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Assessment of Bioenergy Cropping Scenarios for the Boone River Watershed in North Central Iowa, United States

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Abstract

Several biofuel cropping scenarios were evaluated with an improved version of Soil and Water Assessment Tool (SWAT) as part of the CenUSA Bioenergy consortium for the Boone River Watershed (BRW), which drains about 2,370 km2 in north central Iowa. The adoption of corn stover removal, switchgrass, and/or *Miscanthus* biofuel cropping systems was simulated to assess the impact of cellulosic biofuel production on pollutant losses. The stover removal results indicate removal of 20 or 50% of corn stover in the BRW would have negligible effects on streamflow and relatively minor or negligible effects on sediment and nutrient losses, even on higher sloped cropland. Complete cropland conversion into switchgrass or *Miscanthus*, resulted in reductions of streamflow, sediment, nitrate, and other pollutants ranging between 23-99%. The predicted nitrate reductions due to *Miscanthus* adoption were over two times greater compared to switchgrass, with the largest impacts occurring for tile-drained cropland. Targeting of switchgrass or *Miscanthus* on cropland ≥2% slope or ≥7% slope revealed a disproportionate amount of sediment and sediment-bound nutrient reductions could be obtained by protecting these relatively small areas of higher sloped cropland. Overall, the results indicate that all biofuel cropping systems could be effectively implemented in the BRW, with the most robust approach being corn stover removal adopted on tile-drained cropland in combination with a perennial biofuel crop on higher sloped landscapes.

Keywords

SWAT, water quality, tile drains, switchgrass, Miscanthus, corn stover removal

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Natural Resources Management and Policy | Oil, Gas, and Energy | Water Resource Management

Comments

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Abstract: Several biofuel cropping scenarios were evaluated with an improved version of SWAT as part of the CenUSA Bioenergy consortium for the Boone River watershed (BRW), which drains about 2,370 km^2 in north central Iowa. The adoption of corn stover removal, switchgrass, or *Miscanthus* biofuel cropping systems were simulated to assess the impact of cellulosic biofuel production on pollutant losses. The stover removal results indicate removal of 20% or 50% of corn stover in the BRW would have negligible effects on streamflow and relatively minor or negligible effects on sediment and nutrient losses, even on higher sloped cropland. Complete cropland conversion to switchgrass or *Miscanthus* resulted in reductions of streamflow, sediment, nitrate, and other pollutants ranging between 23% to 99%. The predicted nitrate reductions due to *Miscanthus* adoption were over two times greater compared to switchgrass, with the largest impacts occurring for tile-drained cropland. Targeting of switchgrass or *Miscanthus* on cropland ≥ 2% slope or ≥ 7% slope revealed a disproportionate amount of sediment and sediment-bound nutrient reductions could be obtained by protecting these relatively small areas of higher sloped cropland. Overall, the results indicate all biofuel cropping systems could be effectively implemented in the BRW, with the most robust approach being corn stover removal adopted on tile-drained cropland in combination with a perennial biofuel crop on higher sloped landscapes.

(**Key Terms:** SWAT; water quality; tile drains; switchgrass; *Miscanthus*; corn stover removal.)

Introduction

Water quality degradation is a pervasive problem that has impacted the Upper Mississippi River Basin (UMRB) stream system for decades. The Mississippi River and tributary streams have been greatly impacted by excess nitrogen, phosphorus, and sediment loadings from cropland and other sources. The nutrient load discharged from the mouth of the Mississippi River has also been implicated as the primary cause of the northern Gulf of Mexico seasonal oxygen-depleted hypoxic zone (USEPA, 2008), which covered an average area exceeding 14,500 km^2 during 2004 to 2013 (Rabotyagov et al., 2014) and reached 20,000 km^2 in 2010 (Turner et al., 2012). The UMRB was also reported to contribute 39 and 26% of the total nitrogen and phosphorus loads to the Gulf of Mexico during 2001-2005 (USEPA, 2008). Libra et al. (2004) estimated that Iowa streams contributed approximately 20% of the long-term nitrogen load to the Gulf of Mexico based on in-stream measurements performed during 2000-2002. Monitoring performed by Sprague et al. (2011) further revealed that little progress has occurred in reducing nitrate loads in the Mississippi River, UMRB tributaries, and other tributaries during 1980 to 2008.

The Boone River Watershed (BRW) is an intensively cropped region located in north-central Iowa that is located in the Des Moines Lobe landform region, which is the southernmost extent of the North American Prairie Pothole region (Miller et al., 2009). An estimated 95% to 99% of the extensive wetlands, potholes and other permanently or intermittently wet depressional features that originally characterized Des Moines Lobe region landscapes have been drained with subsurface tile drains and/or surface drainage (Miller et al., 2009). Subsurface tile drains are important pathways of nitrate from UMRB cropped landscapes (e.g., Sprague et al., 2011; Schilling and Wolter, 2005; 2009; Ikenberry et al., 2014) and are also increasingly being identified as conduits of phosphorous export (Kleinman et al., 2015). The BRW is one of most intensively tile drained systems in the UMRB and was identified by Libra et al. (2004) as discharging some of the highest nitrogen loads during 2000-2002 among the 68 Iowa watersheds analyzed in their study.

Expanded use of perennial, small grain and/or winter cover crops within row crop cropping systems is a mitigation strategy that has been proposed for reducing nitrate and other pollutant losses in the UMRB and other Corn Belt subregions (e.g., Hatfield et al., 2009; Russelle et al., 2007). Perennial biofuel crops are increasingly envisioned as a viable option of this overall strategy; such perennial biofuel crops have proven to greatly reduce nitrate losses in field studies (McIssac et al., 2010; Smith et al., 2013) and could effectively reduce nonpoint source pollution within the framework of cellulosic biofuel production in the emerging nexus of food, water and energy (Lawford et al., 2013; Keairns et al., 2016). However, the only commercial-scale crop-based cellulosic biorefineries presently operating in the Corn Belt region rely only on corn stover or corn cobs (Brown and Brown, 2013; POET-DSM, Project Liberty: The Future of Renewable Fuel. Accessed April 15, 2016, http://poet-dsm.com/; Dupont, Cellulosic Ethanol Plant – Nevada, Iowa. Accessed April 15, 2016, http://www.dupont.com/products-and-services/industrial-biotechnology/advanced-biofuels/cellulosic-ethanol/nevada-iowa-cellulosic-ethanol-plant.html). Sustainable management of corn-based cellulosic systems, defined by maintaining adequate levels of crop residue on the soil surface, is required to avoid increased soil erosion, depletion of soil carbon and nutrient, and other environmental problems (Graham et al., 2007; McKechnie et al., 2015; Dale et al., 2014).

A comprehensive assessment of perennial crop biofuel production, including feedstock development, placement of perennial crops on vulnerable landscapes and conversion of perennial feedstock into biofuels, has been conducted for the Corn Belt region within the context of U.S. Department of Agriculture (USDA)-funded CenUSA Bioenergy Project (Moore et al., 2014). A key component of CenUSA is the application the Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold et al., 1998; Williams et al., 2008) which has been used to simulate a wide range of water resource problems for watersheds ranging from small plots to entire continents as documented in previous review studies (e.g., Gassman et al., 2007; 2014a; 2014b; Bressiani et al., 2015; Gassman and Wang, 2015; Krysanova and White, 2015). SWAT was used within CenUSA to analyze cellulosic biofuel cropping systems for the BRW in the western Corn Belt, watersheds located in the eastern Corn Belt (Cibin et al., 2017), most of the entire Corn Belt region (Panagopoulos et al., 2017) and overall policy evaluation (Kling et al. 2017). .

SWAT has been used in several previous studies to simulate the impacts of cellulosic biofuel cropping systems on water quantity and water quality in the Corn Belt region. Some evolution in the model algorithms, plant parameters and/or input data assumptions are represented within this overall subset of studies, reflecting advancements over time in representing corn stover removal, switchgrass and/or *Miscanthus* systems in the model. Several studies in the western Corn Belt subregion (Table 1) focused on scenarios of switchgrass adoption, using lowland switchgrass cultivar Alamo crop parameters that have been distributed with SWAT for several years (Neitsch et al., 2004; Arnold et al., 2012a; Trybula et al., 2015), and/or scenarios depicting corn stover removal which feature relevant soil property, corn yield and other input data adjustments (Demissie et al., 2012a; Wu et al., 2012a; 2012b). Ng et al. (2010) further introduced the first *Miscanthus* crop growth parameters used in SWAT which have since been used in several additional studies (Table 1).

Concurrent research in the eastern Corn Belt focused initially on improvements to known deficiencies in SWAT algorithms and plant parameters. An initial phase of these efforts involved correcting underestimation of nutrient removal and other weaknesses in SWAT for corn stover removal scenarios (R. Cibin. 2015. Personal Communication, Purdue University, West Lafayette, IN). A second phase of enhancements focused on: (1) the need for more accurate representation of switchgrass and Miscanthus growth processes in SWAT, and (2) the development of more realistic switchgrass crop growth parameters for the Corn Belt region based on the cultivar Shawnee as well as improved Miscanthus crop growth parameters, both of which were based on measured data collected in field plots in northwest Indiana (Trybula et al., 2015; Cibin, 2013). These improvements were incorporated into SWAT version 2012 (SWAT2012), Revision 615 (Arnold, L. Personal communication. USDA-ARS, Grassland Soil and Water Research Lab.,Temple, TX) and have been applied at varying levels in several recent SWAT-based studies in both the eastern and western Corn Belt subregions (Table 2) including the CenUSA studies.

The BRW research presented here is the first application of SWAT that compares the impacts of corn stover removal, switchgrass and *Miscanthus* bioenergy cropping system for an intensively cropped watershed in the western Corn Belt subregion, that includes the bioenergy cropping system improvements incorporated in SWAT2012. The application of SWAT reported here further builds on original BRW work reported by Gassman (2008) and more recent studies by Valcu et al. (2016) and Valcu-Lisman et al. (2016; 2017). This study includes BRW scenarios that incorporate adoption of either switchgrass or *Miscanthus*, and/or analysis of the impacts of corn stover removal on cropland managed with corn production. Specifically, the primary objectives of this research are to describe: (1) model testing methods and results for crop yields, streamflow and pollutant transport, and (2) hydrologic and water quality impacts of adopting switchgrass, *Miscanthus* and/or corn stover removal for all cropland versus targeting these bioenergy cropping options on sensitive landscapes.

Watershed Description

The BRW drains an area of over 2,370 km^2 from six north central Iowa counties and is one of 131 U.S. Geological Survey (USGS) 8-digit watersheds (USGS, 2013) that are located in the UMRB (Figure 1). The BRW has been subdivided into 30 subwatersheds for the SWAT simulations (Figure 1), which roughly align with 12-digit watersheds (USGS, 2013) that have been defined for the watershed. The locations of available measured streamflow data, pollutant data, and climate data are also shown in Figure 1.

The majority of the BRW is characterized by flat landscapes that consist of slopes < 2%. An extensive network of subsurface tile drains and surface ditches have been installed throughout the watershed, resulting in the elimination of most wetland areas and an intensively cropped landscape. The watershed is dominated by corn (48.5%) and soybean (41.4%) production (grown primarily in two-year rotations of corn and soybean), based on a field-level survey of the entire BRW conducted in the spring of 2005 as described in Gassman, (2008). Other minor land use includes pasture, Conservation Reserve Program (CRP) land (USDA-FSA, Accessed October 8, 2016, Conservation Reserve Program. http://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/index.) and other grassland (5.4%), woodland (2.6%), urban Areas (2.0%) and water or wetlands (<0.1%). The overall land-use distribution determined via the field-level survey agrees closely with the BRW land use distribution reported by the USDA-NRCS (2008).

A total of 128 confined animal feeding operations (CAFOs) were located in the BRW at the time that the field survey was performed in the spring of 2005 (Table 3; Gassman, 2008).

Swine operations were the dominant type of livestock operation in the BRW with over 480,000 head (Table 3). Some increase in the number of swine and chicken operations has occurred in the past few years in the BRW (IDNR, Natural Resources Geographic Information Systems Library. GIS Section, Iowa Geological and Water Survey, Iowa Department of Natural Resources, Des Moines, Iowa. Accessed April 11, 2016, https://programs.iowadnr.gov/nrgislibx/). However, the impact of this increase is minimal relative to the 1984 to 2013 simulation period because most of the increase occurred after 2010.

Nearly 60% of the BRW soils in the watershed are classified as being poorly drained and over 75% of the soils are categorized as being "All Hydric" or "Partially Hydric" soils, where hydric conditions are defined as being saturated, flooded or ponded during enough of the growing season such that anaerobic conditions will result in the soil profile in a manner that could affect crop growth (USDA-NRCS, 2008; Vepraskas, 2016). The most extensive soil associations in the BRW are the combinations of Canisteo-Webster-Nicollet and Canisteo-Nicollet-Clarion, which are both associated with pothole wetlands (USDA-NRCS, 2008).

Description of SWAT

The SWAT model represents a fusion of physical and empirical techniques and is designed for long-term continuous watershed-scale simulations that are usually executed on a daily time step. In SWAT, a watershed is divided into multiple subwatersheds, which are then usually further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, topographic and soil characteristics that are not spatially defined within the model. Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Key components of SWAT include climatic inputs, hydrology, plant growth, soil erosion and sediment transport, nutrient cycling, transport and transformation, pesticide transport and management practices.

Several enhancements were built into SWAT2005 (used by Gassman, 2008), at the time of formal public release (Gassman et al., 2007) including; (1) an alternative runoff curve number (RCN) approach (USDA-NRCS, 2004) computed as a function of evapotranspiration (ET), which requires the use of an RCN coefficient or depletion coefficient denoted as CNCOEF (Kannan et al., 2008), and (2) an improved empirical approach for simulating subsurface tile drain functions that was developed by Du et al. (2005; 2006) and further modified by Green et al. (2006). This tile drainage estimation method is computed as a function of tile drain depth, the time required to drain the soil to field capacity, lateral flow time, drain tile lag time and an impervious layer depth. Both of these algorithms are key components of the SWAT application reported in this study and are described in detail in the current SWAT theoretical documentation (Neitsch et al., 2011).

SWAT version 2012 (SWAT2012), Revision 615 is the specific version of SWAT used in this study and is the same version used in the other CenUSA SWAT applications (Cibin et al., 2017; Panagopoulos et al., 2017). The perennial biofuel crop modifications reported by Trybula et al. (2015) and SWAT algorithm improvements related to simulating corn stover removal (Cibin, 2013) were ultimately ported to SWAT2012, Revision 611 and thus are available in all later revisions (Sammons, N., 2016, personal communication, USDA-ARS, Grassland, Soil and Water Research Laboratory, Temple, Texas).

The revisions performed by Trybula et al. (2015) involved modifications to the SWAT crop growth algorithms that result in a more realistic representation of switchgrass and

Miscanthus plant nutrient uptake, nutrient translocation during senescence, leaf area development, root decay and harvest index processes. Development of improved crop growth parameters for *Miscanthus* and the upland switchgrass cultivar Shawnee were an additional important aspect of the improved representation of both crops in SWAT, especially for the Corn Belt region. The Shawnee switchgrass parameters build on previous upland switchgrass cultivar development by Kiniry et al. (2008; 2011) and are more realistic crop parameters for SWAT Corn Belt applications versus the lowland switchgrass cultivar Alamo parameters that have been the only switchgrass parameters available to date in the SWAT crop parameter database (Neitsch et al., 2004; Arnold et al., 2012a).

The corn stover removal improvements (Cibin, 2013) consisted of correcting algorithms that were not: (1) computing stover removal correctly when using the harvest override management option in SWAT for stover harvest after grain harvest, and (2) accounting correctly for the amount of nitrogen removed in the stover. These improvements were incorporated in corn stover removal scenario results reported by Cibin et al. (2012; 2016; 2017).

Input Data and Assumptions

The required baseline BRW SWAT model input data are described in detail in Gassman (2008) and are briefly mentioned here. As noted above, the BRW was subdivided into 30 subwatersheds (Figure 1), which were further delineated by a total of 2,212 HRUs. The baseline land use, tillage practice, and conservation practice data were collected via the previously described field-by-field survey conducted in 2005. The land use data included estimates of crop rotation patterns as well as the growing season land use for that year. The BRW has been dominated by corn and soybean production since the early 1960s (USDA-NASS, The Census of Agriculture: Quick Stats. U.S. Department of Agriculture, National Agricultural Statistics

Service. Washington, D.C. Accessed May 1, 2016, https://quickstats.nass.usda.gov/). The 2005 field survey results indicate that 94% of the cropland was planted in two-year rotations of corn and soybean, 4.3% in continuous corn, 1.5% in corn-corn-soybean and very small percentages in other rotations, which agrees closely with the rotation percentages reported in USDA-NCRS (2008). The field survey cropland land use data was supplemented by additional land use data (Gassman, 2008) to define forested, urban and other non-cropland areas. Overall, the 2005 land use is representative of the 1984 to 2013 simulation period used for the baseline simulations.

The distribution of tillage practices was collected as part of the 2005 field-by-field reconnaissance and was categorized as conventional (< 30% residue cover), mulch (30% < residue cover < 90%) or notill (> 90% residue cover). Nearly 95% of the row crop area was classified as being managed with mulch till which is reflected in the tillage distribution incorporated in the SWAT applications for this study. The field-level survey also revealed that about 4,000 ha of cropland were treated with conservation practices such as grassed waterways, contouring and contour buffers, and/or field borders (Gassman, 2008), indicating that the use of such practices is limited in the BRW.

The fertilizer and manure nutrient application rates used for the baseline simulation are listed in Table 4. The fertilizer rates are based on aggregated data obtained from a subset of producers in the BRW for the 2004 and 2005 growing seasons (Sutphin, T. 2006. Personal communication. Iowa Soybean Association, Ankeny, Iowa). The manure application rates were derived from an algorithm that took into account the location of each livestock operation (Gassman, 2008). The current application algorithms result in 50% of the cropland planted to corn receiving both fertilizer and manure applications on an annual basis, due to the excess amount of available nutrients in the BRW, as described in further detail in Gassman (2008).

These cropland nutrient inputs were applied as a function of crop rotation (Table 4) and are consistent with BRW nutrient practices used during the period in which in-stream nutrient measurements were collected (2000 to 2013).

RCN, Tile Depth, and Impervious Layer Depth Considerations

A limited number of previous SWAT studies report the application of the alternative ET-based RCN approach (Green et al., 2006; Kannan et al., 2008; Gassman 2008; Atmaya and Jha, 2011; Yen et al., 2015; Ikenberry, 2017). Almost all of these studies concluded that the alternative ET-based RCN method produced more accurate estimates than the traditional RCN approach, based on graphical and statistical evaluations of streamflow results. However, uncertainty is reflected in some of these previous studies regarding the appropriate choice of the Plant ET Curve Number Coefficient (CNCOEF) value, which is defined in Neitsch et al. (2011) as the "ET weighting coefficient used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration". Thus, the CNCOEF value was determined on the basis of a sensitivity analysis for this study (see Supporting Information).

A tile drain depth (DDRAIN) of 1,200 mm was simulated for the BRW study, which is consistent with other several other previous SWAT studies performed in the region (Jha et al., 2007; 2010; Schilling and Wolter, 2009) and is in the range of typical installed tile drain depths in the western Corn Belt region based on previously established expert opinion (Helmers, M. 2010. Personal communication, Agricultural and Biological Engineering Dept., Iowa State Univ., Ames, IA; Randall, G. 2010. Personal communication. Southern Research and Outreach Center, Univ. of Minnesota, Waseca, MN; Cooke, R. 2010. Personal communication. Dept. of Agricultural and Biological Engineering, Univ. of Illinois, Urbana, IL). In addition, it was assumed that all cropland less than 2% in slope was managed with tile drains, based on the methodology described in Gassman (2008), resulting in approximately 83% of the overall cropland being simulated as tile drained. Recent census data collected in 2012 (USDA-NASS, The Census of Agriculture: Quick Stats. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C. Accessed May 1, 2016, https://www.agcensus.usda.gov/Publications/2012/) indicates that about 70% of the cropland is tile drained based on surveys of landowners who live in the six counties that the BRW is located in. Thus the present configuration of tile drained cropland in the BRW SWAT model may be somewhat overestimated.

Green et al. (2006) also introduced an impervious layer (DEP_IMP) in SWAT2005 that was added to support the previously developed tile drain functions (Du et al., 2005; 2006). The exact depth of an impermeable layer within the BRW system is not known and may range considerably across the watershed. Thus the DEP_IMP depth was determined on the basis of a sensitivity analysis described in the Results section.

SWAT Calibration and Validation

A model testing approach was used in this study that incorporates aspects of previously proposed SWAT testing protocols (Nair et al., 2011; Arnold et al., 2012b) and includes assessments of crop yields, streamflow, and pollutant transport. A 30-year (1984 to 2013) simulation period was chosen to perform the SWAT BRW streamflow testing, which was split into a 15-year (1999 to 2013) calibration period and a 15-year (1984 to 1998) validation period. The entire 30-year simulation period (1984 to 2013) was also evaluated. A two-year initialization period was simulated prior to all three simulation periods. Further description of the model testing methods and results are reported in the accompanying supporting documentation.

Description of Bioenergy Cropping Scenarios

The BRW bioenergy cropping scenarios were simulated for the same 30-year period (1984 to 2013) that was used for the baseline testing. Twenty perennial biofuel crop, corn stover removal or combination scenarios were simulated (Table 5). The depiction of perennial biofuel switchgrass. Both 20% and 50% corn stover removal scenarios were also simulated to ascertain the environmental impacts of differing amounts of remaining corn residue protection on cropland landscapes.

Each perennial biofuel crop or corn stover removal scenario was executed for four different subsets of cropland: all cropland, tile drained cropland, ≥ 2% slope and ≥ 7% slope, which comprise 100%, 83%, 17% and 1.4% of the overall cropland (Table 5). The tile drained cropland (≤ 2% slope) is the dominant BRW cropland landscape and is very vulnerable in the sense of excessive nitrate export as previously discussed. The targeting of higher sloped land accounts for more erosive conditions that would be expected for cropland landscapes characterized by higher slopes. The introduction of stover removal on higher sloped cropland is somewhat counter-intuitive due to the greater erosion potential of cropland that ≥ 2% slope. However, the inclusion of these “targeted scenarios” provides a basis for comparison with the perennial biofuel crop scenarios and useful insight regarding the vulnerability of the higher sloped cropland to management systems that incorporate corn stover removal.

Considerable uncertainty exists regarding the optimal nitrogen fertilizer inputs for various perennial biofuel crops (Parrish and F ike, 2005: Brouder et al., 2009; Cadoux et al., 2012). For example, review studies conducted in a European context report that little or no nitrogen fertilizer is required to achieve maximum Miscanthus production levels (Lewandowski et al., 2007; Zub and Brancourt-Hulmel, 2009; McCalmont et al., 2015). This finding has also been echoed by specific field studies in the U.S. (Maughan et al., 2012; Davis et al., 2015). However, other studies conducted in Illinois reveal that Miscanthus biomass yields increased due to nitrogen fertilizer inputs (Wang et al., 2012; Arundale et al., 2014). And this has been further confirmed by ongoing research currently being conducted in both the western and eastern parts of the Corn Belt region (Heaton, E. 2016. Personal communication. Dept. of Agronomy, Iowa State Univ., Ames, IA; Volnec, J. 2016. Personal communication. Dept. of Agronomy, Purdue Univ., West Lafayette, IN).

Thus the nitrogen application rate reported by Trybula et al. (2015) of 122 kg/ha as urea (46% nitrogen; equals a nitrogen application rate of 56 kg/ha) was simulated for both Miscanthus and switchgrass (Table 5), which was originally obtained from research logs maintained for biofuel cropping experiments at the Purdue University Water Quality Field Station (Cibin, R. 2016. Personal communication. Dept. of Agricultural and Biological Engineering, Pennsylvania State Univ.). The application rate of 56 kg/ha was further confirmed as a logical nitrogen input level for *Miscanthus* production based on current research findings (Heaton, E. 2016. Personal communication. Dept. of Agronomy, Iowa State Univ., Ames, IA; Volnec, J. 2016. Personal communication. Dept. of Agronomy, Purdue Univ., West Lafayette, IN).

The baseline nitrogen and phosphate (P_2O_5) fertilizer application rates were adjusted for the simulated corn stover removal scenarios, similar to the reported by Cibin et al. (2012) to replenish nutrients lost in the removed corn stover. The simulated supplemental corn stover nitrogen and P_2O_5 application rates were based on rates reported by Cibin et al. (2012), which resulted in adjusting the baseline nitrogen fertilizer application rate by 8% and the baseline P_2O_5

application rate by 9% to provide the expected needed additional nutrient inputs to replace the nutrients extracted from the soil due to the removed corn stover.

The manure nitrogen and phosphorus applied to 50% of the baseline cropland was also applied to the same cropland parcels, at the application rates listed in Table 4, for all of the bioenergy cropping scenarios (Table 5). These additional manure nutrient inputs are clearly in excess of the crop nutrient requirements, especially for switchgrass and *Miscanthus*, based on the literature review and expert opinion discussed above. However, the manure nutrients were incorporated in the bioenergy scenarios to maintain a consistent basis of comparison with baseline conditions and also to logically represent the fact that livestock production would not be eliminated in the BRW.

Results and Discussion

Biofuel Cropping System Scenario Results

Table 6 lists the estimated BRW bioenergy scenario streamflows and pollutant loads relative to the counterpart baseline levels for the 30-year (1981 to 2013) simulation period. The results reveal that the perennial biofuel crops are predicted to have substantial impacts on both streamflow and pollutant losses, resulting in reductions of pollutant losses of well over 50% for some perennial crop-pollutant constituent combinations. It can also be discerned that the effects of the stover removal scenarios were relatively minor overall on both streamflow and pollutant losses. The effects of these scenarios are described in more detail below in terms of percentage impacts.

The results further underscore that nitrate is the dominant pollutant of concern in the BRW, which exceeded an estimated 5 million kg annually for baseline conditions. The nitrate load comprises 90% of the overall nitrogen load discharged from the outlet and is roughly 1 to 2 orders of magnitude greater than the other nutrient constituent loads listed in Table 6. The predicted baseline export from BRW landscapes (HRUs) averaged 24.5 kg ha^{-1}, with over 90% of the nitrate loss occurring through subsurface pathways. The majority of the nitrate was discharged via subsurface tile drains, which comprised slightly more than 70% of the total exported nitrate load. Establishment of miscanthus and switchgrass across all cropland landscapes resulted in respective per hectare reductions of nitrate loss relative to the baseline of 84% and 40%.

The average annual predicted baseline sediment load of approximately 209,000 t ha^{-1} and corresponding scenario sediment loads reflect a relatively low amount of sediment export for a system that drains over 2,300 km^2. This is further confirmed by the baseline land parcel sediment loss rate of 0.6 t ha^{-1} which is well below the typical soil loss tolerance levels of 2 to 5 t ha^{-1} established for most U.S. soils (Womach, 2005). These effects are consistent with the dominant low slope and mulch tillage practices that characterize BRW baseline conditions. The adoption of miscanthus and switchgrass on all cropland HRUs results in the virtual elimination of eroded sediment, resulting in predicted per hectare soil loss rates of <0.01 t ha^{-1} for both bioenergy crops. Similar impacts were predicted for sediment bound nitrogen and phosphorus losses.

Impacts of Perennial Biofuel Crops

Figure 2 underscores the substantial environmental benefits of adopting *Miscanthus* or switchgrass on either all of the BRW cropland or on the cropland that is managed with tile drains (Table 5). Adoption of Miscanthus and switchgrass on all cropland results in relatively large reductions in streamflow of 33% and 22% which could have negative ramifications for water management in the BRW, especially if future climate conditions were characterized by lower precipitation inputs. In general huge pollutant loss reductions were predicted including a reduction in sediment loss of over 70% and nearly 100% elimination of organic nitrogen and organic phosphorus losses in response to widescale adoption of both crops. The predicted reduction of nitrate was much higher for Miscanthus (84%) compared to switchgrass (40%). However, greater reductions in mineral phosphorus losses were predicted for switchgrass adoption (58%) versus adoption of Miscanthus (47%).

The adoption of the two perennial biofuel crops on just tiled cropland results in impacts on sediment, organic nitrogen, and organic phosphorus losses that are 30% to 40% less relative to adoption on all cropland, reflecting the fact that larger erosion and sediment-bound nutrient losses occur on higher sloped landscapes that are not tiled drained. The impacts of Miscanthus and switchgrass adoption on tile drained cropland also resulted in lower overall impacts on nitrate and mineral phosphorus losses, as compared to adoption on all cropland, but the declines in predicted impacts were not as great as the sediment-related indicators due to higher losses of the soluble forms of both nutrients from the lower sloped landscapes.

Figure 3 shows the impacts of targeting the two perennial biofuel crops on higher sloped cropland that equals or exceeds either a 2% slope or a 7% slope, equivalent to 17% and 1.4% of the total cropland (Table 5). The predicted impacts of these targeted perennial biofuel scenarios are considerably lower relative to those shown in Figure 2 as expected. For example, the predicted declines in streamflow ranged from just 0.5% to 6% for the four combinations of perennial crops and slope constraints. Reductions of nitrate and mineral P were estimated by SWAT to be mostly about 9 to 10%, although *Miscanthus* was predicted to reduce nitrate losses by 17% when planted on all slopes ≥ 2%. However, reductions of sediment, organic nitrogen, and organic phosphorus were predicted to range between 28% and 32% when Miscanthus and switchgrass were targeted cropland with slopes ≥ 2%, revealing the greater erosive vulnerability of the higher sloped cropland.

Impacts of Stover Removal Scenarios

In contrast, dramatically different results occurred when 20% or 50% corn stover removal was simulated in SWAT for the same four types of categories (Table 5); i.e., adoption on all cropland, tile drained cropland or higher sloped cropland (≥2% or 7%) when planted to corn (Figures 4 and 5). The predicted overall impacts of the corn stover removal scenarios are very minor. The largest increases in pollutant losses were predicted for organic phosphorus and mineral phosphorus, both of which increased roughly 2% for the 20% removal scenario and 5% to 8% for the 50% removal scenario when corn stover removal was simulated for all cropland

planted to corn. Other predicted increases in pollutant losses were very small at the watershed level when 20% or 50% stover removal was simulated only for slopes ≥ 7%. However, these higher slopes exhibited greater vulnerability relative to other BRW cropland landscapes; e.g., roughly 15% of the overall cropland sediment loss for the 20% and 50% stover removal scenarios was attributed to landscapes with slopes ≥ 7%, which cover only 1.7% of the land area. This underscores the need for evaluating the potential to exacerbate pollutant losses from sensitive cropland landscapes when implementing corn stover removal practices and similar systems. The impacts on nitrate were actually shown to be a benefit, with predicted nitrate loss reductions ranging from 0% to 8% depending on the amount of stover removal and the amount of cropland that the stover removal was applied to. However, small decreases in corn yields occurred which implies that the amount of replacement nitrogen fertilizer applied for the stover removal scenarios needs to be increased, to maintain baseline corn yield levels. In general, these scenario results demonstrate that corn stover removal would be a sustainable practice if it were to be adopted on a wide scale within the BRW.

The results of the final set of scenarios simulated in SWAT are shown in Figure 6, which consisted of simulating Miscanthus or switchgrass on cropped landscapes ≥ 2% in combination with corn stover removal adoption on tiled drained cropland (Table 5). The predicted effects of these combination scenarios on streamflow were relatively minor, with resultant reductions in the range of 4% to 7%. The predicted reductions of sediment, organic nitrogen, and organic phosphorus ranged between 25% and 31% and were similar for all four scenarios. The estimated declines in losses were about 2% to 4% greater when corn stover removal was limited to 20% as compared to 50% corn stover removal, confirming the slightly higher soil erosion vulnerability for higher sloped BRW landscapes that occurs with larger amounts of corn stover removal as discussed above. The predicted decline in nitrate losses was nearly 24% for the scenario of Miscanthus grown on higher sloped land parcels in combination with tiled cropland managed with 50% corn stover removal. The other three similar combination scenarios resulted in estimated reductions of nitrate between 10% and 18% (Figure6). In contrast, the predicted reductions in mineral phosphorus for the combined *Miscanthus* and corn stover removal scenarios were virtually identical to the effects on mineral phosphorus estimated in response to counterpart combinations of switchgrass and corn stover removal (Figure 6).

Discussion of Bioenergy Crop Scenarios

Only one previous study in the western Corn Belt region accounted for the effects of implementing switchgrass, *Miscanthus* and corn stover removal bioenergy cropping systems (Wu and Liu, 2012; Table 1), which was conducted for the 32,375 km^2 Iowa River basin that drains much of eastern Iowa and a portion of southern Minnesota. Thus the discussion here is focused primarily on evaluating the BRW analyses with the results presented by Wu and Liu. They performed scenarios representing conversion of 10% of the corn production area (4% of the entire basin) or conversion all of the grassland area (5.7% of the entire basin) into either switchgrass or *Miscanthus* production, and adoption of corn stover removal on 40%, 80% and 100% of the Iowa River basin cropland. A key aspect of all of their scenarios was the use of the SWAT auto-fertilization routine for representing nitrogen applications on the corn, switchgrass and *Miscanthus* bioenergy crops.

Perennial Bioenergy Crops

Wu and Liu (2012) report that respective sediment decreases of 4.5% and 0% occurred for both perennial bioenergy crops in response to the 10% conversion from cropland managed with corn and conversion of all grassland. Switchgrass and *Miscanthus* also resulted in very similar sediment reduction impacts in this study for a given scenario but the relative magnitude of the impacts (on the basis of overall annual average percentage reductions) was much greater for converted cropland in the BRW scenarios (Figure 3 and Table 5). Wu and Liu (2012) further found a slight decrease in nitrate loss of 1.6% when switchgrass was adopted on 10% of the corn areas versus no decrease for the same 10% conversion of corn to *Miscanthus*. The results of predicted nitrate losses for the BRW were the opposite of those estimated by Wu and Liu; i.e., *Miscanthus* resulted in considerably higher reductions of nitrate of as much as 100% as compared to switchgrass (Figures 2, 3 and 6).

Wu and Liu also report that conversion of grassland to switchgrass and *Miscanthus* resulted in nitrate increases of roughly 1% and 5%, respectively, due to total annual average simulated nitrogen fertilizer inputs of 24 kg ha^{-1} for switchgrass and 157 kg ha^{-1} for *Miscanthus* versus no nitrogen fertilizer inputs for the baseline grassland areas. They further note that the higher nitrogen rate applied for *Miscanthus* was due to much higher biomass predicted for *Miscanthus* as compared to switchgrass. Their simulated applied nitrogen for *Miscanthus* is a factor of 3 higher than the *Miscanthus* nitrogen fertilizer application rate used in this study (Table 5). However, both perennial crops showed a relatively high sensitivity to the manure nutrient inputs for the BRW, which boosted average annual watershed-level *Miscanthus* yields by slightly over 6 t ha^{-1} and switchgrass yields by about 1.3 t ha^{-1}, compared to sensitivity runs that excluded the manure nutrient inputs. This resulted in total simulated BRW 30-year (1984 to 2013) average annual Switchgrass and *Miscanthus* yields of 12.3 and 25.3 t/ha when all of the cropland were converted to either of the two bioenergy crops. The increased perennial biomass yields in response to the manure nitrogen inputs are questionable, especially for miscanthus. These results indicate that the SWAT crop growth algorithms may be responding in an unrealistic manner to high levels of nitrogen inputs and that further modifications to the code may be needed beyond the work of Trybula et al. (2015).

To date, only a limited set of field studies have been reported in the literature that compare pollutant exports from both switchgrass and *Miscanthus* for the same environmental conditions, time period, fertilizer application rates, and other management practices (McIsaac et al., 2010; Smith et al., 2013; Montgomery, 2015; Ferchaud and Mary, 2016). These studies ranged in length from 2 to 7 years, showed low levels of exported nitrate from both switchgrass and Miscanthus, and further found that switchgrass generally resulted in a stronger reduction of leached nitrate than *Miscanthus*. The latter result is the reverse of what was found in this study and two of the three other watersheds analyzed within the overall CenUSA initiative (Kling et al., 2017). The BRW results and other CenUSA analyses may reflect the potential of *Miscanthus* to scavenge large amounts of nitrates over long periods of time that have not been confirmed in field research yet. However, this lack of consistency between the predicted outcomes versus available field research also underscores the need for future research that further investigates the response of perennial biofuel crops to nitrogen within the SWAT crop growth algorithms.

Corn Stover Removal

Wu and Liu (2012) further report decreases in water yield and nitrate export, and increases in sediment transport, in response to the corn stover removal scenarios performed for 40%, 80% and 100% of the Iowa River basin cropland. The found that predicted sediment yield increased by about 5% when 40% of the corn stover was removed (with considerably higher sediment loss increases predicted for the 80% and 100% corn stover removal scenarios) and that nitrate loads would decrease between 6 to 10% for the three stover removal scenarios. Similar results in response to corn stover removal scenarios were reported for other previous studies performed in the western Corn Belt (Table 1) that pre-date the SWAT code modifications described in the Description of SWAT subsection and in the Supportin Information.

The predicted effects of the corn stover removal scenarios for the BRW (Figures 4 and 5) and related CenUSA studies summarized by Kling et al. (2017) generally mirror the relative trends reported by Wu and Liu (2012), Demissie et al. (2017) and other studies listed in Table 1 that were performed without the revised algorithms described in the Supporting Information. However, sensitivity analyses comparing the original corn stover removal algorithms in SWAT (from SWAT2012, Revision 589) versus the revised algorithms (SWAT2012, Revision 615) used in this study reveal that the revised algorithms result in additional impacts on predicted nutrient indicators, especially nitrogen removal in harvested stover biomass (results are shown in the Supporting Information). It was also found that the estimated baseline annual average corn yield of 10.6 t/ha dropped to 10.1 t/ha and 10. 4 t/ha for the 20% and 50% BRW corn stover removal scenarios, respectively. This indicates that more supplemental nitrogen inputs are needed for the corn stover removal scenarios to maintain baseline corn yield levels.

Conclusions

Total conversion of BRW cropland to switchgrass and *Miscanthus* would virtually eliminate sediment-bound nutrients (organic N and organic P), reduce sediment losses by over 70% and reduce soluble nutrients (nitrate and mineral p) between 40% to 84%. Placement of switchgrass and *Miscanthus* on tiled drained landscapes (83% of the cropland area) would result in reductions of nearly 70% for sediment-bound nutrients, roughly 45% for sediment and 31% to 68% for soluble nutrients. However, a potential drawback of such wide scale adoption of switchgrass and *Miscanthus* are predicted average annual streamflow declines 18% to 33%.

More realistic targeting of the perennial biofuel crops on cropland landscapes with slopes ≥ 2% (17% of the cropland area) resulted in relatively large estimated reductions of sediment and sediment-bound nutrient losses of 28% to 32%. Reductions of soluble nutrients were less beneficial although *Miscanthus* was predicted to reduce nitrate losses by 17% for cropland parcels ≥ 2% slope. Targeting of the two perennial biofuel crops on high sloped cropland ≥ 7% (1.4%) of the cropland area resulted in proportionally high reductions of sediment and sediment-bound nutrients of 6% to 8%, but negligible impacts on nitrate and mineral P. Targeting of switchgrass and *Miscanthus* on landscapes ≥ 2% or 7% clearly demonstrated the increased vulnerability of higher sloped areas to water erosion.

The introduction of corn stover removal in the BRW was predicted overall to result in minimal environmental impact. The highest predicted pollutant loss increases occurred for a 50% corn stover scenario that resulted sediment, organic nitrogen, organic phosphorus and mineral phosphorus losses of 2% to 8% for adoption on all cropland or tile drained cropland. The predicted impacts of a 20% corn stover removal scenario were generally negligible for the corresponding pollutant indicators. The estimated impacts of all eight stover removal scenarios on streamflow and pollutant losses for "targeted higher sloped landscapes" were also negligible and the impacts on nitrate losses were predicted to be beneficial declines ranging up to 8% reductions. However, the nitrate benefits may be overstated due to a probable need to increase supplemental nitrogen inputs to maintain baseline corn yields.

Combined scenarios of perennial biofuel crops targeted on landscapes ≥ 2% and corn stover removal adoption on tile drained cropland reflect a likely ideal approach to introducing biofuel cropping systems to the BRW, resulting in relatively high reductions of predicted losses of 15% to 31% for most of the pollutants and minimal impacts on streamflow.

Overall, the results indicate that perennial-based and corn-based cellulosic biofuel cropping systems are promising options for the BRW and similar watersheds in the Corn Belt region, due to the respective enhanced or limited environmental impacts that would be expected. However, questions have also emerged in this study as to the possibility that SWAT may be overpredicting perennial biofuel crop yields and nutrient loss mitigation impacts in response to excess nitrogen inputs, especially for *Miscanthus*. This concern points to the need for continued research to determine whether further modifications are needed to the SWAT code to improve the model's accuracy for simulating perennial biofuel crops for watersheds characterized by conditions similar to the BRW.

Supporting Information

Additional supporting information may be found online under the Supporting Information tab for this article: (1) SWAT calibration and validation; (2) revisions to harvestop.f subroutine in SWAT2012, Revision 615 to correct problems regarding representation of corn stover removal scenarios; and (3) an example comparison of the results of simulating corn stover removal using the previous harvestop.f algorithms versus the revised algorithms in Revision 615.

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Table 1. Previous SWAT-based studies that report results of bioenergy cropping system applications in the western Corn Belt subregion prior to key revisions performed in eastern Corn Belt research[a]

Study	Watershed (km^2); location	Biofuel cropping systems	Scenario/study notes
Srinivasan et al. (2010)	Upper Mississippi River (492,000)	Switchgrass	Alamo switchgrass crop parameters
Deb et al. (2015)	Upper Mississippi River (492,000)	Switchgrass; stover removal	Alamo switchgrass crop parameters
Demissie et al. (2012a)[b]	Upper Mississippi River (492,000)	Switchgrass; stover removal	Alamo switchgrass crop parameters; soil property, crop yield and other data adjustments for stover removal
Wu et al. (2012a)[b]	Iowa portion of the Upper Mississippi River	Stover removal	Approach based on UMRB model described by Demissie et al. (2012a) and Wu et al. (2012b)
Wu et al. (2012b)[b]	Upper Mississippi River (492,000)	Switchgrass; stover removal	Alamo switchgrass crop parameters; soil property, crop yield and other data adjustments for stover removal
Gu et al. (2015)	Upper Mississippi River (492,000)	Switchgrass	Alamo switchgrass crop parameters[c]
Ha and Wu (2015)	South Fork of the Iowa River (800.3); north central Iowa	Switchgrass	Alamo switchgrass crop parameters
Ng et al. (2010)	Salt Creek (4,800); central Illinois	*Miscanthus*	Development of initial SWAT *Miscanthus* crop parameters
Ng et al. (2014)	Salt Creek (4,800); central Illinois	*Miscanthus*	*Miscanthus* crop parameters (Ng et al., 2010)
Yeager et al. (2014)	Sangamon River (15,000); central Illinois	*Miscanthus*	*Miscanthus* crop parameters (Ng et al., 2010)
Housh et al. (2014)	Sangamon River (15,000); central Illinois	*Miscanthus*	*Miscanthus* crop parameters (Ng et al., 2010)
Wu and Liu (2012)	Iowa River (32,375); eastern Iowa	Switchgrass; stover removal; *Miscanthus*	Alamo switchgrass crop parameters; *Miscanthus* crop parameters (Ng et al., 2010)

[a]Includes switchgrass and miscanthus revisions described by Cibin (2013) and Trybula et al. (2015), and corn stover removal revisions (R. Cibin. 2015. Personal Communication, Purdue University, West Lafayette, IN and in the Supporting Information).
[b]Further description of the data adjustments are provided in Demissie et al. (2012b).
[c]Inferred from citations of SWAT version 2005 model documentation (Neitsch et al., 2005).

Table 2. Previous SWAT-based studies that report results of bioenergy cropping system applications in the Corn Belt region based on key revisions performed in eastern Corn Belt research[a]

Study	Watershed (km^2); location	Biofuel cropping systems	Scenario/study notes
Cibin et al. (2012)	Wildcat Creek (2,083); north central Indiana	Stover removal	Revised corn stover removal routine
Gramig et al. (2013)	Wildcat Creek (2,083); north central Indiana	Stover removal	Revised corn stover removal routine
Hoque et al. (2014)	Wildcat Creek (2,083); north central Indiana	Switchgrass; *Miscanthus*; stover removal	Revised corn stover removal, switchgrass and *Miscanthus* routines, and new Shawnee switchgrass and *Miscanthus* crop parameters
Cibin et al. (2016)	Wildcat Creek (2,083); north central Indiana	Switchgrass; *Miscanthus*; stover removal	Revised corn stover removal, switchgrass and *Miscanthus* routines, and new Shawnee switchgrass and *Miscanthus* crop parameters
Song et al. (2017)	Wildcat Creek (2,083); north central Indiana	Switchgrass; *Miscanthus*; stover removal	Revised corn stover removal, switchgrass and *Miscanthus* routines, and new Shawnee switchgrass and *Miscanthus* crop parameters
Ha and Wu (2017)	South Fork of the Iowa River (800.3); north central Iowa	Switchgrass; stover removal	Revised corn stover removal and switchgrass routines; Shawnee switchgrass crop parameters
Hamada et al. (2015)	Indian Creek (207.4); northeast Illinois	Switchgrass	Revised switchgrass routines; Shawnee switchgrass crop parameters
Ssegane and Negri (2016)	Indian Creek (207.4); northeast Illinois	Switchgrass	Revised switchgrass routines; Shawnee switchgrass crop parameters
Teshager et al. (2016)	Raccoon River (9,393); eastern Iowa	Switchgrass	Revised switchgrass routines; Shawnee switchgrass crop parameters

[a]Includes switchgrass and miscanthus revisions described by Cibin (2013) and Trybula et al. (2015), and corn stover removal revisions (R. Cibin. 2015. Personal Communication, Purdue University, West Lafayette, IN and in the Supporting information).

Table 3. Total number of confined animal feeding operations (CAFOs), and corresponding livestock numbers and animal units, in the Boone River watershed[a]

Livestock type	Total number of operations	Total number of livestock	Total animal units[b]
Swine	109[c]	480,478	192,191
Cattle	13	4,265	4,265
Chickens (layers)	6	6,962,116	69,621

[a]Source: Gassman et al. (2008)

[b]Animal unit equivalencies: swine = 0.4; cattle = 1.0; layer chickens = 0.01

[c]97 are finishing operations and the other 12 are gestating/nursery operations.

Table 4. Annual nutrient application rates on corn by nutrient source[a].

Nutrient source	Time of Year	Crop rotation	Application rate (kg ha^{-1})
Fertilizer (nitrogen)	Fall	Corn-soybean	183
Fertilizer (nitrogen)	Spring	Corn-soybean	172
Fertilizer (nitrogen)	Spring	Continuous corn	196
Fertilizer (P_2O_5)	Fall or spring	Corn-soybean & continuous corn	49
Manure nitrogen	Spring	Corn-soybean & continuous corn	190
Manure phosphorus	Spring	Corn-soybean & continuous corn	69.8

[a]This table is adapted from Table 2 in Valcu-Lisman et al. (2017).

Table 5. Description of bioenergy cropping scenarios executed for the BRW

Scenario number	Bioenergy scenario	Cropland category	% of total cropland	Nutrient applications or adjustments
1	*Miscanthus*	all cropland	100	122 kg/ha (urea)[a]
2	*Miscanthus*	tile-drained cropland	83	122 kg/ha (urea)
3	*Miscanthus*	≥ 2% slope	17	122 kg/ha (urea)
4	*Miscanthus*	≥ 7% slope	1.4	122 kg/ha (urea)
5	Switchgrass	all cropland	100	122 kg/ha (urea)
6	Switchgrass	tile-drained cropland	83	122 kg/ha (urea)
7	Switchgrass	≥ 2% slope	17	122 kg/ha (urea)
8	Switchgrass	≥ 7% slope	1.4	122 kg/ha (urea)
9	20% stover removal	all cropland	100	Supplemental[b]
10	20% stover removal	tile-drained cropland	83	Supplemental
11	20% stover removal	≥ 2% slope	17	Supplemental
12	20% stover removal	≥ 7% slope	1.4	Supplemental
13	50% stover removal	all cropland	100	Supplemental
14	50% stover removal	tile-drained cropland	83	Supplemental
15	50% stover removal	≥ 2% slope	17	Supplemental
16	50% stover removal	≥ 7% slope	1.4	Supplemental
17	*Miscanthus* & 20% stover removal	≥ 2% slope & tiled drained cropland[c]	17/83	122 kg/ha (urea); Supplemental
18	*Miscanthus* & 50% stover removal	≥ 2% slope & tiled drained cropland	17/83	122 kg/ha (urea); Supplemental
19	Switchgrass & 20% stover removal	≥ 2% slope & tiled drained cropland	17/83	122 kg/ha (urea); Supplemental
20	Switchgrass & 50% stover removal	≥ 2% slope & tiled drained cropland	17/83	122 kg/ha (urea); Supplemental

[a]Urea consists of 46% nitrogen.
[b]Supplemental refers to an additional 8% nitrogen and 9% P_2O_5 which were applied to supplement nutrients removed in harvested corn stover.
[c]*Miscanthus* or switchgrass were placed on cropland landscapes with slopes ≥ 2%; corn stover removal was performed on tiled drained cropland.

Table 6. Annul average streamflows and pollutant loads for the BRW baseline and bioenergy scenarios over the 30-year (1984 to 2013) simulation period.

Scenario[a=]	Bioenergy Scenario	Cropland Category	Streamflow (m^3/s)	Sediment (t)	Nitrate (kg)	Organic N (kg)	Mineral P (kg)	Organic P (kg)
Baseline			20	209,150	5,635,017	478,547	76,271	120,946
1	*Miscanthus*	All cropland	13.4	51,282	888,854	5,265	40,241	1,299
2	*Miscanthus*	Tile drained cropland	14.6	110,765	1,825,043	151,217	48,837	37,446
3	*Miscanthus*	≥ 2% slope	15.5	149,574	4,668,207	327,956	68,955	84,252
4	*Miscanthus*	≥ 7% slope	16.3	192,116	5,544,357	448,100	75,624	113,384
5	Switchgrass	All cropland	18.7	60,723	3,387,893	3,697	32,339	925
6	Switchgrass	Tile drained cropland	19.7	119,201	3,877,463	150,300	40,597	37,191
7	Switchgrass	≥ 2% slope	19.1	150,531	5,125,977	327,319	69,008	84,114
8	Switchgrass	≥ 7% slope	19.7	192,051	5,598,050	447,656	75,651	113,295
9	20% stover removal	All cropland	19.7	210,539	5,530,520	483,100	77,337	123,166
10	20% stover removal	Tile drained cropland	19.8	210,001	5,568,363	482,315	77,212	122,458
11	20% stover removal	≥ 2% slope	19.8	209,923	5,622,557	479,880	76,451	121,754
12	20% stover removal	≥ 7% slope	19.8	209,382	5,633,350	478,738	76,288	121,132
13	50% stover removal	All cropland	19.6	217,023	5,185,707	504,843	79,735	130,868
14	50% stover removal	Tile drained cropland	19.6	213,433	5,263,657	497,705	79,162	127,497
15	50% stover removal	≥ 2% slope	19.8	212,729	5,557,530	485,733	76,848	124,316
16	50% stover removal	≥ 7% slope	19.8	210,235	5,627,273	479,550	76,326	121,706
17	*Miscanthus* & 20% stover removal	≥ 2% slope & tiled drained cropland	18.6	150,511	4,601,993	331,713	69,883	85,771
18	*Miscanthus* & 50% stover removal	≥ 2% slope & tiled drained cropland	18.5	154,191	4,297,177	347,135	71,832	90,810
19	Switchgrass & 20% stover removal	≥ 2% slope & tiled drained cropland	19.0	151,494	5,060,033	331,085	69,947	85,631
20	Switchgrass & 20% stover removal	≥ 2% slope & tiled drained cropland	18.9	155,159	4,754,903	346,526	71,892	90,671

[a]See Table 5 for additional details regarding the percentage of cropland affected and the fertilizer application rates for each bioenergy scenario.

List of Figures