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ORIGINAL RESEARCH

WILEY GLOBAL CHANGE BIOLOGY BIOENERGY

Valuation of ecosystem services in alternative bioenergy landscape scenarios

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Abstract

Agricultural land in the Midwest is a source of food and fuel, as well as biodiversity. It is also a cause of excess nutrients that make their way to the Mississippi River and the Gulf of Mexico. To address unsustainable changes to biogeochemical cycles and ecosystem functions, a multidisciplinary approach involving social science, natural science, and engineering is often effective. Given the potential of second-generation biofuels, and capitalizing on the deep-rooted perennial bioenergy crops capable of thriving in poor soils, we demonstrated an integrated socio-environmental analysis of the impacts of growing switchgrass within row-crop landscapes in Illinois. In this study, we model land use scenarios that incorporate switchgrass as a biofuel crop in a Midwest corn-belt watershed using the Soil Water Assessment Tool coupled with an economic analysis for the Vermilion Basin in Illinois. We estimated the values of ecosystem services under an alternative bioenergy landscape, including commodity and bioenergy crops, changes in biogeochemistry, and recreational services. The estimated annual values of nitrate and sediment reduction attributed to bioenergy crops range from \$38 million to \$97 million and \$16,000 to \$197,000, respectively. The annual value of carbon dioxide emission reduction ranges from \$1.8 million to \$6.1 million based on the initial crop rotation pattern. Estimated average annual values for wildlife viewing, water-based recreation, and pheasant hunting are \$1.24 million, \$0.17 million, and \$0.3 million, respectively. To our knowledge, this study represents the first effort to comprehensively quantify ecosystem services using a process-based model, and estimate their value in an alternative bioenergy landscape. The information we generate could aid in understanding the potential for biomass production from marginal land and the total economic value of the landscape at various spatial scales. The framework is useful in fostering alternative bioenergy landscapes with synergies in a food, energy, and conservation nexus.

KEYWORDS

carbon dioxide emission reduction, nitrate loss, nutrient recovery, sustainability, value of ecosystem services

1 | INTRODUCTION

Balancing the food, energy, and environmental nexus in agricultural lands requires innovative solutions. Bioenergy production in marginal lands has gained increasing attention with the recognition of its potential for synergistic increases in food and energy production coupled with the additional benefits of improved ecological functions (Dauber et al., 2012; Ssegane, Negri, Quinn, & Urgun-Demirtas, 2015; Stoof et al., 2015; Valentine et al., 2012; Werling et al., 2014). Bioenergy crops grown on marginal lands can contribute up to 25% of the nation's target for cellulosic biofuels. Such landscapes can also reduce greenhouse gas (GHG) emissions and produce local environmental and ecological benefits (Gelfand et al., 2013; Meehan et al., 2013; Mishra, Torn, & Fingerman, 2013; Parish et al., 2012; Woodbury, Kemanian, Jacobson, & Langholtz, 2018). Identification and valuation of the total economic benefits of bioenergy production in marginal lands is the first step in turning an unprofitable pursuit into an economically beneficial industry for both farmers and society at large. Policies that incorporate the monetary value of environmental benefits through payments for ecosystem services (PES) can improve decision-making in the area of investments in new industries and land use choices to increase food, energy, and environmental sustainability.

The Renewable Fuel Standard of the U.S. Energy Independence and Security Act of 2007 (EISA, 2007) mandates that 45% of the nation's 136 billion liters of renewable fuel production should consist of cellulosic ethanol by 2022. The 2011 U.S. Billion-Ton Report (U.S. DOE, 2011) projected that annual bioenergy crop production supplying biomass for the bioenergy and bioproducts industry would range from 145 million to 585 million dry Mg in 2022. The report also highlighted that, at $50 per dry short ton, bioenergy crops would become the dominant source of lignocellulosic energy after 2022. These bioenergy policy and industry forces, coupled with the revised goal of reducing nitrogen and phosphate concentrations by 20% in the Gulf of Mexico by 2025 (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2016), emphasize the need to investigate innovative bioenergy crop production, especially in marginal lands.

One of the primary drivers of large-scale planting of perennial native grasses to replace row crops on croplands that are highly susceptible to environmental degradation is the conservation reserve program (CRP) (Tomer & Locke, 2011). This federal program administered by the Farm Service Agency provides private landowners with financial incentives for taking environmentally sensitive croplands out of crop production for 10–15 years (Cowan, 2008). CRP grasslands have been shown to provide a wide range of ecosystem benefits (e.g., minimizing soil erosion, soil carbon sequestration, water quality improvement, and landscape wildlife value enhancement) (Baer, Kitchen, Blair, & Rice, 2002; Lant et al., 2005; McLauchlan, Hobbie, & Post, 2006; Murray, Best, Jacobsen, & Braster, 2003; Veech, 2006; Zheng et al., 2004). However, CRP grasslands are primarily designed for conservation purposes. The grasses are not harvested for biofuels or other uses, with the exception of managed haying and grazing, which is only permitted under certain conditions (Cowan, 2008).

Given the growing need for advanced biofuels, and capitalizing on the inherent properties of perennial bioenergy crops, such as deeper root systems, and their ability to thrive in poor soils and in more extreme conditions, we developed and demonstrated an industrial ecology concept where switchgrass was integrated within row-crop landscapes in Illinois (Ssegane et al., 2015). The highly detailed land use model developed by Ssegane and Negri (2016) demonstrated how to identify marginal land for incorporating switchgrass in a row-crop system and how to design an alternative bioenergy landscape (ABL) to mitigate negative environmental impacts of row crops and increase both total economic benefits (revenues from crops such as cereal/legumes and bioenergy) as well as environmental/ecosystem services (Cacho, Negri, Zumpf, & Campbell, 2017; Ferrarini et al., 2017; Graham, Nassauer, Currie, Ssegane, & Negri, 2017; Ssegane & Negri, 2016; Zumpf, Ssegane, Negri, Campbell, & Cacho, 2017). Landscape design is an alternative approach to land management in which landscape patterns are intentionally changed to meet cultural and socioeconomic functions, while preserving the ecosystem's integrity (Nassauer & Opdam, 2008). An ABL rely on a variety of high-quality georeferenced data, such as the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) soil survey geographic database (SSURGO; USDA NRCS, 2012) and current and proven technology platforms (e.g., geographic information systems, remote sensing, precision agriculture, and proximal sensing) (Lobsey, 2010) to characterize accurately the soils, topography, hydrology, water quality, and crop productivity at a sub-field scale (Ssegane et al., 2015).

A large bioenergy economy based on sustainable biomass production, as identified by the 2016 U.S. Billion-Ton Report (U.S. DOE, 2016), will require millions of hectares of marginal lands (Campbell, Lobell, Genova, & Field, 2008; Gopalakrishnan, Negri, & Synder, 2011; Nijsen, Smeets, Stehfest, & Vuuren, 2012). Therefore, such an economy hinges largely on farmers' mass adoption of bioenergy crops. Khanna, Zilberman, and Miao (2017) find that energy crop adoption depends on monetary factors (profits and costs). According to Khanna, Dhungana, and Clifton-Brown (2008), the annualized cost of production of switchgrass is $74.35/dry ton (2016 dollars). The 2016 U.S. Billion Ton Report uses biomass prices of $40, $60, and $80 per dry short ton in their assessment. Thus, at those prices, farmers may not have enough of a financial incentive to adopt bioenergy crops in their farms. In such a scenario, an added benefit stream such as payments for ecosystem services generated by the landscape dedicated to bioenergy crops may incentivize the adoption of the new technology.

We focus on the targeted placement of perennial bioenergy crops because it can support ecosystem services that conventional row crops are unable to provide (McIsaac, David, & Mitchell, 2010; Werling et al., 2014) while diversifying farmers' income streams. Growing native perennial grasses in place of corn or soybeans in low productivity areas in the Midwest represents a shift back toward a native prairie ecosystem with the accompanying benefits of improving impaired waterbodies, land, and habitat of native faunal species, as well as reducing GHG emissions (Illinois Environmental Protection Agency & Illinois Department of Agriculture, [IEPA & IDOA], 2015; Koh et al., 2016; Smakhtin, Shilpakar, & Hughes, 2006). Because it is deep-rooted, switchgrass can provide net positive subsoil carbon sequestration (Lemus & Lal, 2005), especially if planted in environmentally degraded land. Such ABL can also provide water quality benefits (Cacho et al., 2017) by intercepting excess nutrient losses from commodity crops (Ssegane et al., 2015; Zumpf et al., 2017) and reducing surface runoff (Hernandez-Santana et al., 2013) and soil erosion (Helmers et al., 2012). Switchgrass also provides important cover and nesting sites for quail, pheasants, rabbits, deer, and turkey, which use switchgrass stands for winter bedding (Adler, Grosso, & Parton, 2007; Harper & Keyser, 2008; Semere & Slater, 2007). Native grasses such as switchgrass increase the habitat area for pollinators (Graham et al., 2017), as well as insect predators and parasites (Werling et al., 2014) that can provide pollination services and biological pest control for farmers. Thus, ABLs can generate provisioning services (food and energy crops), as well as regulating and cultural services at local to global scales. The studies discussed so far quantify the changes in environmental quality attributable to ABLs, but they do not monetize the value of the incremental change in associated ecosystem services.

It is important to note that the benefits of the ecosystem services generated by an ABL do not generally accrue to the service producers. While some of the ecosystem services benefit the producers and the local economy, others are more regional and global. This is why payments for ecosystem services are critical policy tools. For example, erosion control and nutrient cycling, and the maintenance of soil carbon provide direct benefits to individual farmers as well as to local water treatment facilities and lake/dam operators (Boyd & Banzhaf, 2007; Zhang, Ricketts, Kremen, Carney, & Swinton, 2007). Other services associated with perennial biofuel crops, such as enhanced hunting and fishing opportunities, freshwater recreation, and wildlife viewing, are of benefit to local economies (Gascoigne et al., 2011; Jenkins, Murray, Kramer, & Faulkner, 2010). Reductions in GHG emissions, on the other hand, provide benefits to people globally. To that end, this paper estimates the economic value of ecosystem services generated by an ABL in a Midwest corn-belt watershed of the United States. Coupling a process-based biophysical model with economic analysis in an integrated assessment framework, we identify marginal land that could potentially be converted to bioenergy crop production. We then quantify and estimate the value of the corresponding ecosystem services from the ABL. This includes estimating the values of the reduction in sediment losses, nitrate losses, and GHG emissions, and the value of habitat creation for important faunal species. We focus on the ecosystem services that had adequate data available from secondary sources for valuation and that were relevant for supporting the dual goals of a bioenergy industry and reducing nitrogen concentration. The analysis allows us to compare the total value of the landscape with and without incorporating the value of ecosystem services generated by the strategic planting of switchgrass. Since not all these benefits accrue to farmers, the value calculated is for society as a whole, and mechanisms such as PES would be needed to create incentives for farmers to plant bioenergy crops such as switchgrass.

2 | MATERIALS AND METHODS

2.1 | Study area

The study site is located in the Vermilion River Basin (Hydrologic Unit Code or HUC 07130002) in Illinois (Figure 1), which is on the Illinois Environmental Protection Agency's 2016 list of impaired waters (Section 303 [d]) list due to excess nitrate levels. The water quality-impaired Vermilion River Basin is considered to be a high priority watershed in Illinois' Nutrient Reduction Strategy (IEPA & IDOA, 2015), because it drains to the Illinois River, which is a tributary of the Mississippi River, a major source of excess nutrient loading to the Gulf of Mexico. Specifically, the study area is comprised of three 10-digit HUC basins: the North Fork Vermilion River (HUC 0713000203), the South Fork Vermilion River (HUC 0713000202), and the Kelly Creek – North Fork Vermilion River (HUC 0713000201). In this project, we refer to these basins collectively as the Upper Vermilion River Basin or watershed. This basin drains portions of four counties (Livingston, McLean, Ford, and Iroquois) and has an area of 147,800 ha, 88% of which is under row crops (USDA NASS, 2016). The analysis of a 10-m digital elevation model showed that approximately 87% of the areas within the Upper Vermilion River Basin have less than a two percent slope. Predominant soils in the basin include Ashkum silty clay loam, Bryce silty clay, and Pella silty clay loam. The mean annual precipitation, based on a 32-year (1981–2013) record at station USC00112923, is 862 mm.

The Indian Creek watershed drains a portion of the South Fork Vermilion River, including parts of three counties

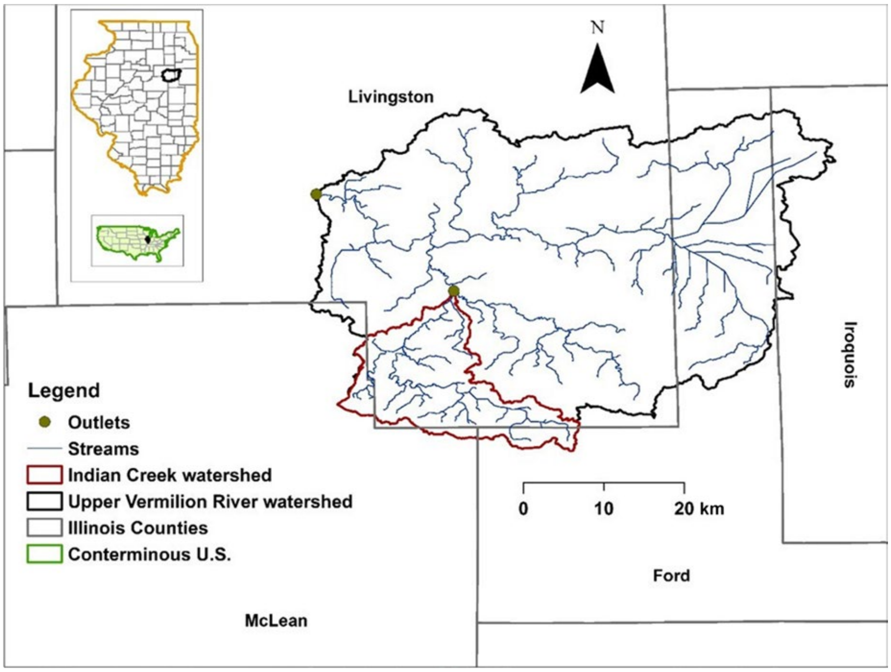

FIGURE 1 Study area in Illinois

(Livingston, McLean, and Ford); it has a total drainage area of 20,700 ha. The Indian Creek watershed has a flat topography; most areas within this watershed have a slope of less than two percent. Soils in the watershed are predominantly Drummer silty clay loam, Reddick clay loam, and Saybrook silt loam. The mean annual precipitation over a 31-year period (1981–2011) and actual total evapotranspiration, based on a 13-year record (2002–2012), are 887 mm and 661 mm, respectively (Ssegane & Negri, 2016). Major crop rotations include continuous corn (10.7%), corn-soybean (31.3%), soybean-corn (31.2%), and corn-corn-soybean (11.0%), and are mostly under tile drainage due to the watershed's low topographic gradient and poorly drained soils (Hamada, Ssegane, & Negri, 2015). The basin is a representative impaired corn-belt basin of the Midwest. We have been conducting monitoring, measurement, and modeling work in the Indian Creek watershed over the past 8 years (as reported in Cacho et al., 2017; Gopalakrishnan, Negri, & Salas, 2012; Gopalakrishnan et al., 2011; Graham et al., 2017; Hamada et al., 2015; Ssegane & Negri, 2016; Ssegane et al., 2015; Zumpf et al., 2017).

2.2 | Integrated assessment framework

We developed an integrated assessment framework (IAF) that couples biophysical models and economic models to facilitate the systematic analysis of an alternative bioenergy landscape (Figure 2). This framework uses five sequential steps to comprehensively assess the landscape with switchgrass. First, we used biophysical models to quantify the physical, chemical, and biological changes in soil and water attributed to switching from row crops to switchgrass. Second, we established the connection between the quantified changes in physical, chemical, and biological parameters and the corresponding ecological endpoints. Ecological endpoints are biophysical characteristics that are concrete, tangible, and measurable, and are directly or intuitively connected to human wellbeing (Boyd, 2007). Third, we estimated the monetary value of the ecosystem services via benefit transfer and explored the integration of the benefits. Fourth, we estimated and compared the costs and revenues for various land use scenarios. Fifth, we estimated and compared the total economic value of land use, including the value from crops (grains and bioenergy crops) and the ecosystem services for various scenarios. The components of the IAF are explained next. The second to fifth components are incorporated under the subheading "Economic Analysis."

2.3 | Quantification of nutrient, sediment, carbon dioxide emission, and recreational changes in an alternative bioenergy landscape

2.3.1 | Nitrate and sediment

We conducted a biophysical modeling exercise in the Indian Creek watershed. The estimates on the reduction of nutrient (specifically nitrate) and sediment loading were then used to scale up the quantification and monetization of benefits of introducing bioenergy crops in the marginal land identified in the Upper Vermilion River Basin.

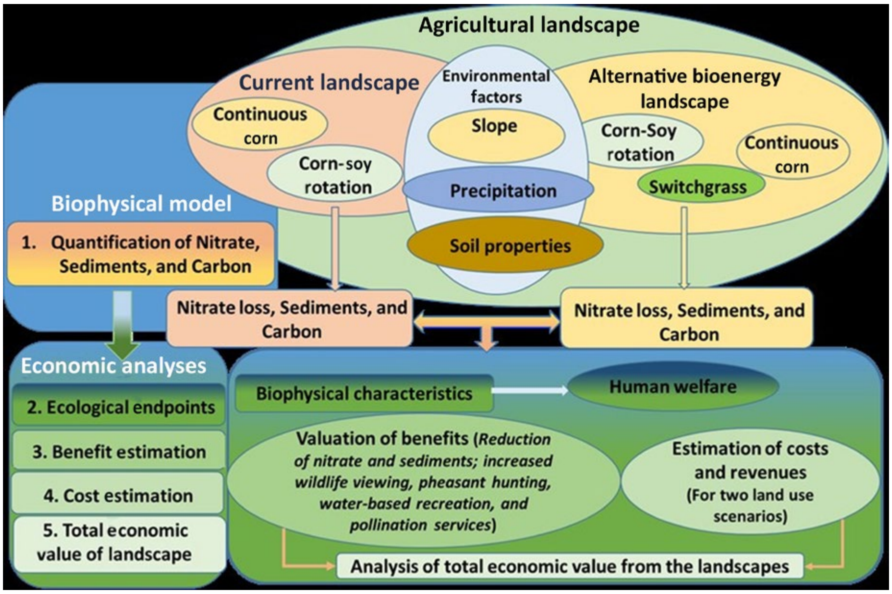

FIGURE 2 Integrated assessment framework for valuation of alternative bioenergy landscape

We used the soil and water assessment tool (SWAT) model (Arnold & Allen, 1996; Arnold, Srinivasan, Muttiah, & Williams, 1998) to predict sediment and nitrate loads, as well as crop (commodity and bioenergy) yield under business as usual (BAU) and ABL scenarios. SWAT is a distributed model capable of predicting the long-term hydrologic and water-quality impacts of changes in land use and/or climate at a watershed or river basin scale (Arnold & Allen, 1996; Arnold et al., 1998). Ssegane and Negri (2016) summarize various applications of SWAT including nitrogen (N) transport, best management practices (BMPs), land use change, climate change, and bioenergy at various spatial scales. We used results of the SWAT-based biophysical modeling for the Indian Creek watershed published by Ssegane and Negri (2016) as the foundation for this study.

Briefly, the major inputs used in the SWAT model for the Indian Creek watershed included a 10-m digital elevation model, land use land cover (USDA NASS, 2016), soil type (SSURGO), and weather data. The SWAT model was calibrated using 4 years (2010-2013) of measured daily streamflow data near the outlet of the study site (the Indian Creek watershed). The 2010-2013 period was chosen for model calibration since it covered not only the period of the watershed's most current crop rotation, but also because the watershed experienced dry (657 mm rainfall) and wet (958 mm rainfall) years in 2012 and 2013, respectively, providing desired weather conditions for calibrating a biophysical model. The hydrologically calibrated model was subsequently validated using measured daily nitrate flux data.

Calibration and validation were conducted under current land use and management operations (referred to as the BAU scenario), which were created within SWAT using its management utility module. Major crop rotations were generated using 2010 to 2012 data from USDA NASS (2016) that included continuous corn (10.7%), corn-soybean (31.3%), soybean-corn (31.2%), and corn-corn-soybean (11.0%) under BAU. The SWAT model was able to successfully represent the hydrologic and water quality processes, particularly nitrate loading of the study site (Ssegane & Negri, 2016), based on an acceptable range of values of the recommended metrics for assessing model performance (Moriasi et al., 2007).

We conducted marginal land classification using the multi-criteria decision analysis (MCDA) technique (Malczewski, 2006) and implemented it using the Environmental System Research Institute's (ESRI's) ArcGIS Desktop 10.3.1 software package. Details about the marginal land analysis and classification for the Indian Creek watershed can be found in Ssegane and Negri (2016). We used the results of the marginal land analysis and classification as the bases for creating future land-use scenarios in SWAT by replacing the subfield areas that 1) exhibit two or more environmental degradation metrics (e.g., aquifer susceptibility to nitrate or pesticide losses, surface soil erosion, flooding frequency), and 2) have a low crop productivity index (CPI); i.e., commodity croplands that are not economically viable (Ssegane & Negri, 2016). We used switchgrass (Shawnee) information from Trybula et al. (2015) to modify default (Alamo) values to represent SWAT crop parameters for switchgrass in the Midwest landscape. Readers are referred to Ssegane and Negri (2016) for a detailed description of the calibration and validation procedures, statistics of model performance, and definition of land marginalities.

After conducting the SWAT modeling exercise in the Indian Creek watershed, we estimated the benefits of an ABL for the watershed in biophysical terms. We then scaled up the estimates of nitrate loss and sediment reduction to monetize the benefits of introducing bioenergy crops in the marginal land identified in the Upper Vermilion River Basin. We used ESRI's ArcGIS Desktop 10.3.1 software package following the marginal land criteria and classification techniques developed in Ssegane and Negri (2016) to identify marginal lands in the Upper Vermilion basin. We translated the benefits for the Indian Creek watershed to benefits per hectare of switchgrass substitution in marginal land in the watershed. The information on the benefits estimated per hectare and the marginal land area identified for the Upper Vermilion River Basin were used to estimate the total benefits for the basin.

2.3.2 | Economic analysis

The overarching objective of the economic analysis was to estimate the total economic benefits and the costs of cultivating a row-crop landscape and compare them to those of an ABL. We estimated the economic benefits of ABLs as the marginal increase in the value of ecosystem services (provisioning, regulating, cultural) and supporting services, according to the Millennium Ecosystem Assessment (2005). The increased net benefit from an ABL includes the change in revenue stream from the crops mix (grains and switchgrass), the recreational benefits from the reduction in pollutants downstream, the increase in biodiversity, and the global benefit of a reduction in GHG emissions.

We used the information on total costs of production, prices, and quantity of production to estimate the revenues from crops for various land use scenarios and corresponding costs of cultivation. The details are in the section entitled "Estimation and Comparison of Costs and Revenue from Commodity and Bioenergy Crops." In order to estimate the monetary value of regulating and cultural ecosystem services, we used environmental valuation techniques, as described below.

We estimated the benefit *(B)* of incorporating switchgrass in the row-crop landscape by first quantifying the change in environmental or ecosystem attributes associated with incorporation of switchgrass followed by monetizing the benefits (Equation 1):

$$B_i = \left(EA_{\mathrm{ABL}} - EA_{\mathrm{BAU}}\right)_i * V_i \qquad (1)$$

where B_i is the estimated benefit for ecosystem service i, EA_{ABL} is the quantity of identified environmental or ecosystem attribute under the ABL design with switchgrass, EA_{BAU} is the measure of the EA under the business as usual (BAU) scenario (i.e., without switchgrass), and V_i is the per-unit value of the environmental or ecosystem attribute. The values V_i are adjusted to 2016 dollars.

We estimated the change in the quantity of EA using the SWAT model discussed earlier in this manuscript. A range of environmental valuation techniques can be used to estimate the per-unit value of ecosystem/environmental attribute Vi. Earlier studies have used the contingent valuation method to estimate the willingness to pay for nitrate reduction downstream, and the travel cost method for the valuation of freshwater recreational services or fishing. The focus of this work is to evaluate and assemble a number of ecosystem services benefits associated with an ABL based on existing information, since conducting a separate study for each ecosystem service and collecting primary data for the analysis would require substantial time and resources. Under such resource and time constraints, the benefit transfer method is commonly used (Rosenberger & Loomis, 2001). The benefit transfer method uses the ecosystem service value that has been estimated at a study site (the site where the study was originally conducted) to quantify the value of ecosystem services at a policy site (the new site where its value has not been estimated) with similar characteristics (Boyle & Bergstrom, 1992; Wilson & Hoehn, 2006). The derivation of value for benefit transfer for each environmental attribute follows.

Nitrate reduction

Nitrate reduction has multiple benefits, which are often idiosyncratic and place specific. Therefore, often the avoided cost is used, both in the scientific literature and in regulation (Griffiths et al., 2012). The costs of nitrate reduction vary based on the methods used to reduce nitrates at various point and nonpoint sources, downstream activities, the existence of or potential for nitrate trading mechanisms, and the type of trade mechanism. For example, Woodbury et al. (2018) estimated that the cost of N loading reduction in the Chesapeake Bay using switchgrass in a portion of corn cropland with and without fertilizer would be \$29.75 and \$39.50 per kg, respectively. In contrast, Ribaudo, Heimlich, and Peters (2005) estimated a one-to-one N reduction based on a potential nutrient credit-trading scheme in the Corn Belt region as \$20.90 per kg (in 1990 dollars). This value was calculated using the supply curve of N reduction credits from agriculture and N reduction demand curve of downstream facilities with a mandatory N limit on their discharge. The estimated value of an N reduction credit (Ribaudo et al., 2005) in the Corn Belt region is more appropriate for point benefit transfer to Vermilion, Illinois, than results at other study sites that are dissimilar to our policy site. Therefore, we used the adjusted dollar value of \$38.37 per kg (in 2016 dollars) from Ribaudo et al. (2005) to estimate the value of nitrate reduction (Table 1). While the value of N reduction is estimated using the supply and demand of credit at the county level, the value presented in the paper is averaged at the regional level. The only information available in the paper is the point estimate, which was not sufficient to conduct a sensitivity analysis.

Sediment reduction

The soil conservation benefit associated with reduced sediment export includes improved reservoir services, navigation, irrigation ditches and channels, road drainage ditches, municipal water treatment, flood damage, freshwater

TABLE 1 Value of Ecosystem Services from the Literature Review

Ecosystem Service	Value	Source	2016 Dollars
Nitrate reduction	\$20.90 per kg nitrate	Ribaudo et al. (2005)	\$38.37 per kg nitrate
Sediment reduction	\$3.12 per Mg	Hansen and Ribaudo (2008)	\$4.35 per Mg
Carbon dioxide emission reduction	a. \$33.19 per Mg CO_2eq b. 6.3 Mg and 1.84 Mg CO_2eq per ha per year[b]	a. Interagency Working Group (2016) b. Bhattrai and Secchi (under review)	\$209.10 and \$61.07 per ha per year[b]
Recreational value			
Water-based recreation	\$2.59 to \$6.15 per ha	Baylis et al. (2002)	\$3.45 to \$8.21 per ha
Wildlife viewing	\$24.75 per ha[a]	Feather et al. (1999)	\$42.36 per ha
Pheasant hunting	\$5.83 per ha[a]	Feather et al. (1999)	\$9.97 per ha

[a]Value per ha converted from cropland to grassland [b]Values are respectively for converting BAU with continuous corn and corn-soy rotation to an ABL

fisheries, municipal and industrial water use, steam power plants, and soil productivity. The services were valued at \$2.83 (in 2000 dollars) per short ton of soil conserved for the Vermilion Watershed (Hansen & Ribaudo, 2008).[1] This is the most recent valuation study conducted at the watershed level for the U.S. Other studies on the valuation of sediment reduction do not provide the same level of spatial disaggregation. Hansen and Ribaudo (2008) use the revealed preference method which is considered less controversial than the stated preference method.[2] Therefore, we selected Hansen and Ribaudo (2008) for the benefit transfer. We converted the value per short ton to a value per Mg of \$3.12 and adjusted to 2016 dollars, for a total of \$4.35 per Mg of sediment reduction for the benefits transfer (Table 1).

Greenhouse gas emission reduction

Growing biofuel crops in place of row crops has the potential to reduce carbon emissions through less intensive land management practices that sequester more carbon due to the characteristics of biofuel crops such as switchgrass. In a cradle-to-farm gate carbon footprint analysis of three cropping practices, Bhattarai and Secchi (under review) found that switching from continuous corn and corn-soybean rotations to switchgrass would reduce overall GHG emissions by 6.3 and 1.84 Mg CO_2eq per ha per year, respectively. Using a social carbon cost of \$33.19 per Mg CO_2eq (IAWG, 2016), we found that the reduction in GHG emission benefits of converting continuous corn or a corn-soybean rotation to switchgrass would be valued at \$209.10 and \$61.07 per ha per year, respectively.

Water-based recreation

Baylis, Feather, Padgitt, and Sandretto (2002) estimated the improved value of water-based recreation attributed to enrolling row cropland into the CRP as \$2.59 to \$6.15 per ha per year. Although there are various studies (Alvarez, Asci, & Vorotnikova, 2016; Keeler et al., 2012; Sohngen, King, Howard, Newton, & Forster, 2015) that focus on estimating water-based recreational values, the Baylis et al. (2002) study is the best suited for benefit transfer in the Upper Vermilion River Basin. This is because erosion control and downstream soil conservation benefits of land enrolled in the CRP program most closely match the impacts of the introduction of bioenergy crops in an intensively cropped landscape. The values are adjusted to 2016 values and correspond to \$3.45 to \$8.21 per ha per year in the Upper Vermilion River Basin.

Wildlife viewing

Wildlife habitat has been identified as a prime motivator for many early switchgrass adopters, and switchgrass has been given high marks for aesthetic value (Hipple & Duffy, 2002). Feather, Hellerstein, and Hansen (1999) estimated the national economic impact of CRP lands on wildlife-oriented recreation (wildlife viewing) at \$24.75 per ha per year (1992 dollars) in the United States. The authors also estimated the values for various regions; the estimated value for the northeastern

[1]Hansen and Ribaudo (2008) estimated the total value of soil conservation at \$4.7 per ton, which includes a water-based recreation value of \$1.9/ton. This study treats water-based recreation as a separate component of the value of ecosystem service assessment. We therefore used a net value of sediment reduction of \$2.83/ton.

[2]Revealed preference methods are the environmental valuation techniques which estimate the value of the resource based on actual payment information for the use of environmental resources (e.g. travel cost method, hedonic pricing method). Stated preference methods, on the other hand, are based on the analysis of the willingness to accept or the willingness to pay as stated by the potential consumers/suppliers of environmental goods. Readers are referred to materials on environmental valuation techniques for more information on the two methods.

region that includes Illinois is $87.5 per ha per year. The value estimated for this region, which includes the majority of the Great Lakes, other major lakes and rivers with large cities and metropolitan centers, may not represent the recreational value for rural Livingston County in the heart of Illinois, which has a comparatively low population density and per capita income. Therefore, we decided to use the national annual value adjusted for 2016 of $42.36 per ha for estimating the value of wildlife viewing increased due to habitat provided by ABL.

Pheasant hunting

Feather et al. (1999) estimated that the increase in consumer surplus associated with CRP's habitat and its positive effects on pheasant hunting would be $5.83 per ha per year. For the reasons mentioned in the "Wildlife viewing" section above, we used this national average value for our analysis. The value was adjusted for 2016 to $9.97 per ha per year and used for estimating the value of increased pheasant hunting attributed to ABL.

Pollinator services

Koh et al. (2016) modeled a 23% decline in wild bee abundance in U.S. land area between 2008 and 2013. This decline was associated with the conversion of natural habitat to row crops. Honeybees are three to four times more abundant in switchgrass than in corn (Gardiner et al., 2010; Meehan et al., 2013). Conversion to switchgrass has high nesting scores (the same as native prairie or grassland), but low foraging scores due to a lack of floral resources; however, switchgrass nesting and foraging scores overall are better than those for corn and soybean (Lonsdorf et al., 2009). Illinois' major pollination-dependent and economically important crops are apple, peach, and pumpkin based on the crops' pollination dependency on insects (Losey & Vaughan, 2006). We assessed pollination services for the study area by scaling up the results from Mishra et al. (under review), which uses a modified production method for estimating the value of pollination services provided by additional habitat. We found that the Upper Vermilion watershed had about 150 ha of land scattered across the watershed, where low pollinator abundance areas coincided with area under highly pollination dependent crops.

2.4 | Estimation and comparison of costs and revenue from commodity and bioenergy crops

We calculated the costs and revenues for continuous corn and corn-soybean rotations for each scenario using the Iowa State University Ag Decision Maker Crop Rotation Summary Tool (Ag Decision Maker, 2016a) assuming conventional tillage practices. We used this crop budget tool because it allows for modifications to fertilizer application rates, in addition to other variable costs, which provide an accurate accounting of costs. We adjusted costs for preharvest machinery, seed, fertilizer, chemicals, insurance, interest rates, labor, and harvest machinery based on their average annual historic prices (Duffy, 2013). Cash rents were based on average annual historic prices for Livingston County, Illinois (FarmDoc, 2016). Revenues for corn and soybean crops were based on modeled yields and historic average annual prices for high-productivity farmland in central Illinois (Schnitkey, 2015).

We calculated costs and revenues for switchgrass production using the Iowa State University Ag Decision Maker tool for comparing returns for switchgrass with conventional crops (Ag Decision Maker, 2016a). We maintained default values for preharvest machinery operations, operating expenses, and harvest machinery operations with the exception of fertilizer prices, interest rates, and land rents. We explored two scenarios for calculating switchgrass revenues – the first bases switchgrass yields on SWAT model results, and the second uses expected average yields for switchgrass in the Corn Belt region (Ag Decision Maker, 2016b). In both scenarios, we valued switchgrass yields at $60 per dry Mg (U.S. DOE, 2011).

3 | RESULTS

3.1 | Marginal land areas

We estimated the total amount of marginal land areas currently planted under continuous corn, corn-soybean rotation, and pasture that could be converted to switchgrass in the Indian Creek watershed and Upper Vermilion River Basin, respectively, to be 4,500 and 29,300 ha (Figure 3). We calculated the low-CPI area, a subset of the marginal land area under continuous corn and corn-soybean rotation which could potentially be converted to switchgrass production, at 550 and 22,400 ha, respectively, for the two watersheds.

3.2 | Estimated quantity of nitrate reduction and sediment reduction (SWAT model)

The SWAT-modeled fluxes for total nitrate show an average annual reduction of 289,323 kg per year, for the marginal scenario relative to the baseline in the Indian Creek watershed (Table 2). This equates to an average N flux reduction of 65 kg ha^{-1} year^{-1} (34.18 to 86.35 kg ha^{-1} year^{-1}), for introducing switchgrass in marginal land, or 14 kg ha^{-1} year^{-1}, for the overall watershed.

The SWAT-modeled fluxes for total sediment showed an average annual reduction of 3,609 Mg year^{-1} for the marginal scenario relative to the baseline (Table 2). This equates to an average sediment flux reduction of 0.81 Mg ha^{-1} year^{-1} in marginal land, or 0.17 Mg ha^{-1} year^{-1} for the overall watershed.

TABLE 2 SWAT-modeled annual total sediment and nitrogen output for land use scenarios in the Indian Creek watershed

	Baseline: row crops (corn or corn/soy) in all cropland		Switchgrass in low-CPI land only		Switchgrass in all marginal land	
Years	Nitrate (kg)	Sediment (Mg)	Nitrate (kg)	Sediment (Mg)	Nitrate (kg)	Sediment (Mg)
2007	1,309,740	17,975	1,227,309	19,429	1,027,218	12,581
2008	1,104,434	20,733	1,052,290	19,222	832,341	14,033
2009	1,664,907	10,158	1,578,621	10,047	1,314,996	7,180
2010	849,486	3,873	811,730	4,060	654,467	2,691
2011	1,457,683	4,631	1,377,706	4,254	1,071,099	3,066
2012	551,873	1,996	488,496	2,125	398,855	1,447
2013	1,596,414	20,860	1,512,539	20,246	1,210,301	13,963
Average	1,219,220	11,461	1,149,813	11,340	929,897	7,852

3.3 | Ecosystem service values for the experimental site and the larger watershed

We estimated the value of each ecosystem service associated with the substitution of row crops by switchgrass in the marginal land in the Indian Creek watershed and the Upper Vermilion River Basin. The estimated annual value of nitrate reduction ranged from \$5.8 to \$14.8 million and from \$38 to \$97 million for the Indian Creek watershed and the Upper Vermilion River Basin, respectively (Table 3). We estimated the value of carbon dioxide emission reduction to be 3.5 times higher if the marginal lands were converted to switchgrass from continuous corn compared to a corn-soy rotation. We estimated that the value of this reduction ranges annually from \$0.3 to \$0.9 million for the Indian Creek watershed and from \$1.8 to \$6.1 million for the Upper Vermilion River Basin. Values associated with cultural and recreational services for the Upper Vermilion River Basin were about \$1.25 million for wildlife viewing and \$0.1 to \$0.24 million for water-based recreation. The pollinator population increase from habitat created for natural pollinators contributed to crop production. For the current major crops in the watersheds, corn and soybean, we did not find pollination benefits to be significant and thus did not report them. Recognizing the potential for double counting of the ecosystem services evaluated, we did not estimate the total value of all the ecosystem services. It is important to emphasize that using benefit transfer can add error to the estimates, and that, although we are incorporating multiple ecosystem services in the analysis, other services could be affected by the change in land use. Although the model and land use change are different, our conceptual approach is similar to Jenkins et al. (2010).

3.4 | Estimation of economic value from annual row crops and biomass production

Corn and soybean crops covered 675,866 ha (50.81%) and 445,719 ha (33.51%) of land, respectively, in the Upper Vermilion River Basin in 2016 (USDA NASS, 2016). In the BAU scenario, corn and soybean yields averaged 8,428 and 3,504 kg ha^{-1} year^{-1}, respectively. This results in a total value of \$1.34 billion for annual row crops and switchgrass (Table 4). We averaged the yield over 5 years. In the ABL scenario,

TABLE 3 Ecosystem services value per year (2016 U.S. dollars)

Ecosystem services	Value for Indian Creek Watershed	Value for Upper Vermilion River Basin
Nitrate reduction	\$5.87 to \$14.84 million	\$38.55 to \$97.38 million
Sediments reduction	\$2,400 to \$30,000	\$16,000 to \$197,000
Carbon dioxide emission reduction		
Corn-soy to switchgrass	\$0.27 million	\$1.8 million
Continuous corn to switchgrass	\$0.94 million	\$6.1 million
Cultural and recreational services		
Water-based recreation	\$15,000 to \$37,000	\$0.1 to \$0.24 million
Wildlife viewing	\$0.19 million	\$1.24 million
Pheasant hunting	\$45,000	\$0.3 million

we subtracted a marginal land area of 29,300 ha from corn and soybean production and replaced it with switchgrass. We estimate that the areas of corn and soybean replaced by switchgrass in marginal lands were 14,880 and 9,813 ha, respectively. Under the ABL scenario, continuous and rotation corn yields in the non-marginal area increased by 140 and 31 kg ha^{-1} year^{-1}, respectively, while the average soybean yields increased by 1 kg ha^{-1} year^{-1}. Average modeled switchgrass yields were 7,341 and 7,604 kg ha^{-1} year^{-1} for the low-CPI and marginal lands, respectively.

The estimated change in value associated with converting some of the corn and soybean area to switchgrass in the Upper Vermilion River Basin ranges from \$3.8 to \$17.2 million in loss, depending upon the price of the switchgrass (\$20/Mg to \$80/Mg) (Table 4). However, the loss represents an incomplete picture because it does not account for other streams of economic benefits attributed to the six aforementioned ecosystem services. For example, adding the value of reduced nitrate losses changes the net effect of strategically planting switchgrass from a loss into a total benefit that ranges from \$19.98 to \$90.2 million, depending upon the price of switchgrass and that for nitrate loss reductions.

4 | DISCUSSION

Biodiversity consistently increases ecosystem stability and resistance (Isbell et al., 2015). Targeted placement of perennial bioenergy crops can create a biodiverse landscape that is more stable and has greater resilience. More importantly, the resultant multifunctional landscapes have the potential to improve the provision of a variety of ecosystem services in agricultural lands, reduce impacts of crop production, and increase economic value. However, the ecosystem services generated by such landscapes are often forgotten or neglected in land use decision making (Scott, Carter, Hardman, Grayson, & Slaney, 2018). Our work illustrates an approach whereby ecosystem services can be incorporated in the assessment of land use choices.

The major challenges to be addressed in order to develop a sustainable bioenergy landscape are the need to improve the precision of the valuation of the broad suite of ecosystem services generated by the landscape, as well as the need to stack or bundle ecosystem services in the context of facilitating/creating a PES mechanism. In this study, we integrated biophysical data on soil properties, precipitation, slope, and land use to quantify the change in a number of ecosystem services under an ABL scenario in the Upper Vermilion River Basin. We then attempted to marry economics to agricultural and biological sciences, as suggested by Khanna, Swinton, and Messer (2018), to address some of these challenges. Our results show that an average annual reduction of 65 kg ha^{-1} year^{-1} for nitrogen and 810 kg ha^{-1} year^{-1} for sediment can be achieved through replacement of corn by switchgrass in marginal lands. We estimated the value of the changes of six ecosystem services generated by ABLs. There are only a few examples of this multi-ecosystem service valuation approach because historically the modeling has been limited to a single ecosystem service (e.g., nitrate loss reduction by Woodbury et al., 2018; and biodiversity/pest control by Werling et al., 2014), though some recent work includes valuation of multiple services associated with land use change (see Gascoigne et al., 2011; Ingraham & Foster, 2008; Jenkins et al., 2010).

A viable PES system would require a methodology to stack or bundle ecosystem services. More importantly, it would require the creation of new institutions or the modification of existing ones to develop acceptable methodologies for credit verification and appropriate time scales for the contracts (Banerjee, Secchi, Fargione, Polasky, & Kraft, 2013). Although we estimated the value of multiple ecosystem

TABLE 4 Average annual Crop Yields from the SWAT-modeled land-use scenarios and values in the Upper Vermilion River Basin

Crops	Yield (kg/ha)	Production (Mgs)	Value (2016 \$ million) at switchgrass price		
			\$20/Mg	\$50/Mg	\$80/Mg
Business as usual scenario:					
Corn	8,428	5,695,861	769.11		
Soybeans	3,504	1,561,799	565.20		
Switchgrass	0	0	0.00		
Total			1,334.31		
Alternative bioenergy landscape scenario:					
Corn	8,513	5,626,550	759.75	759.75	759.75
Soybeans	3,505	1,527,733	552.87	552.87	552.87
Switchgrass	7,604	223,432	4.47	11.17	17.87
Total			1,317.09	1,323.80	1,330.50

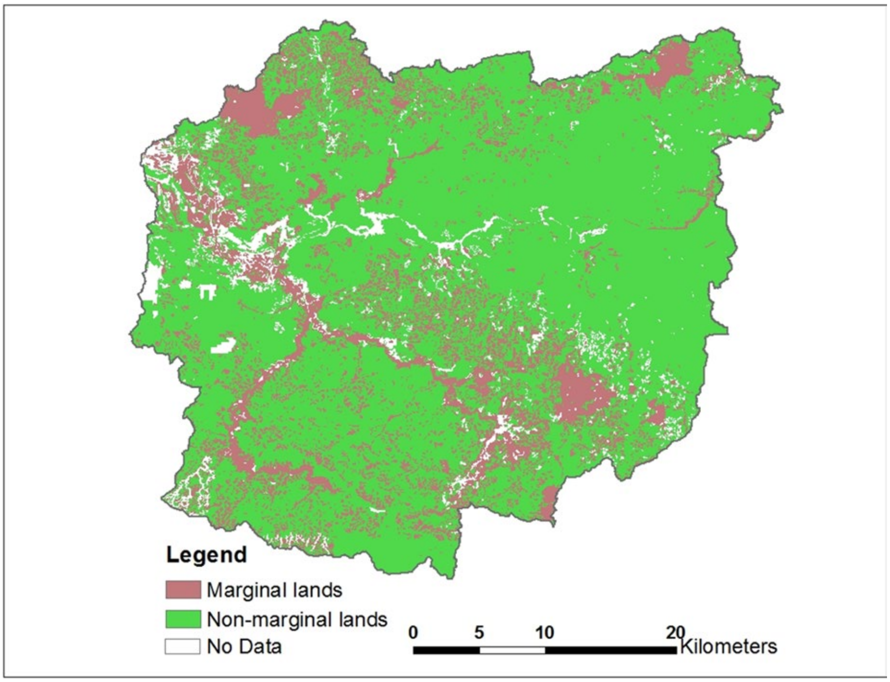

FIGURE 3 Marginal land potentially used for switchgrass cultivation in the Upper Vermilion River Basin (Source: USDA NASS 2016)

services of an ABL scenario, more work is required to bundle them and initiate a PES. The institutional challenges to PES schemes are not trivial (Daily & Matson, 2008). In the United States in particular, the implementation of these schemes is heavily linked to the fortunes of the Farm Bill (Baylis et al., 2002; Matzdorf & Meyer, 2014). However, such schemes could have substantial positive impacts. Facilitating a PES mechanism to pay the managers of landscapes for generating the ecosystem services could pave the way toward developing sustainable ABLs in the Midwest Corn Belt.

Corn outcompetes switchgrass when the economic analysis accounts for only the aboveground productivity, the farmers' revenue stream, and the existing incentives for corn (Werling et al., 2014). Our results demonstrate that the farmers' benefit from aboveground products alone from an ABL does not exceed that of row crops when the price of switchgrass ranges from \$20 to \$80 per dry short ton. However, similar to Xu, Wu, and Ha (2018) and Werling et al. (2014), our study also finds that the relative value of bioenergy crops could be increased by incorporating ecosystem services into the equation.

This study does not capture the value to individual farmers of increased switchgrass production due to the uptake of applied nitrogen fertilizer through its deep root systems. It also does not account for other benefits from reducing downstream nitrate export. For example, if the 20% reduction in nitrate export in the marginal landscape scenario could be expanded to the entire Corn Belt region, it would have significant implications for a region identified as the primary source of nitrate to the Gulf of Mexico Dead Zone (IEPA & IDOA, 2015). This is particularly relevant since, as we note, if we were able to compensate the farmers for the value of reduced nitrate loss, planting switchgrass in marginal lands would be a profitable activity for them. We also did not include in our analysis the on-farm monetary value of soil conservation, which includes the benefits from increased yield associated with reduced erosion.

As noted above, many ecosystem services were not captured by our analysis. Native grasses such as switchgrass increase the habitat area for insect predators that can provide some degree of biological pest control for farmers (Werling et al., 2014). If this were to be quantified and proven to have a net positive pest control benefit, it would represent a potential economic gain for farmers, because it would reduce their losses to crop pests and their dependence on insecticides.

There are several practical limitations to capturing the economic value found in this study. First, our landscape design was based on soil and landscape characteristics that model certain areas as marginal or as having a low crop productivity index. These areas are spatially dispersed and generally not uniform in shape. From the farmer's perspective, planting just these areas would be logistically challenging and would increase costs and time requirements during planting and harvest. Farmers have indicated they would prefer to plant crops in geometric shapes that can be more efficiently planted and harvested (based on field level discussions with farmers). Planting in this manner would likely reduce some of the benefits gained from a more targeted planting. Second, our analysis is based on the implicit assumption that the benefits to hunting and wildlife viewing would be captured by the farmer or local markets. Supporting businesses such as hotels and restaurants would be required, along with the willingness of farmers to convert private agricultural land to hunting land to capture the benefits of improved hunting and wildlife viewing opportunities provided by the switchgrass acreage. Finally, several of the ecosystem services values we used are predicated on the assumption that switchgrass acreage grown for biofuel feedstock would provide the same wildlife benefits as CRP land. Therefore, further consideration of switchgrass harvest practices and schedules would be required to maximize the wildlife habitat benefits of switchgrass grown for biofuels. Finally, we note that primary data collection to value each of the ecosystem services, either using revealed or stated preference approaches, for the study site is ideal, as suggested by Rosenberger and Loomis (2001). We used a benefit transfer approach, which has its own limitations. Further research is required to address these limitations.

While practices such as cover crops or other BMPs may generate some of the ecosystem services generated by bioenergy crops (e.g. nitrate loss reduction), the broad suite of ecosystem services generated by an ABL is not possible through either cover crops or BMPs. It is important to note that the BMPs are not substitutes for an ABL; rather, these could be practiced synergistically to optimize the total economic value of a landscape.

This paper is the first of its kind to estimate the value of a list of ecosystem services associated with bioenergy crops coupling biophysical process-based methods with economic valuation methods in an IAF. The framework we developed is applicable to estimating the economic benefits of a number of ecosystem services associated with ABLs and for upscaling the estimated benefits to a larger area. The current estimates and their applicability could be improved by a more detailed valuation study examining potential nearby and downstream beneficiaries of the ecosystem services, ranging from the potential of land use scenarios such as the ones modeled here for low-cost nutrient pollution reduction trading, the impact of such land use scenarios on downstream water-based recreation sites and their usage, and on regional hunting practices. A larger study based on this pilot could be useful in understanding bioenergy landscape design and economic incentives for increasing biomass for cellulosic biofuel and advanced fuels and bioproducts while improving the sustainability of landscapes and water quality downstream and in the Gulf of Mexico.

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