Hydrologic and water quality impacts of biofuel feedstock production in the Ohio River Basin

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Abstract

This study addresses the uncertainties related to potential changes in land use and management and associated impacts on hydrology and water quality resulting from increased production of biofuel from the conventional and cellulosic feedstock. The Soil Water Assessment Tool (SWAT) was used to assess the impacts on regional and field scale evapotranspiration, soil moisture content, stream flow, sediment, and nutrient loadings in the Ohio River Basin. The model incorporates spatially and temporally detailed hydrologic, climate and agricultural practice data that are pertinent to simulate biofuel feedstock production, watershed hydrology and water quality. Three future biofuel production scenarios in the region were considered, including a feedstock projection from the DOE Billion-Ton (BT2) Study, a change in corn rotations to continuous corn, and harvest of 50% corn stover. The impacts were evaluated on the basis of relative changes in hydrology and water quality from historical baseline and future business-as-usual conditions of the basin. The overall impact on water quality is an order of magnitude higher than the impact on hydrology. For all the three future scenarios, the sub-basin results indicated an overall increase in annual evapotranspiration of up to 6%, a decrease in runoff up to 10% and minimal change in soil moisture. The sediment and phosphorous loading at both regional and field levels increased considerably (up to 40–90%) for all the biofuel feedstock scenario considered, while the nitrogen loading increased up to 45% in some regions under the BT2 Study scenario, decreased up to 10% when corn are grown continuously instead of in rotations, and changed minimally when 50% of the stover are harvested. Field level analyses revealed significant variability in hydrology and water quality impacts that can further be used to identify suitable locations for the feedstock productions without causing major impacts on water quantity and quality.

Keywords: billion-ton study, bioenergy, corn rotation, evapotranspiration, nutrient loading, runoff, sediment loading, soil moisture, stover harvest

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Introduction

It has been almost a decade since bioenergy has emerged as an important source of alternative energy to supplement fossil fuels used in transportation. As of 2015, 64 countries have adopted biofuel production goals to substitute 15–27% of gasoline and diesel with biofuels by 2020–2022 (Wise & Cole, 2015). In the United States, the renewable fuel standard program sets statutory biofuel production target of 136 billion liters per year (BL yr⁻¹) by 2022, of which 58 BL yr⁻¹ were expected to come from corn ethanol and the rest from switchgrass, crop and forest residues, and other advanced energy crops (EPA, 2010). However, production and market constraints have limited the expected development of the cellulosic biofuel and make the targeted timeline for the growth in renewable fuel use difficult to achieve (Chen et al., 2016; GAO, 2016). Consequently, the Environmental Protection Agency (EPA) reduced the 2017 biofuel production target by 20% from 91 to 73 BL (EPA, 2017). Despite this revised target and the current challenge and uncertainty in cellulosic biofuel productions and market, EPA still expects ‘the renewable fuel standard program to deliver steady and ambitious growth in the total amount of renewable fuel produced and used in the United States, consistent with the original goal of the program’ (EPA, 2017).

Another source of uncertainty and a potential challenge to meet the biofuel target is related to the extent of the associated impact on regional and field scale land use (Wright & Wimberly, 2013; Mladenoff et al., 2016), net carbon emission (Searchinger et al., 2008), agricultural practices, and water resources (Fixen, 2007; NRC, 2008; Simpson et al., 2008; Dominguez-Faus et al., 2009; GAO, 2009; Xue & Landis, 2009; Payne, 2010; Powers

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et al., 2010; Welch et al., 2010; Secchi et al., 2011; Chiu & Wu, 2012; Yang et al., 2012). Increased biofuel production could be achieved by changes in land use, crop rotations, and crop yield (Keeney & Hertel, 2009; Kolodski et al., 2009; Dale et al., 2010; Marshall et al., 2011; Perlack & Stokes, 2011; Smith et al., 2012). The Biomass Research and Development Board (Board, 2009) projected that producing the targeted 58 BL yr\(^{-1}\) of corn ethanol in the United States would require an estimated 1.5 million hectares of additional corn lands from that of 2007, if corn yield remains unchanged. Some of these additional lands may come by growing more corn in a row than in rotations (Bales et al., 2010) and converting grasslands and wetlands to cropland (Wright & Wimberly, 2013). Marginal lands have also been widely targeted in recent years for sustainable production of perennial cellulosic crops (Gopalakrishnan et al., 2011; Mladenoff et al., 2016).

The increased agricultural activities associated with the biofuel feedstock productions also raise serious concerns regarding their potential impacts on regional and local water resources (De Fraiture et al., 2008; Donner & Kucharik, 2008; Mubako & Lant, 2008; NRC, 2008; Costello et al., 2009; Dominguez-Faus et al., 2009; Service, 2009; McIsaac et al., 2010; Payne, 2010; Powers et al., 2010; Welch et al., 2010; Vanloocke et al., 2010; Le et al., 2011; Secchi et al., 2011; Wu et al., 2012a,b; Cibin et al., 2016). Particularly, it is not clear how regional and local water resources will be impacted when a variety of feedstock mixes and agricultural practices are used to meet the future biofuel demand. A comprehensive and site-specific modeling that accounts for detailed hydrologic and agricultural factors is necessary for simulating the watershed hydrology, water quality, and biomass production under various production scenarios. This study addresses this research need and evaluates the impacts of increased biofuel feedstock productions from three different scenarios on water quality and water resources in the Ohio River Basin (ORB). The Soil Water Assessment Tool (SWAT2009) (Neitsch et al., 2009), with modified database to incorporate spatial and temporal variability in crop parameters and agricultural practices such as harvesting ratio, is used for integrated simulations of hydrology, soil erosion, nutrient cycles, and crop growth. The current study is built on the results of our earlier research on the Upper Mississippi River Basin (UMRB) (Demissie et al., 2012a,b), but look closely at the associated impacts at the field as well as regional scales under various feedstock production mixes and field characteristics such as slope. The model is calibrated for corn yield at the sub-basin levels, stream flow, and loadings at different locations. The impact analyses were conducted on three plausible future biofuel production scenarios, which entail different types of land use and managements changes, including a mix of conventional and cellulosic feedstock.

Despite the ORB being an important basin for current and future biofuel feedstock productions, to date, limited studies explored the associated impacts on the basin water resources (Alshawaf et al., 2016; Panagopoulos et al., 2017). Alshawaf et al. (2016) applied the SPARROW regression model for the entire Mississippi River basin to assess the land use needs and nitrogen flux to meet the 2022 biofuel target from increased production of hay, corn, and switchgrass. Panagopoulos et al. (2017) applied SWAT for the Upper Mississippi, Ohio, and Tennessee Rivers basins to assess the changes in the rivers discharges and water qualities related to different levels of stover harvest and the inclusion of switchgrass and Miscanthus on marginal and nonmarginal lands. The results from the two studies show significant water quality benefits from perennial feedstock and a decrease in river discharge. In this study, in addition to the 50% stover harvesting scenario considered by Panagopoulos et al. (2017), we have presented additional biofuel feedstock production scenarios from changes in current corn rotations and implementation of the DOE’s Billion-Ton (BT2) Study, which provides different land use and management changes for environmentally sustainable biofuel feedstock production (Perlack & Stokes, 2011). The impact assessment also includes soil moisture and evapotranspiration and look at the hydrology and water quality impacts at major sub-basins level, Hydrologic Response Unit (HRU) level, and different slope groups.

**Materials and methods**

**The Ohio River Basin**

The ORB is one of the six main sub-basins contributing to the Mississippi River (Fig. 1). The basin has more than 42 million hectares, partially covering 11 Eastern and Midwestern states in the United States. Although this area represents only 20% of the Mississippi River basin area, the ORB is considered to be one of the primary sources of flow (49%), phosphorus (29%), and nitrogen (32%) to the Mississippi River, which eventually flows into the Gulf of Mexico (Goolsby et al., 1999; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). The land use in the region is predominantly forest (51%), followed by pasture, hay, and alfalfa (20%). The agricultural land for corn, soybean, and wheat constitutes about 17% of the total area, while urban areas make up about 10%. This region is expected to supply a large amount of corn grain, stover, and perennial grass biomass for biofuel (Perlack & Stokes, 2011). More detail descriptions of the basin, including the geographically distributed data used to develop the model, can be found in the Supporting Information.
SWAT model (ORB-SWAT)

The study used the SWAT version 2009, which is a physically based model that can simulate daily or hourly hydrology and nutrient cycles, soil erosion, and plant growth under various soil, climate, land use, and management conditions of a watershed. The model has been satisfactorily validated for different watershed and climate conditions (Gassman et al., 2007, 2014; Krysanova & White, 2015; Panagopoulos et al., 2015a; Volk et al., 2016), and it is capable of simulating conventional and cellulosic biomass production through land use and management changes, as well as their associated impacts on regional and local water resources (Demissie et al., 2012a,b; Wu et al., 2012a; Wu & Liu, 2012; Deb et al., 2015; Cibin et al., 2016; Chen et al., 2017; Panagopoulos et al., 2017). SWAT was used for the ORB to study the impacts of climate change on hydrology, water quality, and crop productivity (Panagopoulos et al., 2015b), the water quality benefits of conservation practices (Santhi et al., 2014). The ORB-SWAT model specifically (i) incorporated the typical land use dynamics in the region through four-year rotations of corn, soybean, wheat, and hay from 2003 to 2006, (ii) used recently and spatially distributed data in agricultural practices and climate, (iii) validated for its performance to adequately simulate the biofuel crop production in addition to the basin hydrology and water quality, and (iv) used modified crop database to account for spatial variations in the corn growth parameters and harvest indices. The basin was discretized to 120 sub-basins based on the USGS’s 8-digits HUC map (USGS, 2014), which are further discretized to 14,280 HRUs that represent the unique combinations of land use, slope, soil, and management. The hydrology and water quality results from affected HRUs were used for the field scale assessment of the impacts of biofuel feedstock productions.

The model simulates the daily hydrology and water quality of the basin from 1987 to 2009. The first 3 years were used for tuning or warm-up the model, while the remaining years were used for calibration (1990–2004) and validation (2005–2009). Extensive model parameters sensitivity were conducted using 20 years of observed water quality and stream discharge data from seven USGS gauges located along the mainstream and tributaries. The model’s ability to estimate spatially varying crop growth and biomass production was validated by comparing modeling result with observed corn and soybean yields from 2006 to 2009 baseline years (see the Supporting Information for detail). For the scenario analysis, the model was run for 8 years (including 4 years warm-up) under the three future biofuel scenarios. The corn growth parameters in the ORB-SWAT were adjusted during the scenario runs to fit the anticipated increase in corn yield in 2022. Splitting some of the HRUs was also needed to implement the land use conversions as projected by the DOE’s BT2 Study. The daily average model results from the four-year baseline and future scenarios were used to determine the relative impacts of the biofuel scenarios. The resulting changes in hydrology and water quality were
summarized and analyzed at both the sub-basin and HRU levels.

**Biofuel feedstock production scenarios**

In response to the growing feedstock demand for biofuel production, the current corn rotation, stover harvest, and other land use and management practices might be changed in the ORB. This study examined the potential impacts of these changes on annual hydrology and stream quality of the basin, with the overall goal of providing a much needed site-specific insight about the sustainability of increasing biofuel feedstock production in the basin. Historically, corn is grown in the region mostly in rotation with soybean and wheat to maintain the soil productivity, control weeds, and decrease the need for supplemental fertilizer inputs. However, based on the cropland data layers obtained from the USDA’s National Agriculture Statistics Service, over the past decade, the area of continuous corn has increased in the ORB region by up to 15.5%. The ‘Continuous Corn’ scenario considered in this study assumed this trend to continue in the future as the demand for ethanol increases. The ‘Stover Harvest’ scenario assumed that portion of corn stover will be harvested from the field as the demand and production capacity for the cellulosic-based biofuel increases in the future. The ‘Billion-Ton Study’ scenario applied the biofuel feedstock projection by DOE (Perlack & Stokes, 2011) through changes in land use, crop management, and harvest of agricultural residuals. The results from the above three future scenarios were compared with both the historical ‘Baseline’ (2006–2009) and a future ‘Business-as-usual (BAU)’ scenario, which represents the increased crop yield without changes in land use in 2022. The relative changes in nitrogen, phosphorus, and sediment loadings, as well as evapotranspiration, soil moisture content, and stream discharge, were determined at sub-basin and HRU (field) scales. Table 1 presents a summary of the baseline and the future scenarios, and the associated change in corn areas, fertilizer applications, and tillage practices for the major tributaries in the ORB.

**Baseline and business-as-usual scenarios**

Land use and agricultural practices from 2006 to 2009 were used for developing the baseline scenario, which represents the basin condition under the observed large-scale production of biofuel in 2007. The average corn area during the baseline years is 3.6 million hectares, which is about 8.6% of the basin area, with 61% of this area located in the Wabash River sub-basin and 21% in the Lower Ohio, Big Sandy, and Great Miami River sub-basins. The basin average corn yield, nitrogen, and phosphorus applications rates are 6532, 160, and 72.6 kg ha\(^{-1}\), respectively. Conventional tillage, reduced tillage, and no tillage are used for approximately 53%, 22%, and 26% of the corn areas. The results on hydrology and water quality from the baseline model run were used as a reference for assessing the relative changes within the basin under the future scenarios.

A BAU scenario was developed in which the future crop acreage and agricultural practices remain the same as those in the baseline, while the corn yield and the corresponding nitrogen fertilizer application were increased (Table 1). We assumed a steady 1% annual increase in corn yield from 2006 to 2022, which leads to a 16.4% increase in basin-wide average corn yield. The required additional nitrogen fertilizers for each sub-basin were computed according to historical trends and using equations developed by Wu et al. (2012a). The basin average nitrogen application rate is 170.5 kg ha\(^{-1}\), which is a 6.5% increase from baseline application rate. The application rates for the phosphorus fertilizer remain the same as that of the baseline rates.

**Continuous Corn Scenario**

During the 2006–2009 baseline years, continuous corn accounts for 18% of the corn cultivating areas in the ORB, while the rest of the corn areas were in one (10%), two (66%), or three (6%) years of crop rotations with soybean, wheat, and hay. The scenario assumes replacement of these corn rotations from the baseline time period with continuous corn in the future, which resulted in an additional 2.3 million hectares of corn land (Table 1). Given the benefits of the rotations for the soil and its nutrients, replacing all the corn rotations with continuous corn for 4 years might be considered as an extreme scenario. However, with increasing demand for corn and uses of supplemental fertilizers, more areas may start growing corn in a row for 4 years than in rotation in the future. Nitrogen and phosphorus fertilizer application rates for corn remain at the same level as the baseline rates, while switching to continuous corn production resulted in an increased total corn area and overall fertilizer inputs. It is a standard practice in the region to increase the nitrogen fertilizer when corn is grown in a row (Sawyer et al., 2006). Further study is needed to assess the impact of this scenario under adjusted nitrogen fertilizer. Conventional tillage was assumed to be used in the newly converted corn land from soybean, wheat, and hay. Corn has relatively high residue and high root carbon-to-nitrogen (C/N) ratio of 48 : 1, making the residues to decompose less quickly than legume crops like soybean. Conventional tillage is thus often needed in continuous corn acres to help reduce soil compaction, incorporate fertilizer, and break up residue from the previous season (Randall et al., 1996). The scenario was implemented in the calibrated ORB-SWAT model by incorporating the new corn rotations into the land use parameter and adjusting the corresponding agricultural practices for each sub-basin. The corn growth parameters and potential yield remained the same as those in the baseline scenario. As shown in Table 1, the majority of the baseline corn production occurred in the Wabash River sub-basin, which was also affected significantly by the change in rotation.

**Stover harvest scenario**

Agricultural residues, including corn stover, are widely recognized to play an important transitional role from grain-based first-generation biofuel feedstock to cellulosic biofuel feedstock, with the additional advantage that extra cultivation land is not required. In this scenario, based on the EPA (2010)
## Table 1  Scenarios descriptions showing changing in corn land areas and management for the major tributaries in the Ohio River basin

| Basins of major tributaries | Allegheny | Monongahela | Upper Ohio | Muskingum | Kanawha | Big Sandy | Great Miami | Middle Ohio | Kentucky-Licking | Green | Wabash | Cumberland | Lower Ohio | ORB |
|-----------------------------|-----------|-------------|------------|-----------|---------|-----------|------------|------------|-----------------|-------|--------|------------|-----------|-----|
| Baseline Area               | 88.5      | 19.1        | 65.3       | 86.7      | 9.3     | 22.4      | 272.3      | 77.5       | 18.6            | 138.0 | 2221.0 | 127.2      | 271.7     | 3551.1 |
| Yield                       | 5.6       | 5.9         | 6.8        | 7.4       | 7.5     | 6.7       | 8.6        | 8.2        | 6.6             | 7.2   | 12.0   | 6.3        | 5.1       | 1.7  |
| NP                          | 82.32     | 67.26       | 125.50     | 165.68    | 131.83  | 184.75    | 181.78     | 145.60     | 156.57          | 185.67| 160.77 | 118.55     | 166.68    | 164.74 |
| NT/RT                       | 22.30     | 33.60       | 28.25      | 28.16     | 44.11   | 22.16     | 27.23      | 29.23      | 59.25           | 71.2  | 17.22  | 67.32      | 48.19     | 2621  |
| Values                      | 38.61     | 61.47       | 47.56      | 45.45     | 42.62   | 50.48     | 16.16      | 7.48       | 6.1             | 7.6   | 61.49  | 1.33       | 33.50     | 52.78 |
| Billion-Ton Area            | 30.4      | 7.1         | 60.8       | 139.7     | 1.8     | 27.57     | 32.06      | 108.3      | 14.7            | 167.7 | 2520.6 | 107.5      | 30.00     | 4084.9 |
| Study Area                  | 6.7       | 6.8         | 8.1        | 8.8       | 7.8     | 8.6       | 11.5       | 9.0        | 7.3             | 8.7   | 9.77   | 8.4        | 8.2       | 9.4   |
| NP                          | 88.32     | 74.26       | 134.32     | 183.72    | 130.83  | 200.81    | 207.87     | 150.62     | 156.57          | 194.09| 197.85 | 128.56     | 175.71    | 190.80 |
| NT/RT                       | 33.14     | 44.13       | 35.18      | 32.15     | 68.14   | 34.11     | 38.14      | 36.16      | 62.12           | 78.10 | 23.15  | 80.15      | 53.13     | 3214  |
| CT                          | 33.43     | 47.53       | 47.53      | 18.55     | 48.48   | 48.26     | 12.62      | 34.33      | 5.37            | 1.33  | 75.12  | 1.75       | 13.85     | 24.23 |
| Stover**                    | 0.0       | 0.0         | 29.3       | 178.5     | 0.0     | 522.5     | 942.4      | 119.2      | 0.0             | 166.6 | 4988.1 | 0.0        | 35.9      | 7284.5 |
| BAU Yield                   | 6.8       | 7.4         | 7.9        | 9.0       | 8.1    | 7.6       | 9.6        | 9.1        | 7.3             | 8.1   | 8.7    | 8.3        | 7.9       | 8.6   |
| NP                          | 88.32     | 88.26       | 130.30     | 172.68    | 131.83  | 184.75    | 186.78     | 145.60     | 156.57          | 190.67| 175.77 | 128.55     | 167.88    | 175.74 |
| Continuous Area             | 90.5      | 21.5        | 66.7       | 91.1      | 10.4   | 397.1     | 464.8      | 114.1      | 20.5            | 167.0 | 4011.7 | 136.5      | 373.7     | 5092.9 |
| Corn Yield                  | 5.3       | 5.6         | 6.6        | 7.1       | 6.2    | 6.4       | 8.2        | 8.1        | 6.1             | 7.0   | 6.9    | 6.5        | 6.8       | 6.9   |
| Stover Yield                | 4.8       | 5.3         | 5.6        | 6.0       | 5.8    | 5.9       | 7.6        | 7.7        | 5.8             | 6.6   | 6.3    | 6.1        | 6.9       | 6.4   |
| Harvest Area                | 91.36     | 78.31       | 136.54     | 178.73    | 143.88  | 197.81    | 19082      | 15664      | 16761           | 191.09| 166.79 | 131.60     | 176.72    | 171.77 |
| Stover                      | 206.9     | 46.9        | 147.0      | 249.5     | 29.7   | 608.7     | 1010.4     | 291.0      | 53.8            | 52.6  | 7013.6 | 417.6      | 954.9     | 11556 |

*Major sub-basins within the ORB excluding the Scioto River basin which has relatively smaller corn area.
†Corn areas in thousand hectares. As there are no explicit land use changes for the BAU and Stover scenarios, the corn areas in those scenarios are the same as that of the Baseline.
‡Corn yield in dry-ton per hectares. The corn growth parameters in the ORB-SWAT model were calibrated to fit the spatially varying historical corn yield for the Baseline scenario, and future yield for the feedstock projection and BAU scenarios.
§Commercial nitrogen and phosphorus fertilizer applications rates in kg ha⁻¹. The baseline application rates are used for the Stover and Continuous Corn scenarios, while they were modified for the BAU based on projected increase in corn yield, plus amount of stover harvested for the feedstock projection.
¶Percentages of corn areas under no tillage (NT), reduce tillage (RT), and conventional tillage (CT). Except for the feedstock projection scenario, the tillage proportions from the Baseline scenario were applied for all the scenarios.
**Corn stover yield in thousand dry-ton. The corn grain assumed constituting 50% of the aboveground biomass up on harvesting. The Baseline, BAU, and Continuous Corn scenarios assumed that the entire stover were left on the field, while some fractions of the stover were harvested for cellulosic biofuel for feedstock projection and Stover scenarios.
estimates of sustainable stover harvest, we have considered 50% stover harvest after harvesting the grains from the existing corn fields. This was implemented in the model by changing the corn harvest index, which represents the fraction of the aboveground biomass that is removed during the harvest operation, in the plant database from 0.5 (the corn grain proportion that was obtained from the calibration) to 0.75. In addition, the baseline nitrogen and phosphorus fertilizer application rates were increased accordingly to supplement the amount of nutrients removed with the harvested stover, which was assumed to contain 0.0035 g of nitrogen and 0.0014 g of phosphorus per gram of stover (Neitsch et al., 2009). The scenario yields approximately 10.5 billion kg of feedstock annually of which more than half came from the Wabash River sub-basin (Table 1). Corn parameters and tillage remain the same as in the baseline years. The basin average nitrogen and phosphorus application rates increased to 167.5 kg ha⁻¹ (5% increase from baseline) and 75.5 kg ha⁻¹ (4% increase from baseline), respectively.

Billion-Ton study scenario

This scenario applied changes in feedstock production and agricultural practices projected by a selected future scenario from the DOE’s BT2 study (Perlack & Stokes, 2011). Perlack & Stokes (2011) estimated the U.S. cellulosic feedstock resources for the sustainable production of biofuel under different future feedstock prices ranging from $20 to $80 per dry-ton and annual crop yield increase from 1% to 4%, as driven by market demand. The feedstock projection scenario for the 2022 projection year was selected based on the USDA projection of about 1% increase in corn yield (USDA, 2012) and assuming an average cellulosic feedstock price of $50.0 ton⁻¹. Unlike the other two scenarios we have considered, this scenario involves multiple changes in land use and management changes that vary across the basin. Corn, soybean, wheat, and idle land areas are expected to gain about 444, 91, 26, and 451 thousand hectares, respectively, while hay and pasture loss is expected to be about 1012 thousand hectares, in comparison with the baseline land use. In addition, 7.3 million dry-tons of stover are expected to be harvested from approximately one-third of the corn farms in the basin, with a harvest rate (percent of stover harvested to stover grown) of up to 18%. In this scenario, nitrogen fertilizer was applied in the newly converted corn land at the same rate as that used in the BAU scenario. The rate of phosphorus fertilizer application remains the same as that of the baseline. Application rates of supplemental nitrogen and phosphorus when stover is harvested are consistent with the rates used in the stover harvest scenario. The feedstock projection scenario also incorporates increased conservation tillage (reduced-till or no-till) and decreased conventional tillage (Table 1). These changes were implemented in the ORB-SWAT model by modifying the corresponding HRU and management files as described in Demissie et al. (2012a,b). A further description of the individual land use and management changes within the sub-basin as well as their implementation into the model is provided in the Supporting Information.

Results

Feedstock and biofuel productions

Analyses of the feedstock production potential of the different scenarios indicated the critical role that the ORB can play in future biofuel production (Table 2). An increase in corn yield alone would increase corn production from approximately 23.9 billion dry-kilogram (BDK) of corn grain in the baseline years to 28.1 BDK of grain by 2022 under the BAU scenario. Assuming 41% of the grain is harvested for biofuel with a conversion rate of 10.79 L per 25.40 dry-kg (or one bushel) of corn (EPA, 2010), biofuel production in the basin would increase from baseline 4.16 billion liters (BL) to BAU 4.88 BL (17.8% increase). If corn is grown continuously, instead of in rotation with soybean and other crops, an additional 2.3 million hectares of land would be available to cultivate corn and produce an additional 13.6 BDK of grain compared to the baseline scenario. This yield enables the production of 6.51 BL of biofuel from the ORB. On a per hectare basis, the corn yield was found to be less when corn is grown continuously than in rotations, highlighting the need to increase the nitrogen fertilizer when corn is grown following corn.

The Stover scenario resulted in a slight decrease in corn yield; however, the overall production generated under the scenario is expected to be 21.1 BDK of corn grain and 10.5 BDT of stover. The decrease in the corn yield is likely because the supplemental nitrogen added to replace for the nitrogen removed in stover was not sufficient to maintain the baseline yield. As described earlier, we have added 5% supplemental nitrogen for the HRUs affected by stover removal, but a recent similar study by Panagopoulos et al. (2017) added 20% nitrogen for 50% stover removal and still observed a slight decrease in the corn yield. Using 10.79 and 349.4 L per 25.40 dry-kg for grain and stover conversions, respectively (EPA, 2010), a total of 7.68 BL of biofuel would be produced from the ORB. Finally, the BT2 scenario provides the largest amount of biomass among the future scenarios from corn and stover. The biomass production under this scenario is expected to be 35.1 BDK of corn grain and 6.6 BDK of stover that can be used to produce about 8.67 BL of biofuel, which is more than double of the amount of biofuel produced in the baseline scenario.

Watershed and sub-basin level impacts on hydrology and water quality

Figure 2 shows the percentage changes in basin average annual evapotranspiration, soil moisture content, water yield (or flow), total nitrogen, total phosphorus, and
suspended sediment loadings for the four future scenarios relative to the baseline scenario. The box-plots represent the variations in the 120 sub-basins of the ORB. As noted in earlier studies (e.g., Demissie et al., 2012a,b; Cibin et al., 2016), the overall impacts of biofuel production are order of magnitude higher on water quality than water quantity. The average annual evapotranspiration \((ET)\) in the ORB was 648.4 mm in the baseline years. Compared to this value, both the future biofuel and BAU scenarios have relatively higher rates from the majority of the sub-basins, with the impact on sub-basins being more noticeable for the BT2 scenario (up to 5%) followed by the Continuous Corn (1%), Stover and BAU scenarios (0.5%) (Fig. 2). Changes in runoff (water yield) reflect the ET and the soil moisture conditions of a sub-basin, as more ET and less soil moisture lead to less runoff and streamflow. Consequently, the runoff contributions from the majority of the sub-basins were decreased, with the reduction being higher for the BT2 (up to 10%), Continuous Corn (2%), Stover and BAU (1%) scenarios from the average annual runoff of 487.2 mm during the baseline years. There are no clear trends in sub-basin soil moisture in the future scenarios, except for the Stover scenario, in which soil moisture from all the sub-basins slightly decreased.

The average annual sediment, nitrogen, and phosphorus loadings from the basin during the baseline years are estimated to be 0.78 ton ha\(^{-1}\), 9.6 kg ha\(^{-1}\), and 1.22 kg ha\(^{-1}\), respectively. Except for the BAU scenario, the three biofuel scenarios showed increased sediment loading from the majority of the sub-basins ranging up to 90% for the BT2 scenario, 16% for the Stover scenario, and 14% for the Continuous Corn scenario despite estimated reduction in runoff volume from all the scenarios. The nitrogen loading in a majority of the sub-basins decreased by up to 8% (or 1.5 kg ha\(^{-1}\)) for the BAU scenario and by up to 12% (or 3.0 kg ha\(^{-1}\)) for the Continuous Corn scenario. The effect of the Stover scenario on basin-wide nitrogen loading is relatively minor, in which sub-basin showed either increased or decreased loadings. For the BT2 scenario, nitrogen loading increased in most sub-basins, with some of these sub-basins showing approximately 50% increases. The phosphorus loadings from most of the sub-basins increased

Table 2  Available feedstock and biofuel productions under baseline and future scenarios we have considered

| Feedstock | Baseline | BAU | Continuous Corn | Stover Harvest | Billion-Ton Study (BT2) |
|-----------|----------|-----|-----------------|----------------|------------------------|
| Biomass (BDK) | 23.9 | 28.1 | 37.5 | 21.1 | 10.5 | 35.1 | 6.62 |
| Biofuel (BL) | 4.16 | 4.88 | 6.51 | 3.63 | 4.05 | 6.13 | 2.54 |

Fig. 2  Percentage changes on sub-basin annual hydrology (evapotranspiration ET, soil moisture SW, water yield FLOW) and water quality (suspended sediment SED, total nitrogen TN, total phosphorus TP) of the biofuel and business-as-usual scenarios from the baseline conditions. The box-plots represent the variations of the impacts over the 120 sub-basins of the Ohio River basin. The bottom (Q1) and top (Q3) of the boxes are the 25th and 75th percentiles, the whiskers extend by 1.5 interquartile range (Q3–Q1), and the circles are outliers and represent individual sub-basins.
for the three biofuel scenarios with the Continuous Corn and BT2 scenarios showing comparable increases followed by the Stover scenario.

It is also worth noting that there are many sub-basins in the ORB (including the Kanawha, Kentucky-Licking, and Monongahela Rivers sub-basins) that are not predominantly agricultural, where corn was cultivated in less than 1% of the areas in the sub-basins. In fact, these areas are heavily covered by forest and pasture, and there are no land use changes under any of the future scenarios. Consequently, changes in water quality and hydrology in these sub-basins were largely zero and could skew the basin average value toward zero as indicated by the box-plots. The water quality impacts at the sub-basin level are presented in Fig. 3, while the hydrology impacts are presented in the (Appendix S6). Considering the Wabash, Great Miami, Big Sandy, and Lower Ohio River sub-basins, which contain large portions of the corn production areas (>90%), the sediment loadings from most of the affected HRUs within those sub-basins show a considerable decrease in the BAU scenarios but increase in the other three biofuel scenarios. The nitrogen loadings decrease in the BAU and Continuous Corn scenarios for all of those HRUs, but increase in the BT2 scenario and vary in the Stover scenario with the Lower Ohio sub-basin showing increased loadings and the Great Miami sub-basin showing decreased loadings. The phosphorus loading from those four sub-basins increased considerably with the Continuous Corn and BT2 scenarios, with both scenarios showing similar levels of increases.

**HRIU level impacts on hydrology and water quality**

Figure 4 demonstrates the hydrology and water quality impacts on the individual HRUs affected by the BAU, Continuous Corn, and Stover harvest scenarios as functions of slope groups in the ORB. Each data points represents a single HRU that grew corn during both baseline and future scenarios years. As expected, most of the corn growing areas are located on relatively flatter fields: 60% on a slope range of 0–1% and 36.8% on a slope range of 1–4%. The changes in ET for the BAU scenario showed no apparent average trends for the slope groups <4%, but showed increased trends for most of the HRUs with slopes ≥4%. The ET from Continuous Corn scenario was higher for most of the HRUs, with the impact being more pronounced as slopes increase. While the ET from the Stover scenario increased for all the HRUs by similar levels (up to 20 mm yr⁻¹) independent to their slope groups. Similar to the results from the sub-basin level analysis, the change in ET is also reflected in soil moisture and runoff changes, with the soil moisture content and runoff for the majority of the HRUs showing a noticeable reduction over the entire slope groups for the three scenarios, with the reductions becoming more apparent with increasing slope.

The sediment loading from the HRUs decreased in the BAU scenario, in comparison with the sediment loading associated with the baseline, particularly in higher slope areas. In contrast, the Continuous Corn scenario yields higher sediment loading from the HRUs, which increased with increasing slope. The sediment loading for the Stover scenarios has increased for all the HRUs, with the increase being higher from steep slope HRUs. No apparent increasing or decreasing trends were observed for the phosphorus loading from the HRUs under the BAU scenario, while considerable increase in the phosphorus loading was noted for both the Continuous Corn and Stover scenarios, with the increased being order of magnitude higher for the Continuous Corn scenario. Unlike to the sediment and phosphorus loadings, the impacts of the three scenarios on the nitrogen loading were not obvious or consistent. Overall, the nitrogen loading seems to decrease slightly for majority of the HRUs in the BAU and Continuous Corn scenarios regardless of slope, but it showed no clear trend in the Stover scenario.

Figure 5 shows the impacts of hydrology and water quality on HRUs as a result of the BT2 scenario. Each circle represents a single HRU, and the land use conversions are denoted from baseline crops – BT2 crops on the x-axis. Note that corn yield in the baseline scenario (e.g., corn-soybean yield in the figure) is lower than that in the feedstock projection scenario (e.g., soybean-corn yield). As the ORB gains 444 thousand hectares of corn, 451 thousand hectares of idle land, 91 and 26 thousand of soybean and wheat in the BT2 scenario, the changes in the HRU are expected to vary significantly depending on the types of land use changes. Conversion of pasture and idle lands to row crops (such as corn, soybean, and wheat) led to increased annual ET and decreased soil moisture and runoff from the HRUs (and vice versa). The sediment, nitrogen and phosphorus loadings also increased when pasture and idle lands were converted to row crops, with the impacts being relatively higher for pasture-corn conversions. Further, the conversion of soybean to corn had a relatively minor impact on nitrogen loading but tended to increase the sediment and phosphorus loading.

Figure 5 shows the impacts of hydrology and water quality on HRUs as a result of the BT2 scenario. Each circle represents a single HRU, and the land use conversions are denoted from baseline crops – BT2 crops on the x-axis. Note that corn yield in the baseline scenario
(e.g., corn-soybean yield in the figure) is lower than that in the feedstock projection scenario (e.g., soybean-corn yield). As the ORB gains 444 thousand hectares of corn, 451 thousand hectares of idle land, 91 and 26 thousand of soybean and wheat in the BT2 scenario, the changes in the HRU are expected to vary significantly depending on the types of land use changes. Conversion of pasture and idle lands to row crops (such as corn, soybean, and wheat) led to increased annual ET and decreased soil moisture and runoff from the HRUs (and vice-versa). The sediment, nitrogen and phosphorus loadings also increased when pasture and idle lands were converted to row crops, with the impacts being relatively higher for pasture-corn conversions. Further, the conversion of soybean to corn had a relatively minor impact on nitrogen loading but tended to increase the sediment and phosphorus loading, which, again, suggests that phosphorus storage in the soil in this region is sufficient and that the need for phosphorus fertilization may be reduced. Compared to our earlier SWAT simulation results obtained for the BT2 scenario for the upper Mississippi River basin (Demissie et al., 2012a,b), the differences in nitrogen loading between the two river basins are mostly attributed to the types of land use changes associated with the feedstock projection scenarios.

**Discussion**

**Regional impacts on hydrology and water quality**

The average annual evapotranspiration (ET) in both the future biofuel and BAU scenarios has relatively higher rates from the majority of the sub-basins (Fig. 2). The
increased in ET can be partly attributed to increased corn biomass (BAU and BT2) in the future with relatively large crop and root sizes, high leaf-area indices that result in higher water usage and ET during the growing season. In addition, converting hay land to corn in the Continuous Corn and BT2 scenarios [in the northern ORB (Appendix S5)] would require tillage, leading to more evaporation from the soil. Nevertheless, some of the increased ET rates from a cornfield could be offset by increased conservation tillage (reduce or no tillage) and decreased conventional tillage in the BT2 scenario (Table 1). On the other hand, the decreased ET rates in some of the sub-basins in the BT2 scenario could be caused by increased idle land (451 thousand hectares) in the southwestern ORB (Appendix S5). A small increase in annual ET for the Stover scenario could be caused by the exposure of soil to more evaporation when stover is harvested from the field. The runoff decrease in the BAU scenario can be attributed to the increased future corn biomass and its utilization of more water to grow. For the Stover harvest scenario, runoff might increase from specific storms when the soil is not covered well. However, as our analysis is an annual based, in which case soil moisture condition and evaporation play major roles in the water balance as a dry soil (because of exposure) tends to infiltrate more rainfall, leading to a potential decrease in runoff from all entire sub-basins. There are no clear trends in sub-basin soil moisture in the future scenarios, except for the Stover scenario, in which soil moisture from all the sub-basins slightly decreased. This might be caused by the exposure of the soil surface for evaporation when stover is harvested from the field. A more detailed assessment would be necessary to capture the long-term annual soil moisture by rerunning the model for multiple years.

The increase in sediment loadings at the basin and sub-basin levels (Fig. 2) is mostly attributable to (i) the increased conventional tillage when corn is cultivated continuously without rotation with hay land in the case of the Continuous Corn scenario, (ii) the conversions of
pasture and hay to corn in the case of the BT2 scenario, and (iii) the crop residue not sufficiently cover the soil from erosion when 50% stover is harvested in the case of the Stover scenario. Without increased tillage and stover removal, an increase in corn biomass and yield alone as in the case of the BAU scenario could enable the corn to better hold the soil in place and protect it from the impact of rainfall during the growing season and leave more stover to cover the soil after the harvesting season, which consequently lead to a decrease in suspended sediments loadings for the BAU scenario.

The phosphorus loadings from most of the sub-basins increased for the three biofuel scenarios. The increased phosphorus loading in the Continuous Corn scenario indicates an excess of phosphorus fertilizer input in the land that was converted from soybean and hay to corn. It also suggests the presence of phosphorus storage in the soil in this region because of the relative immobility of phosphorus. The same is true with the BT2 scenario. In addition, some of the increase in phosphorus loading, particularly for the Stover scenario, might be related to the increase in sediment loading from those scenarios. Cibin et al. (2012) also used the SWAT model to study the water quality of harvesting stover, and their results showed an overall increase in nutrients transported with sediment and reduction in nutrients transported in solution. In comparison, the BAU scenario for which phosphorus fertilizer input does not increase while corn biomass increased showed little change in phosphorus loading (Fig. 2). Similar observations were reported by our earlier studies (Demissie et al., 2012a,b; Wu et al., 2012a).

Compared to the impacts on sediment and phosphorus loadings, the impacts on the nitrogen loading was small, with the loading decreased from most of the sub-basins in the BAU and Continuous Corn scenarios, increased for the BT2 scenarios and showed no apparent change for the Stover scenario. The corn biomass in the BAU scenario is relatively large with better roots to uptake the nitrogen input compared to corns in the baseline scenario. For the Continuous Corn scenario, traditionally rotating corn with soybean and other legume crops can help maintain the nitrogen content of the soil, which consequently might leave more nitrogen in the soil (especially after the crop growing season) and make it susceptible to nitrogen runoff and leaching. Therefore, converting rotating corn to continuous corn (e.g., by replacing soybean with corn) could reduce the off-season soil nitrogen content and thus decrease annual nitrogen loading. In addition, the current nitrogen application rate to corn after rotated with soybean might be higher given the soil already maintained some amount of nitrogen from the previous year or alternatively, there is less amount of excess nitrogen for corn
grew continuously without supplemental nitrogen. A field study results by Klokce et al. (1999) also showed that continuous corn production can result in similar or lower nitrogen losses than corn-soy rotation. A similar finding was reported by Jones et al. (2016) who identified soybean as the main source of nitrate in the corn-soybean rotations. On the other hand, other studies such as Randall & Mulla (2001) have found increased nitrate loading from continuous corn plots that than of the soybean-corn plots.

The effect of the Stover scenario on basin-wide nitrogen loading is relatively minor, in which sub-basin showed either increased or decreased loadings. Stover left on the ground after harvesting the grain adds nutrients to the soil. Thus, harvesting stover at a high level would reduce nutrient input and the soil nitrogen, which could lead to a reduction in annual nitrogen loading. Another factor affecting nitrogen loadings is the sequence of corn-related rotations. If corn is followed by soybean, harvesting part of the corn residues might help reduce the nitrogen in the soil and runoff during the soybean growing season. The same was also mentioned in Cibin et al. (2012) and Panagopoulos et al. (2017). For the BT2 scenario, nitrogen loading increased in most sub-basins. The increase might have been caused by converting some of the pasture and hay to row crops (corn, soybean, and wheat), which increases nitrogen fertilizer inputs in the basin.

Field level impacts on hydrology and water quality

Hydrologic Response Unit level analyses were conducted to determine the field level impacts of the biofuel feedstock production on hydrology and water quality. In general, a given HRU may contain more than one field that has similar slope, soil type, land use, and management. The hydrologic and water quality responses from these fields are considered to be the same and represented by the HRU responses. The ET from Continuous Corn and Stover scenarios were higher, with the impact being more pronounced for the Continuous Corn scenario as slopes increase. These indicate that harvesting half of the corn stover and changing land use to continuous corn in combination with increased conventional tillage would expose the soil to more evaporation on all slope ranges. In addition, corn might be rotated with hay and alfalfa on steep slope HRUs during baseline years, resulting in potentially increased ET due to the continuous cultivation of corn on those HRUs in the Continuous Corn scenario.

Similar to the results from the sub-basin level analysis, the change in ET is also reflected in soil moisture and runoff changes, with the soil moisture content and runoff for the majority of the HRUs showing a noticeable reduction over the entire slope groups for the three scenarios, with the reductions becoming more apparent with increasing slope. For the BT2 scenario (Fig. 5), HRUs affected by the land use conversions from pasture, hay, and idle lands to crop lands showed large increase in ET, decrease in runoff and soil moisture content.

The decrease in sediment loading from the HRUs in the BAU scenario can be attributed to the relatively greater biomass and planting density of the corn used in the future BAU scenario compared to the baseline corn biomass (Fig. 4). In contrast, the increased sediment loading from the HRUs in the Continuous Corn and Stover highlights the important functions that leaving stover on the field and rotating corn with hay or alfalfa may have on controlling soil erosion, particularly for areas with steep slopes. A similar increase in sediment loading was also observed when noncrop lands were used for crop production in the BT2 scenario (Fig. 5). The nitrogen loading decreased slightly for most of the HRUs in the BAU and Continuous Corn scenarios, but it showed no clear trend in the Stover scenario. The corn in BAU scenarios is able to uptake and utilize the nutrient more effectively than the corn in the baseline years for similar fertilizer application rates. The Continuous Corn scenario, which involves changing soybean, pasture, and corn rotations to continuous corn could improve the potential over-application of fertilizer and reduce the nitrogen storage in the soil. The loadings from the Continuous Corn scenario showed relatively higher variability, which might be the result of the original land use of soybean, hay, or wheat. In general, the conversion of soybean to corn had a relatively minor impact on nitrogen loading but tended to increase the sediment and phosphorus loading, which suggests the possibility of having excess phosphorus fertilization applications in the region. Consequently, it is a standard practice in the region to apply supplemental fertilizer only for nitrogen when corn is grown following corn. The increase in nitrogen and phosphorus loadings for the BT2 scenario was caused due to the conversion of some of the pasture and hay to row crops (corn, soybean, and wheat), which increases nitrogen fertilizer inputs in the basin. Compared to our earlier SWAT simulation results obtained for the BT2 scenario for the upper Mississippi River basin (Demissie et al., 2012a), the differences in nitrogen loading between the two river basins are mostly attributed to the types of land use changes associated with the feedstock projection scenarios.
In summary, the study explored the implications of land use and management changes associated with biofuel feedstock productions on the Ohio River basin hydrology and water quality using the SWAT model. Three feedstock production scenarios were considered, including land use and management changes projections from the DOE’s BT2 Study, a shift in corn rotation to continuous corn, and harvesting of 50% corn stover. The results from the three scenarios indicate an overall increase in the sub-basins sediment loading reaching up to 10–90%, phosphorus loading up to 5–40%, and a decrease in stream discharges up to 1–10%. The sub-basins nitrogen loading increased up to 40% for the BT2 scenario, decreased up to 10% for the continuous corn scenario, and minimally impacted for the stover scenario.

Compared to the three scenarios, the BT2 scenario results in a large amount of feedstock production, however, with noticeably higher impacts on the basin water resources. Given that the BT2 study aimed at identifying the potential supply of biofuel feedstock without adversely affecting the environment, the result from our study highlights the needs for revising the BT2’s feedstock projections taking into consideration their potential impacts on water resources. Further, caution should be taken regarding land use changes from hay to row crops. Conservation tillage can effectively reduce soil runoff and is especially recommended in the area that land use change from pasture or hay to row crops. The results for the continuous corn scenario indicate an increase in phosphorus loading but a decrease in nitrogen loading, which is partly attributed to the lack of supplemental nitrogen fertilizer. It is a standard practice in the region to increase the nitrogen fertilizer when corn is grown in a row than in a rotation; thus, future modeling analysis for this scenario needs to take this practice into consideration. Compared to the other two scenarios, the stover scenario has relatively lower impacts on both the hydrology and water quality of the basin, particularly in the mild slope regions. Determining the stover harvest levels on the basis of soil characteristics and landscape as suggested by Wilhelm et al. (2010) can help to further improve the associated impacts on water resources. In addition, the implementation of mitigating measures, such as planting a winter cover crop, should be performed in areas in which stover is harvested. The recent versions of SWAT2012 since the revision 615 have been modified to account for errors in the stover removal process that were observed by Dr. Cibin Raj. Even though the overall results from the present study are not expected to change significantly, future modeling of the stover harvest scenario will benefit from this SWAT revision. Finally, we believe this study elucidated the need for developing a sustainability program for agricultural management and practices that, together with the development of resource assessment scenarios, would help policy makers and the biofuel industry to achieve environmentally responsible and sustainable production of biofuel.

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Conflict of interest

The authors declare no competing financial interest.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Appendix S1. Descriptions of the Ohio River basin (ORB).
Appendix S2. Descriptions of the ORB-SWAT model and its input datasets.
Appendix S3. Sensitivity analysis.
Appendix S4. Calibration.
Appendix S5. Billion-Ton (BT2) scenario.
Appendix S6. Impacts of biofuel on regional or subbasin impacts on hydrology and water quality.
Table S1. Summary of groundwater and surface water withdrawal and consumptive uses by the different sectors in the ORB.
Figure S1. The ORB location map, landuse distribution, major reservoirs, and calibration gauges. The outlet of the watershed was chosen upstream of the confluence of the Ohio and Tennessee Rivers.
Figure S2. Commercial fertilizers, tillage practices, and water use distributions used for the ORB-SWAT model inputs.
Figure S3. Results for the local sensitivity analyses of the 60 parameters considered on the model annual flow and sediment predictions at the basin outlet.
Figure S4. Calibration (1990–2005) and validation (2005–2009) results for average monthly stream discharge and nitrate at a USGS’s gauge located near to the basin outlet, as well as estimated and predicted corn yields over the 120 subbasins in 2006.
Figure S5. Projected landuse changes and stover harvest for the BT2 scenario.
Figure S6. Impacts of changing corn rotations to continuous corn on the major (4-digit HUC) watersheds within the ORB.
Figure S7. Impacts of harvesting stover on the major (4-digit HUC) watersheds within the ORB.
Figure S8. Impacts of the BT2 scenario on the major (4-digit HUC) watersheds within the ORB.