Recognizing economic value in multifunctional buffers in the lower Mississippi river basin

Hui Xu, May Wu, and Miae Ha, Energy Systems Division, Argonne National Laboratory, Lemont, Illinois 60439, USA

Received January 12, 2018; revised July 23, 2018; accepted July 26, 2018
View online at August 31, 2018 Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.1930; Biofuels, Bioprod. Bioref. 13:55–73 (2019)

Abstract. Integrating conservation practices with bioenergy has been recommended as a promising strategy to improve bioeconomy and water quality but the literature on the economics of this strategy is limited. This study evaluated the value proposition of reducing nutrient loss from cropland by implementing switchgrass riparian buffers in the Lower Mississippi River Basin (LMRB). Nutrient loss was simulated by using the Soil and Water Assessment Tool. The value proposition of nutrient abatement was quantified by estimating (1) value of trapped nutrients as fertilizer and (2) potential net returns of harvesting switchgrass as bioenergy feedstock at different farm-gate prices. Results suggest that switchgrass buffers may reduce mean annual total nitrogen and total phosphorus loads from cropland in the LMRB by 23% and 31%, respectively. The value of trapped nutrients is considerable (mean = $69 ha\(^{-1}\) year\(^{-1}\)) but far less than the cost of implementing a switchgrass buffer (mean = $163 ha\(^{-1}\) year\(^{-1}\)). At biomass prices of $20, $40, $60, and $80 per dry-ton, mean net returns of switchgrass buffers (without considering land-use change from cropland to buffers) were estimated to be around −$66, $199, $463, and $727 ha\(^{-1}\) year\(^{-1}\), respectively. Total net returns for the LMRB may be reduced by 20% if switchgrass is grown without the addition of commercial fertilizer. The results highlight the potential of switchgrass buffers for improving water sustainability of both agricultural and bioenergy production. The value proposition of switchgrass buffers is nevertheless sensitive to future feedstock price. The impact of fertilizer prices change and forgone income on benefit analysis is also presented.

© 2018 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: riparian buffer; bioenergy; economics; nutrient retention; water quality
Introduction

Excessive nutrient loads from cropland in the Mississippi River Basin (MRB) are considered to be the major factor contributing to the seasonally hypoxic zone in the northern Gulf of Mexico,1,2 which is the second largest in the world. The Gulf of Mexico Hypoxia Task Force set up an action plan in 2008 and updated its goal framework in 2015, aiming to reduce nitrogen and phosphorus loading by 20% by 2025 and to reduce the area extent of the hypoxic zone to less than 5000 km² by 2035.3,4 If the 5000 km² goal is to be met, a 60% reduction in nutrient loads is needed.5 Among possible nutrient abatement strategies, conservation practices2,6,7 and improving spatial land use management have been recommended.1,8–10 For instance, the US Department of Agriculture (USDA) National Resources Conservation Service (NRCS) has promoted the adoption of conservation practices on cultivated cropland since 1985. In particular, perennial grasses, such as switchgrass, are seen as promising cellulosic biofuel feedstock.11 Switchgrass has also been demonstrated to be a good choice for riparian buffers because of its relatively highly effective nutrient removal.12–15

Recent developments have focused on integrating agricultural conservation practices and cellulosic biomass production through a landscape-management approach.10,13,16 While conservation practices like riparian buffers, constructed wetlands, and bioreactors are effective at reducing nutrient loss through surface runoff, the costs associated with conservation practices are typically viewed implicitly as a financial burden to the public sector.2,17,18 Although studies have tried to justify the costs of conservation practices by monetizing the benefits obtained through enhanced water quality and ecological services,19–21 the economic benefits for in situ recovery of leached nutrients are rarely considered. When integrated with biomass production, the intercepted nutrients may be reused by energy crops, like switchgrass, to generate economic returns.22 In recent years, integrated landscape management strategies, such as using riparian buffers with perennial grasses or woody biomass crops have been gaining increased attention13,23–25 because they can take advantage of both the effectiveness of conservation practices in reducing nutrient loss and the economic potential of cellulosic biomass as bioenergy feedstock.

Although riparian buffers for biomass feedstock are of great interest, the literature on the economics of large-scale implementation is limited.25 Ssegane et al.24 analyzed the costs and benefits of growing shrub willow as a bioenergy buffer in an agricultural watershed in central Illinois and found that a willow buffer has negative net returns if biomass is marketed at the price of $71.5/dry ton, largely because of the high land costs in the Corn Belt region. In the Chesapeake Bay region, Woodbury et al.8 found that subsidizing switchgrass can be more cost-effective than planting cover crops for nitrogen loading reduction, but the biomass value of switchgrass was not assessed. In the MRB region, the USDA NRCS has assessed the effects of various conservation practices on cultivated cropland but not the economic costs and benefits of doing so. In recent years, a number of studies have estimated the cost effectiveness of selected common conservation practices26–28 and cropland retirement1 on nutrient abatement in the MRB. Nonetheless, few studies to date have evaluated the value proposition of reducing nutrient loss from cropland by integrating switchgrass riparian buffers with bioenergy feedstock production, especially in the LMRB. Although some studies have conducted economic analysis of switchgrass as a crop for nutrient abatement purposes,15,29,30 establishing switchgrass as a multifunctional riparian buffer can be quite different.23,31 For instance, understanding the economic benefits of growing biomass in riparian buffers requires a detailed analysis of factors that affect costs (e.g. establishment, biomass cultivation, and harvest) and benefits (e.g. fertilizer prices, biomass market price). Given the importance of the LMRB to the Gulf of Mexico and its prominence in future large-scale biofuel feedstock production,11 there is a clear need to understand the economics and interactions among conservation practices, bioenergy feedstock production, and water-quality improvement.

The objective of this study is to develop a spatially explicit estimation of the water quality and economic benefits of implementing switchgrass-based riparian buffers in the LMRB. The effects of riparian buffers on nutrient load reductions were simulated by using the Soil and Water Assessment Tool (SWAT) model.32,33 The economic benefits of switchgrass buffers were quantified by (1) measuring the value of nutrients trapped in the buffer zone as fertilizers and (2) estimating the potential economic returns of growing switchgrass as bioenergy feedstock in riparian buffers, both with and without fertilizer additions. The total economic benefits of switchgrass based riparian buffers include direct economic benefits from biomass production as well as the other benefits attributed to reduced nutrients and top soil loss, decreased sedimentation, improved water quality, habitat for native species, pollination services, reduced greenhouse gas emission, and recreational benefits. The benefits are channeled to farmers...
as well as other stakeholders at local and global level. Here we focus on the economic benefit to the farmers only, so the value proposition represents a lower bound estimate of total benefits.

**Data and methods**

**Study area**

The LMRB drains an area of nearly 253,279 km² and flows through seven states in the Mississippi River Basin: Arkansas, Illinois, Kentucky, Missouri, Tennessee, and Louisiana. It receives streamflows from four major river basins, including the Arkansas River Basin, Missouri River Basin, Upper Mississippi River Basin, and the Ohio-Tennessee River Basin. Major land-use types in the LMRB include forest (48.9%) and cultivated croplands (24.8%), followed by pasture/grassland (17.6%), urban land (4.9%), shrubland (2.5%), and water bodies (1.3%) (Fig. 1(a)). Based on land-use and terrain characteristics, the LMRB can be divided into three major clusters: the central valley has a flat landscape (slope < 1%) and land-use type is dominated by cropland (Fig. 1). Forests and pasture/grasslands dominate the western sub-basins, and the slope is higher than 5% for most of the area in the cluster. The eastern sub-basins has a mix of cropland and forests, and slope ranges from 1% to 5% in most parts of the cluster (Fig. 1).

**SWAT model for the LMRB and riparian buffer simulation**

The SWAT model is a continuous, physically based watershed model developed by the USDA Agriculture Research Service (ARS). The model has been widely used to evaluate the impacts of land management on water, sediment, and nutrient cycling for large river basins. Major input data include terrain, stream network, soil properties, climate, and land-use and management practices. In this study, the LMRB boundary was delineated using eight-digit hydrologic unit codes (HUCs) and divided into 76 sub-basins and 6724 hydrologic response units (HRUs).

Model parameterization and calibration methods have been detailed in Ha et al. The simulation period...
Table 1. Model input data sources for the LMRB.

| Data type | Resolution or scale | Source | Description |
|-----------|---------------------|--------|-------------|
| Digital Elevation Model (DEM) | 30 m | US Geological Survey (USGS) | Elevation and terrain |
| National Hydrography Dataset (NHD) high resolution | 1:24 000 | USGS | Stream network |
| Land use (cropland data layer) | 30–56 m | US Department of Agriculture (USDA)-National Agriculture Statistics Services (NASS) (https://www.nass.usda.gov/Research and Science/Cropland/sarsfaqs2.php) | Land use and crop types for cropland classification from 2008–2011 |
| Soil (STASGO) | 1:250 000 | USDA-Natural Resource Conservation Service (NRCS) | Physical soil properties like pH, texture, and organic content |
| Climate | 73 stations | National Oceanic and Atmospheric Administration (NOAA)-National Climatic Data Center (NCDC) | Daily precipitation and maximum and minimum temperature |
| Streamflow and nutrient | Hydrologic unit code (HUC)-8 | USGS-National Water Information System (NWIS) (https://waterdata.usgs.gov/nwis) | Measured daily and monthly streamflow and nutrient discharges at USGS gages |
| Point source | 215 facilities | US Environmental Protection Agency (EPA)-Permit Compliance System (PCS) (https://www.epa.gov/enviro/data-downloads) | Measured effluents from permitted companies |
| Agricultural management operation | Fertilizer: state Tillage: HUC-8 | Fertilizer: USDA-Economic Research Service (ERS) Tillage: Conservation Tillage Information Center (CTIC) | Fertilizer application rates and tillage practices |

is 21 years from 1990 to 2010. The LMRB SWAT model was calibrated and validated for streamflow, sediment, and nutrients (total nitrogen (TN) and total phosphorous (TP)). Data source and inputs for model development are summarized in Table 1. More details on model calibration and validation can be found in supporting information (Tables S1–S4).

Switchgrass-based riparian buffers were implemented along the edges of agricultural fields adjacent to streams in the LMRB. According to USDA NRCS, the width of the riparian herbaceous buffer should range from about 9 to 37 m. Thirty-meter buffers were selected because previous studies found that a 30 m buffer is more effective than a narrower one, but reduction rates remain flat when the buffer width increased beyond 30 m. The SWAT uses the vegetative filter strip (VFS) model to simulate the effect of riparian buffers on hydrology and nutrient loads. By overlaying a land-use map with flow lines obtained from the National Hydrography Dataset, buffer-implemented areas along streams were calculated using the ArcGIS software. The ratio of buffer area to total field area is about 0.1. We also assumed that the fraction of HRU area that drains to the most concentrated 10% of the buffer zone is 0.5 and that none of the concentrated flow is fully channelized, which is consistent with previous studies.

Fertilizer value of nutrient stored in riparian buffers

The economic value of the nutrients trapped by riparian buffers was estimated by using market fertilizer prices at the sub-basin level (Eqn (1)):

$$ v_i = (F_{N,i} \times N_{\text{reduc},i} + F_{P,i} \times P_{\text{reduc},i}) \times A_{rb,i} $$

where $v_i$ ($/year$) represents the value of nutrients (N and P) intercepted by riparian buffers in sub-basin $i$; $F_{N,i}$ ($/kg N$) and $F_{P,i}$ ($/kg P$) are nitrogen and phosphorous fertilizer prices in sub-basin $i$, respectively; and $N_{\text{reduc},i}$ (kg N ha$^{-1}$ year$^{-1}$) and $P_{\text{reduc},i}$ (kg P ha$^{-1}$ year$^{-1}$) represent percentare reductions in mean annual N and P loads in sub-basin $i$, respectively. Finally, $A_{rb,i}$ (ha) refers to the size (ha) of the buffer-implemented area in sub-basin $i$.

Economic value of growing switchgrass as bioenergy feedstock in riparian buffers

Annualized economic returns ($\pi_i$, $/year$) of growing switchgrass as biomass feedstock in riparian buffers were calculated as the difference between potential revenues from biomass sales and total cost of switchgrass riparian buffer implementation at the sub-basin level (Eqn (2)):

$$ \pi_i = (P_{SWG,i} \times Y_{SWG,i} \times 0.925 - C_{RB,i} - M_{SWG,i} - H_{SWG,i}) \times A_{rb,i} $$
where $P_{SWG,i}$ represents the potential biomass price ($/dry ton) in sub-basin $i$; $Y_{SWG,i}$ represents estimated mean switchgrass yield (dry ton/ha) in sub-basin $i$; $C_{RB,i}$ ($/ha$) represents establishment costs of a riparian buffer in sub-basin $i$; $M_{SWG,i}$ represents maintenance costs ($/ha$) for switchgrass in sub-basin $i$, including fertilizer and herbicides, and $H_{SWG,i}$ is the cost of harvesting switchgrass biomass ($/ha$). Harvest cost was assumed to be $114/ha$. Switchgrass was assumed to have a lifespan of 10 years from the initial establishment year to the final harvest year. A conversion factor (0.925) was used to adjust annualized yields because we assumed a 50% harvest in year 1, a 75% harvest in year 2, and a 100% harvest in years 3 through 10. In this study, market prices (farm-gate prices) for biomass feedstock were assumed to be $20 and $40 per dry ton for low-price scenarios, and $60 and $80 per dry ton for high-biomass-price scenarios. The $40, $60, and $80 per dry ton price scenarios were used in the 2016 U.S. Billion Ton Report (BT16) to cover a range of possible price scenarios for analyzing the economic availability of feedstock. In this study, we added $20 per dry ton as a low-price scenario.

Fertilizer application rates for switchgrass were calculated based on the assumption that 4.54 kg N and 1.81 kg P inputs would be needed per dry ton of biomass removed. Thus, N and P rates vary by sub-basins, depending on projected yields for each sub-basin (Fig. 2). The VFS module used in the current SWAT model does not support the simulation of plant growth within riparian buffers. For this reason, simulated yields for lowland switchgrass were obtained from the WATER model (http://water.es.anl.gov/). The estimation was originally based on the 2011 US Billion Ton Update report (BT2) and Jager et al. County-level mean lowland switchgrass yields were then aggregated to the sub-basin level by using an areal-weighting method, weighting factors were (1) calculated based on the area of the sub-basin that fell inside each county separately and then (2) aggregated to obtain area-weighted mean values at the sub-basin level. Further assumptions were that nutrient demands would be met by nutrients trapped in buffers first, and that fertilizers would be applied only if there were any remaining nutrient deficit. The fertilizer cost reduces to zero if reusing trapped nutrients is sufficient to meet switchgrass needs, or switchgrass is produced without fertilizer additions.

We calculated establishment costs both with and without the consideration of forgone income (i.e. revenue loss due to land conversion to riparian buffers) because the land

![Figure 2. Geospatial distribution of switchgrass yield (dry ton/ha) in the LMRB at the sub-basin level. Panel (a) shows potential switchgrass yield (with commercial fertilizer addition) obtained from the literature. Panel (b) shows switchgrass yield without commercial fertilizer addition estimated in this study.](image)
close to the riverbank may be prime land rather than marginal land in certain areas. Establishment costs of switchgrass (Table 2) were represented by grass-based riparian buffer implementation costs and annualized establishment cost was calculated by dividing total cost by 10 years, which is the lifespan of a riparian buffer. State-level riparian buffer implementation costs were obtained from the USDA NRCS Field Office Technical Guide (FOTG) (Table 2). Establishment costs include equipment installation (chemical, seeding, tillage, and tractor), materials, labor, and mobilization. A previous study estimated that about 3% of cropland in LMRB has adopted vegetative buffers as conservation practices. For economic benefit analysis, we considered potential switchgrass biomass from both existing and additional riparian buffers in cropland; buffers in other land uses (e.g. pasture) were not considered. Implementing 30 m riparian buffers in LMRB would occupy about 10% of cropland. For the case that forgone income was considered, we assumed that additional riparian buffers (7% of existing cropland) would carry the burden of forgone income as establishment costs.

### Switchgrass production without fertilizer addition

Actual switchgrass yields may be lower than potential yields if fertilizers are not applied. The yield response curve might be quadratic, or a hybrid function in which the yield increases proportionally with fertilizer inputs until a plateau is reached (Eqns (3) and (4)). The hybrid function is adopted in this work to estimate switchgrass yield when fertilizers are not applied. Recent field experiments in Tennessee, Mississippi, and Oklahoma found that the mean annual yield of switchgrass may be reduced by 22–36% if N fertilizer is not applied. As a conservative estimate, we assumed in the present study that the yield of switchgrass without any N input is 60% of the projected potential yield. As riparian buffers will provide some, if not all, N input for switchgrass through cropland runoff, estimated switchgrass yield would always be higher than 60% of projected yield regardless of whether commercial N fertilizer is added or not. We did not consider yield response to P fertilizer rates because previous studies found switchgrass is not very sensitive to P fertilization, at least in the short term.

$$Y_{SWG, i, NF} = Y_{SWG, i} \times \left(0.6 + \frac{N_{rb, i}}{N_{dm, i}} \times 0.4\right) \quad \text{if} \quad N_{rb, i} < N_{plat, i}$$  \hspace{1cm} (3)

$$Y_{SWG, i, NF} = Y_{SWG, i} \quad \text{if} \quad N_{rb, i} \geq N_{plat, i}$$  \hspace{1cm} (4)

where $Y_{SWG, i, NF}$ represents estimated mean switchgrass yield (dry ton/ha) in sub-basin $i$ when commercial fertilizer is not added; $N_{rb, i}$ is the average N trapped in riparian buffers (kg N ha$^{-1}$ year$^{-1}$) in sub-basin $i$, simulated by

---

**Table 2. Riparian buffer implementation costs ($/acre) by state.**

| State       | Year of report | Illinois | Missouri | Kentucky | Arkansas | Tennessee | Mississippi | Louisiana |
|-------------|----------------|----------|----------|----------|----------|-----------|-------------|-----------|
|             |                | 2017     | 2016     | 2016     | 2015     | 2014      | 2014        | 2015      |
| Equipment installation costs | |       |        |         |          |           |             |           |
| Chemical    |                | 6.19     | 6.26     | 12.58    | 0        | 0         | 5.67        | 0         |
| Seeding     |                | 21.54    | 21.78    | 21.9     | 18.93    | 20.39     | 19.75       | 19        |
| Tillage     |                | 0        | 0        | 0        | 9.87     | 10.64     | 0           | 9.92      |
| Tractor$^a$ |                | 110.18   | 110.18   | 110.18   | 110.18   | 110.18    | 110.18      | 110.18    |
| Materials costs | |           |         |         |          |           |             |           |
| Herbicide   |                | 17.48    | 17.48    | 34.97    | 0        | 0         | 15.83       | 0         |
| Native grass|                | 181.28   | 181.28   | 181.28   | 182.91   | 94.57     | 65.95       | 186.18    |
| Labor (operators, 1 h)$^c$ | | 20       | 20       | 20       | 19.78    | 20.4      | 20          | 22.7      |
| Mobilization$^a$ | | 346.98   | 346.98   | 346.98   | 346.98   | 346.98    | 346.98      | 346.98    |
| Forgone income | | 415.11   | 415.11   | 351.08   | 248.01   | 286.77    | 248.01      | 261.72    |
| Total without forgone income | | 703.65   | 703.96   | 727.89   | 688.65   | 603.16    | 584.36      | 694.96    |
| Total with forgone income | | 1118.76  | 1119.06  | 1078.87  | 936.66   | 889.93    | 832.37      | 956.68    |

$^a$Switchgrass harvest cost was assumed to be $58.2/acre ($114/ha),$ and it was included in switchgrass production cost rather than riparian buffer implementation cost.

$^b$Mississippi data were based on grass filer strips, as grass riparian buffer data were not available.

$^c$For states without a labor rate, a $20/hour rate was applied.

$^d$Mobilization cost data were based on the Tennessee report.

$^e$Tractor data were based on the Tennessee report.

$^f$Establishment costs of switchgrass (Table 2) were represented by grass-based riparian buffer implementation costs and annualized establishment cost was calculated by dividing total cost by 10 years, which is the lifespan of a riparian buffer. State-level riparian buffer implementation costs were obtained from the USDA NRCS Field Office Technical Guide (FOTG) (Table 2). Establishment costs include equipment installation (chemical, seeding, tillage, and tractor), materials, labor, and mobilization. A previous study estimated that about 3% of cropland in LMRB has adopted vegetative buffers as conservation practices. For economic benefit analysis, we considered potential switchgrass biomass from both existing and additional riparian buffers in cropland; buffers in other land uses (e.g. pasture) were not considered. Implementing 30 m riparian buffers in LMRB would occupy about 10% of cropland. For the case that forgone income was considered, we assumed that additional riparian buffers (7% of existing cropland) would carry the burden of forgone income as establishment costs.

---

© 2018 The Authors. Biofuels, Bioproducts, Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

| Biofuels, Bioprod. Bioref. 13:55–73 (2019); DOI: 10.1002/bbb | H Xu, M Wu, M Ha Modeling and Analysis: The value proposition of multifunctional riparian buffers | DOI: 10.1002/bbb |
the SWAT model; $N_{\text{plat},i}$ is the amount of N (N ha$^{-1}$ year$^{-1}$) needed for switchgrass to reach potential yield (plateau) in sub-basin $i$; $N_{\text{fertil},i}$ is the amount of N fertilizer needed for switchgrass production (kg N ha$^{-1}$ year$^{-1}$) in sub-basin $i$.

Data sources for the value proposition analysis

Input data for the SWAT model are detailed in Table 1. State-level fertilizer prices for Illinois and other states were collected from the USDA and University Extensions (Table 3), respectively. Fertilizer prices have varied substantially over recent years. Mean nitrogen and phosphorus (P$_2$O$_5$-P) fertilizer prices for the seven states in the LMRB between 2004 and 2016 varied from $0.33/lb N to $0.64 lb (Table S5) and $0.67/lb P$_2$O$_5$-P to $2.00/lb P$_2$O$_5$-P (Table S6). In this study, 2016 fertilizer prices (Table 3) were used to reflect more recent market conditions. The phosphate price was converted to the phosphorus price by a factor of 2.29. For economic analysis, sub-basins located within the state boundary share the same data. Note that for sub-basins that crossed the boundaries of more than one state, mean values at the sub-basin level were calculated using the area-weighting method.

Results and discussion

Effects of riparian buffers on reducing nutrient loads from cropland

The SWAT simulated results suggest that baseline mean annual (1990–2010) TN and TP loads from cultivated cropland in the LMRB were around 98.6 billion ton (BT)/year and 15.2 BT year$^{-1}$, respectively. At the sub-basin level, mean annual TN and TP loads ranged from 0.32 metric ton (MT) N/year to 10.42 BT N year$^{-1}$ (Fig. S1(a)) and 0.09 MT P year$^{-1}$ to 1.59 BT P year$^{-1}$ (Fig. S1(b)), respectively. Sub-basins with higher nutrient loads are clustered in the central valley (Fig. S2), which is reasonable because most cropland is located within that area (Fig. 1(a)). Simulation results suggest that installing switchgrass riparian buffers on the edge of cropland may reduce mean annual TN and TP loads in the LMRB by 22.85 BT N year$^{-1}$, or 23%, and 4.75 BT N year$^{-1}$, or 31%, respectively.

Nutrient intercepting efficiency, measured as the percentage of reductions in nutrient loads, is lower in the central valley than neighboring sub-basins (Fig. 3). Lower trapping efficiency in the central valley can be attributed to the flat landscape (slope < 1%). According to USDA NRCS, the drainage area above the vegetative buffer or filter zone should have a slope of 1% or greater for the buffer zone to achieve its designed performance. In terms of the amount of reductions in nutrient loss, sub-basins in the central and eastern LMRB presented the highest numbers (Fig. 3). At the sub-basin, reductions in mean annual TN and TP loads (Fig. 3) ranged from 0.2 MT N year$^{-1}$ to 1.89 BT N year$^{-1}$ and 0.07 MT P year$^{-1}$ to 422.2 MT P year$^{-1}$, respectively. Although sub-basins in the western basin presented the highest percentage reductions, the amount of TN and TP load reductions were negligible (< 100 Mt/year/sub-basin) when compared to those in the central and eastern basin, largely because there is not much agricultural runoff to be filtered out in the western basin. On a monthly basis, reductions in nutrient loads were most evident in April and May for TN and for TP (Fig. S2), respectively. Monthly reductions were strongly correlated to monthly nutrient loads (Fig. S1(c) and (d)) because nutrient intercepting efficiencies did not vary much across months: between 1990 and 2010, mean monthly TN and TP intercepting efficiency in the LMRB ranged from 25.6% to 28.9% and 30.8% to 36.2%, respectively.

| Table 3. Nitrogen and Phosphorus (P$_2$O$_5$-P) fertilizer prices (2016) for states in the LMRB region. |
| --- |
| **State** | **Nitrogen fertilizer price ($/lb N)** | **Phosphorus fertilizer price ($/lb P)** | **Data source** |
| Kentucky | 0.32 | 0.92 | University of Kentucky Cooperative Extension Service$^{52}$ |
| Arkansas | 0.35 | 0.94 | University of Arkansas Cooperative Extension Service$^{53}$ |
| Mississippi | 0.36 | 1.09 | Mississippi State University Department of Agricultural Economics Budget reports$^{54}$ |
| Tennessee | 0.36 | 0.94 | University of Tennessee Field Crop Budgets$^{55}$ |
| Illinois | 0.38 | 1.05 | USDA-Illinois Department of Agricultural Market News Service$^{56}$ |
| Missouri | 0.34 | 0.76 | University of Missouri Extension Crop Budget$^{57}$ |
| Louisiana | 0.32 | 1.12 | Louisiana State University Agricultural Center$^{68}$ |
| Average | 0.35 | 0.97 | |

© 2018 The Authors. Biofuels, Bioproducts, Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd. Biofuels, Bioprod. Bioref. 13:55–73 (2019); DOI: 10.1002/bbb
Figure 3. Spatial distribution of reductions in annual nutrient loads discharged from cropland after riparian buffers were installed. Panels (a) and (b) show reductions in annual TN and TP loads (Mt/year) at the sub-basin level; panels (c) and (d) show percentage reductions in annual TN and TP loads at the sub-basin level.

Value of intercepted nutrients

When measured by chemical fertilizer prices, the value of nutrients (N and P) stored in riparian buffers ranged from $11 to $260 ha$^{-1}$ year$^{-1}$ (mean = 69, SD = 47.1) (Table 4). At the sub-basin level, the value of trapped nutrients ranged from $301/year to $2.18 Million (M)/year (Fig. 4), with sub-basins in the central valley presenting the highest values (Fig. 4). Between N and P, contributions from N dominated all sub-basins (Fig. 4). This is because annual T loads were five times more than annual P loads in the LMRB, while the average P fertilizer price in 2016 ($0.97/lb. P2O5-P) is only about two times higher than N fertilizer price ($0.35/lb. N) (Table 3). In the LMRB, nutrient loading from croplands peaks between April and May (Fig. S2), which generally matches with nutrient demand of switchgrass, since field experiments suggest that increases in switchgrass biomass are highest in May and June. Although the value of trapped nutrients as fertilizer is considerable ($28 M year$^{-1}$ for the LMRB), the costs of riparian buffer implementation are much higher. On a per-hectare basis, annualized riparian buffer implementation costs (i.e. dividing overall cost by 10 years, which is the designed lifetime of riparian buffer) ranged from $144 to $180 ha$^{-1}$ year$^{-1}$ (Fig. 5(a)). At the sub-basin level, total costs of riparian buffer implementation ranged from $197/year to $10.6 M year$^{-1}$ (Fig. 5(b)). This large variation can largely be explained by differences in buffer area across sub-basins. For instance, riparian buffer area in the sub-basin with a cost of $197 year$^{-1}$ and $10.6 M year$^{-1}$ were estimated to be around 0.01 and 622.8 km$^2$, respectively, in this study. The total cost of installing riparian buffers on all cropland in the LMRB would be around $101.6 M year$^{-1}$, which is more than three times higher than the value of trapped nutrients (Table 4). The high
### Table 4. Costs and benefits of riparian buffer implementation in the LMRB.

| Item                                                                 | Without forgone income | With forgone income |
|----------------------------------------------------------------------|------------------------|---------------------|
|                                                                      | LMRB total benefit from | Per hectare of riparian buffer installed (\$ ha\(^{-1}\) year\(^{-1}\)), estimated at  |
|                                                                      | cropland ($M/basin/year) | sub-basin level     |
|                                                                      | Mean (SD)               | range               |
|                                                                      | range                   | Mean (SD)           | range               |
| Value of total nitrogen (TN) and total phosphorous (TP) stored in riparian buffer | 28.03 (47.1)            | 11–60               | 28.03 (47.1)        | 11–60               |
| Riparian buffer installation cost on all agricultural land, divided by 10 years | 101.63 (12.3)           | 144–180             | 134.80 (21.3)       | 187–246             |
| Savings in fertilizer costs of switchgrass production by utilizing nutrients stored in riparian buffer | 26.21 (27.1)            | 11–113              | 26.21 (27.1)        | 11–113              |
| Net returns of growing switchgrass in riparian buffer                 |                         |                     |                     |                     |
| $20/dry ton price, without commercial fertilizer input                | –53.17 (41.3)           | –146–21             | –384.94 (120.1)     | –836 to –420        |
| $20/dry ton price                                                   | –46.53 (40.7)           | –133–21             | –378.32 (128.6)     | –832 to –420        |
| $40/dry ton price                                                   | 108.84 (66.7)           | 22–334              | –222.93 (110.7)     | –547 to –113        |
| $40/dry ton price, without commercial fertilizer input               | 88.24 (80.4)            | 34–334              | –243.55 (128.6)     | –644 to 113         |
| $60/dry ton price                                                   | 270.85 (96.9)           | 189–650             | –60.92 (110.8)      | –263 to 195         |
| $60/dry ton price, without commercial fertilizer input               | 223.01 (120.7)          | 201–650             | –108.78 (147.7)     | –456 to 195         |
| $80/dry ton price                                                   | 432.86 (128.6)          | 356–967             | 101.08 (120.4)      | –96 to 502          |
| $80/dry ton price, without commercial fertilizer input               | 357.78 (161.2)          | 369–967             | 25.99 (174.3)       | –268–502            |
Figure 4. Economic value of (a) total N, (b) total P, and (c) total N and P stored in the riparian buffer (RB) zone at the sub-basin level. Nutrient value refers to the value of TN and TP stored in the RB zone, estimated using N and P fertilizer prices. The average value of nitrogen and phosphorous remaining in the soil when the RB was implemented was simulated using the SWAT model.
costs of riparian buffers suggest that preserving nutrients alone is unlikely to convince farmers to install conservation buffers on their farmland. Either additional revenues from buffers (e.g., biomass production) or incentive payments from the public sector would be needed to encourage broader participation. Given that financial resources for conservation efforts are limited, integrating bioenergy production with conservation buffers may be preferred because revenues through biomass feedstock production may offset, at least partially, the costs of riparian buffers.

**Economics of switchgrass riparian buffers for bioenergy**

Our analysis suggests that whether harvesting switchgrass as biomass feedstock can offset the costs of riparian buffers or not largely depends on the projected feedstock prices (Fig. 6). At a biomass price of $20, $40, $60, or $80 per dry ton we found that the annualized net returns of switchgrass riparian buffers would be −$66 ha⁻¹ year⁻¹ (SD = 41.3), $199 ha⁻¹ year⁻¹ (SD = 66.7), $463 ha⁻¹ year⁻¹ (SD = 106.6), respectively.
production costs, so that value of intercepted nutrients was not double counted. According to nutrient interception simulated by SWAT and market prices for chemical fertilizers for the LMRB, our results suggest that farmers may save around $58.17 ha\(^{-1}\) year\(^{-1}\) (SD = 27.1) on average on fertilizer costs if trapped nutrients can be used by switchgrass grown in riparian buffers. For the LMRB, total avoided fertilizer costs would be around $26.2 M year\(^{-1}\), which means more than 90% of the fertilizer value of intercepted nutrients ($28 M year\(^{-1}\)) may be recovered. These results demonstrate that integrating perennial grasses with conservation practices could be a synergic strategy for economic development of bioenergy and water quality improvement.

Geospatially, there are significant spatial variations in both riparian buffer costs and economic returns (Fig. 5) estimated in this study. The economic returns of switchgrass buffers at the sub-basin level are highest in the central valley of the LMRB (Fig. 5(a) and (b)). Spatial variations in per-hectare riparian buffer costs (Fig. 5(a)) seem to have little impact on sub-basin-level economic returns. This is because buffer in agricultural land and therefore the biomass potential is closely related to the area of cropland and the location of stream lines in that sub-basin. For the same reason, sub-basin level net returns is less sensitive to spatial variation in switchgrass yields (Fig. 2(a)) than differences in riparian buffer area. For instance, at a biomass price of $60 or $80 per dry ton, sub-basin-level total economic returns would be higher than $20 or $35 M year\(^{-1}\), respectively, in the central valley (Fig. 5(c) and (d)), where cropland is the dominate land-use type. In contrast, sub-basin-level economic returns outside the central valley are mostly less than $10 M year\(^{-1}\).

In terms of both nutrient abatement and economic returns, simulation results suggest that implementing switchgrass riparian buffers in the central sub-basins tended to be more effective than in other sub-basins (Fig. 5). Among the 76 sub-basins in the LMRB, riparian buffers can only reduce TN loads in seven sub-basins by more than 850 Mt year\(^{-1}\) (Fig. 3). Specifically, five of the seven sub-basins are located in the central valley and the other two are located in the eastern basin (Fig. 3). Although sub-basins in the northern basin are also dominated by agricultural production, simulated results suggest that both nutrient loads and the amount of reductions that can be achieved by riparian buffers would be significantly lower than those for sub-basins in the central and eastern basin. For the seven sub-basins mentioned above, the total cost of riparian buffers estimated in this study was around $39.8 M year\(^{-1}\), which is about 40% of total riparian buffer costs.
cost in the LMRB. However, when biomass production is considered, net returns from the seven sub-basins alone also constitute about 40% of total net revenues in the LMRB.

**Growing switchgrass without fertilizer additions**

Growing switchgrass without commercial fertilizer addition in the LMRB may reduce biomass potential moderately from 14.29 dry ton/ha (SD = 1.8) (Fig. 2(a)) to 12.79 dry ton ha\(^{-1}\) (SD = 2.2) (Fig. 2(b)), on average. The reduction is moderate (10%) because nutrients trapped in riparian buffers can largely meet the needs of switchgrass. At the sub-basin level, average N fertilizer needed for switchgrass production is about 59.9 kg ha\(^{-1}\) year\(^{-1}\) (range = 37.9–71.8), whereas TN intercepted in buffer zone would be around 54.3 kg ha\(^{-1}\) year\(^{-1}\) (range = 8.8–182.4). Nonetheless, our results suggest that the impacts of trapped nutrients on yields varied significantly across sub-basins. The changes are more evident in the northern and central sub-basins (Fig. 2(b)) than in other areas, because the amount of N trapped by buffers is estimated by the SWAT model to be lower in these sub-basins on a per-hectare basis (Fig. 7(a)). The spatial pattern of N deficit, which is calculated as the difference between required N fertilizer rates and the amount of N trapped in riparian buffers, clearly demonstrates that relying on N trapped in buffers alone is not sufficient to achieve the desired switchgrass yields in the northern and central sub-basins. In the central valley, the estimated N deficit ranged from 17.7 to 38.6 kg ha\(^{-1}\) year\(^{-1}\) for most sub-basins (Fig. 7(b)). Estimated N deficits in the northern sub-basins were found to be substantially higher (mean = 45 kg ha\(^{-1}\), SD = 7.5) than in other regions, because of the combined effects of higher switchgrass yields (Fig. 2(a)), which means higher N fertilizer demands and lower N availability from riparian buffers (Fig. 7(a)).

In terms of economic returns, growing switchgrass without fertilizer addition may still generate substantial revenues, after accounting for reductions in yields, if feedstock price is higher than $40/dry ton. At a biomass price of $20/dry ton, $40/dry ton, $60/dry ton, or $80/dry ton, we found annualized mean economic returns would be around −$55, $182, $418, or $654 ha\(^{-1}\) year\(^{-1}\) (Fig. 6). With the same biomass price scenarios, simulation results suggest that total net economic returns for the LMRB ranged from −$46 to $357.8 M year\(^{-1}\) (Table 4). Compared to the switchgrass production scenarios with fertilizer applications, growing switchgrass without fertilizer additions may actually increase total net returns by 13% when feedstock price is $20/dry ton. With higher feedstock prices (i.e., $40/dry ton −$80/dry ton), total net returns for the LMRB may be reduced by up to 20% (Table 4). At the sub-basin level, changes in economic returns vary significantly. For instance, at a biomass price
of $60/dry ton, changes in net returns at the sub-basin level ranged from −$8.5 to $0.3 M year$^{-1}$ (mean = −$0.6) (Fig. 8(a)), or from −44% to 7% (mean = −10%) (Fig. 8(b)). Across the LMRB, reductions in net returns are most evident in the northern and central sub-basins (Fig. 8), which is consistent with the spatial pattern of yield changes mentioned above.

The results suggest that, when the biomass feedstock price for switchgrass is higher than $40/dry ton, establishing low-input switchgrass production without fertilizer additions in conservation buffers could be an economically viable solution to reconcile the tradeoffs between water quality and agricultural production. However, when feedstock price is low (e.g., $20/dry ton), increased yields are unlikely to compensate for the extra cost of chemical fertilizer.

**Impact of forgone income and fertilizer price variation on economic analysis**

Depending on local soil and field conditions, cropland near riverbanks may be prime land rather than marginal land. If forgone income (i.e. revenue loss due to conversion of productive land to riparian buffers) is considered, then the average establishment cost would increase significantly from $163 to $683 ha$^{-1}$ year$^{-1}$ (SD = 126) (Table 4). This means net returns for switchgrass production would decrease by around $520 ha$^{-1}$ year$^{-1}$ (SD = 118.8) on average (Table 4) under all four feedstock price scenarios. Mean net returns (with commercial fertilizer addition) under $40/dry ton and $60/dry ton scenarios would be −$321 ha$^{-1}$ year$^{-1}$ (SD = 110.7) and −$57 ha$^{-1}$ year$^{-1}$ (SD = 110.8), respectively. In this case, substantial financial incentives might be needed to encourage wide adoption of switchgrass riparian buffers. Nonetheless, if feedstock price can reach $80/dry ton, net returns would still be around $207 ha$^{-1}$ year$^{-1}$ (SD = 120.4). When forgone income is taken into account, we estimated LMRB total net returns (with fertilizer additions) for the four price scenarios (i.e. $20, $40, $60, $80) to be −$384.9, $−222.9, $−60.9 , and $ 101.1 M year$^{-1}$, respectively (Table 4).

Uncertainty due to fertilizer prices change is another important factor to consider. Using fertilizer price data between 2004 and 2016, we calculated 95% confidence intervals of N and P fertilizer prices for each state (Tables S5 and S6). At the LMRB level, upper (95%) and lower bounds (5%) of historical N fertilizer prices are $0.42/lb N and $0.53/lb N (Table S5); 95% confidence intervals for P fertilizer prices are $0.89/lb P2O5-P (lower bound) and $1.28/lb P2O5-P (upper bound) (Table S6). We found that...
the value of trapped nutrients would increase noticeably based on either the lower bound or the upper bound of historical fertilizer prices (Fig. 9). This is because fertilizer prices in 2016 were more or less the lowest since 2004 (Tables S5 and S6). Among the seven states contributing to the LMRB, increase in the value of trapped nutrients (with upper bound prices) ranges from $13.3 ha\(^{-1}\) year\(^{-1}\) in Illinois to $54.9 ha\(^{-1}\) year\(^{-1}\) in Tennessee (Fig. 9). The increase is lower for sub-basins within Illinois because the amount of nutrients intercepted by riparian buffers is much lower than other sub-basins (Fig. 7), owing to their flat terrain (the slope is close to zero). Across the sub-basins, the average value of intercepted nutrients (with upper bound prices) will increase from $69 ha\(^{-1}\) year\(^{-1}\) (SD=47.1) to $104 ha\(^{-1}\) year\(^{-1}\) (SD=71.6). The LMRB-level total nutrient value will increase from $28 to $42 M year\(^{-1}\). When the lower bounds of fertilizer prices were used, per-hectare and LMRB total nutrient value were estimated to be around $75 ha\(^{-1}\) year\(^{-1}\) (SD=49.6) and $31 M year\(^{-1}\) (Table 4) in this study, respectively.

**Limitations and future work**

Using switchgrass-based riparian buffers as an example, the analysis presented in this study quantified the water quality and economic benefits obtainable through integrating cellulosic biomass production with conservation practices. The economic value of buffer-trapped nutrients can be estimated on the basis of fertilizer prices, although fertilizer prices vary significantly across years. The estimations of net returns of growing switchgrass for bioenergy purposes are also highly uncertain. At this time, observed data on large-scale switchgrass production are not available and estimated biomass production costs vary substantially in the literature.\(^{11,71-73}\) Depending on the assumptions made on biomass price and production cost, estimated economic returns could be quite different. For instance, mobilization ($367/ha) is a major part of the riparian buffer implementation cost. Mobilization cost covers transportation of equipment, and this cost may be lower if it can be spread among large areas, assuming the same equipment can be shared in adjacent fields. Furthermore, the value proposition was based on possible farm-gate feedstock prices\(^{11}\) but off-farm factors (e.g., transportation costs and capacities of biorefineries) are also important factors to be considered.\(^{30}\) The actual costs of biomass from riparian buffers could also be higher than those from dedicated large biomass farms because the logistics of managing small amounts of biomass generated in a distributed way across the landscape are also more complex than production in contiguous large farms.\(^{24}\)

For future studies, the analysis can be improved in a number of ways. For instance, in addition to the economic benefits obtained through in situ nutrient recycling, improvements in water quality can also reduce water treatment costs downstream. Including savings in municipal water treatment costs would be helpful for a more complete value proposition analysis. Furthermore, switchgrass yield was estimated by using an off-line model. Improvements in the VFS model, which is used by SWAT to simulate riparian buffers, are desirable to enable the dynamic simulation of nutrient cycles and plant growth in the riparian buffer zone.

**Conclusion**

Combining conservation practices with bioenergy feedstock productions in the MRB to address the reoccurring hypoxia problem in the Gulf of Mexico is of growing interest. However, studies on the economics of the large-scale implementation of this integrated land-management strategy are rather limited. In this study, we evaluated the value proposition of switchgrass-based riparian buffers in the LMRB. The value proposition of implementing switchgrass riparian buffers in the LMRB was quantified by estimating (1) the value of nutrients trapped in riparian buffers as fertilizers, and (2) the potential economic returns of producing switchgrass as biofuel feedstocks in riparian buffers, both with and without fertilizer addi-

---

Figure 9. Changes in value of intercepted nutrients ($ha^{-1}\ year^{-1}$) relative to 2016 fertilizer prices. Upper and lower bounds of fertilizer prices (N and P2O5-P) for each state were calculated based on 95% confidence intervals of 13 years’ fertilizer price data (2004–2016) (Tables S5 and S6) for each state.
tions. Compared to the cost of riparian buffer implementation (mean = $163 ha$−1 year$−1$, $SD = 12.3$), the value of trapped nutrients was estimated to be only about $69 ha$−1 year$−1$ ($SD = 47.1$), suggesting that nutrient preservation alone is unlikely to promote wide adoption of riparian buffers. As the fertilizer price varies substantially, the value of intercepted nutrients could be $104 ha$−1 year$−1$ ($SD=71.6$) based on the upper side of the 95% confidence bound of historical fertilizer prices (2004–2016). When switchgrass is harvested as bioenergy feedstock, estimated mean annualized per-hectare net economic returns of switchgrass riparian buffers in the LMRB ranged from −$66 ha$−1 year$−1$ to $727 ha$−1 year$−1$, depending on the assumed future biomass prices. Total net returns for the LMRB were estimated to range from −$53 M year$−1$ (with a $20/dry ton price) to $432 M year$−1$ (with an $80/dry ton price). If forgone income is considered, net returns will decrease by $520 ha$−1 year$−1$ ($SD = 118.8$). Spatially, sub-basin-level analysis demonstrated that future conservation planning should target fields located in the central and eastern sub-basins because fields in these areas offered the highest potential for both nutrient reductions and economic returns. Growing switchgrass without fertilizer additions result in moderate reduction of yield (< 20%) in the agriculture region in LMRB because most of nutrient demand of switchgrass can be met by trapped nutrients. In fact, utilizing trapped nutrients to grow switchgrass buffer may save $26.2 M year$−1$ in fertilizer cost.

Our results suggest that when there is a mature market for cellulosic biomass and the feedstock price is higher than $40 ha$−1 year$−1$, integrating perennial bioenergy crops into agricultural conservation practices might be an economically viable strategy to reconcile the tradeoffs among energy, agriculture, and the environment. However, if biomass price is kept at a low level (e.g., $20 ha$−1 year$−1$), it is unlikely that switchgrass riparian buffers will be profitable, and financial support or incentives might be required to encourage more farmers to adopt switchgrass riparian buffers on their cropland. When forgone income is considered, biomass price needs to reach a high level ($80/ dry ton) for switchgrass riparian buffers to be profitable. Because the estimated economic value from switchgrass based riparian buffer does not include all economic benefits (e.g. water quality improvement), the value proposition presented in this study is the lower bound estimate. Evaluation of the other benefits may change the scenario to a higher benefit-to-cost ratio. The spatially explicit value proposition presented in this study can help decision makers to take the value proposition of nutrient reductions achieved by integrated land management strategies, such as switchgrass riparian buffers, into consideration when planning for water sustainable agricultural and bioenergy industry development.

Acknowledgements

This work was made possible by funding from the US Department of Energy, Bioenergy sTechnologies Office (BETO), Office of Energy Efficiency and Renewable Energy, under contract # DE-AC02-06CH11357. We would like to thank Kristen Johnson of BETO for her support and valuable inputs throughout this study. The authors are grateful to the two anonymous reviewers for their constructive suggestions.

References

1. Whittaker G, Barnhart BL, Srinivasan R and Arnold JG, Cost of areal reduction of gulf hypoxia through agricultural practice. Sci Total Environ 505:149–153 (2015).
2. Rabotyagov SS, Campbell TD, White M, Arnold JG, Atwood J, Norfleet ML et al., Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. Proc Natl Acad Sci 111(52):18530–18535 (2014).
3. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, Gulf hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi. [Online]. Washington, DC, 2008;86. Available: https://www.epa.gov/sites/production/files/2015-03/documents/2008_8_28 msbasin_ghap2008_update082608.pdf [17 November 2017].
4. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, New Goal Framework. [Online]. 2015. Available: https://www.epa.gov/ms-htf/hypoxia-task-force-new-goal-framework [17 November 2017].
5. Scaida D, Evans MA and Obenour DR, A scenario and forecast model for gulf of mexico hypoxic area and volume. Environ Sci Technol 47(18):10423–10428 (2013).
6. Garcia AM, Alexander RB, Arnold JG, Norfleet L, White MJ, Robertson DM et al., Regional effects of agricultural conservation practices on nutrient transport in the Upper Mississippi River Basin. Environ Sci Technol 50(13):6991–7000 (2016).
7. McLellan E, Robertson D, Schilling K, Tomer M, Kostel J, Smith D et al., Reducing nitrogen export from the corn belt to the gulf of mexico: Agricultural strategies for remediating hypoxia. J Am Water Resour Assoc 51(1):263–289 (2015).
8. Woodbury PB, Kemanian AR, Jacobson M, Langhoft M, Improving water quality in the Chesapeake Bay using payments for ecosystem services for perennial biomass for bioenergy and biofuel production. Biomass Bioenergy 114:132–142 (2018).
9. Xu H, Brown DG, Moore MR and Currie WS, Optimizing spatial land management to balance water quality and economic returns in a Lake Erie watershed. Ecol Econ 145:104–114 (2018).
10. Dale VH, Kline KL, Buford MA, Volk TA, Tattersall Smith C, Stupak I, Incorporating bioenergy into sustainable landscape designs. Renewable Sustainable Energy Rev 56:1158–1171 (2016).
Modeling and Analysis: The value proposition of multifunctional riparian buffers

H Xu, M Wu, M Ha

11. U.S. Department of Energy, 2016 Billion-ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstock, Langholtz MH, Stokes BJ and Eaton LM (Leads), ORNL/TM-2016/160. Oak Ridge, TN, 448 p (2016). doi: 10.2172/1217651. Available: http://energy.gov/eere/bioenergy/2016-billion-ton-report.

12. Lai L, Oh Hong C, Kumar S, Osborne SL, Lehman RM and Owens VN, Soil nitrogen dynamics in switchgrass seeded to a marginal cropland in South Dakota. GCB Bioenergy 10(1):28–38 (2018).

13. Ha M and Wu M, Simulating and evaluating best management practices for integrated landscape management scenarios in biofuel feedstock production. Biofuels, Bioprod Biorefin 9(6):709–721 (2015).

14. Baskaran L, Jager H, Schweizer P and Srivinasan R, Progress toward evaluating the sustainability of switchgrass as a bioenergy crop using the SWAT model. Trans ASABE 53(5):1547–1556 (2010).

15. U.S. Department of Energy, Water quality responses to simulated management practices on agricultural lands producing biomass feedstocks in two tributary basins of the Mississippi river, in 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1, ed. by Efroymson RA, Langholtz MH, Johnson KE and Stokes BJ, ORNL/TM-2016/727. Oak Ridge, TN (2017). Available: doi 10.2172/1358837.

16. Gopalakrishnan BG, Negri MC and Synder SW, Redesigning agricultural landscapes for sustainability using bioenergy crops: Quantifying the tradeoffs between agriculture, energy, and the environment. Asp Appl Biol 112:139–146 (2015).

17. Naidoo R, Balmford A, Ferraro PJ, Polasky S, Ricketts TH and Rouget M, Integrating economic costs into conservation planning. Trends Ecol Evol 21:681–687 (2006).

18. Claassen R, Cattaneo A and Johansson R, Cost-effective design of agri-environmental payment programs: US experience in theory and practice. Ecol Econ 65(4):737–752 (2008).

19. Grossmann M, Economic value of the nutrient retention function of restored floodplain wetlands in the Elbe River basin. Ecol Econ 83:108–117 (2012).

20. Jenkins WA, Murray BC, Kramer RA and Faulkner SP, Valuing ecosystem services from wetlands restoration in the Mississippi Alkavil Valley. Ecol Econ 69(5):1051–1061 (2010).

21. Rabotyagov SS, Kling CL, Gassman PW, Rabalais NN, Turner RE, The economics of dead zones: Causes, impacts, policy challenges, and a model of the Gulf of Mexico hypoxic zone. Rev Environ Econ Policy 8(1):58–79 (2014).

22. Ssegane H, Negri MC, Quinn J and Urgun-Demirtas M, Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. Biomass Bioenergy 80:179–190 (2015).

23. Ferrarini A, Serra P, Almagro M, Trevisan M and Amaducci S, Multiple ecosystem services provision and biomass logistics management in bioenergy buffers: A state-of-the-art review. Renewable Sustainable Energy Rev. 73:277–290 (2017).

24. Ssegane H, Zumpf C, Cristina Negri M, Campbell P, Heavey JP and Volk TA, The economics of growing shrub willow as a bioenergy buffer on agricultural fields: A case study in the Midwest Corn Belt. Biofuels, Bioprod Biorefin 10(6):776–789 (2016).

25. Golkskowa K, Rugani B, Koster D and Van Oers C, Environmental and economic assessment of biomass sourcing from extensively cultivated buffer strips along water bodies. Environ Sci Policy 57:31–39 (2016).

26. Roley SS, Tank JL, Tyndall JC and Witter JD, How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River Basin? Water Resour Econ 15:43–56 (2016).

27. Rabotyagov S, Campbell T, Jha M, Gassman PW, Arnold J, Kurkalova L et al. Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone. Ecol Appl 20(6):1542–1555 (2010).

28. Christianson R, Christianson L, Wong C, Helmers M, McIsaac G, Mulla D et al., Beyond the nutrient strategies: Common ground to accelerate agricultural water quality improvement in the upper Midwest. J Environ Manage 206:1072–1080 (2015).

29. Zhou XY, Clark CD, Nair SS, Hawkins SA and Lambert DM, Environmental and economic analysis of using SWAT to simulate the effects of switchgrass production on water quality in an impaired watershed. Agric Water Manag 160:1–13 (2015).

30. Song J, Gramig BM, Cibin R and Chaubey I, Integrated economic and environmental assessment of cellulosic biofuel production in an agricultural watershed. Bioenergy Res 10(2):509–524 (2017).

31. Stutter MI, Chardon WJ and Kronvang B, Riparian buffer strips as a multifunctional management tool in agricultural landscapes: Introduction. J Environ Qual 41(2):297 (2012).

32. Arnold JG, Srivinasan R, Mutthia RS and Williams JR, Large area hydrologic modeling and assessment part I: Model development. J Am Water Resour Assoc 34(1):73–89 (1998).

33. Gassman PW, Reyes MR, Green CH and Arnold JG, The soil and water assessment tool: Historical development, applications, and future research directions. Trans Asabe 50(4):1211–1250 (2007).

34. Ha M, Zhang Z and Wu M, Biomass production in the Lower Mississippi River Basin: Mitigating associated nutrient and sediment discharge to the Gulf of Mexico. Sci Total Environ 635:1585–1599 (2018).

35. Gesch D, Oimoen M, Greenlee S, Nelson C, Steuck M and Tyler D, The national elevation dataset. Photogramm Eng Remote Sensing 68:5–11 (2002).

36. USGS (U.S. Geological Survey), National Hydrography Dataset. [Online]. The National Map (2016). Available: https://nhd.usgs.gov/NHD_High_Resolution.html [3 February 2017].

37. USDA NRCS, Web Soil Survey. [Online]. Available: [2 October 2017].

38. USDA NRCS, Conservation Practice Standard - Riparian Herbaceous Cover - Code 390. Kentucky (2015).

39. Chaubey I, Chiang L, Giltai MW and Mohamed S, Effectiveness of best management practices in improving water quality in a pasture-dominated watershed. J Soil Water Conserv 65(6):424–437 (2010).

40. Neiltsch S., Arnold J., Kiniry J. and Williams J, The national elevation dataset. Photogramm Eng Remote Sensing 68:5–11 (2002).

41. ESRI (Environmental Systems Resource Institute), ArcGIS Desktop: Release 10.4. Redlands CA (2016).

42. Ha M and Wu M, Land management strategies for improving water quality in biomass production under changing climate. Environ Res Lett 12(3), Article ID 034015 (2017).

43. Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson PA and Stokes BJ, ORNL/TM-2016/727. Oak Ridge, TN (2017). Available: doi 10.2172/1358837.

© 2018 The Authors. Biofuels, Bioproducts, Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

| Biofuels, Bioprod. Bioref. 13:55–73 (2019); DOI: 10.1002/bbb | 71
H Xu, M Wu, M Ha Modeling and Analysis: The value proposition of multifunctional riparian buffers

44. U.S. Department of Energy, U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry, Perdick RD and Stokes BJ (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN, 227 p. [Online], Available: https://www.energy.gov/sites/prod/files/2015/01/f19/billion_ton_update_0.pdf [11 June 2018].

45. USDA NRCS, Practice 390 – Riparian Herbaceous Cover. [Online]. Illinois (2017). Available: https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcspcred1329469 &ext=pdf [2 June 2017].

46. USDA NRCS, Practice 390 - Riparian Herbaceous Cover. [Online]. Missouri (2016). Available: https://efotg.sc.egov.usda.gov/references/public/MO/390_RiparianHerbaceousCover_ FY16.pdf [24 April 2017].

47. USDA NRCS, Practice 390 – Riparian Herbaceous Cover. [Online]. Kentucky (2016). Available: https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcspred132 9473&ext=pdf [19 June 2017].

48. USDA NRCS, Practice 390 – Riparian Herbaceous Cover. [Online]. (2015). Available: https://efotg.sc.egov.usda.gov/references/public/AR/390-Riparian_Herbaceous_Cover.pdf [24 May 2017].

49. USDA NRCS, Practice 390 – Riparian Herbaceous Cover. [Online]. Tennessee (2014). Available: https://efotg.sc.egov.usda.gov/references/public/TN/CostScenarios_390_Riparian_ Herbaceous_Cover.pdf [4 May 2017].

50. USDA NRCS, Practice 393 - Filter Strip. [Online]. Mississippi (2014). Available: https://efotg.sc.egov.usda.gov/references/public/MS/393FilterStrip.pdf [24 April 2017].

51. USDA NRCS, Practice 390 – Riparian Herbaceous Cover. [Online]. Louisiana (2015). Available: https://efotg.sc.egov.usda.gov/references/public/LA/RiparianHerbaceousCover(390) Costscenario.pdf [4 May 2017].

52. Santhi C, Arnold JG, White M, Di Luzzio M, Kannan N, Norfleet L et al., Effects of agricultural conservation practices on N loads in the Mississippi–Atchafalaya River Basin. J Environ Qual 43(6):1903 (2014).

53. Boyer CN, Tyler DD, Roberts RK, English BC and Larson JA, Switchgrass yield response functions and profit-maximizing nitrogen rates on four landscapes in Tennessee. Agron J 104(6):1579–1588 (2012).

54. Haque M, Epplin FM and Talafiero CM, Nitrogen and harvest frequency effect on yield and cost for four perennial grasses. Agron J 101(6):1463 (2009).

55. Aravindhakshan SC, Epplin FM and Talafiero CM, Switchgrass, Bermudagrass, flaccidgrass, and lovegrass biomass yield response to nitrogen for single and double harvest. Biomass Bioenergy 36(1):308–319 (2011).

56. Garten CT, Brice DJ, Castro HF, Graham RL, Mayes MA, Phillips JR et al. Response of ‘Alamo’ switchgrass tissue chemical and biomass to nitrogen fertilization in West Tennessee, USA. Agric Ecosyst Environ 140(1–2):289–297 (2011).

57. Searpaul R, Macoon B, Reddy KR and Evans WB, Harvest timing and N application rate effects on switchgrass yield, nutrient cycling, and partitioning. J Plant Nutr 30(9):1261–1276 (2017).

58. Thomason WE, Raun WR, Johnson G V, Talafiero CM, Freeman KW, Wynn KJ et al. Switchgrass response to harvest frequency and time and rate of applied nitrogen. J Plant Nutr 27(7):1199–1226 (2004).

59. Guretzky JA, Biermacher JT, Cook BJ, Kering MK and Mosali J, Switchgrass for forage and bioenergy: Harvest and nitrogen rate effects on biomass yields and nutrient composition. Plant Soil 339(1):69–81 (2011).

60. Muir JP, Sanderson MA, Ocampo WH, Jones RM and Reed RL, Biomass production of ‘Alamo’ switchgrass in response to nitrogen, phosphorus, and row spacing. Agron J 93(4):896–901 (2001).

61. Kering MK, Biermacher JT, Butler TJ, Mosali J and Guretzky JA, Biomass yield and nutrient responses of switchgrass to phosphorus application. Bioenerg Res 5(1):71–78 (2012).

62. Halich G and Shockely J, Sorghum-Corn Comparison Budget 2016. [Online]. University of Kentucky, Lexington, KY (2016). Available: http://www.uky.edu/AgriculturalEconomics/ pubs/extsorghumcorn201630.xlsx [15 May 2017].

63. Flanders A and Watkins B, 2017 Crop Enterprise Budgets. [Online]. University of Arkansas, Fayetteville, AR (2016). Available: https://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/budgets/2017Manuscript.pdf [14 April 2017].

64. Williams B, Bond J, Catchot A, Cook D, Golden B and Gore J, Corn, Grain Sorghum, and Wheat – 2017 Planning Budgets. [Online]. Mississippi State University, Starkville, MS (2016). Available: http://extension.msstate.edu/publications/publications/corn-grain-sorghum-and-wheat-2017-planning-budgets [14 April 2017].

65. Smith A, Bowling B and Danehower S, Field Crop Budgets for 2017. [Online]. University of Tennessee, Knoxville, TN (2016). Available: https://ag.tennessee.edu/arec/Documents/budgets/crops/2017/FieldCropBudgets2017.pdf [17 April 2017].

66. David Humphreys, Illinois Production Cost Report. [Online]. USDA-Illinois Department of Agricultural Market News Service, Springfield, IL (2016). Available: www.ams.usda.gov/LPSMarketNewsPage [15 April 2017].

67. David Reinhart, Southeast Missouri Crop Budgets 2017. [Online]. University of Missouri, Benton, MO (2016). Available: http://extension.missouri.edu/arec/Documents/ag/Crop-Budgets-Archive/SEMO Crop Budgets 2017.pdf [20 June 2017].

68. Deliberto M, Hibbun B and Salassi M, Crop Enterprise Budgets for Corn Production in Louisiana, 2017. Louisiana State University, Baton Rouge, LA (2016).

69. USDA NRCS, Conservation Practice Standard – Filter Strip – Code 393. [Online]. Arkansas (2017). Available: https://efotg.sc.egov.usda.gov/references/public/AR/393_Filter_Strip_ Standard.pdf [4 May 2017].

70. Wagle P and Kakani VG, Seasonal variability in net ecosystem carbon dioxide exchange over a young Switchgrass stand. GCB Bioenergy 6(4):339–350 (2014).

71. Jain AK, Khanna M, Erickson M and Huang HX, An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States. Glob Chang Biol Bioenergy 2:217–234 (2010).

72. Bansal A, Ilukpitiya P, Singh SP and Teegene F, Economic competitiveness of ethanol production from cellulosic feedstock in Tennessee. Renew Energy 59:53–57 (2013).

73. University of Missouri Extension, Switchgrass and Miscanthus: Economics of Perennial Grasses Grown for Bioenergy. [Online]. (2013). Available: http://extension.missouri.edu/p/g4980 [15 June 2017].
Hui Xu is a postdoctoral appointee in the Energy Systems Division at Argonne National Laboratory, USA. His research interests include modeling the environmental sustainability of bioenergy feedstock production, integrated spatial land management, and lifecycle analysis of biofuels. His research integrates computational modeling (e.g., watershed modeling) with geospatial and economic analysis to identify more efficient and sustainable natural resource-management strategies. He holds a PhD in natural resources and environment from the University of Michigan, Ann Arbor.

May Wu is a principal environmental system analyst in the Energy Systems Division at Argonne National Laboratory, USA. As a principal investigator of a multiyear bioenergy sustainability project supported by the US Department of Energy, Dr Wu’s research addresses water resource use and availability and water quality by developing biofuel water footprints and SWAT models for Mississippi River Basin tributaries. She is a member of the Global Bioenergy Partnership (GBEP) Bioenergy and Water working group and has extensive experience in water and wastewater treatment and analysis. Dr Wu holds several US patents, has authored 50+ publications, and holds a dual PhD in environmental engineering and environmental toxicology from Michigan State University.

Miae Ha is an assistant hydrologist in the Energy Systems Division at Argonne National Laboratory, USA. She has extensive experience in watershed modeling, which examines water quality and hydrology in the agricultural landscape. Her research interests include development of hydrologic models at multiple scales, integrated land use and management, and simulation of best management practices (BMPs) for sustainable bioenergy production under various climate scenarios. She holds a PhD in water management and hydrological science from Texas A&M University.