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INFLUENCE OF BIOENERGY CROP PRODUCTION AND CLIMATE CHANGE ON ECOSYSTEM SERVICES[1]

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ABSTRACT: Land use change can significantly affect the provision of ecosystem services and the effects could be exacerbated by projected climate change. We quantify ecosystem services of bioenergy-based land use change and estimate the potential changes of ecosystem services due to climate change projections. We considered 17 bioenergy-based scenarios with *Miscanthus*, switchgrass, and corn stover as candidate bioenergy feedstock. Soil and Water Assessment Tool simulations of biomass/grain yield, hydrology, and water quality were used to quantify ecosystem services freshwater provision (FWPI), food (FPI) and fuel provision, erosion regulation (ERI), and flood regulation (FRI). Nine climate projections from Coupled Model Intercomparison Project phase-3 were used to quantify the potential climate change variability. Overall, ecosystem services of heavily row cropped Wildcat Creek watershed were lower than St. Joseph River watershed which had more forested and perennial pasture lands. The provision of ecosystem services for both study watersheds were improved with bioenergy production scenarios. *Miscanthus* in marginal lands of Wildcat Creek (9% of total area) increased FWPI by 27% and ERI by 14% and decreased FPI by 12% from the baseline. For St. Joseph watershed, *Miscanthus* in marginal lands (18% of total area) improved FWPI by 87% and ERI by 23% while decreasing FPI by 46%. The relative impacts of land use change were considerably larger than climate change impacts in this paper. ***Editor's note****: This paper is part of the featured series on SWAT Applications for Emerging Hydrologic and Water Quality Challenges. See the February 2017 issue for the introduction and background to the series.*

(KEY TERMS: ecosystem services; bioenergy impacts; *Miscanthus*; switchgrass; corn stover; freshwater provision; food and fuel provision; SWAT.)

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INTRODUCTION

Climate variability and change, land use, and land management change can put increasing pressure on our natural resources, especially water, land, and food resources. The increasing global emphasis on bioenergy production can introduce fast-growing high biomass yielding perennial grasses and trees to

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commercial agriculture under favorable economic conditions. Anticipated climate change and variability can exacerbate the potential impacts of land use changes. In general, the inclusion of perennial grasses instead of conventionally managed row cropping is expected to have environmental benefits. Numerous studies have highlighted water quality benefits of perennial grass production (Self-Davis *et al.*, 2003; Parrish and Fike, 2005; McIsaac *et al.*, 2010; Diaz-Chavez *et al.*, 2011; Feng *et al.*, 2015; Cibin *et al.*, 2016) while a crop residue-based bioenergy production is predicted to increase soil erosion and sediment loadings to the receiving streams (Delgado, 2010; Johnson *et al.*, 2010; van Donk *et al.*, 2010; Cibin *et al.*, 2012). Conventional agriculture bioenergy crop production has also raised concern over food and fuel competition (Pimentel *et al.*, 2009) and carbon sequestration (Franko *et al.*, 2015). A careful environmental impact assessment from different stakeholder perspectives and optimum planning of different land use and management practices are required for inclusion of energy crops into commercial agriculture.

Environmental impacts of bioenergy production can be assessed in different ways, such as (1) sustainability indicator analysis (McBride *et al.*, 2011), (2) risk-vulnerability-reliability assessment (Hoque *et al.*, 2014), and (3) absolute and percentage change impact assessment with baseline reference (Feng *et al.*, 2015; Cibin *et al.*, 2016), *etc.* Ecosystem services evaluation for bioenergy production is another metric which can compare different aspects of ecosystem benefits to people from bioenergy production. Ecosystem services can be classified under supporting (nutrient cycling, soil formation, primary production, *etc.*), provisioning (food, freshwater, wood and fiber, fuel, *etc.*), regulating (climate regulation, flood regulation, erosion regulation, disease regulation, *etc.*), and cultural (esthetic, spiritual, educational, recreational, *etc.*) services (MEA, 2005). In an ideal sustainably managed ecosystem there should be a good balance between all ecosystem services (Foley *et al.*, 2005). However, in current intensive agricultural ecosystems, the primary focus is on maximizing food provisioning while other ecosystem services are often not prioritized (Foley *et al.*, 2005).

Quantifying ecosystem services of a system is challenging due to lack of quantifying methods and data availability (Seppelt *et al.*, 2011; Logsdon and Chaubey, 2012; Volk, 2013). In addition, not all the valuation metrics perform equally well for the different ecosystem services (Farber *et al.*, 2006), and there is a lack of standardization in how they are valued (Polasky *et al.*, 2015; Boithias *et al.*, 2016). To the best of our knowledge, there are no reported efforts on quantification of ecosystem services for bioenergy production systems. In the case of bioenergy systems, measured data at large scale are not available for the United States (U.S.) since large bioenergy production is not yet established. Application of mathematical simulation models can give realistic scenario realizations if bioenergy production scenarios are adequately represented in the models. Logsdon and Chaubey (2013) proposed a methodology to quantify freshwater provisioning, food provisioning, fuel provisioning, flood regulation, and erosion regulation using Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold *et al.*, 1998) simulations, which is part of a broader recent thrust identified in the literature to fully utilize the capabilities of SWAT to model ecosystem services (Francesconi *et al.*, 2016).

Two key sets of improved bioenergy cropping system- related algorithms have recently been incorporated in SWAT: (1) Cibin (2013) introduced corrections to SWAT that enable more accurate representation of corn stover removal, and (2) Trybula *et al.* (2015) parameterized and improved SWAT to better physiologically represent perennial bioenergy crops such as *Miscanthus* and switchgrass in the Midwest U.S. These improved SWAT bioenergy algorithms were ported to SWAT version 2012 (SWAT, 2012), Revision 611 and have only been applied in limited recent SWAT applications including Chen *et al.* (2016), Cibin *et al.* (2016), Gassman *et al.* (2017), and Panagopoulos *et al.* (2017). These SWAT improvements, coupled with the methodology advanced by Logsdon and Chaubey (2013), support the overall goal of this paper to quantify ecosystem services of futuristic bioenergy production scenarios.

Climate change and variability along with land use changes can affect ecosystem services in a watershed. Quantifying of ecosystem service of futuristic climate and land use change can help in developing better adaptation strategies to overcome potential negative impacts and maximize benefits. This research is part of a four-study series discussing policy implications (Kling *et al.*, 2017) and environmental impacts at different spatial scales (Gassman *et al.*, 2017; Panagopoulos *et al.*, 2017), within the broader context of research being conducted within CenUSA Bioenergy (Moore *et al.*, 2014), and quantifies the potential impacts of futuristic bioenergy production scenarios on ecosystem services under current and projected future climate scenarios in the U.S. Corn Belt region. The specific objectives of the study are to: (1) quantify the ecosystem services of plausible bioenergy production scenarios for two watersheds in the Midwest U.S., and (2) estimate the variability in the provision of ecosystem services due to climate change.

METHODOLOGY

Seventeen plausible futuristic bioenergy-based scenarios were developed with *Miscanthus (Miscanthus × giganteus)* and Shawnee, an upland switchgrass *(Panicum virgatum* L.) variety as perennial dedicated bioenergy crops and corn *(Zea mays* L.) stover as crop residue for biofuel production. The scenarios were developed with bioenergy crop production from marginal lands, current pasture lands and prime agricultural lands using SWAT version 2012 (SWAT, 2012), Revision 615, which is the same version used in the other CenUSA Bioenergy project applications (Gassman *et al.*, 2017; Panagopoulos *et al.*, 2017). SWAT was used to represent the scenarios in the study watersheds. The model was parameterized and improved for better physical representation of perennial grasses, specifically upland switchgrass and *Miscanthus* using field measurements in the region by Trybula *et al.* (2015), and for representation of corn stover removal using the methods described by Cibin (2013). The improved model was used in this study to estimate streamflow, erosion, nutrient loading, and crop yield for different bioenergy scenarios to quantify ecosystem services from these scenarios. Five ecosystem services were evaluated including freshwater provision (FWPI), food provision (FPI), fuel provision (FuPI), erosion regulation (ERI), and flood regulation (FRI). Daily and annual time step SWAT simulations were used to calculate the biophysical value of ecosystem services. Simulations were conducted in a parallel computing framework on Linux computer clusters maintained by research computing, a high-performance computing facility located at Purdue University (Purdue, 2016).

Study Area

The study was conducted in two agriculturally dominant watersheds located primarily in Indiana in the eastern Corn Belt (Figure 1): (1) Wildcat Creek, which drains 2,045 km^2 of predominantly agricultural land characterized by 70% corn/soybean production, 9% forest, and 5% pasture, and (2) St. Joseph River, with a 2,800 km^2 drainage area that is also predominantly agricultural but with lower corn/soybean production (37%), 25% pasture, 12% forest, and 8% forested wetlands. The Wildcat Creek watershed is located in central Indiana with flat terrain, highly productive corn/soybean areas and drains to the Wabash River and eventually to the Gulf of Mexico. The St. Joseph River watershed is located in northern Indiana with drainage areas in Indiana, Michigan, and Ohio. The watershed has a hilly terrain with marginal agricultural lands and pasture areas. The St. Joseph River drains to Lake Erie which has experienced excess algal blooms and eutrophication in recent years (Obenour *et al.*, 2014; Scavia *et al.*, 2016). Soils of both

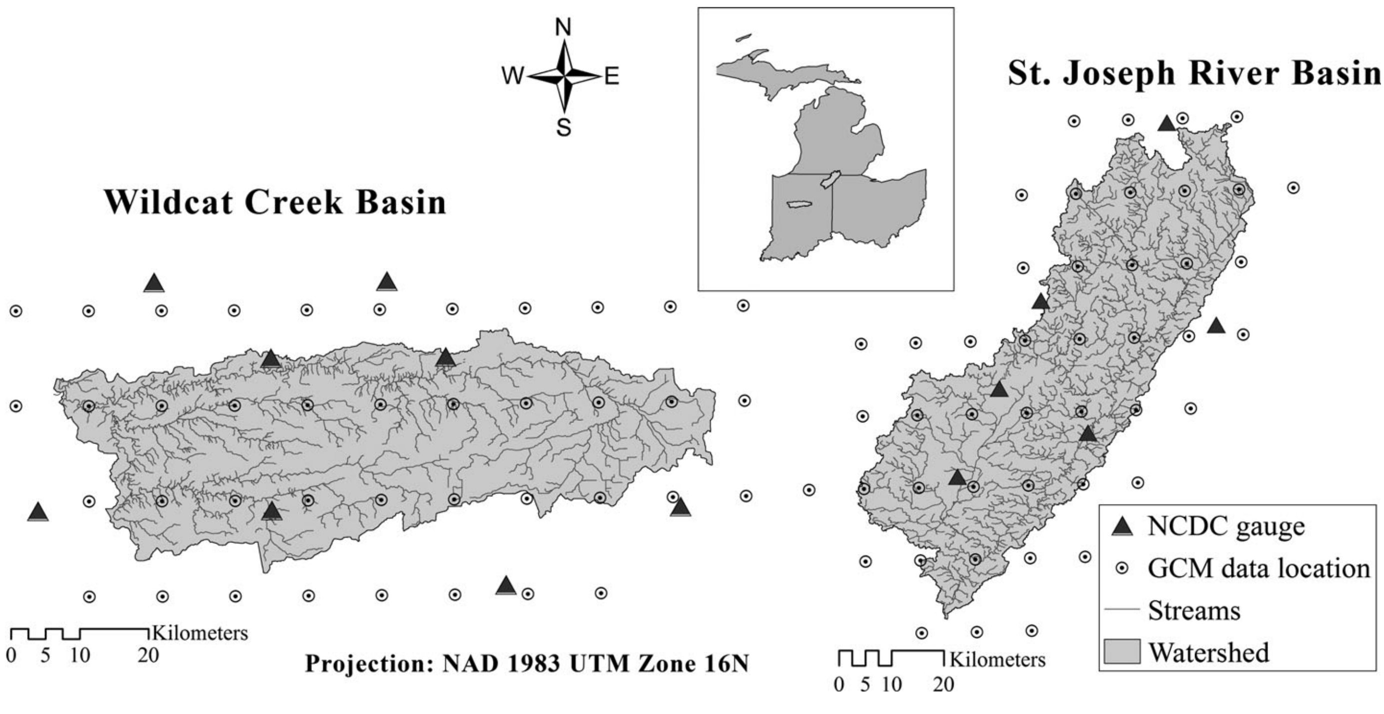

FIGURE 1. Location Map of the Two Study Watersheds with Locations of Observational Weather Stations and Future Climate Projection Grids Identified. NCDC, National Climatic Data Center; GCM, general circulation climate.

watersheds were formed from compacted glacial till and are classified as good agricultural soils. The dominant soil textures are silt loam, silty clay loam, and clay loam. Annual precipitation of both watersheds were near 1,000 mm with Wildcat Creek watershed receiving slightly more precipitation than St. Joseph River watershed. The two watersheds represent distinctive terrain, land use and management characteristics of the Midwest U.S. watersheds. SWAT was parameterized for the two watersheds with detailed spatial representation and was calibrated and validated for crop yield, streamflow, and water quality (Cibin *et al.*, 2016). Daily stream flow Nash-Sutcliffe efficiency of calibrated model was above 0.65 for all stream gauge stations in both watersheds under calibration and validation periods. We encourage readers to refer to the supplementary information of Cibin *et al.* (2016) to find detailed discussion on model development, calibration, and validation. Hydrology and water quality impacts of growing bioenergy crops in these two watersheds were studied using SWAT and results indicated improved water health with the introduction of perennial bioenergy crops in the watershed (Cibin *et al.*, 2016). Two sets of climate data were used in this study: (1) measured precipitation and temperature data from the National Climatic Data Center (http://www.ncdc.noaa.gov/) for 14 years (1996-2009), and (2) climate projection data representing future climate change scenarios discussed below. Solar radiation, wind speed, and relative humidity were generated by SWAT using long-term mean monthly data for the region.

Climate Projection Data

The climate projection-based analyses were done using precipitation and temperature data from nine general circulation climate (GCM) model projections obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) (WRCP, 2016). These nine projections consisted of: three GCM models (GFDL CM2.0.1, UKMO HadCM3 3.1, and NCAR PCM 1.3) in combination with each of the three future emission scenarios (A1B, A2, B1). Further description of these GCMs and projections are provided by WRCP (2016). The three models used in this study were identified to be representative of previous impact assessments in the region (*e.g.,* Kling *et al.*, 2003). Precipitation and temperature data were bias corrected and statistically downscaled with a resolution of 1/8°. Bias correction was done using empirical statistical technique mapping the probability density functions for monthly precipitation and temperature from climate model projections and measured data. Bias corrected monthly precipitation and temperature was disintegrated to daily by selecting daily time series from the monthly historic climatology. A detailed discussion of downscaling and bias correction methodology can be obtained from Cherkauer and Sinha (2010). Climate data from 1950 to 2050 was used for the analysis considering the first 10 years for model warm up, and three 30-year periods representing past (1960-1989), present (1990-2019), and future (2020-2049) climate conditions. The gridded precipitation and temperature data were input to SWAT. In general, average monthly temperature and precipitation increased with all three emission scenarios for the future time period (2020-2049) compared to past (1960-1989) (Table S1).

Bioenergy Scenarios

Plausible futuristic bioenergy scenarios for the region were carefully defined with marginal lands as potential areas for growing bioenergy crops as well as the prime agricultural land conversion as somewhat extreme case scenarios when bioenergy production becomes more economical. The stover residue from corn after grain harvest is identified as immediate biofeedstock for biofuel production in the Corn Belt region due to wide availability (Lal, 2004; Wilhelm *et al.*, 2004). The only stover removal scenario considered included 50% stover removal from low slope (<2% slope) areas. Table 1 provides details of the 17 scenarios considered in this study and area distribution in the two watersheds under each scenario. Marginal lands are proposed as viable first choice areas for growing bioenergy crops due to less competition between food and fuel production and potential environmental benefits (Robertson *et al.*, 2008; Gopalakrishnan *et al.*, 2009; Cai *et al.*, 2010). Agricultural marginal lands in the study watersheds were identified with three conditions: (1) highly erodible areas; or (2) agricultural low productive marginal lands; or (3) land capability-based marginal lands. These criteria are generally consistent with the definition of marginal lands used within CenUSA Bioenergy (Moore *et al.*, 2014). Corn/soybean areas with ≥2% slope were considered as potential highly erodible marginal lands in the study. Agriculturally lower productive areas were identified as areas with less than 5th-percentile SWAT simulated corn yield in the watershed (Cibin *et al.*, 2016). Soils with land capability class >2 were identified as land capability-based marginal lands (Feng *et al.*, 2015). Hypothetical extreme case prime agricultural land conversion into bioenergy crops were considered in this study to understand the potential impacts of extreme case scenarios. Six prime agricultural land conversion

TABLE 1. Description of Biofuel Scenarios.

				Area Converted			
				Wildcat Creek		St. Joseph	
Scenarios	Bioenergy Crops	Land Use Converted	Scenario Name	Area (km^2)	% of Watershed Area	Area (km^2)	% of Watershed Area
1	*Miscanthus*	High slope marginal land (slope ≥ 2%)	SlopeMarg-M	119.5	6	347	13
2	Switchgrass	High slope marginal land (slope ≥ 2%)	SlopeMarg-S	119.5	6	347	13
3	*Miscanthus*	Agricultural marginal land	AgMarg-M	59.6	3	119.1	4
4	Switchgrass	Agricultural marginal land	AgMarg-S	59.6	3	119.1	4
5	*Miscanthus*	Land capability marginal land (LCC > 2)	LccMarg-M	22.8	1	186.4	7
6	Switchgrass	Land capability marginal land (LCC > 2)	LccMarg-S	22.8	1	186.4	7
7	*Miscanthus*	Combined marginal land	AllMarg-M	177.9	9	496.8	18
8	Switchgrass	Combined marginal land	AllMarg-S	177.9	9	496.8	18
9	Stover 50	Low slope corn/soybean	Stover50	1,329.6	65	702.3	25
10	*Miscanthus*	Pasture area conversion	Past-M	102.5	5	710.4	26
11	Switchgrass	Pasture area conversion	Past-S	102.5	5	710.4	26
12	*Miscanthus*	100% CS conversion	100CS-M	1,449.1	71	1,049.2	38
13	Switchgrass	100% CS conversion	100CS-S	1,449.1	71	1,049.2	38
14	*Miscanthus*	50% CS conversion-random selection	50CS-M-Rand	725.6	35	524	19
15	Switchgrass	50% CS conversion-random selection	50CS-S-Rand	725.6	35	524	19
16	*Miscanthus*	50% CS conversion-strategic selection	50CS-M-Strat	723.6	35	524.7	19
17	Switchgrass	50% CS conversion-strategic selection	50CS-S-Strat	723.6	35	524.7	19

Notes: CS, corn/soybean; LCC, land capability class; Stover 50, harvest 50% of stover available during harvest operation.
Baseline scenario describes current land use in the watersheds. *Miscanthus* was modeled as *Miscanthus* × *giganteus*, switchgrass was modeled as *Panicum virgatum*. The total watershed area for Wildcat Creek is 2,045 km^2 and St. Joseph watershed is 2,756 km^2.

scenarios were considered with 50% and 100% corn/soybean area conversion into perennial grasses. In 50% agricultural area conversion scenarios the areas were selected using random selection and strategic selection methods. Strategic selection was based on slope criteria, with the top 50% highest slope corn/soybean areas selected for land conversion into bioenergy crops. The comparison of random and strategic selection should provide insight toward the opportunities in design of optimum cropping patterns. The improved SWAT model (Trybula *et al.*, 2015) was used in this study to represent the perennial bioenergy crops. A detailed discussion of stover removal representation and bioenergy crop representation in the study watersheds can be obtained from Cibin *et al.* (2012, 2016).

Ecosystem Services Quantification

The ecosystem services related to FWPI, FPI, FuPI, ERI, and FRI were quantified for the baseline and bioenergy scenarios with current and future climate scenarios. Ecosystem services were quantified using the methodology developed by Logsdon and Chaubey (2013). Ecosystem services are estimated by comparing the current state (or simulated scenario results) with standard or targeted values in each ecosystem service attribute. For example, FWPI is estimated by comparing simulated streamflow and water quality with minimum and seasonal flow requirement, sediment, and nutrient concentration standards. An ecosystem service index ≥1 indicates that the watershed is meeting the service target. An ecosystem service index less than 1, represents that the system is not meeting the service target. Logsdon and Chaubey (2013) have provided suggestions on standards/targets and have evaluated ecosystem services for a few land use scenarios in the Wildcat Creek watershed. This study used similar standards (parameters, Table 2) for quantifying ecosystem services for the baseline and bioenergy scenarios. Fuel provisioning was estimated in this study by comparing whether the watershed can support a medium sized (30 million gallon) biofuel refinery. Only cellulosic biofeedstock-based fuel production was

TABLE 2. Ecosystem Service Quantification Parameters Used for the Two Study Watersheds, Based on the Methods of Logsdon and Chaubey (2013).

Ecosystem Service	Parameters	Estimated As	Units	Wildcat Creek	St. Joseph
Freshwater provisioning	Minimum required flow	30% of long-term mean USGS flow	m^3/s	6.7	9.0
	Seasonal environmental flow requirement	10% seasonal mean flow	m^3/s (winter)	2.4	3.6
			m^3/s (summer)	2.1	2.4
	TSS standard	IDEM (2011)	mg/L	46.3	46.3
	Nitrate	IDEM (2011)	mg/L	10	10
	Total phosphorus	IDEM (2011)	mg/L	0.03	0.03
Food provisioning	Minimum grain yield	10-year average corn yield (NASS)	Mg/yr	6.5E+05	2.9E+05
		10-year average soybean yield (NASS)	Mg/yr	2.3E+05	1.6E+05
Fuel provisioning	Feedstock to support 30 million gallon ethanol plant		Mg/yr	3.5E+05	3.5E+05
Erosion regulation	Max allowable erosion rate	USDA T factor	Mg/ha/yr	4.4	4.1
Flood regulation	Flood flow	Q_{10} of flow	m^3/s	49	77.9
	Long-term average flood duration		Days	4.8	5.3
	Long-term average flood frequency		Count	7.8	7.3
	Long-term average flood magnitude		m^3/s	84.0	127.7

Note: TSS, total suspended solids; USGS, U.S. Geological Survey; NASS, National Agricultural Statistics Service.

considered in the fuel provisioning estimation. The ecosystem services were quantified annually, and average annual values for each scenario were analyzed in detail at the watershed outlet.

RESULTS AND DISCUSSION

Ecosystem Services of Current Land Use (Baseline Scenario)

The ecosystem services of the baseline scenario indicated good (close to one) freshwater provisioning for the St. Joseph River watershed while for the Wildcat Creek watershed, freshwater provisioning was low (Figure 2). A detailed analysis of the different components of freshwater provisioning indicated that streamflow for both watersheds was generally above the environmental flow requirements (Figures S2 and S3). The predicted sediment concentrations for the Wildcat Creek watershed was much higher than that of the St. Joseph River watershed. A higher sediment concentration from the Wildcat Creek watershed could be attributed to intensively managed cropping lands in the watershed which accounted for about 70% of the total area and a lower streamflow. Even though the St. Joseph River watershed has a hilly terrain, the percentages of forested and grassland (pasture) areas were much higher than the Wildcat Creek watershed which tend to reduce soil erosion. The simulated nutrient loading from Wildcat Creek was also higher than St. Joseph River watershed (Figures S2 and S3). The total phosphorus concentration was higher than the water quality standard of 0.3 mg/L for both watersheds and the loading trend was similar to sediment loading. The predicted nitrate concentration in Wildcat Creek was estimated (2.9 mg/L) to be higher than the St. Joseph River (1.5 mg/L) and was above the drinking water standard (10 mg/L) for many days (Figures S2 and S3). Almost 90% of the cropped land in the Wildcat Creek watershed has tile drainage, a pathway of nitrate nitrogen export (Kladivko *et al.*, 2004). The total amount of nitrogen and phosphorus fertilizer applied in the Wildcat Creek watershed is also more than in the St. Joseph River watershed due to larger cropped area. The flood regulation service for both watersheds was low with values of 0.3 and 0.4 for Wildcat Creek and St. Joseph River, respectively, and the Erosion Regulation Index greater than 1.8 for both watersheds, indicating that the erosion from the watersheds never exceeded the tolerable soil loss. Food provisioning for the baseline scenarios was estimated as close to one and fuel provisioning was zero for both watersheds. The minimum grain yield parameter for food provisioning was assumed as the 10-year mean grain yield from the corresponding watershed and the model was calibrated during the same period based on USDA-NASS (2016) data. Food provisioning for the St. Joseph River watershed was slightly more than one (1.25) since the model overestimated grain yield from the watershed. This signifies the importance of model calibration in the application of simulation models in quantifying ecosystem

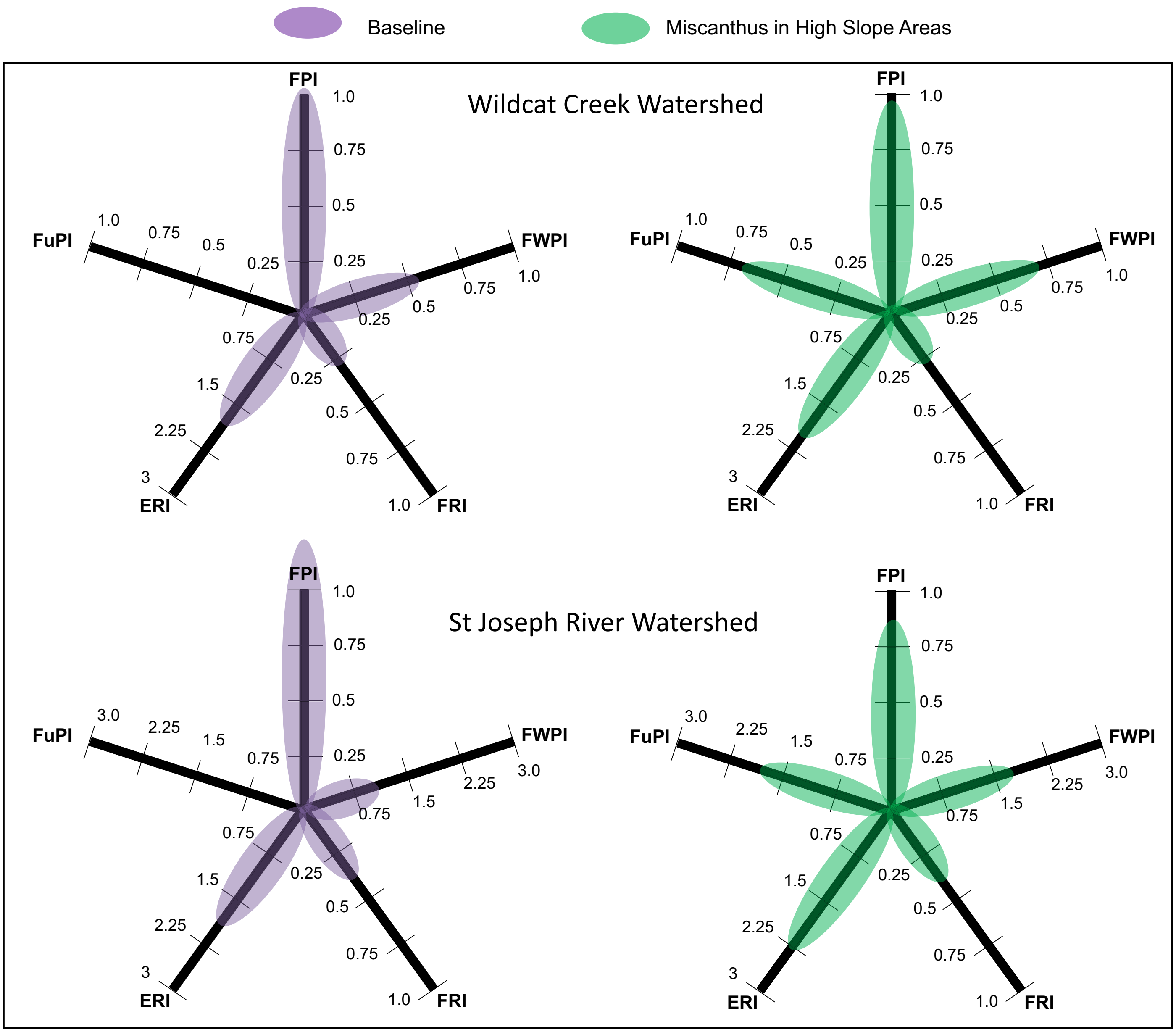

FIGURE 2. Quantification of Ecosystem Services for Base Line and *Miscanthus* in High Slope (≥2% slope) Areas in Wildcat Creek Watershed (top) and St. Joseph River Watershed (bottom). Ecosystem services considered were freshwater provisioning (FWPI), food provisioning (FPI), fuel provisioning (FuPI), erosion regulation (ERI), and flood regulation (FRI).

services. Some of the corn grain produced in the watershed could be used in the grain-based ethanol production. However, this study considered only second generation biofuel production from bioenergy crops as the source of fuel production and thus the baseline fuel provisioning is estimated as zero for both watersheds.

Ecosystem Service of Bioenergy Scenarios

The provision of ecosystem services generally improved in both watersheds with the introduction of perennial energy crops into agricultural production (Figure 3). Introducing *Miscanthus* on high slope corn/soybean (CS) areas (Scenario 1) of the Wildcat Creek watershed (Table 1) increased fuel provisioning to 0.7 which is equivalent to 21 million gallons of biofuel production, with an associated 8% reduction in food provisioning, improving freshwater provisioning by 22% and erosion regulation by 12% in comparison to the baseline scenario (Figure 2). Adoption of *Miscanthus* on marginal lands in the St. Joseph River watershed, which has more area with ≥2% slope (Table 1), improved freshwater provisioning to 1.7 and could potentially produce about 56 million gallons of biofuel

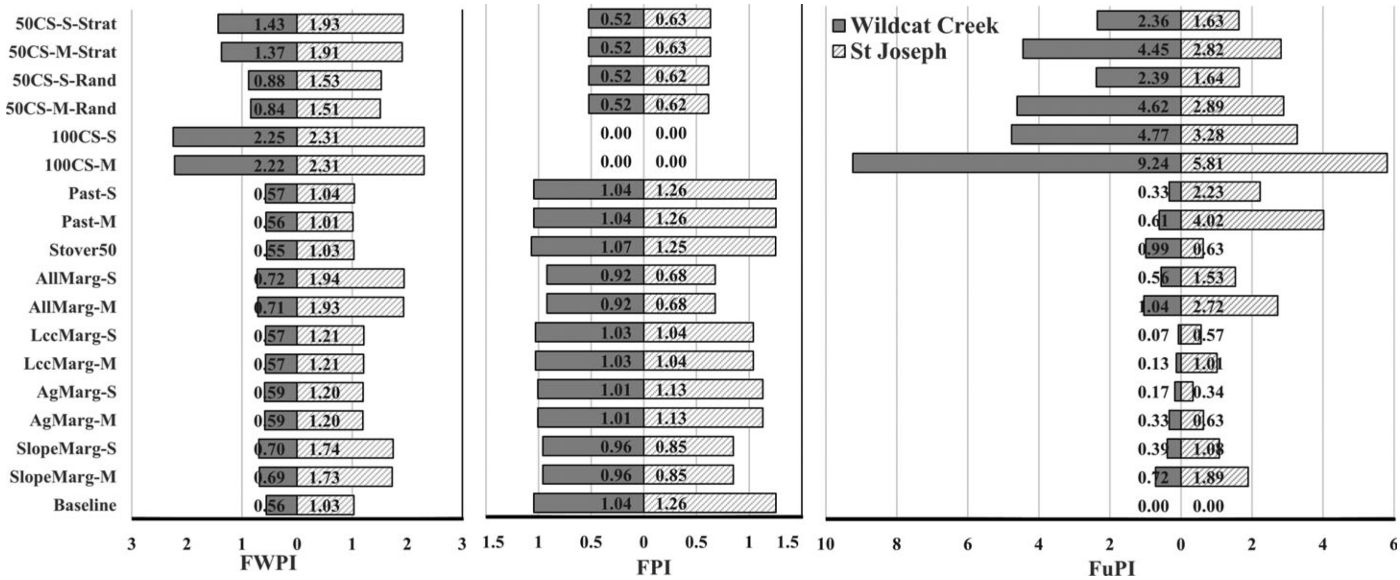

FIGURE 3. FWPI, FPI, and FuPI for the 17 Bioenergy Scenarios Compared with Baseline Scenario.

(Figure 3). Food provisioning from the watershed is reduced to 0.8 or about a 32% reduction from the baseline. Inclusion of bioenergy crops in agriculture did not have a significant impact for flood regulation. The flood regulation ranged between 0.29 and 0.34 for Wildcat Creek and between 0.4 and 0.43 for the St. Joseph River (Table S1). Previous simulation studies also reported that the impacts on streamflow with inclusion of bioenergy crops to agriculture was minimal compared to water quality impacts (Cibin *et al.*, 2016).

Maximum improvement in freshwater provisioning, flood regulation, and erosion regulation for both watersheds was estimated with conversion of all CS area to switchgrass (Scenario 13, Table S1). The maximum fuel provisioning was with *Miscanthus* grown in all CS areas (Scenario 12) in the Wildcat Creek watershed, with a potential 277 million gallons of biofuel production. The maximum biofuel production potential from the St. Joseph River watershed was also with *Miscanthus* growing in all CS areas (174 million gallons) followed by *Miscanthus* in all pasture areas (120 million gallons). The corn stover removal scenario resulted in maximum fuel provisioning and minimal impacts on food provisioning and other ecosystem services. The magnitude of changes in ecosystem services were heavily associated with the magnitude of land use change. A normalized comparison of change in ecosystem service with change in land use area (Figure S4) indicates that bioenergy placement with high slope areas resulted in the maximum environmental benefits.

Ecosystem services from *Miscanthus* and switchgrass scenarios were very similar except for fuel provisioning (Figure 3, Table S1). The predicted *Miscanthus* yields were almost twice as much as the Shawnee switchgrass yields with a similar difference in fuel provisioning services. Water quality benefits of both grasses were reported to be in a similar range (Trybula *et al.*, 2015), thus freshwater provisioning and erosion regulation remained similar for both grasses. Both perennial grasses were simulated with the same fertilization rates as described in Trybula *et al.* (2015). Also the SWAT parameters related to soil erosion simulation are considered to be the same as those suggested in Trybula *et al.* (2015). For example, SWAT uses the Modified Universal Soil Loss Equation (USLE) (Williams and Berndt, 1976) to estimate soil erosion and the USLE minimum crop factor (C factor) for both perennial grasses was set at 0.003. These factors also contributed toward similar values for freshwater provisioning and erosion regulation for both grasses. The changes in food provisioning are driven by the amount of CS land use change and thus remained the same for both *Miscanthus* and switchgrass scenarios.

Marginal land area conversion into bioenergy crops are considered as the first choice for bioenergy production in the case of agricultural area conversion due to potential environmental benefits and associated minimal impacts on food production. This study considered three types of marginal land definitions and the results indicate that slope-based marginal land conversions have maximum benefits in freshwater provisioning and erosion regulation. Crop productivity-based marginal lands (Scenarios 3 and 4) were found to have less impact on food provisioning (Figure S4). The St. Joseph River watershed had more marginal land area available and could potentially produce 81 million gallons of biofuel when *Miscanthus* was grown in all marginal lands (Scenario 7). The Wildcat Creek watershed can support one 30 million gallon refinery if all marginal land areas were converted to *Miscanthus* production with an associated 12% reduction in food provisioning.

Corn stover removal in low slope CS areas (Scenario 9) increased fuel provisioning in both watersheds (Figure 3, Table S1). Freshwater provisioning and erosion regulation were slightly reduced (<5%) for the corn stover removal scenario compared to the baseline. Corn stover is generally left in the field after grain harvest and is expected to improve soil cover, soil moisture retention, and reduce sediment and nutrient losses. Previous studies have reported reduced streamflow and nitrate loading, and increased sediment and phosphorus loading with stover removal (Cibin *et al.*, 2012). The combined effect of these factors may have canceled out the negative impacts of stover removal with less impact on freshwater provisioning. Simulations showed that stover removal from the low slope areas had relatively minor environmental impacts, and therefore, could be considered as a future best management practice, if stover is utilized as a biofeedstock for biofuel production. Improved fuel provisioning from stover removal with minimal impacts on food provisioning and other ecosystem services also suggests stover as a suitable biofeedstock from the region. Pasture area conversion for bioenergy production also increased fuel provisioning with minimal impacts on other ecosystem services. Introducing *Miscanthus* in pasture areas yields fuel provisioning of 0.6 and 0.4 for the Wildcat Creek and St. Joseph River watersheds, respectively. Only corn/soybean yield was considered in the food provisioning, thus pasture area conversion had no impact. In pasture area conversion into biofuel production, one perennial grass (*Miscanthus* or switchgrass) replaces another perennial grass (Tall fescue) and thus simulation results showed minimal impacts on ecosystem services.

Prime agricultural land conversion into bioenergy crops significantly improved freshwater, fuel provisioning, and erosion regulation while significantly reducing food provisioning (Figure 3). Comparison of random placement and strategic placement of bioenergy crops within the watersheds yields higher freshwater provisioning and erosion regulation with strategic placement of energy crops. Food provisioning from both random and strategic placement is very similar while the fuel provisioning was estimated slightly lower for the strategic selection scenario compared to random placement. The random selection scenario improved freshwater provisioning with *Miscanthus* by 50% from the baseline while the strategic placement scenario improved freshwater provisioning by 145% from the baseline in the Wildcat Creek watershed. For the St. Joseph River watershed, randomly selected 50% CS area conversion had lower freshwater provisioning (1.5) than that of high slope marginal lands (1.73) which accounted for 33% of the CS area. Comparison of random and strategic selection provides prospects on improving ecosystem service benefits from bioenergy production with careful selection of areas where bioenergy crops could be grown.

Ecosystem Service of Bioenergy Scenarios under Climate Change Scenarios

Changes in ecosystem services of both the baseline and bioenergy scenarios, in response to climate change and variability, was quantified using the previously described nine projections of future climate (three GCMs each executed with three emission scenarios). Each future climate scenario was used as input to SWAT in the two watersheds for 100 years (10-year warm up, three 30-year periods of past, present, and future).

The climate projection simulation results show that current (1990-2019) and future climate periods (2020-2049) have lower ecosystem services compared to the past time period (1960-1989) for baseline scenario. The reduction in freshwater provisioning, flood regulation, and erosion regulation are less than 6% in both watersheds (Tables S2 and S3) and the changes in ecosystem services were within the uncertainty band of the nine future climate projections (Figures 4 and 5). Among all ecosystem services considered, climate change had the greatest effect on food provisioning. Baseline scenario food provisioning decreased by 9% due to the future climate compared to past climate in both watersheds. Air temperature increased in all future climate scenarios compared to the past climate (Figure S1). Precipitation trends varied across different seasons with increased precipitation in spring months (March-May) and reduced summer precipitation (June-August) (Figure S1). The changes in temperature and growing season precipitation had more impact on crop growth in the future climate period compared to other ecosystem services. Flood regulation for the baseline scenario in the St. Joseph watershed was reduced by 6% in 1990-2019 compared to 1960-1989 and increased by 3% in 2020-2049 compared to 1990-2019. A similar trend was also seen in the Wildcat Creek watershed with a reduction in flood regulation between current and past climates, and no change in flood regulation under future climate compared to current conditions. The changes in flood regulation were very small and this fell within the climate change prediction uncertainty between the nine projections (Figures 4 and 5).

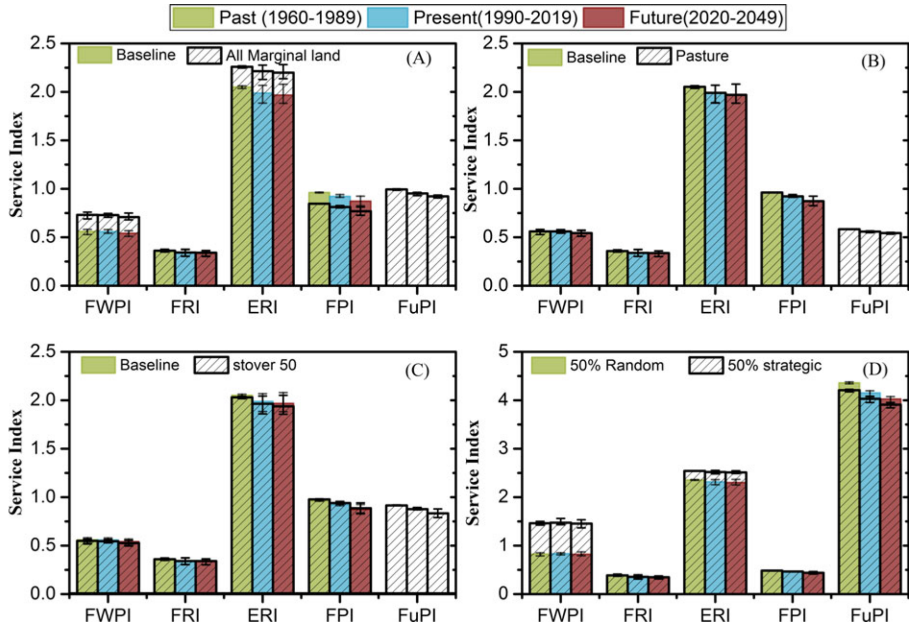

FIGURE 4. Ecosystem Service Comparison of Different Scenarios under Climate Change Scenarios for the Wildcat Creek Watershed. The error bar in each figure indicates the range of ecosystem services between the nine projections of future climate. (A) Compares baseline scenario with all marginal land converted to *Miscanthus* (Scenario 7); (B) compares baseline with pasture area converted to *Miscanthus* (Scenario 10); (C) compares baseline with 50% stover removal (Scenario 9); and (D) compares random and strategic conversion of 50% CS area to *Miscanthus* (Scenarios 14 and 16).

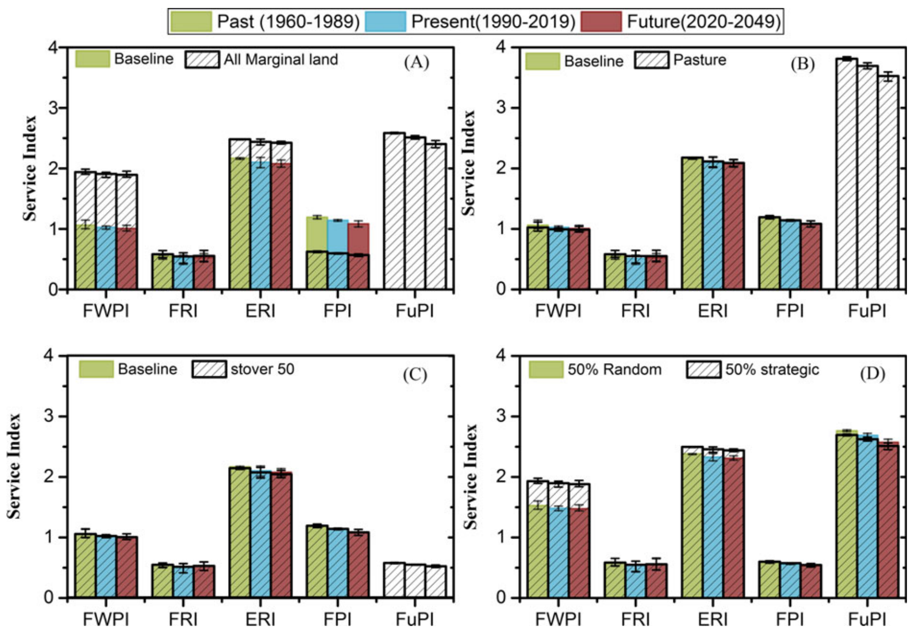

FIGURE 5. Ecosystem Service Comparison of Different Scenarios under Climate Change Scenario for St. Joseph River Watershed. The error bar in figure indicates the range of ecosystem services between the nine projections of future climate. (A) Compares baseline scenario with all marginal land converted to *Miscanthus* (Scenario 7); (B) compares baseline with pasture area converted to *Miscanthus* (Scenario 10); (C) compares baseline with 50% stover removal (Scenario 9); and (D) compares random and strategic conversion of 50% CS area to *Miscanthus* (Scenarios 14 and 16).

There was little difference in ecosystem services between the three emission scenarios (A1B, A2, and B1) for the future climate period (2020-2049) (Figure S5). The largest observed difference was with the A1B emission scenario, which had an improved flood regulation index (0.57) compared to the other two emission scenarios (0.5) in the St. Joseph River watershed. Flood regulation of 0.57 with A1B emission scenario represents 2.53 flood events with 84.4 m^3/s magnitude and 4.37 days duration per year, while 0.5 flood regulation with A2 and B1 scenarios represents 2.96 flood events with 93.2 m^3/s magnitude and 6 days duration per year.

The changes in ecosystem services in response to future climate change for different bioenergy scenarios followed similar trends to those of the baseline scenarios (Figures 4 and 5). Similar to food provisioning in the baseline, the food and fuel provisioning for biofuel scenarios also indicated higher variations with climate change compared to other ecosystem services. Changes in food provisioning was consistently around 9% for all scenarios in both watersheds for future climate. Impacts of climate change on fuel provisioning was slightly more for switchgrass-based scenarios (9%, average change in all switchgrass scenarios comparing future and past climate) compared to *Miscanthus* (7%, average change in all switchgrass scenarios comparing future and past climate) for all land use change scenarios. Prime agricultural area conversion into perennials (Scenarios 12-17) had maximum impacts with climate change on flood regulation (10% in Wildcat Creek and 6% in St. Joseph watershed, comparing future and past climates). Climate change had minimal impacts on freshwater provisioning and erosion regulation in both watersheds with all scenarios, with changes less than 5%. In general, land use change is a more significant driver affecting ecosystem services than climate change for the conditions evaluated in this study. For example in Scenario 7 of St. Joseph watershed, land use change induces 82% change in freshwater provisioning while climate change induces only 2% change in future climate compared to past climate (Figure 5A). This could be due to the scale of land use change scenarios discussed in this study and considering the future climate change only until 2050.

CONCLUSIONS

Five provisioning and regulating ecosystem services were evaluated for 17 futuristic bioenergy-based land use change scenarios for two watersheds in the U.S. Corn Belt region. Uncertainty in ecosystem services from climate change and variability was assessed using climate projection data. SWAT was used to represent the bioenergy production scenarios. In general, water quality is improved with perennial grasses in agricultural areas. All ecosystem services except food provisioning were improved with bioenergy production compared to the baseline. Introduction of bioenergy production provided a balanced ecosystem with regard to all five ecosystem services considered in this study. The major findings of the study include:

- The comparison of the baseline scenarios for the two study watersheds shows that an increase in agricultural area reduces freshwater provisioning of the watershed.
- Perennial bioenergy crops in agricultural areas improve freshwater provisioning and erosion regulation in both watersheds.
- Corn stover for bioenergy production increases fuel provisioning from watersheds with minimal impact on other ecosystem services if stover removal occurs primarily on low-sloping lands.
- Flood regulation is least affected among the five ecosystem services with bioenergy-based land use changes.
- Perennial bioenergy crop production in high slope areas substantially increases ecosystem service benefits.
- Impacts of land use change on ecosystem services is expected to be greater than the climate change and variability impacts.
- Climate change had more impact on food and fuel provisioning compared to other ecosystem services considered in this study.

In this study, ecosystem services were evaluated using SWAT simulations. There is a need to quantify uncertainty in the model simulations. Additionally, only five ecosystem services were considered in this study, and future work should include the quantification of more ecosystem services. Real implications of bioenergy production on certain ecosystem services are not limited to the watershed scale evaluated in this study. For example, changes in corn or soybean production in a watershed may not affect the food requirement of people in the watershed since a majority of the food production is exported and consumed outside the watershed. However, evaluation of watershed-scale ecosystem services for bioenergy production helps in estimating relative change in ecosystem services for different "what-if scenarios" and can guide decision making related to meeting bioenergy production goals while enhancing ecosystem services.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Figures include evaluation of climate projections, comparison of SWAT simulation with ecosystem service parameters, comparison of percent change in ecosystem services and land use change, and ecosystem service comparison for emission scenarios. Tables include ecosystem service evaluated with measured and projected weather data.

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