Regulators' and Stakeholders' Perspectives in a Framework for Bioenergy Development

Abstract

In this study, ten bioenergy crop rotations (corn, corn-stover, sorghum, soybean, corn-soybean, corn-soybean-canola, corn-stover-soybean, miscanthus, switchgrass, and sorghum-soybean) were selected based on local stakeholder (economically motivated) and regulator (environmentally motivated) preferences. These crops were implemented on diverse landscapes (agricultural, marginal, and agricultural plus marginal lands) one at time for 17 years using a SWAT model of the Saginaw River Watershed in Michigan. The bioenergy crops were evaluated based on 100 percent, 50 percent, and zero percent weight assigned to both stakeholders' and regulators' preferences using analytic hierarchy process (AHP), an optimization and decision-making technique that aims to satisfy multiple conflicting objectives. The corn-soybean-canola rotation was selected in all landscapes based on economic benefits (stakeholders' preferences). Meanwhile, perennial grasses (miscanthus and switchgrass) were selected based on environmental benefits (regulators' preferences), because they maintain permanent cover, require fewer inputs than traditional row crops, and are less management intensive. When implementing bioenergy crops on marginal lands, pollution generation greatly increased at the field level, indicating that these lands are likely not viable for bioenergy crop production to meet potential future renewable energy demand.

Keywords: Analytic Hierarchy Process; SWAT; Marginal Lands; Impact Assessment; Bioenergy

1. INTRODUCTION:

Global energy consumption is projected to increase by 57% in the next 25 years (Rooney et al., 2007), while fossil fuels account for approximately 80% of the total global energy supply

(Goldemberg, 2007). However, fossil fuels are a finite resource and will be exhausted within a century or two based on current consumption rates (CRC, 2002). Increasing energy demand and fossil fuel prices have prompted a need for renewable energy sources, especially in the transportation sector (Engel et al., 2010). One method to supplement fossil fuels is through producing biofuel from crops (Graham-Rowe, 2011; Robbins, 2011). Biofuels are renewable and have a smaller carbon footprint than fossil fuels because the carbon emitted during combustion was removed from the atmosphere by the plant during photosynthesis (Tan et al. 2009).

In the year 2000, the United States proposed to expand bioenergy crop production to fulfill up to 30 percent of the transportation sector's fuel requirements (Perlack et al., 2005). However, the expansion of bioenergy crops would either replace existing farmland used for food or feed production or threaten remaining fertile lands by converting land into agricultural production, which could devastate fragile ecosystems (Londo and Deurwaarder, 2007; Rajagopal and Zilberman, 2007). In addition, demand for higher crop yields leads to the application of more fertilizers and pesticides, which, without proper management, can degrade rivers and lakes (Love and Nejadhashemi, 2011a). Increased nutrient loads in freshwaters negatively impacts human health and aquatic ecosystems, including fish kills, habitat degradation, increased phytoplankton biomass, and taste and odor problems (Carpenter et al., 1998). Therefore, both the positive and negative aspects of bioenergy crop expansion should be considered (Nyakatawa et al., 2006). Trade-offs between bioenergy crop production/expansion and its environmental impact need to be evaluated. Characterizing these trade-offs requires the use of optimization techniques, which examine possible combinations of given parameters to satisfy multiple objectives. However, it is difficult to make decisions when the criteria are expressed in different units. For example, net

return from corn production is expressed in dollars per hectare (economic impact) whereas increase in sediment generation due to corn production is expressed in tonnes per hectare (environmental impact).

One such optimization technique is the genetic algorithm (GA), a heuristic global search algorithm that examines all possible combinations of parameters in the domain to reach a near optimal solution (Maringanti et al., 2009). GAs include selection, inheritance, crossover, and mutation processes to reach a near optimal solution. This optimization technique has been used in long-term ground water monitoring, water supply portfolio planning, and rainfall runoff calibration (Reed et al., 2013). Some studies have used optimization techniques for allocation of best management practices (BMPs) to control nonpoint source pollution (Artita et al., 2013; Ciou et al., 2012; Rodriguez et al., 2011; Maringanti et al., 2009). Others have used optimization algorithms to determine habitat suitability of terrestrial and aquatic ecosystems (Holzkamper et al., 2006; Seppelt et al., 2013; Whittaker, 2005). However, few studies have used optimization techniques in the context of bioenergy crop production (Tan et al., 2009; Parish et al., 2012; Lautenbach et al., 2013; Gramig et al., 2013).

Tan et al. (2009) integrated fuzzy optimization with input-output based life cycle models to optimize biodiesel production while minimizing bioenergy system footprints (land use, water, and carbon) in the Philippines. Parish et al. (2012) used the Biomass Location for Optimal Sustainability Model (BLOSM) to identify switchgrass planting locations for biorefineries in a Tennessee watershed. Optimization results concluded that switchgrass planting on 1.3% of the watershed could satisfy their environmental and economic constraints. Lautenbach et al. (2013)

integrated the Soil and Water Assessment Tool (SWAT) and a multi-objective genetic algorithm to determine the trade-offs between bioenergy and food crop production with regard to water quality and water quantity in a German watershed. They found that intermediate rapeseed production could improve water quality and quantity with an objective of maximizing food and fodder yield. Gramig et al. (2013) used the SWAT model, the DayCent biogeochemical model, and a multi-objective optimization tool to optimize corn stover production in an Indiana watershed. They found that nitrate and phosphorus loss to surface water were reduced while sediment and greenhouse gas emissions were increased by maximizing stover production. In these studies, optimization of bioenergy crops is often performed without considering stakeholders' input. This is a major drawback, because stakeholders are reluctant to accept the results obtained from optimization when their opinions are not considered during the decision making process. Output from decision-making processes are accepted to a greater extent when stakeholder preferences are included (Nejadhashemi et al., 2009). Bosch et al. (2012) and Giupponi and Sgobbi (2008) stated that the likelihood of creating a successful watershed management plan depends on effective stakeholder involvement because it builds public support. To address both stakeholders' input and regulators' preferences in this study, a unique optimization technique called the Analytical Hierarchy Process (AHP) was used. The AHP addresses different influential criteria with unique units during the optimization process (Young et al, 2009). Therefore, the objectives of this study were to (1) evaluate the impacts of bioenergy crop expansion on water resources, (2) identify suitable bioenergy crops and locations in order to maximize income from biofuel production from the stakeholder's perspective while minimizing environmental impacts in the regulators' interests, and (3) determine environmental implications of the best bioenergy crops implementation strategies according to AHP. The results of this study

will find mutually beneficial bioenergy crops expansion solutions for stakeholders and regulators.

2. MATERIALS AND METHODS:

2.1 Study Area

This study was conducted in the Saginaw River Watershed (hydrologic unit code 040802) located in Michigan (Figure 1). This watershed was selected for this study because it is one of the most predominant agricultural watersheds in Michigan. In fact, it is one of the most diverse watersheds in Michigan, supporting agriculture, manufacturing, tourism, and habitat for wildlife. (USEPA, 2009). Additionally, it contains the largest contiguous freshwater coastal wetlands in the United States (USEPA, 2009). The total watershed area is 15,663 km², out of which 42% is forest, 23% is agriculture (primarily corn and soybean), 17% is pasture, 11% is wetlands, and 7% is urban. The soil in the watershed consists of hydrologic soil groups A, B, C, and D; out of which 58% belongs to soil group B, 26% is soil group A, 15% is soil group C, and the remaining one percent is soil group D. The maximum watershed elevation is 470 m and the minimum watershed elevation is 172 m, with a mean elevation of 241 m.

Figure 1. Location of Saginaw River Watershed.

2.2 Model Description

SWAT (version 2012) was used to examining the impacts of different bioenergy crops on water resources at subbasin and watershed outlet scales. SWAT is a physically based and semi-distributed watershed model developed by United States Department of Agriculture, Agricultural Research Service (USDS-ARS) that estimates streamflow, sediment, nutrients, and pesticide transport using topography, land use, soil, slope, weather, and crop management data (Arnold et al., 1998; Neitsch et al., 2005; Gassman et al., 2008). The SWAT model uses a topography map to divide the watershed to subbasins. Then each subbasin is further divided into hydrologic

response units (HRUs) based on homogeneous land use, soil type, slope, and management practices.

Several spatial and temporal datasets are required to setup SWAT. The 90 m resolution digital elevation model (DEM) was obtained from the United States Geological Survey (USGS) National Elevation Dataset (NED, 2014). The 2009 Cropland Data Layer was obtained from the USDA National Agricultural Statistics Service (NASS, 2009) to characterize land use. The State Soil Geographic Database (STATSGO) developed by the National Cooperative Soil Survey was used to represent the soil in the watershed (Muttiah and Wurbs, 2002). The stream network was downloaded from the United States Geological Survey National Hydrography Dataset (NHD, 2014). Observed climatic data from nineteen precipitation and eleven temperature stations observed data for a period of twenty years (1990-2009), was downloaded from the National Climatic Data Center (NCDC, 2014). The remaining climatic data (relative humidity, wind speed, and solar radiation) were estimated by the SWAT weather generator. Detailed bioenergy crop rotations such as tillage, planting dates, amount and timing of fertilizer and pesticide application, and harvest dates were created using information from Michigan State University Extension, local farmers, and Natural Resources Conservation Service (NRCS) personnel. Detailed descriptions of each operation is presented in Love and Nejadhashemi (2011b).

2.3 Sensitivity Analysis and Calibration

Sensitivity analysis was conducted to determine the most influential parameters related to streamflow, sediment, total nitrogen (TN), and total phosphorus (TP) in the watershed. The most sensitive parameters were used in the calibration process. In the SWAT model, the Latin Hypercube Sampling One factor-at-a-time sampling technique was used in order to rank the most

influential parameters in flow, sediment, TN, and TP simulation. Calibration and validation was performed on a monthly time-step for streamflow, sediment, TN, and TP with a two year initial warm-up period (2000-2001). It is recommended that the calibration and validation are performed for a period between three to five years (Moriassi et al., 2007). The calibration period was from 2002-2003, while the validation period was from 2004-2005. The monthly observed streamflow data was downloaded from USGS station 04157000 while water quality data was acquired from a STORET sampling site managed by the Michigan Department of Environmental Quality (Figure 1). Three criteria were used to evaluate the SWAT model performance: 1) coefficient of determination (R^2); 2) Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970); and 3) and percent bias (PBIAS). The model performance is considered satisfactory for monthly basis if $R^2 > 0.5$ (Santhi et al., 2001), $NSE > 0.5$ (Moriassi et al., 2007), and $PBIAS \pm 25\%$ for flow, $\pm 55\%$ for sediment, and $\pm 70\%$ for N and P (Moriassi et al., 2007). The SWAT model used in this study was successfully calibrated and validated for flow, sediment, TN, and TP (Giri et al., 2012). The overall coefficient of determination for flow, sediment, TN, and TP were reported as 0.74, 0.77, 0.78, and 0.72, respectively. The model performance considering NSE for flow, sediment, TN, and TP were 0.74, 0.72, 0.76, and 0.53, respectively. Reported PBIAS for the SWAT model for flow, sediment, TN, and TP were 3.47%, -36.66%, -16.99%, and 39.39%, respectively (Giri et al., 2012).

2.4 Bioenergy Crops Implementation in SWAT

Ten bioenergy crop rotations (corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG)) were identified based on information provided by the Michigan State University Extension and Natural Resources Conversation

Service (NRCS) staff in the watershed. The corn rotation consisted of five years of corn and soybean in the sixth year. The corn-stover rotation was the same as the corn rotation except an additional step (removal of residue after harvest of corn grain) was performed during the corn years. The sorghum rotation was composed of continuous five years of sorghum and soybean in the sixth year. The soybean rotation consisted of two years of soybean and corn in the third year. The corn-soybean rotation consisted of one year of corn and a second year of soybean. The corn-soybean-canola rotation consisted of a first year of corn, a second year of soybean, and a third year of canola. The corn-stover-soybean rotation consisted of a first year of corn and a second year of soybean. This rotation is similar to corn-soybean rotation except the corn residue was removed from the field after harvesting. The miscanthus rotation was comprised of continuous miscanthus growth with planting in the first year, while the switchgrass rotation was comprised of a ten year crop rotation. Out of the ten years, the first year was corn, the second year was soybean, and the remaining years were switchgrass. The sorghum-soybean rotation consisted of a first year of sorghum and a second year of soybean. A detailed description of each rotation can be found in Love and Nejadhashemi (2011b).

2.5 Identify Suitable Bioenergy Crops and Locations

The goal of this section is to identify suitable bioenergy crops and locations in order to minimize environmental impacts from the regulators' viewpoint while maximizing income from the stakeholder's perspective using the Analytic Hierarchy Process (AHP). The process begins by individually assessing environmental and economic aspects of bioenergy crop production before performing the overall analysis.

Three scenarios were developed and bioenergy crops were implemented one at a time to evaluate both local (subbasin) and global (watershed outlet) aspects of each implementation plan. The subbasin level analysis provides information about the overall pollution generation while the watershed level analysis provides information about in-stream pollution transport to the watershed outlet. In *Scenario 1*, bioenergy crops were applied on the current agricultural lands of the watershed. In *Scenario 2*, bioenergy crops were implemented only on marginal lands. Here, pasture, wastelands, and fallow croplands were considered as marginal lands (Love and Nejadhashemi, 2011b). In *Scenario 3*, bioenergy crops were implemented on both agricultural and marginal lands. A detailed description of the process and scenarios are presented below:

2.5.1 Regulators' perspective: Environmental aspect of bioenergy crops

The Saginaw River Watershed was divided into 129 subbasins by the SWAT model, out of which 33 subbasins contained agricultural land and 19 subbasins contained marginal land. In *Scenario 1* all ten bioenergy crop rotations (mentioned in section 2.4) were implemented one-at-a-time in the 33 subbasins for a total of 330 SWAT simulations. However, in *Scenario 2*, only four (CO, COSC, MS, and SG) of the ten bioenergy crop rotations were implemented in 19 subbasins one-at-a-time for a total of 76 SWAT simulations. This is due to likelihood of acceptance of production value of the land into bioenergy crops, farmers' willingness for capital investment in new equipment for different agricultural operations such as planting and harvesting, low yield, and environmental concerns of protecting the low level soil organic content (Love and Nejadhashemi, 2011b). For example, corn-stover was not selected for implementation on marginal land because it would reduce the soil organic content further by removing the residue left after the harvest of corn. In *Scenario 3*, only four bioenergy crops were

applicable for both Scenario 1 and Scenario 2. Therefore, a total of 208 (132 for *Scenario 1* plus 76 for *Scenario 2*) SWAT simulations were performed to evaluate the effect of bioenergy crops in the combined agricultural and marginal lands.

2.5.2 Stakeholders' perspective: Socioeconomic aspect of bioenergy crops

The SWAT model was simulated from 1992 to 2008 (17 years) for each bioenergy crop rotation in order to evaluate the environmental aspect of the bioenergy crops. To maintain the consistency with the environmental component, the net return of each crop rotation was also calculated for 17 years. The net return was calculated based on series of assumptions about production cost, yield, and prices that do not include market fluctuation, climate variabilities, and the discount rate (MSUE, 2013). Therefore, a linear forecasting model was adapted. For example, the corn rotation consists of five consecutive years of corn and soybean in the sixth year. Hence, 17 years continuous corn rotation would consist of 15 years of corn and two years of soybean. The net return of the corn rotation for 17 years was obtained by multiplying the net return of corn per hectare with 15 plus two times of net income of soybean per hectare. After that, the average net return of the corn rotation was calculated by dividing 17 into the 17-year net return of the rotation. The average net return for all crop rotations is presented in Table 1. The net return of each bioenergy crop per hectare was obtained from Michigan State University Extension (MSUE, 2013). The negative net return of sorghum is due to higher cost of production compared to revenue generated. In addition, negative net return was observed by Johnson and Falconer (2001) in a profitability study of grain sorghum in Texas. The negative net return in case of *Miscanthus* is primarily due to limited to no biomass production during the establishment period, which was also found by Miao and Khanna (2013).

Table 1. Average yearly net return for different crop rotation (MSUE, 2013).

Rotation*	Overall	17 years net return (\$/ha)	Average net return (\$/ha)
CO	15 years corn, 2 years soybean	4394	259
COS	9 years corn, 8 years soybean	4670	274
COSC	6 years corn, 6 years soybean, 5 years canola	4967	292
CS	15 years corn, 2 years soybean	4347	255
CSS	9 years corn, 8 years soybean	4641	272
MS	17 years miscanthus	-32309	-1900
SM	15 years sorghum, 2 years soybean	-1836	-106
SMS	9 years sorghum, 8 years soybean	929	54
SB	12 years soybean, 5 years corn	4853	284
SG	3 years corn, 3 years soybean, 11 years switchgrass	1596	94

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

2.6 Analytical Hierarchy Process

The AHP (Saaty, 1980) is a multi-criteria decision making tool that solves complex decision-making processes. It does not contain an objective function, but evaluates alternatives systematically and ranks them based on predefined criteria (Young et al., 2009). AHP is widely applied in different fields of research, such as selection of long-term water management plans (Srdjevic, 2007), placement of green infrastructure for stormwater management (Young et al., 2009), housing development site selection (Meng et al., 2011), environmental vulnerability assessments (Chang and Chao, 2012), and selection of agricultural best management practices (Giri and Nejadhashemi, 2014). Below, the application of AHP for *Scenario 1* is discussed. The same procedure was performed for *Scenario 2* and *Scenario 3*.

2.6.1 Implementation of bioenergy crops in agricultural lands (Scenario 1)

To evaluate the water quality impacts of bioenergy crops, changes in sediment, TN, and TP loads were calculated at subbasin level and watershed outlet compared to current conditions (obtained

from NASS 2009). This was done for the ten bioenergy crops one at a time. Meanwhile, the economic aspect of the bioenergy crops was analyzed based on the average annual net return per hectare as presented in Table 1.

In order to illustrate the procedure, the implementation of AHP technique is provided for subbasin 20 (Figure S1) but repeated for 33 subbasins that have agricultural lands. The AHP is a four-step process (Young et al., 2009): (1) construction of the pairwise matrix, (2) computation of the priority vector, (3) calculation of the consistency ratio, and (4) ranking of alternatives.

Step 1: Construction of the pairwise matrix. The pairwise comparison matrices for sediment, TN, and TP changes for subbasin 20 at the subbasin level are presented in Tables 2, S1, and S2, respectively. Similar tables were developed to compare the watershed level impacts of bioenergy crops and presented in the supplementary materials for sediment (Table S3), TN (Table S4), and TP (Table S5). Each number in the pairwise comparison matrix represents the relative pollution reduction among two alternative crop rotation scenarios. In regard to socioeconomic analysis, the pairwise comparison matrix (Table 3) represents the relative return among two alternative crop rotation scenarios.

Table 2. Pairwise comparison matrix for sediment reduction for subbasin 20 at the subbasin level.

Rotation*	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	2.70	9.00	0.61	1.40	0.11	9.00	9.00	9.00	0.14
COS	0.37	1.00	9.00	0.23	0.52	0.11	9.00	9.00	9.00	0.11
COSC	0.11	0.11	1.00	0.11	0.11	0.11	1.00	1.00	1.00	0.11
CS	1.63	4.39	9.09	1.00	2.28	0.18	9.00	9.00	9.00	0.22
CSS	0.71	1.93	9.09	0.44	1.00	0.11	9.00	9.00	9.00	0.11
MS	8.89	9.09	9.09	5.46	9.09	1.00	9.00	9.00	9.00	1.20
SM	0.11	0.11	1.00	0.11	0.11	0.11	1.00	1.00	1.00	0.11
SMS	0.11	0.11	1.00	1.00	0.11	0.11	1.00	1.00	1.00	0.11
SB	0.11	0.11	1.00	0.11	0.11	0.11	1.00	1.00	1.00	0.11
SG	7.40	9.09	9.09	4.54	9.09	0.83	9.09	9.09	9.09	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table 3. Pairwise comparison of net return per hectare among the bioenergy crops.

Rotation*	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	0.94	0.88	1.01	0.95	9.00	9.00	4.72	0.91	2.75
COS	1.06	1.00	0.94	1.07	1.01	9.00	9.00	5.02	0.96	2.93
COSC	1.13	1.06	1.00	1.14	1.07	9.00	9.00	5.34	1.02	3.11
CS	0.99	0.93	0.88	1.00	0.94	9.00	9.00	4.67	0.90	2.72
CSS	1.06	0.99	0.93	1.07	1.00	9.00	9.00	4.99	0.96	2.91
MS	0.11	0.11	0.11	0.11	0.11	1.00	0.11	0.11	0.11	0.11
SM	0.11	0.11	0.11	0.11	0.11	9.09	1.00	0.11	0.11	0.11
SMS	0.21	0.20	0.19	0.19	0.20	9.09	9.09	1.00	0.19	0.58
SB	1.10	1.04	0.98	1.12	1.05	9.09	9.09	5.22	1.00	3.04
SG	0.36	0.34	0.32	0.37	0.34	9.09	9.09	1.72	0.33	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Step 2: Computation of the priority vector. The priority vector is created based on a normalized principal eigenvector. To do this, each value in the pairwise comparison matrix is divided by the sum of all values in the respective column. The priority vector is calculated by averaging all values of each row. The priority vectors for sediment, TN, and TP are presented in Table 4 at the subbasin level and Table S6 at the watershed outlet. The priority vector for average annual net return of bioenergy crop production is presented in Table 5.

Table 4. Priority vector for sediment, TN, and TP reduction for subbasin 20 at the subbasin level.

Rotation*	Sediment-Weight	TN-Weight	TP-Weight
CO	0.0886	0.1386	0.0139
COS	0.0653	0.0676	0.0139
COSC	0.0137	0.0136	0.0139
CS	0.1007	0.0137	0.0139
CSS	0.0774	0.0136	0.0139
MS	0.3171	0.2907	0.299
SM	0.0136	0.06	0.0935
SMS	0.021	0.1145	0.1874
SB	0.0136	0.0136	0.0639
SG	0.2889	0.274	0.2866

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table 5. Priority vector for bioenergy crops net return

Rotation*	Economic-Weight
CO	0.1376
COS	0.1438
COSC	0.1497
CS	0.139
CSS	0.1403
MS	0.0108
SM	0.0203
SMS	0.0479
SB	0.1457
SG	0.0649

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Step 3: Calculation of the consistency ratio. The consistency ratio is a relative measure of judgment between the current problem in hand and large random samples (IHU, 2014). Consistency ratios larger than 0.1 are considered as an untrustworthy judgment and the pairwise comparison matrix should be rearranged. The consistency ratio is calculated using Equation 1 (Saaty, 1980):

$$\text{Consistency ratio} = \frac{(\lambda_{\max} - n)}{\text{Random index} \times (n-1)} \quad (1)$$

where, n is the number of rows in the pairwise comparison matrix, $\lambda_{\max}$ is the maximum eigenvalue that is estimated as a result of multiplication of the pairwise comparison matrix and the priority vector and then dividing each variable in the new matrix by the priority vector and averaging it (Giri and Nejadhashemi, 2014). The random index is obtained from Saaty (1980). For the subbasin 20, consistency ratio for sediment, TN, and TP were 0.1, 0.0, and 0.1 at the subbasin level and 0.09, 0.095, and 0.1 at the watershed outlet. Meanwhile, the value for net return is 0.07. All of these ratios were acceptable.

Step 4: Ranking of alternatives. In this step, the priority vectors calculated in step 3 (Tables 4 and 5) were combined in a decision matrix for the subbasin (Table 6) and watershed level (Table S7) analyses. These decision matrices were multiplied by the criteria priority vector to rank the alternative bioenergy crop rotations. Two criteria vectors (regulators' and stakeholders' perspectives) were considered during the bioenergy crop evaluation process. The criteria weights were divided into three scenarios: a) Regulators/Stakeholders (0/100), b) Regulators/Stakeholders (50/50) and c) Regulators/Stakeholders (100/0), and. Furthermore, the regulators' criteria weight vector was equally divided among sediment, TN, and TP. The final weights of each bioenergy crop are presented in Table 7 for subbasin analysis and Table S8 for watershed analysis.

Table 6. Decision matrix of bioenergy crop rotation for all criteria for subbasin 20 (subbasin level analysis).

Rotation *	Sediment-Weight	TN-Weight	TP-Weight	Economic-Weight
CO	0.0886	0.1386	0.0139	0.1376
COS	0.0653	0.0676	0.0139	0.1438
COSC	0.0137	0.0136	0.0139	0.1497
CS	0.1007	0.0137	0.0139	0.139
CSS	0.0774	0.0136	0.0139	0.1403
MS	0.3171	0.2907	0.299	0.0108
SM	0.0136	0.06	0.0935	0.0203
SMS	0.021	0.1145	0.1874	0.0479
SB	0.0136	0.0136	0.0639	0.1457
SG	0.2889	0.274	0.2866	0.0649

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table 7. Final ranking of alternatives bioenergy crops for subbasin 20 based on subbasin analysis.

Rotation *	Regulators/Stakeholders (100/0)	Regulators/Stakeholders (50/50)	Regulators/Stakeholders (0/100)
CO	0.0804	0.1090	0.1376
COS	0.0489	0.0964	0.1438
COSC	0.0137	0.0817	0.1497
CS	0.0428	0.0909	0.139
CSS	0.0350	0.0876	0.1403
MS	0.3023	0.1565	0.0108
SM	0.0557	0.0380	0.0203
SMS	0.1076	0.0778	0.0479
SB	0.0304	0.0880	0.1457
SG	0.2832	0.1740	0.0649

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

3. RESULTS AND DISCUSSION

3.1 Impacts of Bioenergy Crop Expansion on Water Resources

The objective of this section was to assess the potential impact of placement and expansion of bioenergy crops on water resources without considering the regulators' and stakeholders' perspectives into the decision making process. The results of this section were obtained from

simulating 10 bioenergy crops on agricultural lands (*Scenario 1*), four bioenergy crops on marginal lands (*Scenario 2*), and 14 bioenergy crops on agricultural plus marginal lands (*Scenario 3*) over a 17-year period. Figure 2 presents the environmental impacts of these three scenarios.

At subbasin level, the median sediment production for *Scenario 1* was approximately 700,000 tons, whereas in marginal land it was nearly 300,000 tons (Figure 2a). The higher sediment production in the agricultural lands compared to marginal lands is due to size of the agricultural land, which is approximately four times larger than the marginal lands. The total bioenergy crop implementation area for agricultural and marginal lands were 443,172 ha and 110,592 ha, respectively. When compared to the current scenario, the median sediment production is lower in *Scenario 1* and much higher in *Scenario 2*. This suggests that marginal lands are not suitable for growing bioenergy crops since the negative environmental impact is almost doubled. Concerning *Scenario 3*, the median value is lower than the current scenario but the 50% variation (25 to 75%) is very large (150,000 1,300,000 tons). The large level of variability is alarming from an environmental standpoint and can be detrimental to aquatic ecosystems although lower sediment is expected to be generated at the subbasin scale in the long-term.

In Figure 2a, *Scenario 1* contains two extreme low points (miscanthus and switchgrass), which generate a negligible amount of sediment compared to the median of all other rotations in that scenario. This is due to the well-developed rooting system and dense canopy cover that protects the ground throughout the year resulting in minimal soil erosion. These perennial crops require soil disturbances only during the planting period, whereas the other crops such as corn generally require tillage and have less groundcover before planting and after harvest. Similar result were found by Love and Nejadhashemi (2011c).

The median TN production by the bioenergy crops in *Scenario 1* was approximately 7,500 tons, whereas in *Scenario 2* it was nearly 1,000 tons, and in *Scenario 3* it was roughly 5,000 tons (Figure 2 b). Similar to sediment generation by bioenergy crops (Figure 2a), TN generation in marginal land is higher compared to current scenario (Figure 2b). In contrast, the median nitrogen load in *Scenario 1* is higher than the current load. However, the median TN loads for all bioenergy crop scenarios (*Scenario 3*) were lower than current practices. Since in *Scenario 3*, the bioenergy crops are applied in larger area than both *Scenario 1* and *Scenario 2*, wider distribution of TN load is experienced, which ultimately brings the median value lower than the current practices. TP trends were similar to sediment trends (Figure 2c). This was expected because sediment main driving force for TP transport. The average median TP production is approximately 800, 200, and 600 tons in *Scenario 1*, *Scenario 2*, and *Scenario 3*, respectively (Figure 2c).

Figure S2 presents the environmental impact of bioenergy crop expansion for the three scenarios at the watershed level (outlet). The trends in environmental impact at the watershed outlet were different than those observed at the subbasin level. Pollutants reaching the watershed outlet from marginal land were greater than that from agricultural land. In addition, the pollutants generated from agricultural plus marginal land were the lowest of all scenarios. The median sediment generation from bioenergy crops (*Scenario 1*) that reached the outlet was about 150,000 tons (Figure S2a), which is almost four times smaller than the sediment generation at the subbasin level (Figure 2a). However, the average median sediment generation in marginal lands was slightly greater than in agricultural lands, which is opposite to what was observed at the subbasin level. This result may be due to in-stream processes and location of marginal lands that are closer to the watershed outlet compared to agricultural lands. Similar to the subbasin level, the

perennial crops (miscanthus and switchgrass) generated less sediment than other bioenergy crops in *Scenario 1* due to denser canopy cover, well-developed rooting systems and limited soil disturbances during the growing period. The average sediment load reaching the watershed outlet from agricultural plus marginal land (*Scenario 3*) was approximately 140,000 tons, which is five times lower than the sediment generated at the subbasin level (Figure S2a). In fact, the lowest sediment load was observed in *Scenario 3*. This may be also attributed to in-stream processes and watershed landscape composition. A similar trend was observed in TN generation (Figure S2b). The average median TN generation by the bioenergy crops in agricultural land, marginal land, and agricultural plus marginal land was approximately 8,500 tons, 9,000 tons, and 6,000 tons, respectively (Figure S2b). As with sediment and TN, a similar trend was observed in TP generation by bioenergy crops in all three scenarios. The average median TP production in agricultural land, marginal land, and agricultural plus marginal land was approximately 700 tons, 850 tons, and 600 tons, respectively (Figure S2c). From nine combinations of scenarios and pollutants, we were expecting higher median pollution load at the watershed outlet for five combinations. However, in the case of TP, only the expansion of bioenergy crops on marginal lands seemed to have a negative environmental impact, due to introduction of agriculture practices in this region.

Figure 2. Range of (a) sediment, (b) TN, and (c) TP generation by different bioenergy crop over 17 years based on subbasin level analysis.

3.2 Identifying Suitable Bioenergy Crops and Locations in the Watershed

The objective of this section was to identify suitable bioenergy crops and locations in order to maximize income from biofuel production from the stakeholder's perspective while minimizing environmental impacts in the regulators' interests. Figure 3 represents the most suitable bioenergy crop and subbasin location for implementation all three scenarios based on the subbasin level analysis, while Figure S3 represents the most suitable one based on the watershed analysis.

When stakeholders' perspective is the only concern for bioenergy crop selection and placement, corn-soybean-canola rotation is selected in all agricultural, marginal, and agricultural plus marginal lands (Figure 3a, b, and c), respectively. This was expected because corn-soybean-canola rotation has the highest annual net return (\$292/ha) among all bioenergy crops (Table 1). However, when stakeholders' and regulators' perspectives are equally important, corn-soybean-canola was replaced by switchgrass in the majority of agricultural lands (Figure 3d and 3f) and by miscanthus in all marginal lands (Figure 3e). This result was due to the greatest pollution reduction efficiency of both perennial crops (switchgrass and miscanthus). Finally, when regulators' perspective is the only concern, miscanthus was selected in all types of lands (Figure 3g, h, and i) due to its greater pollution reduction than other bioenergy crops.

Figure 3. Placement of rank one bioenergy crop based on scenario/subbasin level analysis. (a, b, c) Regulators/Stakeholders (0/100), (d, e, f) Regulators/Stakeholders (50/50), and (g, h, i) Regulators/Stakeholders (100/0)

Based on the watershed outlet analysis, a similar trend was observed when only the stakeholders' perspective was considered (Figure S3a, b, and c). The corn-soybean-canola bioenergy crop was selected in agricultural, marginal, and agricultural plus marginal lands due to highest net return obtained from this rotation compared to others (Table 1). The watershed analysis was similar to the subbasin level analysis when equal weight was considered for stakeholders and regulators. Here, switchgrass was selected for most agricultural lands and miscanthus was placed on most of the marginal lands (Figure S3d and e). The same combination as in the subbasin analysis (switchgrass and miscanthus) was observed in agricultural plus marginal lands (Figure S3f). However, the main difference between subbasin and watershed level analysis was observed for the regulator driven scenario. Miscanthus was selected on approximately 70 percent of the implementation area (agricultural land) whereas the remaining 30 percent selected switchgrass (Figure S3g). However, in the marginal land only miscanthus was selected (Figure S3h) due to the higher pollution reduction efficiency of miscanthus compared to switchgrass. In addition, the mixed agricultural and marginal land combinations, approximately 80 and 20 percent of application area was selected by miscanthus and switchgrass, respectively (Figure S3i).

3.3 Environmental Implications of the Best Bioenergy Crops Implementation Strategies

The objective of this section was to determine the environmental implications of the best bioenergy crops implementation strategies according to AHP analysis. As described in Section 2.6.1, for each of the 33 subbasins that have agricultural lands, the four-step process that includes (1) construction of the pairwise matrix, (2) computation of the priority vector, (3) calculation of the consistency ratio, and (4) ranking of alternatives were performed. Next, the decision matrix for each watershed was multiplied by the criteria priority vector considering three criteria

weights: a) Regulators/Stakeholders (0/100), b) Regulators/Stakeholders (50/50) and c) Regulators/Stakeholders (100/0). Finally, the SWAT model was run based on the selected bioenergy crop rotations identified from the criteria weights. The sediment, TN, and TP loads obtained from new SWAT modeling runs were compared against the current condition and the results are presented in Figures 4 (subbasin level analysis) and S4 (watershed level analysis). Based on the 0/100 regulators/stakeholders preference weights, the sediment reduction is negative (more sediment will be generated) in all future landscape scenarios. The negative sediment reduction is due to selection of corn and soybean rotations. These were selected because of their greater economic return. However, they are more intense than other bioenergy crops, causing more soil disturbance and erosion. Additionally, fewer residues are left on the field after harvest of these crops, further increasing soil erosion. Within the 0/100 regulators/stakeholders preference weights, the sediment load increases also varied between the landscapes. For example, the sediment increase is approximately 80,000 tons in the agricultural land scenario, 500,000 tons in marginal land scenario, and 600,000 in agricultural plus marginal land scenario (Figure 4 a). However, sediment reduction was observed in both 50/50 and 100/0 regulators/stakeholders preference weights due to selection of less intensive rotations such as miscanthus and switchgrass (Figure 3). Like the previous scenario, the sediment reduction also varies between the landscapes. In the 50/50 preference weights, approximately 569,000 tons, 5000 tons, and 600,000 tons of sediment reduction was observed in agricultural, marginal, and agricultural plus marginal land, respectively. Similarly, approximately, 687,000 tons, 5000 tons, and 700,000 tons of sediment reduction was estimated in agricultural, marginal, and agricultural plus marginal land, respectively based on the 100/0 regulators/stakeholders preference weights. The sediment reduction in marginal land remained the same because miscanthus was selected in

the marginal lands of both scenarios. Meanwhile, an increase in sediment reduction was observed both in agricultural and agricultural plus marginal land from 50/50 to 100/0 environmental/economic regulators/stakeholders preference weights due to replacement of switchgrass by miscanthus (Figure 3).

Figure 4. Change in a) sediment, b) TN, and c) TP loads based on the best bioenergy crop implantation strategy and subbasin level analysis (regulators/stakeholders preference).

Similar to sediment reduction, TN and TP loads were increased (negative reduction) in all landscapes scenarios for the 0/100 regulators/stakeholders preference weights (Figure 4b). The negative TN reduction was due to the selection of corn-soybean-canola crop by AHP. Excessive nitrogen and phosphorus loads are mainly attributed to fertilizer application in this rotation. The increase of TN varies among the landscape scenarios. An approximate additional 960 tons of TN and 200 tons of TP were generated by agricultural land, whereas an extra 1800 tons TN and 400 tons of TP left the marginal land, and an increase of 3000 tons of TN and 650 tons of TP were generated by agricultural plus marginal land (Figure 4b and c). In the case of 50/50 preference weights, a positive TN reduction was observed in agricultural and agricultural plus marginal lands, while a minimal TN increase (approximately 58 tons) was observed on marginal land. This result is due to higher levels of fertilizer application in the marginal land in order to improve the soil fertility because marginal land contains less organic matter. A similar result was also found in the 100/0 regulators/stakeholders preference weights. However, approximately 500 tons more TN reduction occurred on agricultural land based on the 100/0 regulators/stakeholders preference weights when compared to the 50/50 case due to replacement of some switchgrass from the 50/50 case to miscanthus in the 100/0 case (Figure 3). Unlike sediment reduction, both reductions and increases in TP were found in both the 50/50 and the 100/0 cases. Approximately 9 tons of TP reduction occurred in the 50/50 and the 100/0 cases due to the selection of the same crop (miscanthus) in both scenarios. However, an increase of 30 tons and 40 tons was observed in agricultural and agricultural plus marginal lands based on the 50/50 and the 100/0 regulators/stakeholders preference weights, respectively. This result was due to the replacement of switchgrass from the 50/50 case to the 100/0 case (Figure 3).

Figure S4 presents environmental implications of the best bioenergy crops implementation strategies based on the watershed level analysis. The trends at the watershed analysis were similar to subbasin level; however, in all cases the magnitudes of changes were smaller than subbasin level. These phenomena can be explained by the in-stream processes such as settling and resuspension of sediment and organic particulates.

4. CONCLUSION

The objectives of this study were to (1) evaluate the impacts of bioenergy crop expansion on water resources, (2) identify suitable bioenergy crops and locations in order to maximize income from biofuel production from the stakeholder's perspective while minimizing environmental impacts in the regulators' interests, and (3) determine environmental implications of the best bioenergy crops implementation strategies according to AHP. Ten bioenergy crop rotations were selected and implemented one-at-a-time on agricultural land, marginal land, and both agricultural and marginal land together for 17 years using SWAT. These ten bioenergy crops were evaluated based on three weights (0%, 50%, and 100%) related to environmental and economic preferences using AHP.

The nonpoint source pollution (sediment, TN, and TP) generated by the bioenergy crops was highest on agricultural land and lowest on marginal land based on subbasin level analysis.

However, considering the total pollution generated per unit area, the total load is almost doubled in marginal lands, making them less than desirable for expansion of bioenergy crops. This trend is even more pronounced at the watershed outlet, where greater pollutant transport was observed from marginal lands compared to other landscapes. This was related to proximity of marginal lands to the watershed outlet and in-stream processes effects on pollution transport. Meanwhile,

both at the subbasin and watershed level analysis, perennial grasses (miscanthus and switchgrass) produced the least pollution among all the bioenergy crops.

Out of these ten bioenergy crops, corn-soybean-canola was selected as the best rotation from an economic standpoint as the net revenue from these bioenergy crops was the greatest. However, the environmental consequences of this rotation were significant due to intense land management systems in corn and soybean. Based on equal weights of environmental and economic factors, and complete environmental preference, perennial crops (miscanthus and switchgrass) were selected as the best bioenergy crops based on their effectiveness in reducing nonpoint source pollution.

Based on this study, the expansion of perennial crops (miscanthus and switchgrass) in general can be beneficial from economic and environmental standpoints. However, expansion of bioenergy crops on marginal lands can be complicated and in many cases is not recommended.

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Supplementary Materials

Figure S1. Location of the example subbasin in the Saginaw River Watershed.

Figure S2. Range of (a) sediment, (b) TN, and (c) TP generation by different bioenergy crop based on watershed outlet analysis.

Figure S3. Placement of rank one bioenergy crop based on scenario/watershed level analysis. (a, b, c) Regulators/Stakeholders (0/100), (d, e, f) Regulators/Stakeholders (50/50), and (g, h, i) Regulators/Stakeholders (100/0).

Figure S4. Change in a) sediment, b) TN, and c) TP loads based on the best bioenergy crop implantation strategy and watershed level analysis (regulators/stakeholders preference).

Table S1. Pairwise comparison matrix for TN reduction for subbasin 20 at the subbasin level.

Rotation [*]	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	5.02	9.00	9.00	9.00	0.28	5.00	1.59	9.00	0.31
COS	0.20	1.00	9.00	9.00	9.00	0.11	1.74	0.32	9.00	0.11
COSC	0.11	0.11	1.00	1.00	1.00	0.11	0.11	0.11	1.00	0.11
CS	0.11	0.11	1.00	1.00	1.01	0.11	0.11	0.11	1.00	0.11
CSS	0.11	0.11	1.00	0.99	1.00	0.11	0.11	0.11	1.00	0.11
MS	3.52	9.09	9.09	9.09	9.09	1.00	9.00	5.59	9.00	1.10
SM	0.20	0.58	9.09	9.09	9.09	0.11	1.00	0.18	9.00	0.11
SMS	0.63	3.16	9.09	9.09	9.09	0.18	5.49	1.00	9.00	0.20
SB	0.11	0.11	1.00	1.00	1.00	0.11	0.11	0.11	1.00	0.11
SG	3.21	9.09	9.09	9.09	9.09	0.91	9.09	5.09	9.09	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S2. Pairwise comparison matrix for TP reduction for subbasin 20 at the subbasin level.

Rotation [*]	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
COS	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
COSC	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
CS	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
CSS	1.00	1.00	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11
MS	9.09	9.09	9.09	9.09	9.09	1.00	9.00	5.38	9.00	1.05
SM	9.09	9.09	9.09	9.09	9.09	0.11	1.00	0.11	5.32	0.11
SMS	9.09	9.09	9.09	9.09	9.09	0.19	8.79	1.00	9.00	0.20
SB	9.09	9.09	9.09	9.09	9.09	0.11	0.19	0.11	1.00	0.11
SG	9.09	9.09	9.09	9.09	9.09	0.95	9.09	5.11	9.09	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S3. Pairwise comparison matrix for sediment reduction for subbasin 20 at the watershed level.

Rotation [*]	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	9.09	9.09	9.09	9.09	0.11	9.09	9.09	0.75	0.11
COS	0.11	1.00	2.93	2.17	0.65	0.11	4.51	2.30	0.20	0.11
COSC	0.11	0.34	1.00	0.74	0.22	0.11	1.54	0.79	0.20	0.11
CS	0.11	0.46	1.35	1.00	0.30	0.11	2.08	1.06	0.20	0.11
CSS	0.11	1.53	4.48	3.31	1.00	0.11	6.90	3.52	0.20	0.11
MS	9.00	9.00	9.00	9.00	9.00	1.00	9.09	9.09	9.09	1.10
SM	0.11	0.22	0.65	0.48	0.14	0.11	1.00	0.51	0.20	0.11
SMS	0.11	0.43	1.27	0.94	0.28	0.11	1.96	1.00	0.20	0.11
SB	1.33	5.00	5.00	5.00	5.00	0.11	5.00	5.00	1.00	0.11
SG	9.00	9.00	9.00	9.00	9.00	0.91	9.00	9.00	9.00	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S4. Pairwise comparison matrix for TN reduction for subbasin 20 at the watershed level.

Rotation [*]	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	0.20	9.09	9.09	9.09	0.29	8.17	1.66	9.09	0.31
COS	4.95	1.00	9.09	9.09	9.09	0.11	1.65	0.33	9.09	0.11
COSC	0.11	0.11	1.00	6.01	5.44	0.11	0.11	0.11	0.11	0.11
CS	0.11	0.11	0.17	1.00	0.90	0.11	0.11	0.11	0.11	0.11
CSS	0.11	0.11	0.18	1.11	1.00	0.11	0.11	0.11	0.11	0.11
MS	3.46	9.00	9.00	9.00	9.00	1.00	9.09	5.74	9.09	1.09
SM	0.12	0.61	9.00	9.00	9.00	0.11	1.00	0.20	8.90	0.11
SMS	0.60	2.99	9.00	9.00	9.00	0.17	4.93	1.00	9.09	0.19
SB	0.11	0.11	9.00	9.00	9.00	0.11	0.11	0.11	1.00	0.11
SG	3.18	9.00	9.00	9.00	9.00	0.92	9.00	5.27	9.00	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S5. Pairwise comparison matrix for TP reduction for subbasin 20 at the watershed level.

Rotation*	CO	COS	COSC	CS	CSS	MS	SM	SMS	SB	SG
CO	1.00	0.11	9.09	9.09	8.40	0.11	0.11	0.11	0.11	0.11
COS	9.00	1.00	9.09	9.09	9.09	0.11	0.13	0.11	0.45	0.11
COSC	0.11	0.11	1.00	1.10	0.78	0.11	0.11	0.11	0.11	0.11
CS	0.11	0.11	0.91	1.00	0.71	0.11	0.11	0.11	0.11	0.11
CSS	0.12	0.11	1.29	1.41	1.00	0.11	0.11	0.11	0.11	0.11
MS	9.00	9.00	9.00	9.00	9.00	1.00	9.09	5.23	9.09	1.05
SM	9.00	7.96	9.00	9.00	9.00	0.11	1.00	0.12	3.58	0.11
SMS	9.00	9.00	9.00	9.00	9.00	0.19	8.03	1.00	9.09	0.20
SB	9.00	2.23	9.00	9.00	9.00	0.11	0.28	0.11	1.00	0.11
SG	9.00	9.00	9.00	9.00	9.00	0.95	9.00	4.99	9.00	1.00

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S6. Priority vector for sediment, TN, and TP reduction for subbasin 20 at the watershed level.

Rotation*	Sediment-Weight	TN-Weight	TP-Weight
CO	0.1506	0.1185	0.0515
COS	0.0404	0.1105	0.0704
COSC	0.0198	0.0273	0.0140
CS	0.0236	0.0126	0.0136
CSS	0.0569	0.0129	0.0152
MS	0.2922	0.2515	0.2532
SM	0.0160	0.0702	0.1008
SMS	0.0227	0.1057	0.1585
SB	0.0927	0.0505	0.0753
SG	0.2850	0.2405	0.2475

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S7. Decision matrix of bioenergy crop rotation for all criteria for subbasin 20 (watershed level analysis).

Rotation*	Sediment-Weight	TN-Weight	TP-Weight	Economic-Weight
CO	0.1506	0.1185	0.0515	0.1376
COS	0.0404	0.1105	0.0704	0.1438
COSC	0.0198	0.0273	0.0140	0.1497
CS	0.0236	0.0126	0.0136	0.139
CSS	0.0569	0.0129	0.0152	0.1403
MS	0.2922	0.2515	0.2532	0.0108
SM	0.0160	0.0702	0.1008	0.0203
SMS	0.0227	0.1057	0.1585	0.0479
SB	0.0927	0.0505	0.0753	0.1457
SG	0.2850	0.2405	0.2475	0.0649

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).

Table S8. Final ranking of alternatives bioenergy crops for subbasin 20 based on watershed analysis.

Rotation*	Regulators/Stakeholders (100/0)	Regulators/Stakeholders (50/50)	Regulators/Stakeholders (0/100)
CO	0.1069	0.1222	0.1376
COS	0.0738	0.1088	0.1438
COSC	0.0204	0.0850	0.1497
CS	0.0166	0.0778	0.1390
CSS	0.0283	0.0843	0.1403
MS	0.2656	0.1382	0.0108
SM	0.0623	0.0413	0.0203
SMS	0.0956	0.0718	0.0479
SB	0.0729	0.1093	0.1457
SG	0.2576	0.1613	0.0649

* corn (CO), corn-soybean (COS), corn-soybean-canola (COSC), corn-stover (CS), corn-stover-soybean (CSS), miscanthus (MS), sorghum (SM), sorghum-soybean (SMS), soybean (SB), and switchgrass (SG).