL layers. The USDA Soil Survey Geographic Database (http://websoilsurvey.sc.egov.usda.gov/) was used for the soil data. Precipitation and maximum/minimum temperature data at eight weather stations for SFIR and 12 stations for RRW were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/datasets#GHCND). Daily weather data were provided from 1993 to 2016. Additional climate data, such as wind speed and relative humidity, were generated in the SWAT weather generator. Discharge and water quality data were obtained from the National Water Information Systems from U.S. Geological Survey (USGS) gauging stations (http://waterdata.usgs.gov/nwis/) and the Conservation Effects Assessment Project (CEAP) from the USDA's ARS, (https://www.

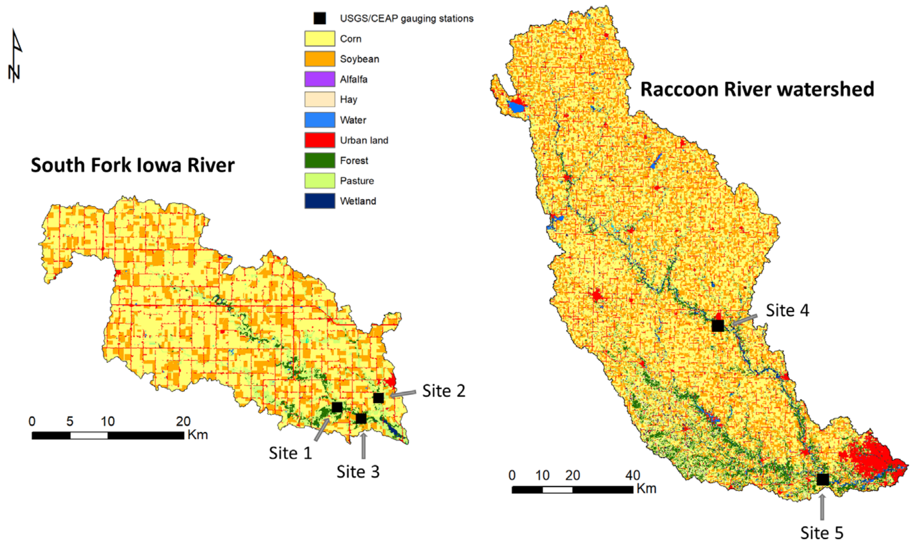

FIGURE 2. Land use map and five gauging stations for observed data. USGS, United States Geological Survey; CEAP, Conservation Effects Assessment Project.

nrrig.mwa.ars.usda.gov/STEWARDS_DOWNLOAD/) for the SFIR, and Des Moines River water quality network (http://home.engineering.iastate.edu/~dslutz/dmrwqn/download.htm) for the RRW.

The simulations ranged from 1996 to 2015 (20 years) for the SFIR and from 1997 to 2016 (20 years) for the RRW, including the warm-up periods required to stabilize initial conditions in the model. The HRUs were delineated by overlaying land use, soil, and slope maps in SWAT. Three slope classes were used for HRU classification: 0%–2% (64% for SFIR and 54% for RRW), 2%–5% (33% for SFIR and 29% for RRW), and steeper than 5% (4% for SFIR and 16% for RRW). The watershed was delineated into eight subbasins and 460 HRUs for SFIR, and 108 subbasins and 4,246 HRUs for RRW (the four subbasins and 163 HRUs for the HRRW).

Crop management practices, especially fertilizer, play a significant role in nonpoint-source pollution from agricultural lands. The autofertilizer option in SWAT used nitrogen (N) as the fertilizer for corn in the two watersheds. The phosphorus (P) fertilizer for corn and soybeans was adopted from the USDA's Economic Research Service (http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26730). The rate at which manure is applied for corn is 200 kg N/ha (Tomer et al. 2008). The areas where they are applied are based on Iowa Department of Natural Resources (IDNR) data, which in turn is based on animal feeding operation confinements. Manure application areas were imported from the IDNR's Natural Resources Geographic Information Systems (NRGIS) library (https://programs.iowadnr.gov/nrgislibx/). Manure is applied one week before planting. Three different tillage operations (no till, reduced tillage, and conservation tillage) were obtained from the Conservation Technology Information Center at the 8-digit HUC level. Reduced tillage was mainly used in corn and soybean files for SFIR (corn 75% and soybean 87%) and for RRW (corn 77% and soybean 84%).

As noted earlier, artificial tile drainage was installed in agricultural lands over 100 years ago, and approximately 80% of the agricultural watershed is tile drained (Green et al. 2006). This includes soils that are not well-drained and those soils defined by poor drainage characteristics. In our study, tile drainage was applied to slopes of <5% on agricultural lands in SFIR. RRW tile-drained areas, based on the tile drainage map from IDNR's NRGIS library, are also areas with slopes <5% in agricultural lands. Tile drainage was simulated in agricultural lands using four parameters in SWAT: 1,000 mm depth to surface drains (DDRAIN), 24–48 hr time to drain the soil field capacity (TDRAIN), 96 hr between the transfer of water from the soil to the drain tile and the tile to the reach (GDRAIN), and a 1,200-mm impervious layer in the soil profile (DEP_IMP).

Calibration and Validation of the Model

The model was calibrated for streamflow, sediment, and nutrients (nitrate and total phosphorus), subject to data availability. SWAT parameters, description, and calibrated values are listed in table. There is a total of five gauging stations with observed data that can be used to perform calibration and validation in the two watersheds (Figure 2): Sites 1–3 for SFIR and Sites 4 and 5 for RRW. Ten years of the measured streamflow data from the CEAP gauging stations (Sites 1, 2, and 3 in Figure 2) and the USGS gauging stations (Sites 3, 4, and 5) were used to calibrate the model (1996–2005 for the SFIR and 1997–2006 for the RRW), and 10 years were used to validate it (2006–2015 for the SFIR and 2007–2016 for the RRW). The locations of the five gauging stations are as follows: Site 1 (IATC325) is located at the lower end of the Tipton Creek watershed; Site 2 (IABC350) is on Beaver Creek near Eldora, Iowa; Site 3 (IASF450 or USGS 05451210) is on the South Fork Iowa River northeast of New Providence, Iowa; Site 4 (USGS 05482500) is on the Raccoon River near Jefferson, Iowa; and Site 5 (USGS 05484500) is on the Raccoon River at Van Meter, Iowa. Figure S1 show monthly observed and simulated streamflow, sediment, and water quality for SFIR and RRW during the calibration and validation periods. Model performances for calibration and validation in the two watersheds were conducted to compare the measured data with simulated values at gauging stations, using the coefficient of determination (R^2), the Nash–Sutcliffe efficiency (Nash and Sutcliffe 1970), and the percentage of bias as the objective functions (Gupta et al. 1999).

In this study, calibration and validation for the SFIR were updated with additional water quality data (five years) based on a previous SFIR study (Ha and Wu 2017). There are limited observed nutrient data available for Sites 1, 2, and 4. Streamflow, suspended sediment, NO_3, and phosphorus were calibrated and validated at Site 3 for SFIR. Streamflow, suspended sediment, total nitrogen, $NO_2 + NO_3$, organic N, and TP were calibrated and validated at Site 5 for RRW. Model performance results are tabulated in Table S2.

Conservation Practices

Conservation practice scenarios were adopted from ACPF practice placement results. ACPF includes conservation planning guidelines for nutrient reduction at field, farm, and watershed scales, and to develop a database to support watershed and practical planning applications (Tomer, Porter, et al. 2015).

RBs were implemented to improve infiltration of runoff from cropland and to trap nutrients and sediments along the waterways. Applied RB areas were imported from ACPF results at the HUC-12 scale, resulting in total RB areas of 55.4 km^2 for the SFIR and 21.3 km^2 for the HRRW. A 90-m width of RB was applied, which provides a land area for environmental filtering and perennial biomass production. The SWAT filter strip option (White and Arnold 2009; Arnold et al. 2012) was used to represent the RBs in the SFIR and HRRW simulations. The filter strips were installed at the start of the warm-up period in SWAT by setting the following parameters in the ops file: MGT_OP = 4 for filter strip; FILTER_RATIO = varies at the subbasin (HUC-12) level for ratio of field area to filter strip area; FILTER_CON = 0.5, assuming 50% of the HRU drains to the most concentrated 10% of the filter strip; and FILTER_CH = 0 to indicate that the fraction of flow through the most concentrated 10% flow is fully channelized (Waidler et al. 2011). The enhanced deposition associated with RBs from upstream areas was updated using SWAT's channel cover (0.2) and erodibility factors (0.2), along with Manning's n (0.1) in the main channel input files (rte files) (Moriasi et al. 2011).

Saturated buffers have demonstrated continuous effectiveness in removing nitrogen from water diverted through RB systems in field study areas, as shown in testing conducted in Iowa (Jaynes and Isenhart 2011; Jaynes 2012; Jaynes and Isenhart 2018). The saturated buffer area applied is 15 km^2 for the SFIR. However, saturated buffers cannot be directly simulated in SWAT; therefore, a BMP operation is used instead (ops files, MGT_OP = 10). According to field test results, saturated buffers have resulted in nitrate removal rates between 8% and 84%, with an approximate average of 50% (Jaynes and Isenhart 2011; Jaynes and Isenhart 2018). Thus, the average removal rate of 50% was applied to SWAT based on expert opinion (verbal communication with T. Isenhart and J. Arnold). The applied saturated buffer areas were selected based on ACPF assessment of riparian lengths suited to the practices.

GRSW were installed at the start of the warm-up period. The applied GRSW acres were adopted from ACPF results. Parameters that were altered in the ops and mgt files included MGT_OP = 7 to simulate GRSW in the HRU. Other parameters include: (1) GWATN = 0.35 for Manning's N value for overland flow; (2) GWATSPCON = 0.001, the linear parameter for calculating sediment in GRSW; (3) GWATD = 0.7 m, the depth of GRSW channel from top of bank to bottom, set to 3/64 $\times$ GWATW; (4) GWATW = 15 m, the average width of a grass waterway (m); (5) GWATL = varies (total 807 km for the SFIR), the length of GRSW (km), adopted from the ACPF results; and (6) GWATS = the HRU slope $\times$ 0.75 m, the average slope of GRSW channel (Waidler et al. 2011; Ahmadi et al. 2013; Liu et al. 2019).

Biomass Production

Table 1 lists the eight scenarios that were simulated in this study. Scenario RB represents perennial

TABLE 1. Biomass production scenarios.

Scenario	Harvest	Conservation practices	Application		
			Applied area	SFIR (km^2)	HRRW (km^2)
RB	SWG	Riparian buffer	ACPF design	55.4	21.3
STV30	Corn stover	—	Ag lands	654.29	368.4
STV30_rye	Corn stover	Cover crop	Ag lands	654.29	368.4
STV45	Corn stover	—	Ag lands	654.29	368.4
STV45_rye	Corn stover	Cover crop	Ag lands	654.29	368.4
STV70	Corn stover	—	Ag lands	654.29	368.4
STV70_rye	Corn stover	Cover crop	Ag lands	654.29	368.4
SWG	Switchgrass	—	Low ROI value areas	75.8	41.6

Note: ROI, return on investment.

vegetation (switchgrass) in the RBs. Scenarios STV30, STV45, and STV70 represent corn stover removal rates of 30%, 45%, and 70% from corn fields, respectively. Scenarios STV30_rye, STV45_rye, and STV70_rye add a winter cereal rye cover crop planted after the corn stover harvest at the rates of 30%, 45%, and 70%. All six of the stover harvest scenarios for the two watersheds were applied in the mgt file in SWAT. A grain or biomass harvest code (IHV_GBM) was used to specify grain or biomass harvest (1 for a grain harvest and 0 for a biomass harvest). Harvest index override (HI_OVE, (kg/ha)/(kg/ha)) defines the ratio of yield to total above-ground biomass for the specified value. Supplemental fertilizers were added to simulated corn fields at a rate of 7,700 g N and 2,000 g P per dry ton of corn stover harvested (Han et al. 2011).

Planting winter cover crops in three stover removal scenarios (STV30/45/70) counters losses of soil organic matter and reduces runoff, erosion, and nutrient losses that can occur from the stover removal (Dabney et al. 2001). The winter rye cereal cover crop is planted after corn and soybeans are harvested and killed before planting the following year's corn or soybean crop.

As illustrated in Figure 3, marginal land, that is, subfields with the lowest return on investment (ROI) values, was chosen to be converted to switchgrass for this study. ROI was calculated as follows: (final value of investment–initial value of investment) initial value of investment.

ROI values for 2013–2016 were based on the total revenues and expenses for each land unit during corn/soybean crop production (Dale et al. 2013), were averaged, and that could be converted to switchgrass. An average ROI value less than or equal to zero indicates a nonprofitable area. The least profitable 10% of the corn and the soybean acreage for the two study areas was defined as "marginal." The actual selected average ROI values were <0.3875 for the SFIR and 0.475 for the HRRW.

RESULTS/DISCUSSION

Impacts of Biomass Production Scenarios on Hydrology

Overall, the proposed scenarios of RB, STV30/45/70, STV30/45/70_rye, and SWG reduced water availability for SFIR and HRRW. Streamflow was predicted to decrease by 0.3% (RB), 2.3% (STV30), 3.3% (STV45), 4.8% (STV70), 4.0% (STV30_rye), 5.0% (STV45_rye), 6.4% (STV70_rye), and 4.4% (SWG) at the watershed outlet of SFIR and by 1.4% (RB), 1.9% (STV30), 3.0% (STV45), 4.7% (STV70), 9.0% (STV30_rye), 10.0% (STV45_rye), 11.7% (STV70_rye), and 7.2% (SWG) for the HRRW (area weighted average of four subwatersheds), as shown in Table 2. There was no change in the annual average hydrology (water yield, evapotranspiration [ET], and tile flow) between the base scenarios and the RB application for SFIR and HRRW at the subbasin level. In this study, the RB scenario was represented by the filter strip option in SWAT, which results in reduced sediment, nutrients, bacteria, and pesticides but does not affect surface runoff (Arnold et al. 2012). Water yield defined as water leaving the HRU before it reaches a stream. With a RB scenario, water yield including tile flow remains unchanged in HRU/subbasin. The water missing from streamflow can be attributed to soil moisture, small transmission losses, deep aquifer contributions or parameter changes in the main channel input of the RB scenario. ET tends to increase in response to the stover removal scenarios both with and without winter cover crops: increases were 5.4 (STV30), 7.6 (STV45), 11.0 (STV70), 9.2 (STV30_rye), 11.4 (STV45_rye), and 14.7 mm (STV70_rye) for the SFIR and 3.1 (STV30), 4.8 (STV45), 7.5 (STV70), 14.3 (STV30_rye), 16.0 (STV45_rye), and 11.2 mm (STV70_rye) for the HRRW. In the stover removal scenarios, the increase in ET reflects the reduction in soil moisture, which

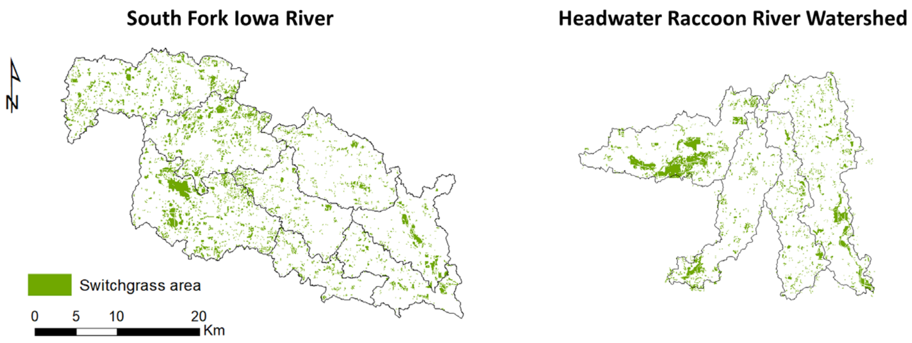

FIGURE 3. A scenario of potential land conversion to SWG based on low ROI values for two watersheds.

TABLE 2. Average annual impact of bioenergy scenarios on streamflow, water yield, evapotranspiration (ET), and tile flow in SFIR and HRRW. Streamflow for SFIR was estimated at the outlet point. The rest are average annual values for the SFIR (eight subbasins) and HRRW (four subbasins).

	SFIR				HRRW			
Scenarios	Streamflow (cms)	Water yield (mm)	ET (mm)	Tile flow (mm)	Streamflow (cms)	Water yield (mm)	ET (mm)	Tile flow (mm)
BASE	5.794	232.8	643.3	69.28	0.555	162.1	613.0	70.1
RB	5.776	232.8	643.3	69.28	0.547	162.1	613.0	70.1
STV30	5.658	227.4	648.7	65.69	0.544	159.0	616.0	68.1
STV45	5.601	225.1	650.9	64.13	0.538	157.3	617.8	66.9
STV70	5.517	221.8	654.3	61.92	0.528	154.6	620.4	65.2
STV30_rye	5.562	223.6	652.5	63.13	0.505	147.8	627.3	61.2
STV45_rye	5.506	221.4	654.7	61.64	0.499	146.1	628.9	60.2
STV70_rye	5.423	218.1	658.0	59.53	0.490	143.5	631.5	58.5
SWG	5.539	222.7	652.9	64.72	0.514	150.8	624.1	64.3

varies based on the amount of stover left on the ground. This explains why the water yield decreases when the stover removal rates are higher. Stover removal scenarios with a winter cover crop produced smaller estimated water yields than stover removal scenarios (STV30/45/70). Planting switchgrass in the marginal lands increased ET by 9.6 (SFIR) and 11.2 mm (HRRW), compared with the base scenario. This is associated with decreased water yields (10.1 mm for the SFIR and 11.3 mm for the HRRW) and tile flows (11.3 mm for the SFIR and 5.8 mm for the HRRW). Reduced water yield includes decreased tile flow.

Spatial Distribution of Water Quality on Conservation Practices

RB, riparian buffer with saturated buffer (RBSB), and GRSW adopted from ACPF practice placement results were applied to the SFIR areas. In response to these conservation practices, SS, NO_3, TN, and TP loadings decreased by up to 1.14 t/ha (SS), 5.43 kg/ha (NO_3), 7.23 kg/ha (TN), and 2.07 kg/ha (TP) at the subbasin level (Figure 4). Downstream of the watershed, sediment, nitrogen, and phosphorus loadings decreased. The percentage of agricultural and hay areas to which RB was applied varied from 5.5% (Subbasin 1, Figure 1) to 15.7% (Subbasin 8, Figure 1) in each subbasin of SFIR. At the subbasin level, nitrogen loadings decreased by up to 7.12 kg/ha in subbasin 4 (Figure 1) for RB, 7.23 kg/ha for RBSB, and 1.76 kg/ha for GRSW after the different conservation practices were applied to SFIR. NO_3 loadings decreased by up to 5.32 kg/ha for RB, 5.43 kg/ha for RBSB, and 0.66 kg/ha for GRSW. Sediment loadings decreased by up to 1.14 t/ha (RB and RBSB) and 0.98 t/ha (GRSW). Sediment loadings decreased more in downstream subbasins. Overall, among the conservation practices applied in this study, RBSBs in the SFIR were the most efficient at removing nutrient loadings. Subbasins at Beaver Creek (Subbasins 3 and 4 in Figure 1) showed more variation than other subbasins, such as those upstream of Tipton Creek (Subbasin 1) and upstream of South Fork Iowa River (Subbasins 5 and 6 in Figure 1). Phosphorus loadings decreased by 2.07 kg/ha for RB and RBSB and 1.92 kg/ha GRSW. Conservation practices can be

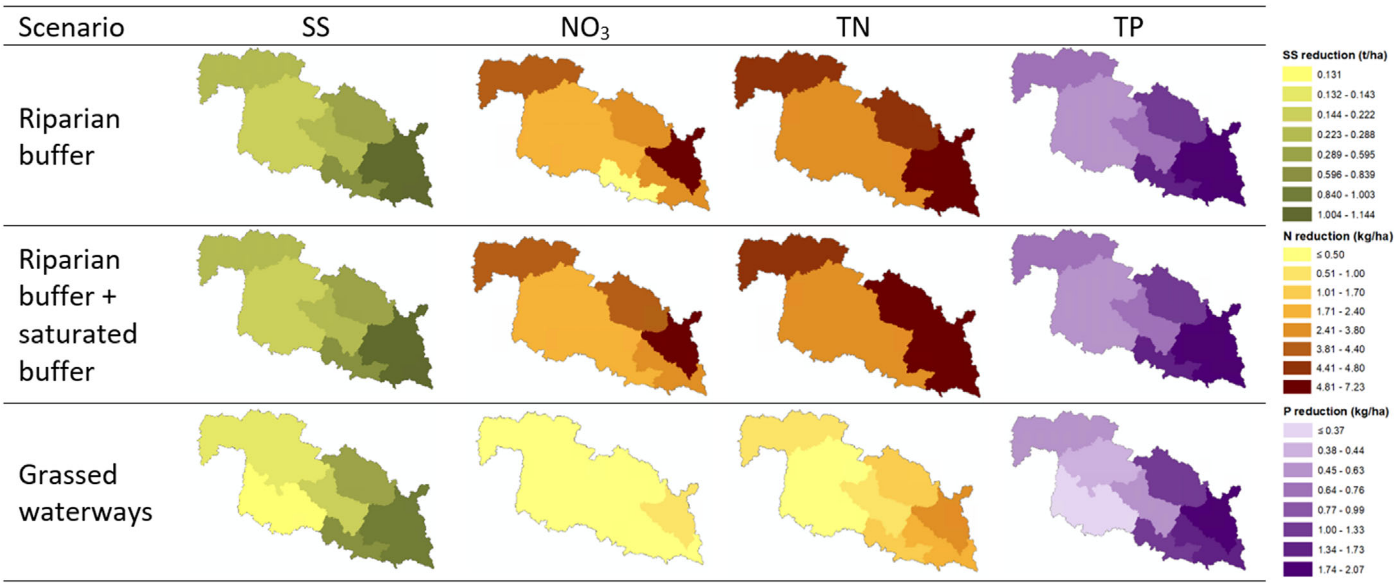

FIGURE 4. Spatial distribution of SS (t/ha), NO_3 (kg/ha), TN (kg/ha), and TP (kg/ha) loading reductions after conservation practices (RB, RBSB, and GRSW) were applied to the base scenarios for the SFIR. RBSB, riparian buffer with saturated buffer; GRSW, grassed waterways.

effective in reducing the direct entry of sediments and nutrients (NRC 2002; Mayer et al. 2007; Smith et al. 2008; Waidler et al. 2011; Liu et al. 2019).

Biomass Production Yield and Water Quality

Figure 5 illustrates the monthly average SS, nitrate, and TP loadings for the base, RB, STV70_rye, and SWG scenarios, which were extracted from agricultural lands at the HRU level for the SFIR and HRRW. The predicted SS loadings and nutrient loadings decreased the most in the RB scenario for the two watersheds. The estimated SS, nitrate, and TP loadings decreased the most in response to the RB scenario for the growing season. In June, the SS loadings decreased up to 0.093 t/ha for SFIR and 0.047 t/ha for HRRW. During this period, the nitrate loadings also decreased up to 0.748 kg/ha for SFIR and 0.154 t/ha for HRRW, and the phosphorus loadings decreased up to 0.177 kg/ha for SFIR and 0.098 kg/ha for HRRW. The SS loadings for STV70_rye increased during the growing season and decreased during the nongrowing season in both the SFIR and HRRW. In the STV70_rye scenario, the results showed that the cover crop in tandem with stover harvest reduced the SS loadings during the nongrowing season. The increase in phosphorus loading for STV70_rye during the growing season (May–September) was similar to the sediment yield during that period. The reduction in soil organic materials due to residue removal following the stover harvest resulted in a reduction of phosphorus loading from October to April. The patterns of phosphorus loadings are highly correlated with sediment loadings for the RB, STV70_rye, and SWG scenarios. Nitrate loadings decreased with RB, STV70_rye, and SWG scenarios in most months, compared to the base scenario, because of the reduced runoff in these scenarios (Table 2). The changes in nitrate loading in the STV70_rye scenario were significantly affected by additional fertilizer application and mineralized nitrogen. The differences in nitrate losses are attributable to the differences in characteristics between the two watersheds. The HRRW has a relatively small land area (4 HUC12s) compared to the SFIR, which has eight HUC12s. The landscape stream networks and soil type distributions are also different in the two watersheds.

Table 3 shows the annual average total biomass production and harvest from agricultural lands in biomass feedstock scenarios with corn stover and switchgrass for SFIR and HRRW. The more corn stover was removed, the less residue was left on fields. Biomass harvest yields were calculated in SWAT, excluding the warm-up period. Switchgrass yields for RB scenarios were calculated based on the Water Analysis Tool for Energy Resources model (http://water.es.anl.gov/). Biofuel production ranged from 10.2 to 75.6 million liters for the SFIR and from 3.3 to 35.3 million liters for the HRRW in different scenarios (Table 3). Biomass yields increased proportionally as stover harvest rates increased from 30% to 70%. With a 70% stover harvest scenario, biomass feedstock per year yields up to 343,773 metric tonnes (7.3 t/ha) for the SFIR and 160,581 metric tonnes (7.8 t/ha) for the HRRW, which would

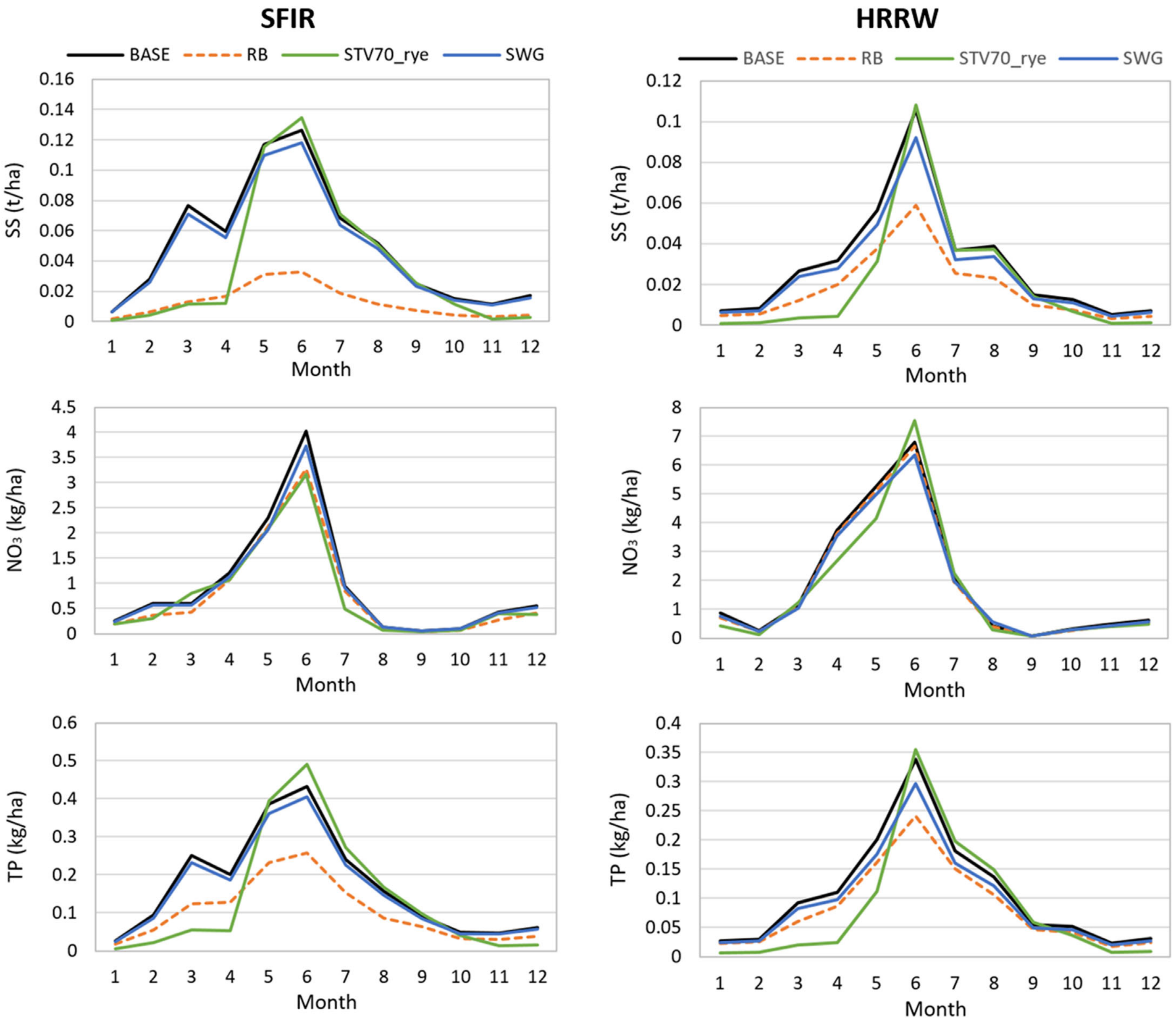

FIGURE 5. Impact of RB, STV70_RYE, and marginal lands in SWG scenarios on average monthly SS, NO_3, and TP loadings from agricultural lands (hydrologic response units [HRUs]), compared to the base scenario.

produce approximately 75.2 million liters of biofuel for the SFIR and 35.3 million liters of biofuel for the HRRW. Areas of switchgrass for landscaping are approximately 9.5% of the SFIR (75.8 km^2) and 9.9% of the HRRW (41.6 km^2), which translate to 16.9 million liters and 8.8 million liters of biofuel, respectively. The simulated corn grain yields (11.4 t/ha for SFIR and 12.1 t/ha for HRRW) in SWAT are close to the observed crop yields (10.7–11.6 t/ha in the four major counties of SFIR and HRRW) under existing land conditions. The measured grain yields were five-year averages (2002, 2007, 2012, 2016, and 2017) in Buena Vista, Hamilton, Hardin, and Pocahontas counties obtained from USDA National Agricultural Statistics Service (https://quickstats.nass.usda.gov/).

Figure 6 shows the average annual changes (%) in SS, nitrogen, and phosphorus loadings for RB as a conservation practice, stover removal (STV30/45/70), stover removal with cover crop (STV30_rye, STV45_rye, and STV70_rye), and marginal land conversion to switchgrass scenarios, compared with the base scenario. RB, stover harvest with cover crop, and the marginal land conversion to switchgrass scenarios evidently have beneficial effects, reducing nutrients, and suspended sediments. Substantial reductions in nutrients and sediment loss were predicted with the RB scenario; reductions are

TABLE 3. Biomass harvest and production with proposed scenarios for SFIR and HRRW.

Watershed	Scenarios	Harvest (tonnes) Stover	Harvest (tonnes) SWG	Biofuel production (ML)
SFIR	RB		46,250	10.2
	STV30	144,523		31.8
	STV45	217,710		47.8
	STV70	343,773		75.6
	STV30_rye	141,128		31.7
	STV45_rye	216,835		47.7
	STV70_rye	342,248		75.2
	SWG		76,952	16.9
HRRW	RB		15,116	3.3
	STV30	67,180		14.8
	STV45	101,210		22.2
	STV70	160,581		35.3
	STV30_rye	66,693		14.7
	STV45_rye	100,580		21.1
	STV70_rye	159,712		35.1
	SWG		40,207	8.8

approximately 17% for nitrogen, 37% for phosphorus, and more than 70% for SS in the SFIR, and 8% for nitrogen, 25% for phosphorus, and 60% for SS in the HRRW. Landscaping scenarios with stover removal (STV30/45/70) resulted in slightly increased SS and phosphorus and reductions in nitrogen loadings, compared to the base scenario. SS and P loadings increased for the STV30/45/70 scenarios, because the soil is not protected after the stover harvest, resulting in soil loss. P loadings also increased, especially the insoluble form, which typically attaches to soil particles. With an increase of stover harvest rates, SS loadings increased up to 3.8% for SFIR and 1.2% for HRRW. It was expected that increases in soil erosion with stover removal would also result in increased P loadings from soil organic phosphorus sources. Loss of soil and phosphorus often appear together in this region (Demissie et al. 2012). Studies for other watersheds show similar nutrient results with stover removal (Wu et al. 2012; Gassman et al. 2017; Panagopoulos et al. 2017; Song et al. 2017).

N loadings decreased even with the application of additional fertilizer, except in the STV70 scenario for the HRRW. Nitrate loadings increase as a result of soil erosion and increased fertilizer application. A decrease in nitrate loadings would likely be attributable to a reduction in the surface runoff and nitrogen mineralization caused by residual removal. In the STV70 scenario, increased N loadings occur due to a higher stover removal rate (70%), and the impact apparently varies between watersheds due to the previously noted variations between the two. Stover removal with winter cover crop scenarios (STV30/45/70_rye) for the SFIR and HRRW resulted in large reductions in N, P, and SS loadings, which show greater efficiency in N, P, and SS than stover harvest only scenarios (STV30/45/70). The model predicted reduced sediment and nutrient loadings at the watershed level for bioenergy production scenarios with conservation practices (Wilson et al. 2014). Nitrate removal efficiency increased with planted rye (Yeo et al. 2014). The reduction in nitrate loadings and concentrations was affected by N uptake by the cover crop; cover cropping with rye could potentially reduce nitrate loss from subsurface drainage discharge (Strock et al. 2004; Kaspar et al. 2007). Stover removal with cover crop application benefits soil health and nutrient protection. Planting switchgrass in marginal lands (SWG scenario) results in reductions in SS and nutrients while producing biomass. Many studies have demonstrated the possibilities for crop diversity, SOC, and environmental benefits for perennial bioenergy crops like switchgrass from corn and soybean fields (McLaughlin and Kszos 2005; Cherubini and Jungmeier 2010; Wright and Turhollow 2010; Ha and Wu 2017; Jones, Oates, et al. 2018).

Higher stover harvest rates resulted in increased sediment loss and P loadings. Conservation practices such as RB and cover crops mitigate sediment and nutrient loadings. Energy crops grown on marginal lands provide biomass production with environmental benefits. Results demonstrated that biomass

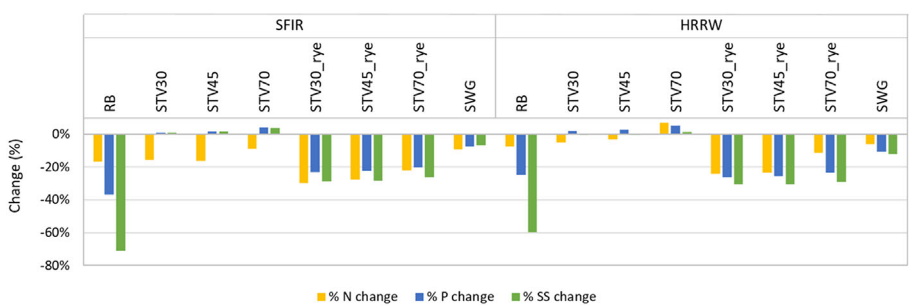

FIGURE 6. Average annual impact of bioenergy scenarios on water quality (N and P) and SS compared to the base scenario for SFIR at the outlet point and for HRRW using the weighted average of four subbasins.

production can be enhanced through landscape design and management while maintaining or improving water quality in watersheds.

DISCLAIMER

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CONCLUSION

The sustainability of bio-feedstock production is the result of a combination of soil erosion, water availability, water quality, biomass production, and biodiversity. Eco-hydrologic models such as SWAT are important tools for assessing the effectiveness of watershed-scale land and crop management. In this research, two SWAT watershed models in Iowa were used to simulate different landscape scenarios with ACPF conservation practice guidelines including RBs, saturated buffers, cover crops, switchgrass in marginal lands, and stover harvest. Findings suggest that biomass production through landscape design, multipurpose buffer conservation practices, and residue management can be beneficial to improve water quality by reducing the loss of nitrogen and phosphorus to the water body and soil erosion in SFIR and HRRW. Both multipurpose buffer and cover crop would be practical in mitigating nutrient and soil loss in the region.

Under the study scenarios, nutrient and sediment reductions would be up to 60%–70% for SS (RB), 20%–30% for nitrogen (stover harvest with cover crop), and 20%–40% for phosphorus (RB and stover harvest with cover crops) relative to historical conditions. Results present substantial improvement of water quality under the stover harvest of 20%–30% with cover crop. Previous studies (Blanco-Canqui and Lal 2009; Kenney et al. 2015) found that only about 25%–50% of stover might be available for removal due to the need for soil fertility and structural stability. Results and conclusion obtained from this study would apply to regions with similar landscape, climate, and soil conductions. An optimized stover harvest rate for each field or area in a subbasin would warrant further investigation based on field or subfield analysis and data.

Management decisions need to be carefully evaluated to weigh the environmental impacts of various biofuel production practices and their effects on yields. This study evaluated the degree to which improvements in biomass feedstock production can be made using the selected conservation practices through landscape management. The conservation practices are recommended by the State of Iowa and have begun to be adopted by landowners across the region. Thus, results contribute to decision making for future planning of biomass production that yields economic and environmental benefits.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Additional tables and figures for detailed description of calibration/validation and model performance for two Iowa watersheds.

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AUTHORS' CONTRIBUTIONS

Miae Ha: Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; visualization; writing-original draft; writing-review & editing. **May Wu:** Conceptualization; formal analysis; funding acquisition; methodology; project administration; resources; supervision; validation; writing-original draft; writing-review & editing. **Mark D. Tomer:** Conceptualization; data curation;

methodology; validation; writing-original draft. **Philip W. Gassman:** Conceptualization; methodology; validation; writing-original draft; writing-review & editing. **Thomas M. Isenhart:** Conceptualization; data curation; methodology; resources. **Jeffrey G. Arnold:** Conceptualization; data curation; methodology; resources; software; validation; writing-original draft. **Michael J. White:** Conceptualization; methodology; resources; software. **Esther Parish:** Conceptualization; data curation; methodology; resources; writing-review & editing. **Kevin S. Comer:** Funding acquisition; project administration; resources; supervision. **Bill Belden:** Funding acquisition; project administration; resources; supervision; writing-original draft.

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