Assessing the potential to decrease the Gulf of Mexico hypoxic zone with Midwest US perennial cellulosic feedstock production

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Abstract

The goal of this research was to determine the changes in streamflow, dissolved inorganic nitrogen (DIN) leaching and export to the Gulf of Mexico associated with a range of large-scale dedicated perennial cellulosic bioenergy production scenarios within in the Mississippi–Atchafalaya River Basin (MARB). To achieve this goal, we used Agro-IBIS, a vegetation model capable of simulating the biogeochemistry of row crops, miscanthus and switchgrass, coupled with THMB, a hydrology model capable of simulating streamflow and DIN export. Simulations were conducted at varying fertilizer application rates (0–200 kg N ha\(^{-1}\)) and fractional replacement (5–25%) of current row crops with miscanthus or switchgrass across the MARB. The analysis also includes two scenarios where miscanthus and switchgrass (MRX and MRS, respectively) each replace the ca. 40% of maize production currently devoted to ethanol. Across the scenarios, there were minor reductions in runoff and streamflow throughout the MARB, with the largest differences (ca. 6%) occurring for miscanthus at the highest fractional replacement scenarios in drier portions of the region. However, differences in total MARB discharge at the basin outlet were less than 1.5% even in the MRX scenario. Reductions in DIN export were much larger on a percentage basis than reductions in runoff, with the highest replacement scenarios decreasing long-term mean DIN export by ca. 15% and 20% for switchgrass and miscanthus, respectively. Fertilization scenarios show that significant reductions in DIN leaching are possible even with application rates of 100 and 150 kg N ha\(^{-1}\) for switchgrass and miscanthus, respectively. These results indicate that, given targeted management strategies, there is potential for miscanthus and switchgrass to provide key ecosystem services by reducing the export of DIN, while avoiding hydrologic impacts of reduced streamflow.

Keywords: Agro-IBIS, hydrology, land use change, miscanthus, nitrate, perennial, stream flow, switchgrass

Introduction

To meet the cellulosic targets set in place by the US 2007 Energy Independence and Security Act (EISA), the Mississippi–Atchafalaya River Basins (MARB) may require significant land use change. Production of the current dominant ethanol feedstock in the United States, maize grain, is capped at 15 billion gallons per year by the Renewable Fuels Standard 2 (RFS2; EPA, 2010) and is at maximum capacity, with ca. 40% of maize production devoted to ethanol (Wallander et al., 2011; https://www.extension.iastate.edu/agdm/crops/outlook/cornbalancesheet.pdf). Numerous studies implementing a wide range of statistical, empirical and numerical techniques have indicated that the leaching of excess nitrogen (N) fertilizer in the form of dissolved inorganic nitrogen (DIN) under current row crop production is a major driver of the Gulf of Mexico hypoxic zone or ‘dead zone’ (Rabalais et al., 1996; Goolsby et al., 2000, 2001; Donner et al., 2004a; Royer et al., 2006; Alexander et al., 2008; David et al., 2010; Turner et al., 2012; Deb et al., 2015).

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In 2008, the Mississippi Basin/Gulf of Mexico Task Force set in place a goal to reduce the size of the hypoxic zone from ~20,000 to ~5,000 km² by the year 2015 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008). However, that goal was not met and the target has now been extended to the year 2035 (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2015). It is predicted that annual DIN export would have to decrease by 30–55% to meet this goal (Donner & Scavia, 2007; Scavia & Donnelly, 2007). It has been suggested that reducing N fertilizer application by ~10% over the MARB could reduce DIN export by ~30%, approaching the EPA target (McIsaac et al., 2001); however, it is uncertain how this change in management might affect maize yields. Increasing maize production beyond current levels to meet cellulosic ethanol production mandates is predicted to increase in DIN leaching and the size of the hypoxic zone (Donner & Kucharik, 2008; Secchi et al., 2011). A potential option to meet the mandated cellulosic production without increasing nutrient inputs while reducing the size of the hypoxic zone is to convert a portion of the land in the MARB to produce dedicated perennial cellulosic feedstocks such as switchgrass and miscanthus (Heaton et al., 2008; Somerville et al., 2010; Deb et al., 2015; Hudiburg et al., 2016).

The benefit of incorporating cellulosic plant material into the energy sector is to decrease the demand for fossil fuels and the pollution they cause, especially with respect to carbon dioxide, a key greenhouse gas (Intergovernmental Panel on Climate Change; IPCC, 2007; Davis et al., 2010; RFS2; Hudiburg et al., 2016). However, it is important to evaluate the production of cellulosic feedstock in the context of environmental trade-offs that may occur, particularly those related to the hydrologic cycle (Rowe et al., 2009; Bagley et al., 2014; Bernacchi & VanLoocke, 2015). It has been shown that miscanthus and switchgrass remove more carbon (C) from the atmosphere (Davis et al., 2010; Zeri et al., 2011, 2013; Anderson-Teixeira et al., 2013), require less nutrient application (Christian et al., 1997; Heaton et al., 2004, 2010) and leach less DIN (Beale & Long, 1997; McIsaac et al., 2010; Smith et al., 2013) relative to annual crops and may present opportunities for additional ecosystem services (Costello et al., 2009; McIsaac et al., 2010; Ng et al., 2010; Davis et al., 2012). These previous findings and ecosystem model simulations show that incorporating perennials, including miscanthus or switchgrass, on land that is currently under maize production for ethanol could reduce significantly DIN leaching and greenhouse gas (GHGs) emissions on a land surface basis (Davis et al., 2012; Iqbal et al., 2015). However, experiments also show that potential cellulosic feedstocks use more water (Hickman et al., 2010; McIsaac et al., 2010; VanLoocke et al., 2010, 2012) than current vegetation that may result in reductions in streamflow (McIsaac et al., 2010). Historic shifts in land use associated with agricultural production have been shown to alter the hydrologic cycle at the basin scale in the MARB, with the transition from perennial grasslands in forests to annual croplands resulting in less ET and greater runoff and streamflow (Twine et al., 2004; Zhang & Schilling, 2006). Conversely, if the hydrologic cycle is altered by an increase in rates of ET associated with miscanthus and switchgrass, less water flowing through streams and rivers could potentially inhibit river transportation of goods and result in higher concentrations of riverine pollutants thereby degrading water quality.

Current research focusing on water quantity and quality changes associated with cellulosic feedstocks fits into three primary categories: (1) plot-scale measurements of nitrate movement within the soil profile (McIsaac et al., 2010; Behnke et al., 2012; Smith et al., 2013), (2) watershed-scale models that do not include mechanistic growth and physiology modules for miscanthus and switchgrass (Costello et al., 2009; Ng et al., 2010; Wu et al., 2012; Deb et al., 2015; Housh et al., 2015), and (3) basin-scale studies that simulate changes in leaching but do not include the routing of DIN and runoff through the MARB to the Gulf of Mexico (Davis et al., 2012). At the plot scale, miscanthus and switchgrass were shown to have significantly lower DIN leaching relative to the maize/soy rotation in central Illinois, with fertilized (57 kg N ha⁻¹) plots of switchgrass showing little or no leaching after reaching maturity (Smith et al., 2013). This reduction in leaching is attributed to extended periods of crop growth, the efficient internal recycling of nutrients and low fertilizer requirements associated with perennial species resulting in relatively small losses of N to the subsoil (Amougou et al., 2012; Cadoux et al., 2012; Smith et al., 2013). At the watershed scale, cellulosic feedstock production is predicted to decrease DIN export (Ng et al., 2010; Deb et al., 2015). At the basin scale, it has been shown that cellulosic production could, depending on type of feedstock and management practice employed, reduce total MARB leaching by up to 22% if maize production for ethanol was displaced by cellulosic feedstocks (Davis et al., 2012).

While these previous studies provided evidence for the potential ecosystem services of transitioning to cellulosic production, it is yet to be estimated what the total change to DIN export and stream flow from the MARB would be under such scenarios. Hydrologic processes are, tightly coupled to the N cycle (Castellano et al., 2010, 2013), key drivers of DIN transport in the MARB (Donner et al., 2002) and sensitive to land use change (Twine et al., 2004). Therefore, it is crucial to
implement a model framework explicitly validated to simulate the hydrology of miscanthus and switchgrass and that is capable of simulating DIN leaching across the entire basin. The goal of this study was to quantify the change in streamflow and DIN export for the MARB under a range of large-scale cellulosic feedstock production scenarios. To accomplish this goal, a series of coupled simulations are conducted using the Integrated Biosphere Simulator – Agricultural version (Agro-IBIS; Kucharik, 2003) and the Terrestrial Hydrology Model with Biogeochemistry (THMB; Coe, 1998, 2000; Donner et al., 2002) to produce output for a range of scenarios aimed at addressing the scale of cellulosic feedstock production necessary to meet the RFS2 mandate (Table 1). The scenarios are only intended to be hypothetical and consist of various fractions of existing crops replaced with miscanthus or switchgrass over a range of fertilizer application rates including two scenarios where miscanthus (MRX) or switchgrass (MRS) replace the ca. 40% of maize grain currently going to ethanol. We anticipate that introducing the production of cellulosic feedstocks will (1) result in a reduction in streamflow proportional to the increase in ET through a decrease in runoff, and (2) result in a reduction in the export of DIN to the Gulf of Mexico proportional to the decrease in DIN leaching associated with the various production scenarios. If the change in DIN leaching is relatively greater than the change in runoff, we also anticipate that (3) the reduction in DIN export will be greater than the reduction in discharge within a given production scenario. Because DIN leaching is greater in the more humid (i.e., greater drainage) portions of the Midwest (Burkart & James, 1999; Goolsby et al., 2000; Donner et al., 2004a,b; Donner & Kucharik, 2008), we also anticipate that (4) the reduction in DIN export will be greater per unit area when miscanthus or switchgrass replace corn/soy in more humid regions relative to dry regions. Finally, because maize typically has the highest rates of ET and DIN leaching (Donner et al., 2004a,b) relative to the other major crops in MARB, we anticipate that (5) the MRX and MRS scenarios will have minimal impacts on streamflow while maximizing reductions in DIN export.

Materials and methods

Model procedure description

The model procedure used in this study builds off of previous implementations of Agro-IBIS and THMB to study effects of land use change on streamflow and biogeochemistry (e.g., Donner et al., 2002; Costa et al., 2003; Donner & Kucharik, 2008; Coe et al., 2011). Agro-IBIS and THMB were run in a semicoupled (Fig. S1) set of simulations (Table 1). The THMB simulations were run at 5 min × 5 min (~7 km × 9 km) spatial resolution and were driven by using simulated monthly mean surface runoff, subsurface drainage and leached DIN from a corresponding 0.5° × 0.5° Agro-IBIS grid cell. An Agro-IBIS spin-up simulation was performed with natural vegetation to allow soil carbon and nitrogen pools to reach a near equilibrium (VanLoocke et al., 2010). A 1-year spin-up was conducted for the THMB simulations to allow mass transport to reach a quasi-steady state. Simulations in both models were run for a domain that encompassed the MARB (50.75° N to 28.75° N; 75.75° W to 115.25° W). This procedure has been evaluated previously for the simulation of streamflow and DIN export in the MARB (Donner et al., 2002; Donner & Kucharik, 2003, 2008). A description of the previous evaluations of THMB and Agro-IBIS against observations in literature is provided in the respective model descriptions sections below.

A total of 54 simulations were conducted (Table 1). Simulations included a baseline scenario for model evaluation purposes with current land use and historic fertilizer application rates. A current land use scenario with approximations of current fertilizer application rates provided the control by which comparisons were made for the cellulosic feedstock scenarios. Experimental scenarios included five fraction coverage scenarios, where land currently in row crop (i.e., maize, soybean and/or wheat) production is converted to miscanthus or switchgrass, at five fertilizer application rates (25 simulations per feedstock). Finally, two simulations were conducted whereby miscanthus (MRX) or switchgrass (MRS) replace the ca. 40% of land currently under maize production that is being used for ethanol production.

| Fraction coverage scenario | Percentage of cropland replaced % | N-Fertilizer kg N ha⁻¹ |
|----------------------------|----------------------------------|------------------------|
| Baseline                   | NA                               | Historic rates*         |
| Control                    | NA                               | Current rates¹         |
| 5                          | 5                                | 0, 50, 100, 150 and 200 |
| 10                         | 10                               | 0, 50, 100, 150 and 200 |
| 15                         | 15                               | 0, 50, 100, 150 and 200 |
| 20                         | 20                               | 0, 50, 100, 150 and 200 |
| 25                         | 25                               | 0, 50, 100, 150 and 200 |
| MRX                        | 40% of maize                     | 0                      |
| MRS                        | 40% of maize                     | 50                     |

*Historic rates are input for each crop (maize, soybean, wheat) based on the USDA state-level agricultural chemical use surveys (www.ers.usda.gov/Data/FertilizerUse).
¹Current rates are 2001–2005 average.
²The 5, 10, 15, 20 and 25 Fraction coverage scenarios were simulated independently for both miscanthus and switchgrass at each of the fertilizer application rates. Five replacement levels each with five fertilizer levels produces 25 scenarios per feedstock, yielding 50 scenarios.
Agro-IBIS description

Agro-IBIS is a dynamic global vegetation model that has been adapted from the original IBIS model (Foley et al., 1996; Kucharik et al., 2000) to simulate the biogeochemical cycles and biophysical processes associated with the production and management of most major US crops (Kucharik & Brye, 2003). Carbon and water exchange are simulated on an hourly time step based on a biological/biochemical approach that includes the C3 and C4 photosynthetic pathways and leaf physiology (Farquhar et al., 1980; Collatz et al., 1991) and canopy scaling (Thompson & Pollard, 1995a,b). Total evapotranspiration is calculated hourly by summing the fluxes of water vapor from transpiration and direct evaporation from puddle, soil and leaf surfaces.

Fluxes and pools of C and nitrogen in soil and plant matter are calculated daily. Soil N pools include soil organic N and DIN. The primary belowground N dynamics represented in Agro-IBIS includes mineralization and immobilization. Plant uptake of N from soil pools to roots is determined by the size of N pools and the transpiration rate. Plant uptake of N is partitioned into the various biomass pools (leaf, stem and root), and the portion that is not removed in harvest is recycled in litter. Limitations are imposed on photosynthesis through modifying carboxylation capacity when the availability of N is suboptimal (Donner & Kucharik, 2003; Kucharik & Brye, 2003). The rate of DIN leaching is dependent on the concentration of DIN and the rate of subsurface drainage (Donner & Kucharik, 2003; Kucharik & Brye, 2003).

For the current analysis, an algorithm was developed and calibrated based on measured data (Himken et al., 1997; Heaton et al., 2009; Dohleman et al., 2012; Wilson et al., 2013; Boersma et al., 2015) to simulate the movement of C and N between aboveground (i.e., shoots) and belowground (i.e., roots and rhizome) pools. Miscanthus and switchgrass each have their own algorithm that is based on the mass balance and tissue-specific N concentration data (Dohleman et al., 2012). Starting on the day of emergence, the algorithm allows for translocation (i.e., the transfer of belowground biomass and N to shoots) to initiate canopy development (Fig. S2). As with annual crops, canopy leaf area is updated daily based on the mass of C allocated to leaves and the specific leaf area, which varies among crop types (Kucharik, 2003). Phenology and C allocation are dynamics throughout the growing season and are dictated by the accumulation of growing degree days or temperature thresholds. At senescence, each algorithm drives translocation of aboveground C and N to belowground storage, which has a low turnover rate over the winter (Dohleman et al., 2012).

Agro-IBIS requires hourly values of air temperature, humidity, solar radiation and wind speed to drive physical processes. These data were derived from a procedure that combined climate data sets from University of East Anglia Climate Research Unit (New et al., 1999; Mitchell & Jones, 2005) and the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data (Kalnay et al., 1996; Kistler et al., 2001). Based on these data, hourly values were generated using a statistical procedure that accounts for diurnal patterns and relationships of atmospheric variables (Campbell & Norman, 1998). Soil texture in Agro-IBIS is prescribed for 11 layers of varying thickness to a depth of 2.5 m based on the CONUS soil data set (Miller & White, 1998). Further description of Agro-IBIS and its predecessor IBIS, including its development and implementation, have been presented in detail elsewhere (Foley et al., 1996; Delire & Foley, 1999; Kucharik et al., 2000; Lenters et al., 2000; Kucharik, 2003; Donner et al., 2004a,b; Kucharik & Twine, 2007; Twine & Kucharik, 2009; Sacks & Kucharik, 2011).

The Agro-IBIS evaluation for the growth and function of current major crops (corn, soy, wheat; Kucharik, 2003; Kucharik & Twine, 2007; Twine & Kucharik, 2008; Twine et al., 2013) as well as for miscanthus and switchgrass (VanLoocke et al., 2010, 2012) has been described previously. Specific evaluations relevant to this work include comparisons to numerous field-based measurements of key N fluxes and pools for both aboveground and belowground dynamics (Kucharik & Brye, 2003). Agro-IBIS simulated maize yields have been compared to US Department of Agriculture yield observations across the Corn Belt (Kucharik, 2003). Simulated maize and soybean canopy fluxes and leaf area have been evaluated against flux observations over numerous growing seasons (Kucharik & Twine, 2007). Agro-IBIS simulation of miscanthus and switchgrass hydrology was evaluated against observations of ET over multiple years using two independent methods and showed strong agreement (VanLoocke et al., 2010, 2012).

THMB description

Terrestrial Hydrology Model with Biogeochemistry simulates the storage, transport and removal of water and N on an hourly time step, based on Agro-IBIS inputs of DIN leaching, surface runoff, subsurface drainage, precipitation and evaporation from surface waters at a 5 min × 5 min spatial resolution (Coe, 1998; Donner et al., 2002). Surface waters in THMB include rivers, wetlands, lakes and anthropogenic reservoirs. In THMB, the transport of input water and N depends on local topography as well as inputs from upstream grid cells. Dissolved inorganic N includes NO3 and NH3, because NO3 represents >95% of DIN reaching the Gulf of Mexico (Aulenbach et al., 2007). THMB transports all DIN together. A portion of leached DIN is lost in the THMB surface waters due to denitrification through the reduction of NO3 to N2O and N2 and is dependent on river bed morphology, solute concentration and water temperature (Donner et al., 2004b).

The ability of THMB and its predecessors, surface water area model (i.e., SWAM) and hydrologic routing algorithm (i.e., HYDRA), to simulate streamflow (discharge) and nutrient export has been tested in numerous studies, covering a wide range of scales and locations. Evaluations include comparison of simulations against annual mean discharge and lake area for major global basins and lakes (Coe, 1998) and the accuracy of the surface hydrology in general circulation models (Coe, 2000). At the continental scale, discharge and DIN export (NO3 yield) for internal sub-basins within the MARB for ca. 30 total US observation stations from the Geological Survey, National Water Service (USGS) and Global Monthly River Discharge Data Set (Donner et al., 2002) showed good agreement with model simulations for discharge. Evaluations of an updated version of the model for the Upper Mississippi River Basin showed stronger correlation of discharge and DIN export to

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USGS observation in the basin (Donner & Kucharik, 2003; Donner et al., 2004a,b) and showed strong agreement with USGS observed DIN export at near the outlet of the MARB (Donner & Kucharik, 2008).

Land use

The fraction crop coverage in each 5 min × 5 min grid cell is aggregated based on an integration of a satellite-based data set of total area in crop production with the USDA county-level data (www.nass.usda.gov) for the area planted in major crops including maize, soybeans, spring and winter wheat (Ramankutty et al., 2008; for a full description, see Donner & Kucharik, 2008). The distribution of natural vegetation in the model domain was determined using vegetation maps (Ramankutty & Foley, 1998) and the International Geosphere Biosphere Programme’s 1-km DISCover land cover data (Loveland & Belward, 1997). There is significant uncertainty surrounding the future locations and intensity of production of cellulosic feedstocks. Therefore, a series of simulations were conducted at varying fraction coverages for miscanthus and switchgrass (Table 1). These scenarios include even coverage across the land currently in production of maize, soy, spring and winter wheat in the MARB domain (Fig. S3a), as well as targeted replacement of existing maize/soy production, with the intent of simulating the displacement of current grain ethanol with dedicated perennial cellulosic ethanol (Fig. S3b).

Management

In the baseline scenario, each of the current crops was fertilized at historic rates, and in the control simulation, the 2001–2005 average application rates were used (Table 1; Donner & Kucharik, 2008). The fertilizer input data are based on the USDA state-level agricultural chemical use surveys (http://www.ers.usda.gov/Data/FertilizerUse/; Donner & Kucharik, 2008). Modern rather than historic fertilizer inputs were chosen for the control run to represent the changes in the system that would occur if perennials are to replace annuals moving forward, rather than the changes that would have occurred over the last 30 years. Further detail on the distribution of fertilizer application and the response of the model to fertilizer input was evaluated previously by Donner et al. (2004a). With respect to the management of perennial feedstocks, there is significant uncertainty surrounding the most likely application rates of fertilizer in the management of switchgrass and miscanthus, a series of simulations were conducted at varying fertilizer levels (Table 1). This range includes the various recommendations made based on study sites for switchgrass and miscanthus (Adler et al., 2007; Miguez et al., 2008; Schmer et al., 2008; Varvel et al., 2008; Cadoux et al., 2012). Following the recommended practices of Smith et al. (2013), the MRX and MRS scenarios were fertilized at 0 and 50 kg N ha⁻¹, respectively.

Model evaluation

Simulated annual mean streamflow and DIN export from the control scenario were compared to USGS observations (Aulenbach et al., 2007) near the outlet of the MARB. Output from the nearest corresponding THMB grid cell was compared to the USGS observations for the Mississippi River at Tambert Landing, MS, Old River Outflow, and the Atchafalaya River at Simmersport, LA. Simulated and observed values from 1980 to 2001 were summed from each of the respective observation points to produce the total MARB DIN export (Fig. 1a) and streamflow at the outlet (i.e., discharge; Fig. 1b).

Results

Comparison of streamflow and DIN export in baseline simulation to observations

The baseline simulation (Table 1) reproduces the observed interannual variability and long-term mean in...
Comparison of runoff in control simulation to replacement scenarios

The Agro-IBIS simulated total annual mean runoff (surface + subsurface) varies significantly across the MARB for the control simulation, with values <50 mm yr\(^{-1}\) in the driest and western-most portions of the domain and >650 mm yr\(^{-1}\) near the Gulf of Mexico outlet (Fig. 2a). The pattern of total annual runoff is similar to annual mean precipitation across the Basin (data not shown), showing a general increase following the gradient in precipitation from north to south as well as west to east. In the cellulosic replacement scenarios (Table 1), runoff is similar for all the fertilizer application rates (data not shown) but varies widely between the various fraction replacement scenarios (Fig. 3).

At the 5% replacement level, there is less than a 2% decrease in runoff (per grid cell) for switchgrass and a 2.4% decrease for miscanthus runoff relative to control (Fig. 3a, e). Differences in runoff are larger at greater replacement levels, with switchgrass decreases ranging from 2% to 8% (Fig. 3e–h) and miscanthus from 4% to 10% (Fig. 3a–d) lower than control for the 15% and 25% replacement scenarios, respectively. Compared to control, throughout the Corn Belt (Iowa, Illinois, Indiana and Ohio), the MRS scenario shows less than a 4% decrease in runoff, while the MRX scenario shows a 4–6% decrease in runoff in the eastern portions and up to 10% in the western portions of the Corn Belt in total runoff.

Neither the MRX nor the MRS scenarios show any differences >2% in total runoff relative to control in the southern portions of the domain near the Lower Mississippi (Fig. 3d, h). Miscanthus and switchgrass both show smaller changes in total runoff under the MRX and MRS scenarios compared to control than under the respective 25% replacement scenarios (Fig. 3c–h). For all scenarios, on a percentage basis, the changes in runoff relative to control were largest in the drier western portions of the domain (Fig. 3), where the absolute values of runoff in the control simulation tended to be the lowest (Fig. 2a).

Comparison of DIN leaching in control simulation to replacement scenarios

Simulated annual mean DIN leaching also varies highly across the domain for the control simulation, with values less than 5 kg N ha\(^{-1}\) yr\(^{-1}\) throughout most of the unmanaged portions of the domain, and values exceeding 50 kg N ha\(^{-1}\) yr\(^{-1}\) in eastern portions of the Corn Belt (Fig. 2b). Portions of the domain dominated by maize production have the highest leaching rates, with portions where wheat or soybean are dominant having generally lower leaching rates. Leaching rates increase with runoff within regions of similar crop production (e.g., the Corn Belt), with leaching rates 25–50% greater in the transect stretching from Eastern Illinois to Western Ohio relative to the Eastern Nebraska and Iowa region (Fig. 2).

In the cellulosic replacement scenarios, DIN leaching varies with the fraction of land replaced. There is little variability across the domain for differences in DIN leaching relative to control within a given cellulosic replacement level; however, there are large differences
Fig. 3 Simulated mean annual percent difference (scenario – control) in total runoff in the Mississippi–Atchafalaya River Basin for the miscanthus (a–d) and switchgrass (e–h) scenarios at 5% (a, e), 15% (b, f) and 25% (c, g) replacement at the 0 kg N ha\(^{-1}\) fertilizer rate as well as the MRX (d), and MRS (h) cellulosic for maize scenarios for the 33-year period spanning 1970–2002.
among scenarios, with the largest differences occurring at the highest replacement levels (Fig. 4). At the 5% replacement level, neither miscanthus nor switchgrass shows reductions in mean DIN leaching exceeding 5% compared to control (Fig. 4a, e); however, as replacement increases to 15%, both show decreases in DIN leaching over 10% (Fig. 4b, f), and at the 25% replacement level, there are portions of the domain showing decreases over 20% (Fig. 4c, g). The largest differences relative to control in mean DIN leaching for both miscanthus and switchgrass occur in the MRX and MRS scenarios, showing over 25% and 20% reductions, respectively, across the majority of the Corn Belt (Fig. 4d, h). As with runoff, miscanthus has a larger decrease in DIN relative to switchgrass throughout the MARB (Fig. 4).

**Comparison of streamflow in control simulation to replacement scenarios**

The THMB-simulated mean streamflow for the various rivers in the MARB network shows a range of flow rates spanning four orders of magnitude, with the fourth- and third-order rivers/streams generally less than 500 m³ s⁻¹, the second-order rivers (e.g., Missouri, Ohio and Arkansas) in the 500–5000 m³ s⁻¹ range and the lower Mississippi and Atchafalaya ranging 5000–30 000 m³ s⁻¹ (Fig. 5a). Similar to the results for runoff, there is little variability in streamflow for the cellulosic replacement scenarios with fertilizer application rates (data not shown). However, there are notable differences in streamflow between the various replacement levels relative to the control. In the cellulosic replacement scenarios, mean streamflow is reduced by <3% relative to control across the domain at the lowest replacement level for both miscanthus and switchgrass (Fig. 6a, e). At the 15% replacement level, switchgrass reductions in mean streamflow relative to control are still <3% throughout the domain, with miscanthus showing 3–6% reductions relative to control in portions of the upper Missouri and surrounding tributaries (Fig. 6b, f). At the 25% level, there are still very few rivers showing over 3% reductions in mean streamflow for switchgrass compared to control; however, reductions of up to 6% in portions of the Missouri and Upper Mississippi rivers and surrounding tributaries are simulated (Fig. 6c, g). Similar to the pattern for runoff, the differences relative to control in streamflow are smaller in the MRX and MRS scenarios compared to the respective 25% replacement scenarios (Fig. 6c–h). The MRX scenario shows a small number of rivers with 3% decreases in streamflow compared to control, while the MRS scenario differences in streamflow are <3% throughout the domain. Overall decreases in mean streamflow relative to control are greater for miscanthus than for switchgrass, with the largest reductions occurring in second- and third-order rivers and corresponding to the areas of greatest decreases in runoff (Figs 5a and 6); however, reductions never exceeded 7% in any scenario.

**Comparison of DIN export in control simulation to replacement scenarios**

Simulated mean DIN export follows a pattern similar to streamflow for the control simulation across the MARB (Fig. 5). As with streamflow, the DIN export spans several orders of magnitude across all rivers, with third- and fourth-order rivers averaging between 500 and 5000 metric tons yr⁻¹ and second-order rivers an order of magnitude larger, and the Lower Mississippi River averaging up to 500 000 metric tons yr⁻¹ (Fig. 5b). As with DIN leaching, only the 0 kg N ha⁻¹ fertilizer application scenarios are shown and discussion of the dependence of DIN export on fertilizer application rate is presented only at the basin outlet.

Unlike the patterns for percent changes in streamflow for the cellulosic scenarios (Fig. 6), differences in mean DIN export relative to control are more evenly distributed across the domain (Fig. 7). At the 5% replacement level, both miscanthus and switchgrass show an even distribution of 1–5% reductions in mean DIN export relative to the control (Fig. 7a, e). The higher replacement levels show greater decreases in mean DIN export compared to control, with the 15% replacement scenario showing reductions of 5–15% (Fig. 7b, f) and the 25% replacement showing most rivers with at least 5% reductions, and up to 15% for miscanthus, throughout the MARB (Fig. 7c, g). Following the pattern in mean DIN leaching, the largest differences in mean DIN export occurs in the MRX and MRS scenarios, with the majority of the domain showing reductions >5% and rivers in the northern portions of the MARB showing over 15% reductions relative to control (Fig. 7d, h). Overall, the percent reductions in DIN export compared to control are ca. three times greater than that for streamflow for the majority of the MARB (Figs 6 and 7).

**The dependence of DIN leaching on fertilizer application rate**

At the 25% fraction replacement level, there is a decrease in DIN leaching for scenarios relative to control across the entire domain for the 0, 50 and 100 kg N ha⁻¹ fertilizer rate scenarios for both miscanthus (Fig. 8a–c) and switchgrass (Fig. 8f–h). The areas in the domain with the largest cellulosic species-based decreases in DIN leaching correspond to where the
Fig. 4  Simulated mean annual percent difference (scenario – control) in DIN leaching in the Mississippi–Atchafalaya River Basin for the miscanthus (a–d) and switchgrass (e–h) scenarios at 5% (a, e), 15% (b, f) and 25% (c, g) replacement as well as the MRX (d), and MRS (h) cellulosic for maize scenarios for the 33-year period spanning 1970–2002.
control simulations had the highest leaching rates (Fig. 2b). The majority of the Corn Belt has decreased DIN leaching for miscanthus relative to the control for the 150 kg N ha$^{-1}$/C0 fertilizer scenario relative to the control (Fig. 8d) but at the 200 kg N ha$^{-1}$/C0 rate, large areas of increased DIN leaching occur for miscanthus (Fig. 8e). On the other hand, switchgrass has minimal decreases in DIN leaching in the Corn Belt for the 150 kg N ha$^{-1}$/C0 and increases in DIN leaching relative to the control for the 200 kg N ha$^{-1}$/C0 scenario across the entire domain (Fig. 8i, j). Smaller fraction replacement scenarios have a similar pattern to the 25% level but with smaller magnitudes of differences (data not shown).

Comparison of monthly mean streamflow and DIN export at the MARB outlet

At the monthly time scale, there is no appreciable shift in the pattern of total discharge at the outlet of the MARB for either miscanthus or switchgrass across any of the scenarios (Fig. 9a, c and b, d). The differences in mean DIN export are much larger than discharge for both species and for the respective scenarios (Fig. 9a, c and b, d); however, there is no appreciable shift in the pattern of monthly mean DIN export at the outlet of the MARB (Fig. 9b, d). The largest differences compared to control occur in May and June and the smallest in September through November for both species, with the MRX and MRS scenarios showing the greatest reductions in mean DIN export for miscanthus and switchgrass (Fig. 9).

Comparison of annual mean streamflow and DIN export at the MARB outlet

At an annual time scale, differences relative to control in mean discharge at the outlet of the MARB are small relative to mean DIN export for both miscanthus and switchgrass for the various scenarios (Fig. 10). In the miscanthus scenarios, the largest decrease relative to control in mean discharge is in the 25% replacement scenario with a ca 1.5% reduction (Fig. 10a). Switchgrass shows a similar pattern; however, the mean difference compared to control for the 25% replacement scenario is <1% (Fig. 10c). Neither miscanthus nor switchgrass shows appreciable differences in discharge between the 0 and 100 kg N ha$^{-1}$/C0 scenarios (Fig. 10a, c).

There are, however, large differences between the control and the replacement scenarios for mean DIN export at the outlet of the MARB. Differences in mean DIN export relative to control increase with higher replacement scenarios, with the MRX and MRS scenarios showing the largest reductions at ca. 20% and 16% for miscanthus and switchgrass, respectively (Fig. 10b, d). Mean DIN export was slightly higher for the 100 kg N ha$^{-1}$/C0 fertilizer scenarios relative to the unfertilized simulations; however, the 95% confidence intervals overlap for the two scenarios for both miscanthus and switchgrass (Fig. 10a, c). The scenarios with rates above 100 kg N ha$^{-1}$/C0, however, have significantly more DIN export relative to control, with larger increases for switchgrass than miscanthus (data not shown) Only the MRS scenario shows no overlap in the 95% confidence interval between the control and switchgrass simulations (Fig. 10d) while both the 25% and MRX scenarios show no overlap in the 95% confidence interval for DIN export in the miscanthus scenarios (Fig. 10b).

Discussion

The goal of this study was to quantify the change in streamflow and DIN export for a range of basin-scale...
Fig. 6 Simulated mean annual percent difference (scenario – control) in streamflow in the Mississippi–Atchafalaya River Basin for the miscanthus (a–d) and switchgrass (e–h) scenarios at 5% (a, e), 15% (b, f) and 25% (c, g) replacement as well as the MRX (d), and MRS (h) cellulosic for maize scenarios for the 33-year period spanning 1970–2002.
Fig. 7  Simulated mean annual percent difference (scenario – control) in DIN export in the Mississippi–Atchafalaya River Basin for the miscanthus (a–d) and switchgrass (e–h) scenarios at 5% (a, e), 15% (b, f) and 25% (c, g) replacement at 0 kg N ha$^{-1}$ as well as the MRX (d), and MRS (h) cellulosic for maize scenarios for the 33-year period spanning 1970–2002.
Fig. 8  Simulated mean annual difference (scenario – control) in DIN leaching for miscanthus (a–e) and switchgrass (f–j) for fertilizer application rates of 0 kg N ha⁻¹ (a, f), 50 kg N ha⁻¹ (b, g), 100 kg N ha⁻¹ (c, h), 150 kg N ha⁻¹ (d, i) and 200 kg N ha⁻¹ (e, j) at the 25% replacement level for the period spanning 1970–2002.

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cellulosic feedstock production scenarios for the MARB, a region that is likely to undergo large-scale shifts in feedstock production to meet the goals of the RFS2 (EPA 2010). The results presented here support anticipations 1 and 2 by showing that increasing the production of the cellulosic feedstocks miscanthus and switchgrass will reduce both the runoff of water and leaching of DIN, with proportional reductions in streamflow and the export of DIN in the MARB. The model indicated that the reduction in DIN leaching was much larger relative to the reduction in runoff, supporting anticipation 3. The relative differences in runoff and DIN leaching varied between the simulated scenarios, with higher fertilizer application rates resulting in smaller reductions in DIN export (Fig. 10). On a percent basis, simulated changes in DIN leaching were similar across the domain for both miscanthus and switchgrass for the unfertilized scenario (Fig. 4). However, because the DIN leaching rates are larger in the more humid, eastern and southern areas (Fig. 2b), the change in the mass of leached DIN was greatest in these regions, supporting anticipation 4. The MRX and MRS scenarios had the lowest mean DIN export of all the scenarios, and the change in mean discharge relative to control was slightly less than the 20 and 25% replacement scenarios (Fig. 10), which supports anticipation 5.

The baseline scenario simulation agreed well with observations (Fig. 1). The magnitude and spatial patterns of DIN leaching across the MARB in the control simulation were similar to modeling studies (Donner et al., 2002, 2004a), which were consistent with observations in the basin (Goolsby et al., 2000). Our simulations show ca. 15 and 20% reductions in long-term mean DIN export and <2% reductions in total discharge, relative to control, for the MRS and MRX scenarios, respectively (Fig. 10). Similar to the findings presented here, Davis et al. (2012) showed that replacing land currently under maize production for ethanol in the Midwest United States with cellulosic feedstocks could reduce N leaching by ca. 20% while providing almost double the biomass for ethanol production without impacting food production. This corresponds to our MRX and MRS
scenarios, which both assumed an even distribution of maize replacement. However, our results suggest replacing current crops in key areas could maximize the reductions in DIN export from the MARB, while minimizing impacts on streamflow. For example, relatively high DIN leaching coupled with low maize productivity in the portions of the domain with highest precipitation suggests that in these areas, transitioning to cellulosic production may have the greatest potential to improve water quality with minimal impacts on water quantity. While changes in total discharge were small relative to DIN export at the outlet of the MARB, there were areas in the western, drier portions of the basin where differences in runoff and streamflow were notable, especially in the higher fraction replacement scenarios for miscanthus (Figs 3 and 6). Our results show that switchgrass has similar water use to maize in these regions; therefore, replacing maize with switchgrass rather than miscanthus in these areas could minimize changes to streamflow (Fig. 6).

The simulations indicated no significant change in DIN export across the 0–100 kg N ha\(^{-1}\) fertilization scenarios for miscanthus and switchgrass, but changes did occur at and above 150 kg N ha\(^{-1}\). The model simulations indicated that most of applied N is being taken up during the growing season and translocated to the rhizome during senescence or removed with biomass at harvest. These simulations agree with measurements made in Central Illinois, where miscanthus and switchgrass averaged peak N content values of ca. 340 and 170 kg N ha\(^{-1}\) during the growing season and declined to ca. 200 and 60 kg N ha\(^{-1}\) by December, respectively, in aboveground biomass (Dohleman et al., 2012). The decrease in aboveground N is largely accounted for by the process of remobilization or translocation to the roots and rhizomes where N is stored. The remaining N is lost through litter fall (Dohleman et al., 2012). The remaining aboveground N would be removed from the agro-ecosystems N cycle during harvest (Heaton et al., 2009; Dohleman et al., 2012) and would not be available for leaching and export by the riverine waters. However, the relatively prolonged period of rigorous growth for perennials, especially miscanthus, compared to annual row crops such as maize and soybean, should

![Simulated annual mean and percent change relative to control with a 95% confidence interval for discharge (a, b) and DIN export (b, d) at the outlet of the Mississippi–Atchafalaya River Basin over the 33-year period spanning 1970–2002 for the control, 0 and 100 kg N ha\(^{-1}\) fertilizer scenarios for the miscanthus (a, b) and switchgrass (c, d) replacement scenarios. The dashed lines represent no change relative to control.](image-url)
reduce losses of DIN that occur during times of drainage prior to and after annual crop growth when the soil is not frozen.

The simulations showing efficient uptake of N that results in low leaching rates are supported by numerous studies for miscanthus and switchgrass (Christian & Riche, 1998; McIsaac et al., 2010; Smith et al., 2013). However, nutrient leaching in miscanthus and switchgrass is dependent on factors including soil type (Behnke et al., 2012), stand maturity (Christian et al., 1997) and successful establishment (Smith et al., 2013; Lesur-Dumoulin et al., 2016). In cases of poor establishment, leaching rates for miscanthus have been shown to be similar to nearby plots in the maize/soy rotation (Smith et al., 2013; Lesur et al., 2014). Variation of reported leaching rates under miscanthus and switchgrass has generally been small, which can be attributed to similar management and soil conditions for the research plots (e.g., McIsaac et al., 2010; Smith et al., 2013). However, one study has indicated significant increases in DIN leaching with increasing fertilizer application rate, which could be attributed to the sandy loam capped soils in that particular field site (Behnke et al., 2012).

This research is the first representation of altered land use to accommodate bioenergy feedstocks that explicitly simulates streamflow and DIN export for the entire MARB. We have focused on major hypothetical scenarios associated with the possibility of large-scale land use change related to percentage fraction of land use conversion (5–25%), nutrient applications rates (0–200 kg N ha⁻¹), biofuel feedstock (miscanthus and switchgrass) and type of current vegetation replaced (existing major croplands in relative proportions or just replacing maize). These scenarios, however, are very general and hypothetical and will need to be refined as the biofuel industry matures. Updates to these scenarios could change the results but are likely to fall within the range and patterns shown for the hypothetical scenarios. Given the long-term and large-scale focus of this study, factors that may increase the DIN leaching such as poor establishment and immaturity of the stand (e.g., Smith et al., 2013) were not considered. The timing of harvest and stand age may also have a significant effect on the N concentrations of biomass (Heaton et al., 2009) and the mass of N removed at harvest (Boersma et al., 2015). In this study, a constant harvest date for miscanthus and switchgrass was used; therefore, the influence of timing of harvest was not accounted for. There are also numerous socioeconomic, agronomic, logistical and policy factors that will influence the selection and management of crops grown in a given area that are not directly considered in the current study. Given the large range of various factors that determine the ultimate fate of maize grain from an area, we made the simplifying assumption that the maize grain used for ethanol comes from an even distribution of land under maize production. Finally, the coupled model does not account for the potential for a feedback to occur between the biosphere and atmosphere whereby changes in surface hydrology associated with increased ET could affect local to regional climate (Georgescu et al., 2011). Due to the nascent nature of the cellulosic industry, each of these factors was considered beyond the scope of this analysis.

Our results indicated a significant potential to reduce DIN export from the MARB under various production scenarios, at the scale required to meet RFS2, for cellulosic feedstocks while having a relatively minor impact on total discharge. However, even the scenarios that simulate total replacement of current maize ethanol with miscanthus or switchgrass, DIN export was reduced to the EPA target levels every year. This suggests that targeted production of cellulosic feedstocks within particularly sensitive portions of the MARB is essential for maximizing the ecosystem services (Blesh & Drinkwater, 2013). Therefore, cellulosic feedstocks can be an important strategy for reducing the Gulf of Mexico ‘dead zone’ while potentially providing a range of additional ecosystem services.

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References

Adler PR, Del Grosso SJ, Parton WJ (2007) Life-cycle assessment of net greenhouse gas flux for bioenergy cropping systems. Ecological Applications, 17, 675–691.
Alexander KB, Smith RA, Schwarz GE, Boyer EW, Niodan JV, Brakebill JW (2008) Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environmental Science & Technology, 42, 822–830.
Amougou N, Bertrand I, Cadoux S, Recous S (2012) Miscanthus × giganteus leaf senescence, decomposition and C and N inputs to soil. Global Change Biology – Bioenergy, 4, 698–707.
Anderson-Texeira KJ, Masters MD, Black CK, Zeri M, Hussain MZ, Bernacchi CJ, DeLucia EH (2013) Altered belowground carbon cycling following land-use change to perennial bioenergy crops. Ecosystems, 16, 508–520.
Aulensbach BT, Buxton HT, Battaglin WA, Coupe IH (2007) Streamflow and Nutrient Fluxes of the Mississippi-Atchafalaya River Basin and Subbasins for the Period of Record Through 2005 (USGS Open-File Report 2007-1080).
Bagley JE, Davis SC, Georgescu M et al. (2014) The biophysical link between climate, water, and vegetation in bioenergy agro-ecosystems. Biomes and Bioenergy, 31, 187–201.
Beale CV, Long SP (1997) Seasonal dynamics of nutrient accumulation and partitioning in the perennial C₄ grasses Miscanthus × giganteus and Spartina cynosuroides. Biomes and Bioenergy, 12, 419–428.
Behnke GD, David MB, Voigt TB (2012) Greenhouse gas emissions, nitrate leaching, and biomass yields from production of Miscanthus × giganteus in Illinois USA. Bioenergy Research, 5, 801–813.
