Final Report

Federal Agency & Organization: Department of Energy – Office of the Biomass Program

Project Title: Watershed Scale Optimization to Meet Sustainable Cellulosic Energy Crop Demand

Award Number: DE-EE0004396

Recipient Organization: Purdue University

Date of Report: May 10, 2016

Written by: Indrajeet Chaubey, R. Cibin, L. Bowling, S. Brouder, K. Cherkauer, B. Engel, J. Frankenberger, R. Goforth, B. Gramig, and J. Volenec

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Executive Summary:

The overall goal of this project was to conduct a watershed-scale sustainability assessment of multiple species of energy crops and removal of crop residues within two watersheds (Wildcat Creek, and St. Joseph River) representative of conditions in the Upper Midwest. The sustainability assessment included bioenergy feedstock production impacts on environmental quality, economic costs of production, and ecosystem services. The following Tasks were completed in this project:

- **Task A:** Improve the simulation of cellulosic energy crops, such as *Miscanthus*, switchgrass, and hybrid poplar, in the Soil and Water Assessment Tool (SWAT) model

- **Task B:** Use the improved model to evaluate the environmental and economic sustainability of likely energy crop scenarios on a watershed scale, including sensitivity to climate variability

- **Task C:** Identify and communicate the optimal selection and placement of energy crops within a watershed for sustainable production.

Bioenergy crop (native prairie, Maize, dual purpose sorghum, Shawnee Switchgrass, and *Miscanthus*) data representing 4696 plot-years were collected in this project at the Throckmorton Purdue Ag Center, the South East Purdue Ag Center, the Northeast Purdue Ag Center, and the Water Quality Field Station (WQFS) at the Agronomy Center for Research and Education. A comparison of the biomass data indicated that *Miscanthus* produced the greatest yield each year and yields of this species were consistent even in 2012 when the region experience severe drought that reduced yield of prairie, maize, and switchgrass plots.

Various Soil and Water Assessment Tool (SWAT) model components were improved and validated with the field measured data. Specifically, the following SWAT improvements were made:

- SWAT model representation of perennial grasses improved and validated with measured data

- Improved representation of hybrid poplar in SWAT

- Development algorithms to represent perennial grass establishment stage

- Improvement of vegetative filter strip representation. SWAT can now represent crop growth in filter strip area and can be used to quantify production of bioenergy crops in filter strip areas

- Improved crop aeration stress representation

- Algorithms to represent dynamic change in CO_2 concentration that enables use of the SWAT model to evaluate effects of climate change on ecohydrologic processes

- Validation of tile drain representation in SWAT

Our research team worked with Dr. Jeff Arnold and the USDA-ARS SWAT team to incorporate the model improvements in the release version of SWAT model (version 615). The improved SWAT model is now distributed to SWAT users globally.

Sensitive fish species richness (SSR) was used as a simple, yet informative, indicator of stream segment biointegrity. We also calculated rarity weighted fish species richness index (RWR) as a simple measure of biodiversity importance. Results suggest that significant increases in RWR and SSR mediated by biofuel cropping of perennial grasses can only be achieved via drastic changes in land use from corn/soybean to *Miscanthus* or switchgrass.

Hydrology and water quality sustainability indices for baseline scenario with future climate data and calibrated SWAT model were quantified to establish the baseline conditions. The GCM projected data from 9 model simulations; three models (GFDL CM2.0.1, UKMO HadCM3 3.1 and NCAR PCM 1.3) for each of three future emission scenarios (A1B, A2, and B1), for three thirty-year periods, viz. 1960-1989 (Past), 1990-2019 (Present), and 2020-2049 (Future) were evaluated.

Scenario analysis principles were used to determine key variables, which were (1) the extent to which corn and soybean continue to be maximized vs. a focus on protecting water quality and the environment, and (2) whether bioenergy refineries continue to be large and centralized, necessitating a high percentage of land conversion vs. a shift to smaller refineries that could accommodate low percentage of crops. Single crop scenarios that consider planting the entire watershed (all agricultural area) in each candidate feedstock were also included because these will serve as inputs to watershed optimization, and to consider uniform adoption of low rates of stover removal from continuous corn, consistent with contracts that are emerging between farmers and cellulosic biorefineries coming online in the near future. Based on these concepts the project evaluated the following 21 different scenarios:

- Perennial energy crops on marginal lands
- Corn stover removal– 20%, 30% and 50%, with and without nutrient replacement
- Perennial bioenergy crops in buffers around corn/soybean areas with different buffer to source area ratios
- Bioenergy crops in all agricultural areas (100% bioenergy crops in existing agricultural fields)
- Bioenergy crops in 50% of agricultural area. One scenario with random 50% of agricultural area and one scenario with 50% of agricultural area selected with plausibility criteria of marginal land, high slope area, pasture area, crop productivity, etc.

The scenario analysis results showed that

- Average stream flow, annual peak flow and number of days over threshold will likely reduce with all bioenergy scenarios
- Energy crop scenarios in general will improve water quality with the exceptions of stover removal that will likely increase sediment load at the watershed outlet
- Water quality benefits due to land use change are generally greater than the effects of climate change and variability
- Comparison of scenarios with randomly selected and strategically selected perennial bioenergy planting areas emphasize the opportunity of maximizing environmental sustainability by optimum landscape planning

Potential contribution of the marginal lands to produce bioenergy crops and associated hydrologic/water quality impacts was completed using APEX model. Marginal lands of the region was identified using the land capability classes and land proximity to streams. Marginal land suitability for growth of perennial biofeedstocks was estimated using fuzzy logic based framework for the Upper Mississippi River Basin. Results indicated that not all marginal lands are suitable for growing perennial biofeedstocks. For example, 40% of the identified marginal lands in the Upper Mississippi River Basin has poor to moderately poor suitability for growth of three targeted biofeedstocks.

Ecosystem services for bioenergy production scenarios were evaluated with measured weather data and climate change data. The results indicate that the ecosystem services will likely improve with bioenergy crops growing in the watershed. Similar to environmental impact analysis, the impacts of land use change on ecosystem services were more dominant than the climate change impacts.

A new method to efficiently optimize land use for bioenergy crop production called Multi-Level Spatial Optimization framework (MLSOPT) was developed. This method was robust and computationally efficient in identifying optimum solutions. Users can download this optimization framework with example files from https://engineering.purdue.edu/ecohydrology/download.html#MLSOPT. This new spatial optimization method was further tested with multi-objective optimization case study to identify optimum stover removal rates from the Wildcat Creek watershed with the minimum impact of sediment loading. Our results indicate that objective functions in optimization are critical in identifying the sustainable solutions. The optimization results generally had good correlation with the biophysical characteristics of the watershed indicating that these characteristics could be used a good surrogate to make bioenergy land management decisions.

We developed a farm-gate partial budget to reflect the per hectare cost of growing an individual feedstock for corn crop residue (corn stover), switchgrass, *Miscanthus* and hybrid poplar. Using the farm-gate production cost together with the simulated biomass yield for each feedstock, we constructed a biomass supply curve for each *individual* feedstock in the watershed. We performed two different types of optimization based on (1) supplying a specified amount of feedstock at the lowest possible cost, and (2) the same biomass production quantity constraints *and* environmental constraints of 25% and 50% reductions in the total amount of nitrogen, phosphorus and sediment delivered to the waterways. One noticeable difference among optimization results with different constraints was that both perennial grass crops are expected to reduce delivery of all three pollutants relative to the baseline cropping practices in place today. Stover removal in combination with continuous no-till may be able to improve sediment loss relative to the baseline corn-soybean rotation under the current agricultural management practices.

The perennial grasses have the highest farm-gate production cost per dry metric of biomass. The opportunity cost of not growing corn and/or soybeans on the high productivity land cannot be overstated as a determinant of the crop(s) that farmers will choose to plant. If markets for cellulosic feedstocks do eventually emerge, this opportunity cost will ultimately determine if farmers ever choose to grow perennial grasses or woody feedstocks in the eastern Corn Belt. In 2015 in Indiana, this opportunity cost on average quality agricultural land in a corn-soybean rotation was expected to be approximately $175 per acre. This means that unless biorefineries are willing to pay prices for switchgrass or *Miscanthus* high enough to generate net revenue per acre greater than or equal to this level, then farmers will not be willing to grow either of these feedstocks and stover is the only realistic feedstock in the watershed.

For the case of hybrid poplar tree production, the results suggest that the most efficient contract type to encourage entry is based on a fixed per acre payment. A payment that guarantees average cost is covered will completely eliminate the (option) value of waiting to plant hybrid poplars until a later date. Another interesting result is that a revenue floor (guaranteed base payment) contract does very little to induce farmer planting of woody crops until it gets to very high levels, although it does significantly lower the threshold for leaving the contract at relatively low levels. The asymmetric nature of uncertainty results in conclusions that differ greatly from models without such asymmetry. More specifically, the premium on entry is significantly lower after netting out yield uncertainty for an idle cellulosic biofuels plant. Contracts are not only useful for sharing risk, they also have a very important role to play in perennial crop production. Contracts—especially per acre payment contracts—reduce uncertainty for a grower and allow them to enter production at a fraction of the net revenue required under a performance based contract.

We developed interagency collaborations with multiple agencies and universities including Iowa State University, USDA-ARS, Texas A&M University, and CenUSA Project. These efforts are continuing beyond the life of this project.

Four Post-Doctoral Research Associates, 14 graduate students were trained as a part of this project.

14 peer-reviewed journal articles have been published from this project. Additional 13 journal articles are currently under review. Our project team made more than 80 different presentations at various local, regional, national and international conferences documenting the results from this project.

Detailed List of Tasks and Accomplishments

Task A: Improve the simulation of cellulosic energy crops, such as *Miscanthus*, switchgrass, and hybrid poplar, in the Soil and Water Assessment Tool (SWAT) model

1. **Tasks performed to complete this objective**:

   A.1. Synthesize available data needed to parameterize the model to effectively simulate the production of various energy crops and identify data gaps

   A.2. Conduct measurements on existing fields where energy crops are grown to obtain parameters not currently available

   A.3. Improve representation and parameterization of processes related to new energy crops in the model

   A.4. Validate the model on existing field/plots and watersheds where energy crop production, water and soil data are collected

2. **Accomplishments**:

- Our project team synthesized available data on perennial energy crops such as *Miscanthus*, switchgrass, and hybrid poplar. Data gaps were identified to parameterize the Soil and Water Assessment Tool (SWAT) model to effectively represent the production of energy crops.
- Field experiments were conducted on existing energy crop fields at the Throckmorton Purdue Ag Center, the South East Purdue Ag Center, the Northeast Purdue Ag Center, and the Water Quality Field Station (WQFS) at the Agronomy Center for Research and Education. 4696 plot-years of bioenergy crops monitoring data were collected. Major findings from field data collection are demonstrated in Figure 1-Figure 4.

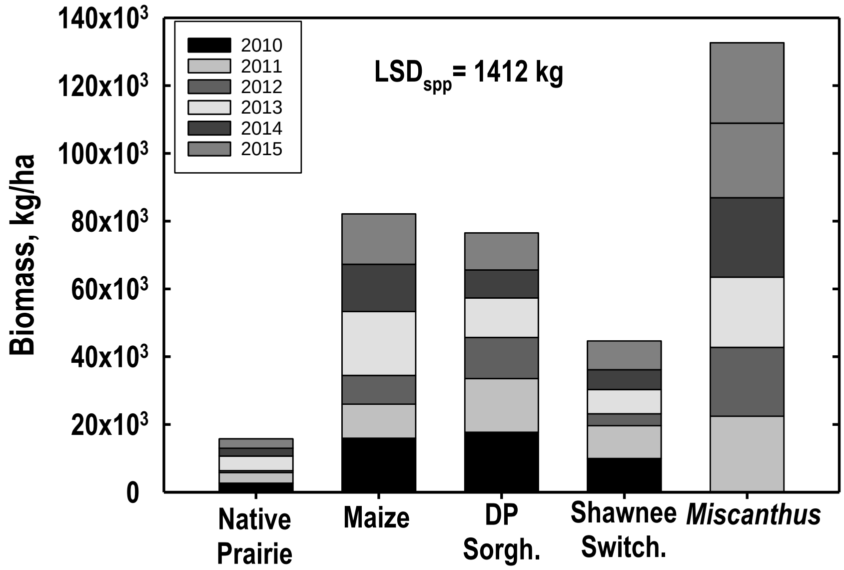

Figure 1. Cumulative biomass yield (dry matter basis) of native prairie, maize, dual-purpose sorghum, switchgrass and Miscanthus on an excellent maize-growing site at the Water Quality Field Station in West Lafayette IN from 2010 to 2015. Miscanthus produced the greatest yield each year and yields of this species were consistent even in 2012 when the region experience severe drought that reduced yield of prairie, maize, and switchgrass plots. The least significant difference (LSD) at the 5% level of probability is shown for the species main effect.

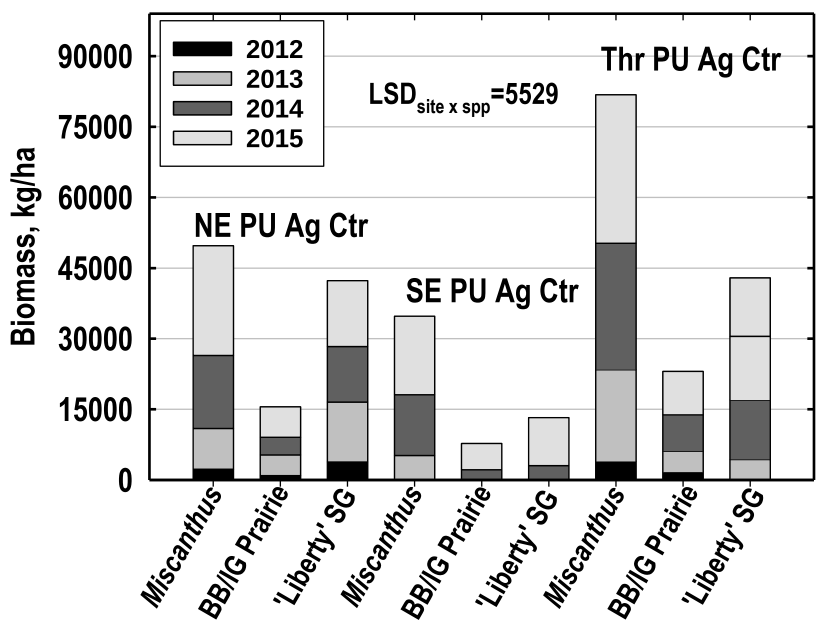

Figure 2. Cumulative biomass yield (dry matter basis) of Miscanthus, a big bluestem/indiangrass prairie, and Liberty switchgrass on marginal soils at the Northeast (NE), Southeast (SE), and Throckmorton (Thr) Purdue Ag. Centers from 2012 to 2015. Once established (2013) Miscanthus produced the greatest yield at each location in each year. The mixed prairie had low yield, especially at SE PU Ag Ctr where plots were established on a landfill cap. Switchgrass yield approached that of Miscanthus at the NE Purdue Ag Center. The least significant difference (LSD) at the 5% level of probability is shown for the site x species interaction.

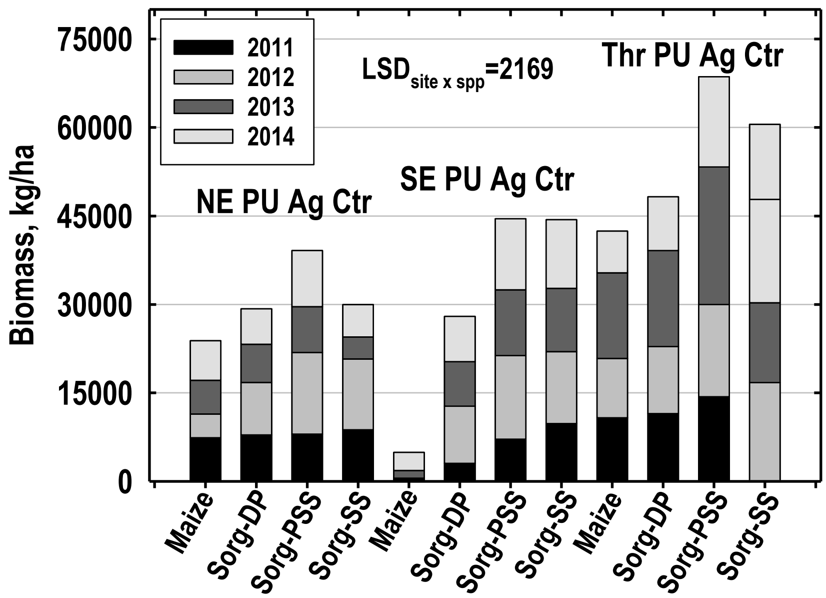

Figure 3. Cumulative biomass yield (dry matter basis) of maize, dual-purpose sorghum (Sorg-DP), photoperiod-sensitive sorghum (Sorg-PSS), and sweet sorghum (Sorg-SS) on marginal soils at the Northeast (NE), Southeast (SE), and Throckmorton (Thr) Purdue Ag. Centers from 2011 to 2014. Within a location, maize yields were always lower than sorghums, and especially at the SE PU site located on a landfill cap. Yields of the photoperiod-sensitive sorghum were generally the highest irrespective of location. The least significant difference (LSD) at the 5% level of probability is shown for the site x species interaction.

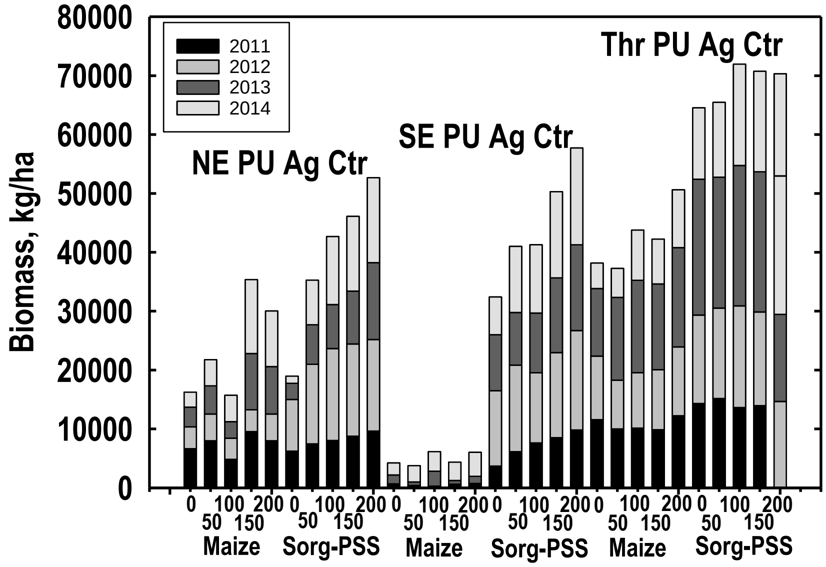

Figure 4. Cumulative biomass yield (dry matter basis) of maize and photoperiod-sensitive sorghum (Sorg-PSS) as influenced by nitrogen (N) fertilizer application on marginal soils at the Northeast (NE), Southeast (SE), and Throckmorton (Thr) Purdue Ag. Centers from 2011 to 2014. Maize yields increased as N additions increased to 200 kg N/ha, except at the SE PU site where N application could not overcome the poor soils. The Sorg-PSS responded in a predictable manner to added N and generally achieved higher biomass yields at comparable N rates within a location suggesting higher N use efficiency.

- Compositional analysis of biomass collected was conducted. This includes sugars, starch, cellulose, hemicellulose, lignin, ash, nitrogen, carbon, potassium, and phosphorus (Figure 5-Figure 11). Plots at the WQFS were also monitored for greenhouse gas emissions, and all sites for soil carbon and plant available nutrients.

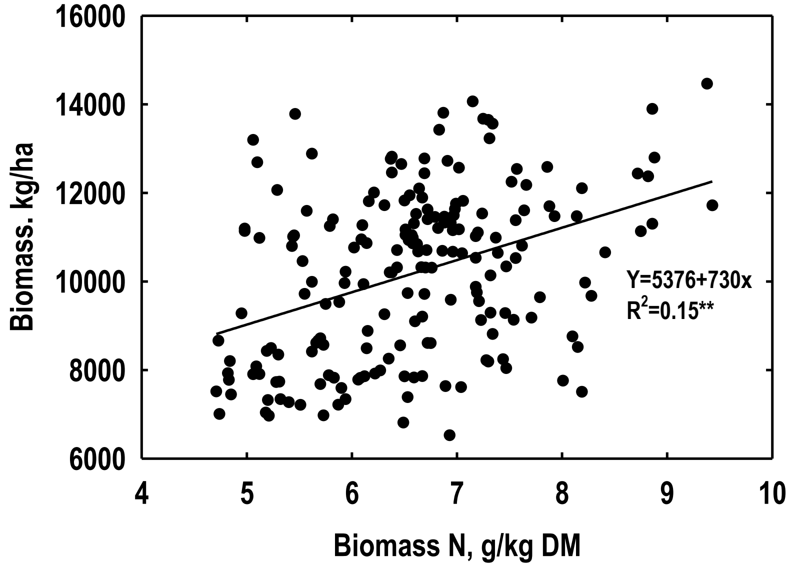

Figure 5 Relationship between biomass yield and tissue nitrogen (N) concentration of Shawnee switchgrass at the Throckmorton Purdue Ag. Center near Lafayette IN. Plots were fertilized with 0, 50, 100, or 150 kg N/ha in spring of each year and plots harvested for biomass yield in October or November. There was no significant effect of N on yield (data not shown). The regression of tissue N on yield is significant (P<0.01), but the low coefficient of determination (R^2) indicates that factors, other than N, influence yield in this experiment.

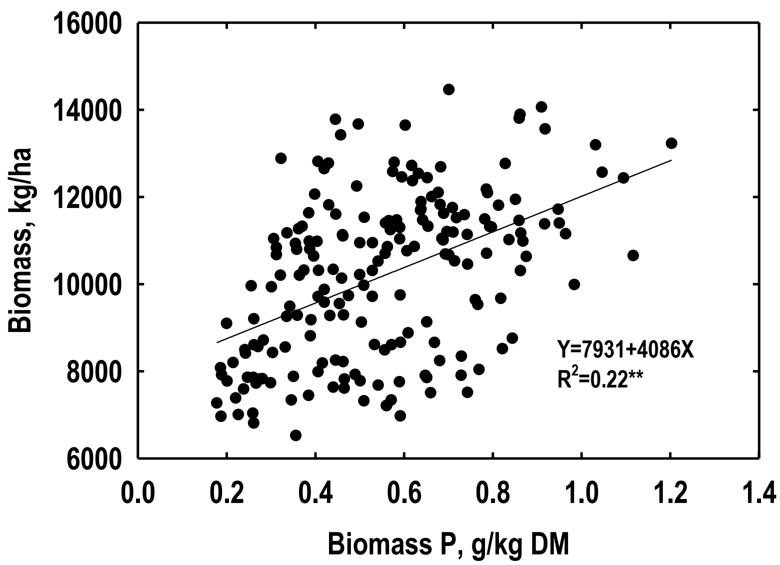

Figure 6. Relationship between biomass yield and tissue phosphorus (P) concentration of Shawnee switchgrass at the Throckmorton Purdue Ag. Center near Lafayette IN. Long-term P fertilizer applications prior to planting switchgrass resulted in large plot-to-plot variation in soil test P ranging from what is considered very low for maize production (<5 mg P/kg soil) to sufficient for maize (> 25 mg P/kg soil). Plots were uniformly fertilized with 50 kg N/ha in spring of each year and harvested for biomass yield in

October or November. The regression of tissue P on yield is significant (P<0.01), but the low coefficient of determination (R^2) indicates that factors, other than P, influence yield in this experiment.

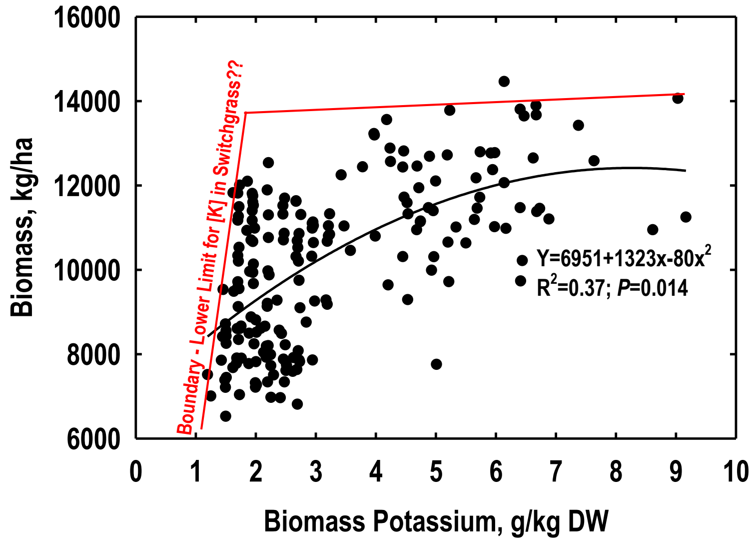

Figure 7. Relationship between biomass yield and tissue potassium (K) concentration of Shawnee switchgrass at the Throckmorton Purdue Ag. Center near Lafayette IN. Long-term K fertilizer applications prior to planting switchgrass resulted in large plot-to-plot variation in soil test K ranging from what is considered very low for maize production (<50 mg K/kg soil) to sufficient for maize (> 150 mg K/kg soil). Plots were uniformly fertilized with 50 kg N/ha in spring of each year and harvested for biomass yield in October or November. The regression of tissue K on yield is significant, but the moderate coefficient of determination (R^2) indicates that factors, other than K, influence yield in this experiment. The red line represents boundary conditions that may limit tissue K (left edge) and biomass yield (upper edge) at this location.

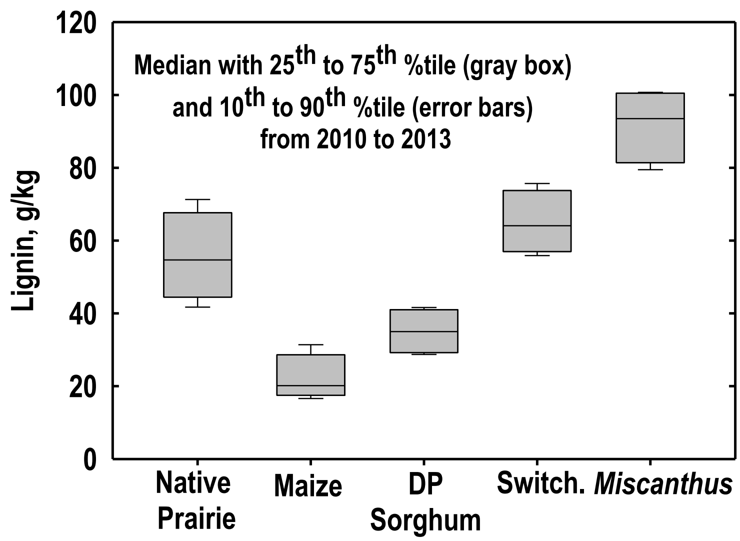

Figure 8. Box plots indicating the median and percentiles for lignin concentrations of native prairie, maize, dual-purpose (DP) sorghum, switchgrass (switch) and Miscanthus at the Water Quality Field Station in West Lafayette IN from 2010 to 2013. Lignin concentrations were consistently greatest in Miscanthus and lowest in maize. Unlike biomass yields (Figure 1), variation in lignin concentration in this experiment was low irrespective of year.

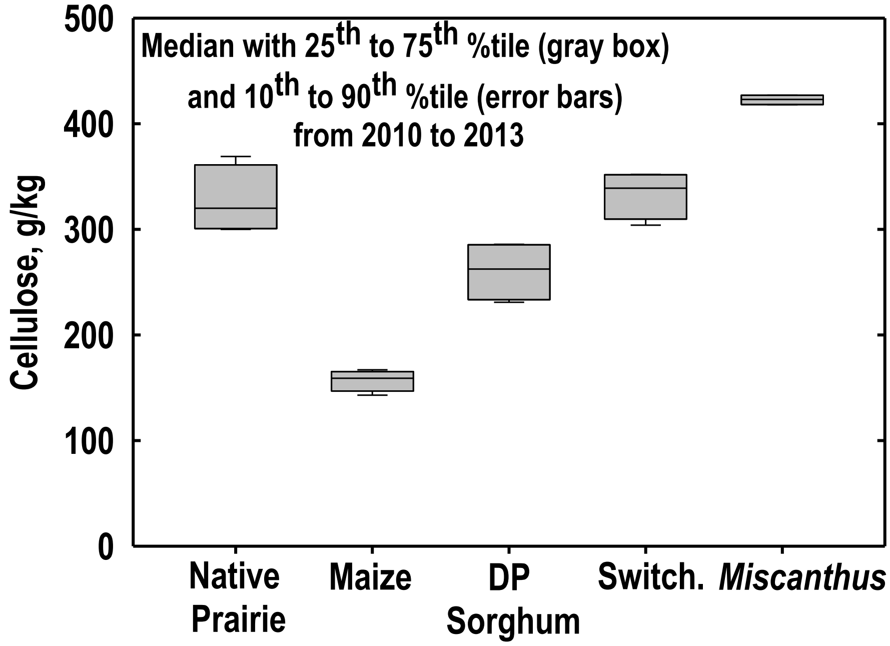

Figure 9. Box plots indicating the median and percentiles for cellulose concentrations of native prairie, maize, dual-purpose (DP) sorghum, switchgrass (switch) and Miscanthus at the Water Quality Field Station in West Lafayette IN from 2010 to 2013. Cellulose concentrations were highest in Miscanthus, lowest in maize, with cellulose concentrations of the other species intermediate. Unlike biomass yields (Figure 1), but similar to lignin (Figure 8), year-to-year variation in cellulose concentration was very low especially in Miscanthus and maize.

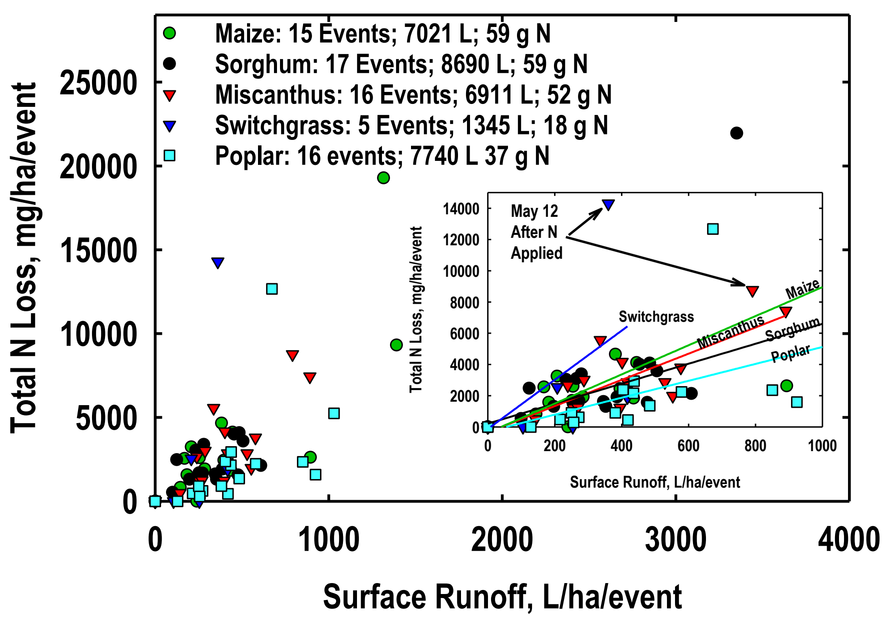

Figure 10. Influence of surface runoff on nitrogen (N) losses in 2014 from plots of maize, dual-purpose sorghum, Miscanthus, Liberty switchgrass, and hybrid poplar grown for biomass. The inset graph expands the horizontal axis so species differences are more readily visible at low runoff rates. The legend provides total runoff events and total water (L) and N (g) losses per hectare from plots in 2014. N loss as runoff per event increases is least for the unfertilized poplar plots, and greatest for the switchgrass plots, with other species intermediate (inset graph). Season-long totals for N loss were highest for maize, sorghum, and

Miscanthus that all lost more than 50 g N in 6911 to 8690 L of runoff in 15 or more runoff events. By comparison, switchgrass had only 5 events where surface runoff occurred and lost only 18 g N in the 1345 L of runoff. Poplar had 16 runoff events with 7740 L of runoff, but lost only 37 g N because this species was not fertilized with N. High N losses occurred on the switchgrass and Miscanthus plots in the runoff event immediately following surface N fertilizer application on May 12.

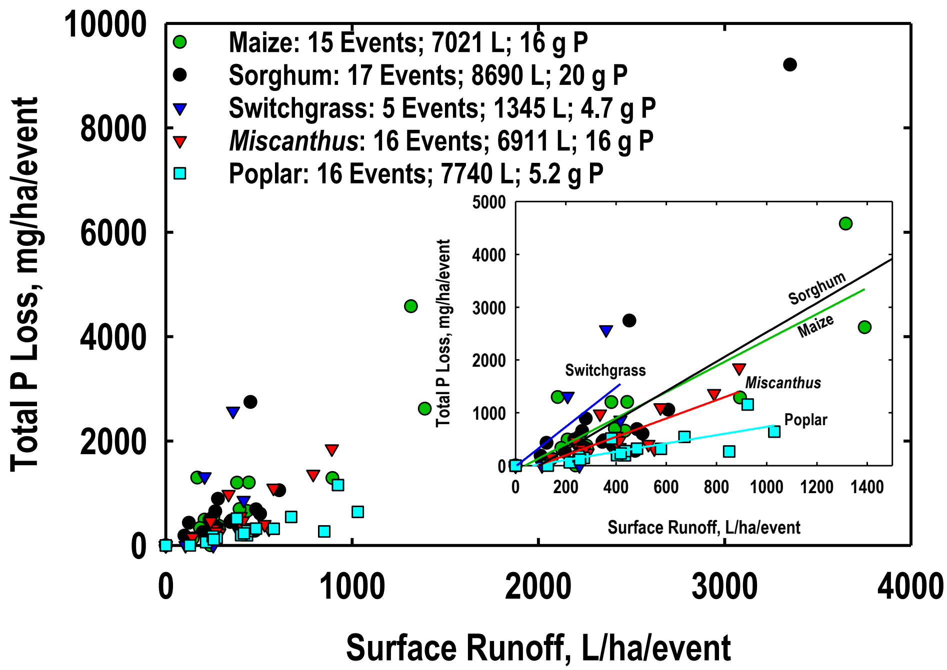

Figure 11. Influence of surface runoff on phosphorus (P) losses in 2014 from plots of maize, dual-purpose sorghum, Miscanthus, Liberty switchgrass, and hybrid poplar grown for biomass. The inset graph expands the horizontal axis so species differences are more readily visible at low runoff rates. The legend provides total runoff events and total water (L) and P (g) losses per hectare from plots in 2014. P loss as runoff per event increases is least for the poplar and Miscanthus plots, greatest for the switchgrass plots, with maize and sorghum intermediate (inset graph). Season-long totals for P loss were highest for maize, sorghum, and Miscanthus that all lost at least 16 g P in 6911 to 8690 L of runoff in 15 or more runoff events. By comparison, switchgrass had only 5 events where surface runoff occurred and lost less than 5 g P in the 1345 L of runoff. Poplar had 16 runoff events with 7740 L of runoff, and lost only 5 g P.

- We have installed soil moisture and soil temperature sensors at two depths and at three locations in maize, switchgrass, *Miscanthus*, and hybrid poplar plots at the Throckmorton Purdue Ag. Center. We have also installed a weather station and have collected meteorologic data from this site.
- Data from the biomass production studies is being summarized and placed in the Purdue University Research Repository. We plan to publish these data sets with a DOI once data analyses are complete.
- We have improved various SWAT model components and validated many subcomponent representations in the model with field measured data. A summary of model improvements are provided below. Detailed discussions can be found in the subsequent sections.
    - SWAT model representation of perennial grasses improved and validated with measured data
    - Improved representation of hybrid poplar in SWAT
    - Development of algorithms to represent perennial grass establishment stage

- Improvement of vegetative filter strip representation. SWAT can now represent crop growth in filter strip area and can be used to quantify production of bioenergy crops in filter strip areas
  - Improved crop aeration stress representation
  - Algorithms to represent dynamic change in CO_2 concentration that enables use of the SWAT model to evaluate effects of climate change on ecohydrologic processes
  - Validation of tile drain representation in model

- SWAT model was parameterized for perennial bioenergy crops from data collected in task A.1 and Task A.2. SWAT model parameterization and model improvements for perennial grass simulation are presented in detail in Trybula *et al*., 2015. We have worked with Dr. Jeff Arnold and the USDA-ARS SWAT team to incorporate all the model improvements in the release version of SWAT model (version 615). The improved model is now distributed to SWAT users globally. Figure 12 and Table 1 highlight some of the model improvements we have made.

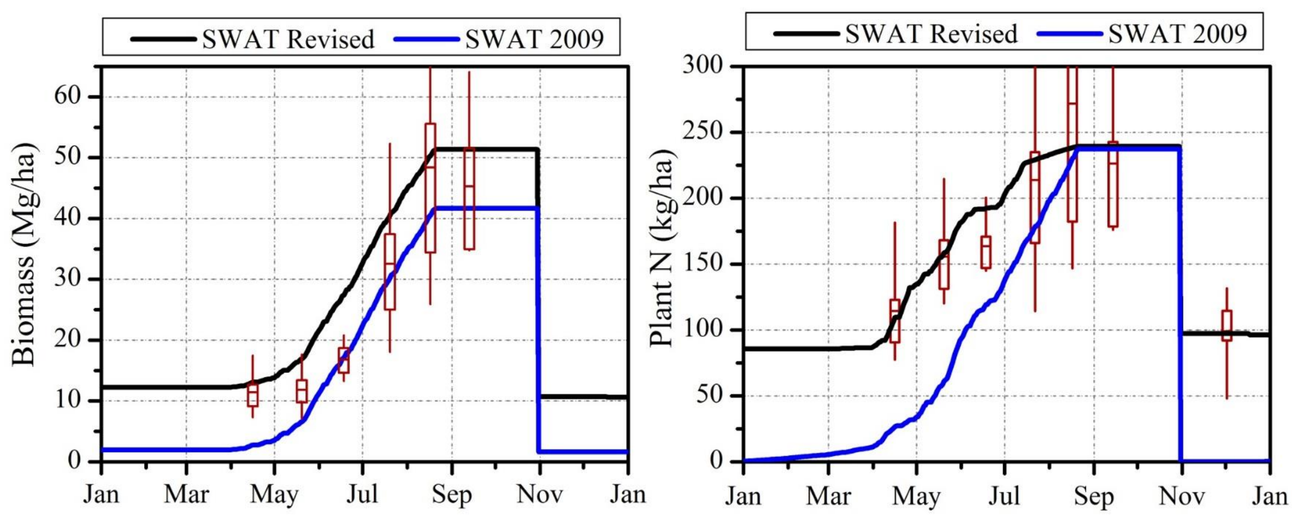

Figure 12. Comparison of Miscanthus simulation using improved SWAT model (Trybula et al., 2014) and default model. The improved model significantly improved the perennial grass growth and nutrient translocation processes

Table 1 Suggested values and potential parameter range for Miscanthus x giganteus and upland switchgrass (P. virgatum) cultivar Shawnee compared to current lowland switchgrass (c.v. Alamo) in the SWAT 2009 crop database. Shaded parameters were estimated from our data and published literature values.

			Miscanthus x *giganteus*		Shawnee Switchgrass (*Panicum virgatum)*		Alamo Switchgrass
			MISG		SWSH		SWCH
Parameter	Acronym	Unit	Suggested	Range	Suggested	Range	Database value
Optimal Temperature (degrees Celsius)	T_OPT[2,3,6]	°C	Existing Alamo value		Existing Alamo value		25
Base Temperature (degrees Celsius) [Potential Heat Units]	T_BASE[1,2,3,4] [PHU]	°C	8 [1830]	7-10 [2100-1600]	10 [1400]	8-12 [1600-1200]	12
Radiation Use Efficiency in ambient CO_2	BIO_E[1,4,5]	$\frac{g}{MJ}$ x 10	41 (39*)	-	17 (12*)	-	47
Root fraction at emergence	RFR1C	NA	0.87	0.76-0.96	0.89	0.80-0.97	Default (0.40)
Root fraction at maturity	RFR2C	NA	0.18	0.12-0.22	0.49	0.44-0.57	Default (0.20)
Harvest Index	HVSTI[7]	NA	1	-	1	-	0.9
Harvest Efficiency	HEFF[1]	NA	0.7	0.65-0.75	0.75	0.7-0.75	
Lower Limit of Harvest Index due to stress	WSYF	NA	1	-	1	-	0.9
Maximum Leaf Area Index (LAI)	BLAI[1]	$\frac{m^2}{m^2}$	11	10-13	8	-	6
Fraction of growing season when growth declines	DLAI[1, 7]	NA	1.1	-	1		0.7
Minimum LAI for plant during dormant period	ALAI_MIN[8]	$\frac{m^2}{m^2}$	0	-	0	-	0
Light extinction coefficient	EXT_COEFF[1]	NA	0.55	0.45-0.65	0.5	0.4-0.55	0.33
First point fraction of BLAI for optimum growth curve	LAIMX1[1,4]	NA	0.1	-	0.1	-	0.2
Second point fraction of BLAI for optimum growth curve	LAIMX2[1,4]	NA	0.85	-	0.85	-	0.95
Fraction of growing season coinciding with LAIMX1	FRGRW1[1,4]	NA	0.1	-	0.1	-	0.1
Fraction of growing season coinciding with LAIMX2	FRGRW2[1,4]	NA	0.45	-	0.4	-	0.2

Plant nitrogen fraction at emergence (whole plant)	PLTNFR(1) [1]	$\frac{kg\ N}{kg\ DM}$	0.0100	0.0097-0.0104	0.0073	0.0066-0.0081	0.035
Plant nitrogen fraction at 50% maturity (whole plant)	PLTNFR(2) [1]	$\frac{kg\ N}{kg\ DM}$	0.0065	0.0062-0.0070	0.0068	0.0067-0.0072	0.015
Plant nitrogen fraction at maturity (whole plant)	PLTNFR(3) [1]	$\frac{kg\ N}{kg\ DM}$	0.0057	0.0053-0.0060	0.0053	0.0051-0.0055	0.0038
Plant nitrogen fraction in harvested (aboveground) mass	CNYLD[1]	$\frac{kg\ N}{kg\ yield}$	0.0035	0.0034-0.0035	0.0054	0.0053-0.0058	0.0160
Plant phosphorus fraction at emergence (whole plant)	PLTPFR(1) [1]	$\frac{kg\ P}{kg\ DM}$	0.0016	0.0016-0.0017	0.0011	0.0010-0.0012	0.0014
Plant phosphorus fraction at 50% maturity (whole plant)	PLTPFR(2)[1]	$\frac{kg\ P}{kg\ DM}$	0.0012	0.0010-0.0014	0.0014	0.0013-0.0016	0.001
Plant phosphorus fraction at maturity (whole plant)	PLTPFR(3)[1]	$\frac{kg\ P}{kg\ DM}$	0.0009	0.0007-0.0011	0.0012	0.0011-0.0012	0.0007
Plant phosphorus fraction in harvested (aboveground) mass	CPYLD[1]	$\frac{kg\ P}{kg\ yield}$	0.0003	0.0003-0.0004	0.0010	0.0010-0.0011	0.0022
Max. Canopy Height (m)	CHTMX[1,6]	m	3.5	-	2	-	2.5
Max. Rooting Depth (m)	RDMX[6]	m	3	2-4	3	2-4	2.2
Min. Crop Factor for Water Erosion	USLE_C[8]	NA	Existing Alamo Value		Existing Alamo Value		0.003
Vapor pressure deficit	VPDFR[8]	kPa	Existing Alamo Value		Existing Alamo Value		4
Stomatal conductance	GSI[8]	$\frac{m}{s}$	Existing Alamo Value		Existing Alamo Value		0.005
GSI fraction corresponding to the second point on the stomatal conductance curve	FRGMAX[8]	NA	Existing Alamo Value		Existing Alamo Value		0.75
Rate of decline in RUE due to increase in vapor pressure deficit	WAVP[8]	NA	Existing Alamo Value		Existing Alamo Value		8.5

[1]*Data collected from the Purdue University Water Quality Field Station;* [2]*Daily minimum, maximum, and mean temperature Indiana State Climate Office;* [3]*Daily minimum, maximum, and mean temperature Illinois Climate Network;* [4]*Heaton, E.M., 2007;* [5]*Kiniry et al., 2011;* [6]*Zub and Brancourt-Hulmel, 2010;* [7]*Modified parameter for perennial rhizomatous grass representation;* [8]*Assumed,* [*]*Preliminary value using top growth data, replaced by value using total biomass data*

- SWAT model was parameterized and improved for hybrid poplar representation (Table 2). We have published a manuscript describing the ALMANAC model (Agricultural Land Management Alternative with Numerical Assessment Criteria) parameterization and improvement to simulate short duration woody crops in *Bioenergy Research* (Guo *et al*., 2015). The model improvements and parameters are now incorporated in the release version of the SWAT model.

Table 2. Values and suggested parameter ranges for hybrid poplar (Populus balsamifera L. × P.tristis Fisch) and cottonwood (Populus deltoides Bartr.) compared to default parameter values for Populus in SWAT2012 database

Acronym	Parameter	*Populus balsamifera* L. × *P.tristis* Fisch (HYPT)		*Populus deltoides* Bartr. (POEC)		*Populus* (POPL)
		Value	Range	Value	Range	Database value
T_BASE* [PHU] *	Base Temperature (℃) Heat Units to Maturity	4 [1750]	0-6 [2150-1500]	8 [2818]	7-15 [2900-2200]	10 -
T_OPT†	Optimal Temperature (℃)	25	25-30	25	25-30	30
BIO_E‡,§	Radiation Use Efficiency in ambient CO_2 (kg ha^{-1})/(MJ m^{-2})	20	20-35	41	30-58	30
EXT_COEF ‡,§	Light Extinction Coefficient	0.30	0.20-0.60	0.60	0.20-0.60	0.45
BLAI‡,¶,**	Maximum LAI	9.50	5.00-9.50	9.50	5.00-9.50	5.00
LAIMX2‡,¶, **	Fraction of BLAI corresponding to 2nd point	0.95	0.95-0.98	0.95	0.95-0.98	0.95
DLAI‡,¶,**	Point in growing season when LAI declines	0.99	0.99	0.99	0.99	0.99
BIO_LEAF	Fraction of tree biomass converted to residue during dormancy	-	-	-	-	0.300
TREED‡,¶,††	Tree leaf area factor	0.500-4.500	0.500-4.500	0.500-4.500	0.500-4.500	-
FRGRW2‡, ¶,**	Fraction of growing season coinciding with LAIMX2	0.40	0.40-0.45	0.40	0.40-0.45	0.40
ALAI_MIN ‡,¶,**	Minimum LAI for plant during dormancy	0.000	0.000-0.750	0.000	0.000-0.750	0.750
FRGRW1‡, ¶,**	Fraction of growing season coinciding with LAIMX1	0.05	0.05-0.07	0.05	0.05-0.07	0.05

LAIMX1‡,¶,**	Fraction of BLAI corresponding to 1st point	0.05	0.05-0.30	0.05	0.05-0.30	0.05
PLTPFR1††,‡‡	Plant P fraction at emergence (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0007
GSI†	Maximum stomatal conductance	0.0070	0.0040-0.0070	0.0070	0.0040-0.0070	0.0040
CHTMX†	Maximum canopy height (m)	Existing value	7.00-15.00	10.00	10.00-15.00	7.50
FRGMAX†	Fraction of GSI corresponding to the 2nd point of stomatal conductance curve	Existing value	Existing value	Existing value	Existing value	0.750
VPDFR†	Vapor pressure deficit (kPa) corresponding to 2nd point of stomatal conductance curve	Existing value	Existing value	Existing value	Existing value	4.00
PLTNFR1††,‡‡	Plant N fraction at emergence (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0060
PLTNFR3††,‡‡	Plant N fraction at maturity (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0015
PLTNFR2††,‡‡	Plant N fraction at 50% maturity (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0020
RSDCO_PL†	Plant residue decomposition coefficient	Existing value	Existing value	Existing value	Existing value	0.0500
RDMX††,‡‡	Maximum rooting depth (m)	Existing value	Existing value	Existing value	Existing value	3.50
CNYLD‡,§§,¶¶	Plant N fraction in harvested biomass	0.0005	0.0005-0.0015	0.0005	0.0005-0.0015	0.0015
CPYLD‡,§§,¶¶	Plant P fraction in harvested biomass	0.0002	0.0002-0.0003	0.0002	0.0002-0.0003	0.0003
PLTPFR2††,‡‡	Plant P fraction at 50% maturity (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0004
PLTPFR3††,‡‡	Plant P fraction at maturity (whole plant)	Existing value	Existing value	Existing value	Existing value	0.0003
USLE_C†	Minimum crop factor for water erosion	Existing value	Existing value	Existing value	Existing value	0.0010

WAVP††,‡‡	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit	Existing value	Existing value	Existing value	Existing value	8.00
CO2HI†	Elevated CO_2 atmospheric concentration (µL CO_2 L^{-1} air) corresponding the 2nd point	Existing value	Existing value	Existing value	Existing value	660.00
BIOHI†	Biomass-energy ratio corresponding to 2nd point	Existing value	Existing value	Existing value	Existing value	31.00
WSYF‡	Lower limit of harvest index ((kg ha^{-1})/(kg ha^{-1}))	0.000	0.000	0.000	0.000	0.010
MAT_YRS ¶,**	Number of years required for tree species to reach full development (years)	6-9	6-9	6-9	6-9	10
BMX_TREES†,‡‡	Maximum biomass for a forest (mt ha^{-1})	Existing value	Existing value	Existing value	Existing value	200
BM_DIEOFF†	Biomass dieoff fraction	Existing value	Existing value	Existing value	Existing value	0.100
HVSTI†††, ‡‡‡	Harvest index for optimal growing conditions	0.65	0.45-0.70	0.60	0.40-0.65	0.76

* *Calculated based on maximum and minimum daily temperature from NCDC weather stations.† Assumption. ‡ Modified value after calibration. § Landsberg and Wright, 1989.¶ Hansen, 1983. ** Zavitkovski, 198. †† Kiniry et al., 1999. ‡‡ MacDonald et al., 2008. §§ Black et al., 2002. ¶¶ McLaughlin et al., 1987. *** J. Kiniry, personal communication. ††† Michael et al., 1988. ‡‡‡ Arnold et al., 2011*

- We have improved SWAT model for simulating establishment period of perennial grasses and validated using measured LAI data from literature (Figure 13) and measured data from Purdue Research stations (Figure 14).

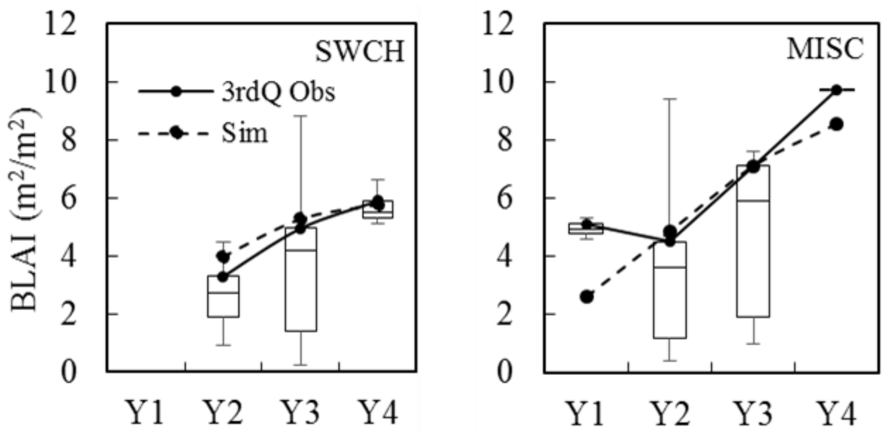

Figure 13. Leaf area index (LAI) developing during the establishment period (when perennial grasses building their growth potential untill the maximum potential is reached). Boxplot were reported observed values of LAI from field experiments. 3rdQ Obs represents the third quartile of observed values and Sim represented the simulated LAI values by the equation used by Miguez et al., 2008.

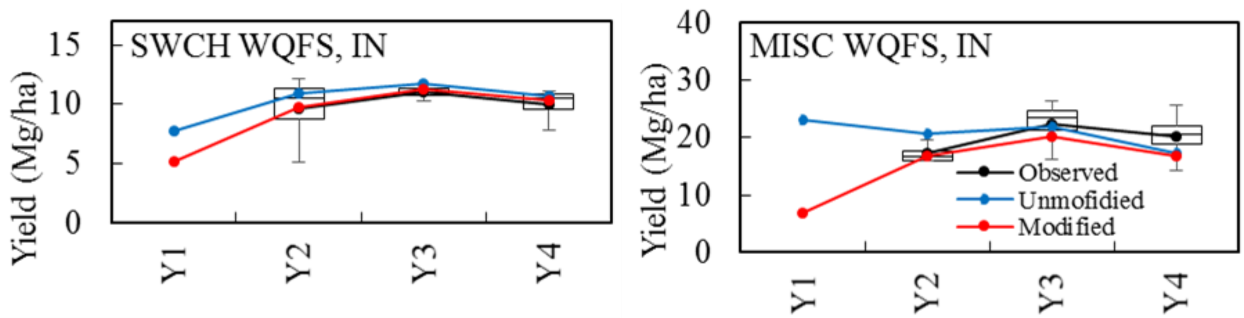

Figure 14 Simulated and observed yield for switchgrass and Miscanthus at Water Quality Field Station (WQFS), Indiana with the unmodified and modified (with improvement for simulation of establishment period). Boxplot represented measured yield for the two perennial grasses at WQFS.

- We have improved the vegetative filter strip representation in SWAT model. The model improvements were validated using paired watershed study from central Iowa (Table 3).

Table 3. Average annual comparison of measured from a paired prairie VFS study in central Iowa and three VFS representation scenarios for the 10% filter strip (edge of field) watersheds, only the measurement data period is considered. Area weighted average of the three study watersheds were considered for the dates of measured data availability. The improved model representation was able to estimate crop growth in filter strip area and effectively estimate filter strip efficiency.

	Field measured		SWAT simulation		
	Control no VFS watershed	VFS watersheds	No VFS	With VFS (Default)	With VFS (Improved)
Runoff (mm)	177.2	69.6	149.9	149.9	89.2
Sediment (Mg/ha)	6.3	0.4	5.4	2.0	0.6
TN (kg/ha)	28.4	3.3	16.5	8.3	4.6
TP (kg/ha)	7.8	0.8	4.4	1.9	0.8
NO3 (kg/ha)	2.7	0.8	3.0	1.5	1.0

- Since watershed-scale biofuel scenarios quantify the trade-offs in food and fuel production and water quality for perennial biofuels crops relative to traditional cash crops, such as corn, we realized early on in the project that it was essential that the simulated response of both the cash crops and the biofuels crops under adverse climate conditions be well represented. In order to investigate the sensitivity of the SWAT corn growth algorithms to climate variability, in particular soil moisture stress, the SWAT model was first calibrated to observed soil moisture profiles at USDA SCAN sites across the Midwest USA. The calibrated model was then used to extend the observational records for 70 years (1941-2010) to compare simulated soil moisture stress with observed county yields.

  As a result of this work, stress parameters were introduced to the SWAT model to regulate model performance in representing both mean yield and interannual yield variability. The following key findings of this task have also been published in "Agricultural and Forest Meteorology" (Wang et al., 2016):
  - Observed corn yield is inversely correlated with drought stress during reproductive stages.
  - The impact of aeration stress on observed yield was not detected at the county scale, potentially due to the small spatial scale of aeration stress; and
  - Drought stress explains the majority of yield reduction across all return periods.

- Landsat TM images and Cropland Data Layer (CDL) images for multiple years (2000-2010) were used to develop a generalized corn growth curve based on NDVI reflecting corn growth dynamics under normal conditions for the St. Joseph River watershed which can be used to calibrate corn growth rather than just final grain yield in the model.

  Crop responses to stress are reflected by the departure of an individual Landsat scene's NDVI from the normal growth curve. The relationship between grain yield, stress and NDVI residual at different growth stages was investigated, and this paper is currently under review in the journal "Remote Sensing". Key findings include:

  - Seasonal NDVI shows the greatest spatial variance at the leaf development and senescence periods.
  - Corn yield is significantly related to the NDVI residuals in the early growing period.
  - Dry weather tends to result in crop growth below normal conditions, while under the conditions observed higher than normal rainfall reduces the risk of yield loss;
  - The fraction of corn pixels below normal growth condition is significantly correlated with water stress.

- We have evaluated and improved the ability of SWAT to simulate tile-drained agricultural fields in Midwestern watersheds. We have obtained tile drainage and watershed outlet flow and water quality data for several small watersheds from researchers at USDA Agricultural Research Service. The required spatial data have been acquired and the SWAT model is set up, which will allow us to determine the appropriate parameters to use with the Hooghoudt-Kirkham drainage routines. These more detailed drainage algorithms have been recently implemented in the SWAT code but guidance on parameterization is lacking. We are conducting evaluations of model predictions, specifically the tile drainage outputs based on various drainage-related parameter options, to determine appropriate parameters for Midwestern tile-drained watersheds.

- An important and informative component of fish Index of Biotic Integrity (IBIs) is the presence of sensitive (i.e., intolerant of degraded environmental conditions) species within a sampled community. Such species are typically highly sensitive to human disturbance and tend to be useful for detecting biotic responses to degraded environmental conditions. We used sensitive fish species richness (SSR) as a simple, yet informative, indicator of stream segment biointegrity. We also calculated rarity weighted fish species richness index (RWR) as a simple measure of biodiversity importance (Williams et al. 1996). We compiled fish community data from the Ohio Environmental Protection Agency (OEPA), all fish were identified to species and classified as sensitive to habitat degradation according to Angermeirer and Karr (1986), Lyons et al. (1996), and the OEPA (2013) to calculate SSR at a site. We compiled water quality data from the OEPA STORET sampling. Median TN ranged from 0.3 to 15.005 mg/L, TP from 0.01 to 0.72 mg/L, and TSS from 5 to 169 mg/L. We linked fish and water quality data using their latitude, longitude, and sampling year, such that each water quality sample and fish sample came from the same site and same year. This resulted in 526 samples from 508 unique sites. We spatially linked data to the NHDPlus hydrologic framework (http://www.horizon-systems.com/nhdplus/), from which we extracted the average discharge (ft^3/s). We modeled stressor-response relationships using quantile regression. This method is useful for modeling the heterogeneous variance that is often encountered in biological responses and for identifying limiting relationships between stressors and responses (Cade and Noon 2003). We modeled the 95^{th} quantile; thus, it is important to note that our predictions do not represent the actual expected condition at a stream segment. Rather, our models represent the ***potential*** biological condition given the stream conditions. As an example, Figure 15 illustrates this relationship for SSR and TN.
  Model selection: We developed models consisting of all possible additive combinations of TN, TP, TSS, and log transformed discharge. Discharge was included because stream size is an important determinant of fish community structure. We developed a candidate set of models by keeping models within four AIC units of the model with the lowest AIC score. We also removed models within two units of our best model that only included one extra parameter to remove the influence of uninformative parameters (Burnham and Anderson 2002). The model-average coefficients can be used to make predictions (Table 4 and Table 5), although it is important to remember that model outputs are on the logit scale and must be transformed as described above to yield data that reflect the original scale.

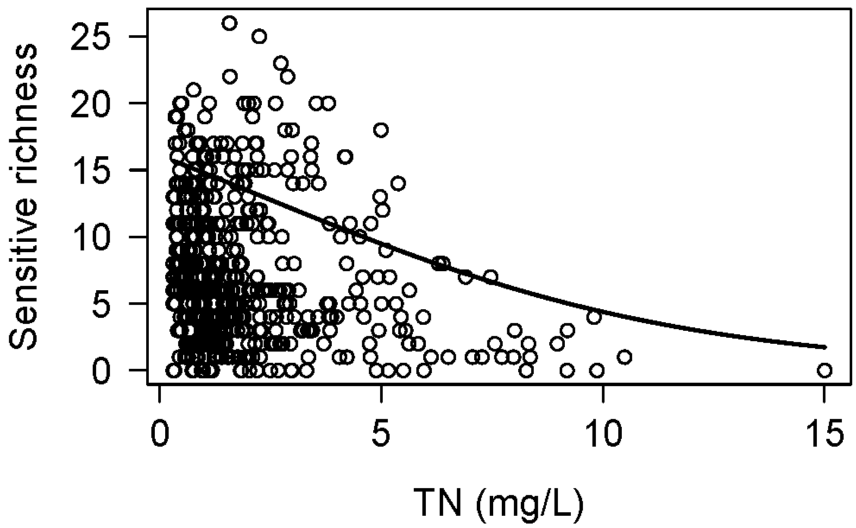

Figure 15 Relationship between sensitive species richness and total nitrogen (TN) relative to the average value of TP, TSS, and discharge. The circles represent observed data and the line is the modeled relationship from a quantile regression of the 95th quantile.

Table 4 Quantile regression results for the sensitive species richness.

Sensitive species richness								
Model	**Intercept**	**log (discharge)**	**TN**	**TP**	**TSS**	**df**	**AIC$_c$**	**Δ AIC$_c$**
1	-1.816	0.678	-0.178	-	-0.002	4.000	1977.472	0.000
2	-1.642	0.623	-0.195	-	-	3.000	1978.653	1.181
3	-1.616	0.611	-0.219	0.880	-	4.000	1979.990	2.518
Model averaged	**-1.733**	**0.651**	**-0.189**	**0.136**	**-0.001**			

Table 5 Quantile regression results for the rarity weighted species richness.

Rarity weighted richness								
Model	**Intercept**	**log (discharge)**	**TN**	**TP**	**TSS**	**df**	**AIC$_c$**	**Δ AIC$_c$**
1	-1.748	0.416	-0.158	0.315	NA	4.000	1675.777	0.000
2	-1.757	0.419	-0.146	NA	NA	3.000	1675.880	0.103
3	-1.759	0.419	-0.145	NA	-0.00005	4.000	1677.863	2.086
Model averaged	**-1.753**	**0.418**	**-0.151**	**0.137**	**-0.00001**			

Thus, the actual models for making predictions are:

$$logit\ (SSR_i) = \beta_0 + B_1 * \ln(Q_i + 1) + \beta_2 * TN_i + \beta_3 * TP_i + \beta_4 * TSS_i$$

and

$$logit\ (RWR_i) = \beta_0 + B_1 * \ln(Q_i + 1) + \beta_2 * TN_i + \beta_3 * TP_i + \beta_4 * TSS_i$$

where SSR_i is the sensitive richness for site i on the logit scale, β0 is the model averaged intercept estimate from Table 4, β1 is the coefficient estimate for discharge from Table 4, log (Qi) is the log transformed discharge (ft3/s) for site i, β2 is the model average coefficient estimate from Table 4, TNi is the TN (mg/L) from site i, β3 is the model average coefficient for TP from Table 1, TPi is the TP (mg/L) for site i, β4 is the model average coefficient estimate for TSS, and TSSi is the suspended sediment (mg/L) for site i. Similarly, RWR_i is the rarity weighed richness for site i, and the coefficient estimates are derived from Table 5.

Task B: Use the improved model to evaluate the environmental and economic sustainability of likely energy crop scenarios on a watershed scale, including sensitivity to climate variability

1. **Tasks performed to complete this objective**:

   B.1. Parameterize, calibrate, and validate the SWAT model for the watersheds

   B.2. Run the calibrated model with future climate scenarios to establish baseline

   B.3. Develop scenarios that represent plausible watershed landscape alternatives, based on scientific assessment and stakeholder input

   B.4. Determine the sustainability of energy crop scenarios through comparison of the baseline to the experimental scenarios

2. **Accomplishments**:

- We develop SWAT model for two watersheds (1) St Joseph River watershed located in Indiana, Michigan, and Ohio; and (2) Wildcat Creek watershed, located in Indiana (Figure 16). Detailed discussion of model development, input data used, and calibration and validation is provided in Cibin *et al.* (2015).

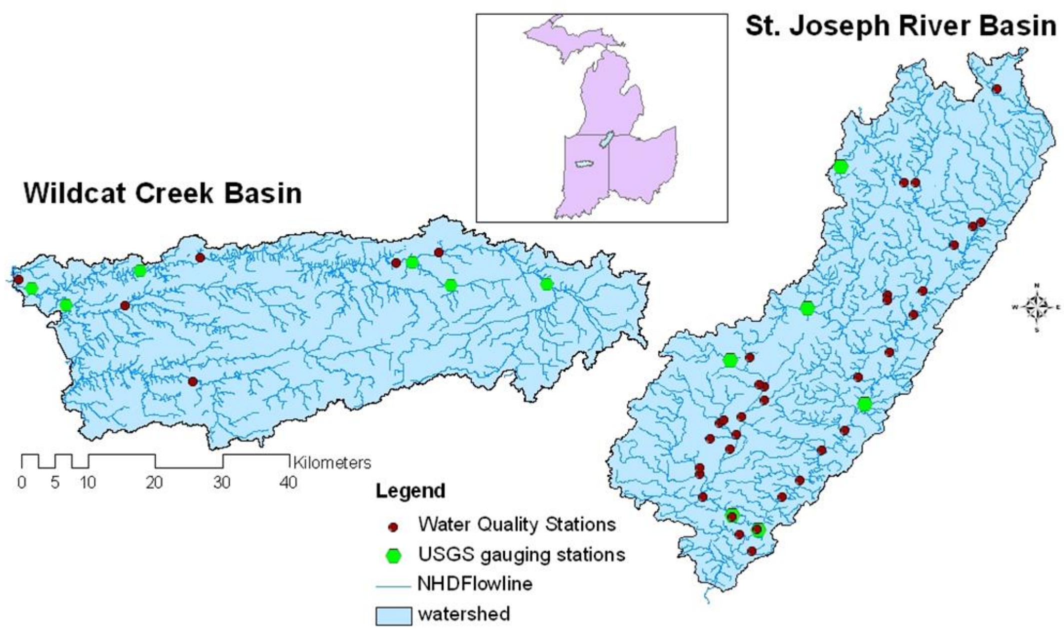

Figure 16. Location map of Wildcat Creek watershed and St Joseph River watershed.

- Model was calibrated and validated for crop growth, stream flow and water quality. The calibration validation statistics and time series plots are provided in Table 6 and Figure 17-Figure 18.

Table 6 Daily and monthly calibration and validation statistics for stream flow in Wildcat Creek watershed and St Joseph River watershed

Station	Station ID	Drainage area (km^2)	Calibration statistics				Validation statistics			
			Daily		Monthly		Daily		Monthly	
			R^2	NS	R^2	NS	R^2	NS	R^2	NS
Wildcat Creek watershed										
Wildcat near Kokomo	3333700	614	0.70	0.70	0.89	0.88	0.67	0.67	0.96	0.95
Wildcat near Owasco	3334000	1009	0.79	0.79	0.92	0.91	0.75	0.73	0.90	0.87
Southfork Creek Lafayette	3334500	642	0.75	0.74	0.91	0.90	0.71	0.66	0.87	0.78
Wildcat near Lafayette	3335000	2045	0.83	0.82	0.90	0.90	0.80	0.79	0.90	0.88
St. Joseph River watershed										
Cedar Creek near Cedarville	4180000	715	0.69	0.68	0.72	0.70	0.77	0.75	0.81	0.76
St. Joseph river near Fort Wayne	4180500	2715	0.72	0.72	0.80	0.80	0.79	0.79	0.91	0.89

R^2: Coefficient of determination
NS: Nash-Sutcliffe efficiency

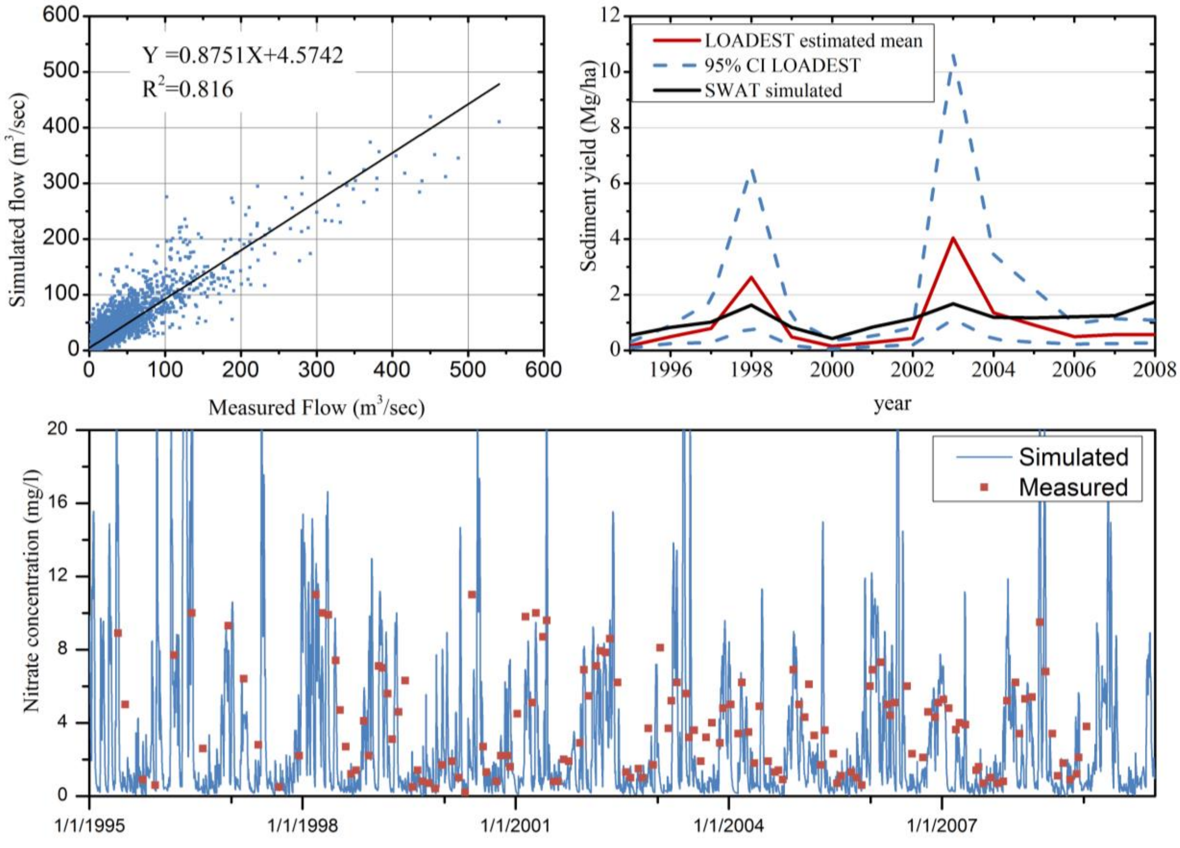

Figure 17. Calibration validation figures for Wildcat Creek watershed. (A-Top left) Scatter plot of observed and simulated daily stream flow. (B-Top right) Time series plot of SWAT simulated, LOADEST estimated mean and 95% confidence interval annual sediment yield (1995-2008), (C-Bottom) time series plot of SWAT simulated and measured for Nitrate for the simulation period (1995-2009).

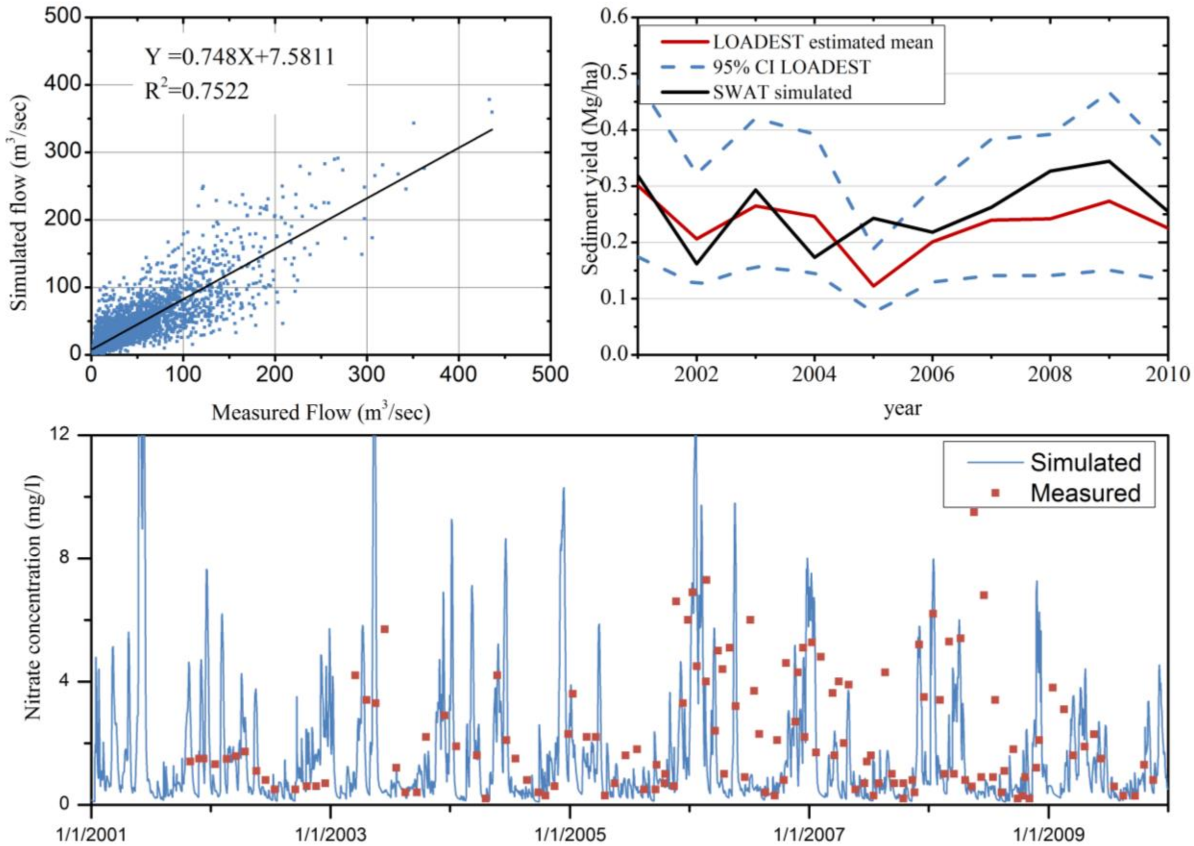

Figure 18. Calibration validation figures for St. Joseph River watershed. (A-Top left) Scatter plot of observed and simulated daily stream flow. (B-Top right) Time series plot of SWAT simulated, LOADEST estimated mean and 95% confidence interval annual sediment yield (1995-2008), (C-Bottom) time series plot of SWAT simulated and measured for Nitrate for the simulation period (1995-2009).

- As an additional experiment, following traditional calibration of the SWAT model in the St Joseph River watershed based on stream discharge and water quality performance, the AMALGAM multi-objective optimization algorithm was applied to constrain model performance in daily streamflow, seasonal corn LAI development (using the generalized corn growth curve developed in Task A.4), and annual crop yield. Key findings include:
    - After multi-objective calibration, the simulated timing and magnitude of corn LAI are better represented,
    - The model is also able to capture mean annual yield, interannual yield variation, and daily streamflow, and
    - Soil moisture dynamics show reasonable seasonal patterns after multi-objective calibration.

  Key findings for this accomplishment have been summarized in a presentation (Wang et al., 2015) at the 2015 International SWAT Conference.

- We develop sustainability indicators to study the environmental and economic sustainability of bioenergy scenarios (Table 7). These indicators were based on recommendations made by McBride et al., 2011; applicability of indicators in the Midwestern watersheds, and ease of data collection to quantify these indicators.

Table 7. Sustainability indicators developed to study the environmental and economic sustainability of bioenergy scenarios

Category	Indicator	Units	Indicator for
Soil erosion and its impact on long-term productivity	Erosion	Mg/ha/year	Soil loss
	Total nitrogen	Kg-N/ha	Soil productivity
	Extractable Phosphorus	Kg-P/ha	Soil productivity
Water Quantity	Annual maxima	m^3/sec	High flow
	Runoff index	-	Stream flow
	Richards-Baker Flashiness Index	-	Variability
	7 day average low flow for year	m^3/sec	Low flow
	Water Stress Index (WSI)		Water use
Water Quality	Sediment load or sediment concentration	Mg/ha/year or mg/L	Suspended sediment
	Nitrate and total nitrogen	Kg-N/ha	Nitrogen loading
	Organic phosphorus and total phosphorus	Kg-P/ha	Phosphorus loading
Biomass and crop production	Total biomass and harvested yield	t/ha	crop production
Profitability	Break-even feedstock price	$	
Aquatic Biodiversity	Sensitive fish species richness (SSR) rarity weighted fish species richness index (RWR)		biodiversity

- SWAT simulations were conducted using CMIP3 future climate projections for the PCM, GFDL and HadCM3 global climate models using three future climate scenario: A2, A1B, and B1. Climate data were down-scaled and bias corrected to support regional hydrologic and crop growth simulations. Monthly GCM climate forcings (air temperature and precipitation) were also disaggregated to daily values for use in driving the SWAT model. Future climate datasets were developed by Sinha and Cherkauer (2010), and have been used to assess climate change impacts on streamflow (Cherkauer and Sinha, 2010), and drought impacts on crop yields (Mishra et al., 2010). For simulations conducted for this project, SWAT was modified to take dynamic CO_2 concentration (daily scale) as model input. Coupled with the model enhancements related to crop growth and stress responses this version of SWAT is considered best for evaluating the impacts of climate change on crop growth.

  The model was applied in the St. Joseph River watershed to investigate climate change and CO_2 enhancement impacts. This involved the design of simulation modeling experiments at different future periods using downscaled and bias-corrected CMIP3 precipitation and temperature, and CO_2 concentration data. The simulation experiment was used to investigate biophysical and hydrological effects of future climate change including trends in CO2 concentrations. Key findings include:

- More interannual variability is expected for both aeration and drought stress in two future periods (2021-2050, 2061-2090), when compared with baseline period (1981-2010)
- Decreased temperature stress in early spring cannot compensate for summer heat effects on future yield reduction.
- There is no significant crop yield risk reduction due to CO_2 enhancement.
- Precipitation and temperature change is still the main driver to affect streamflow at all probability of exceedance.
- The impacts of CO_2 enhancement on streamflow is only visible for very high flow conditions.

Key findings for this accomplishment have been summarized in Wang et al., 20XX (in review).

- Hydrology and water quality sustainability indices for baseline scenario with future climate data (90 year) and calibrated SWAT model were quantified for the Wildcat Creek watershed and St. Joseph River watershed to establish baseline. The GCM projected data from 9 model simulations; three models (GFDL CM2.0.1, UKMO HadCM3 3.1 and NCAR PCM 1.3) for each of three future emission scenarios (A1B, A2, and B1), for three thirty year period 1960-1989 (Past), 1990-2019 (Present), and 2020-2049 (Future) were evaluated. Table 8 shows the baseline sustainability metrics for Wildcat Creek watershed.

Table 8. Sustainability indicators of the baseline scenario for Wildcat Creek Watershed with GCM data for three 30-year simulations; average values from 9 GCM model simulations are provided.

	Unit	**1960-1989**	**1990-2019**	**2020-2049**
Erosion	Mg/ha	1.91	2.13	2.23
Final Org N (Init=13140)	kg/ha	12052	11345	10684
Final Nitrate (Init=64)	kg/ha	80	100	116
Final Org P (Init=1610)	kg/ha	1458	1363	1275
Final Min P (Init=287)	kg/ha	643	912	1187
Avg of Annual Peak flow	m^3/sec	185	201	198
Days over threshold	Days >300 m3/sec	3.9	6.6	8.3
Runoff Index	-	0.537	0.519	0.516
R-B Index	-	0.215	0.208	0.208
7day Avg low flow	-	0.039	0.095	0.11
Water Stress index	-	0.594	0.573	0.585
Sediment load (outlet)	Mg/ha	0.83	0.94	0.98
Nitrate load (outlet)	kg/ha	12.5	14.6	14.9
TN load (outlet)	kg/ha	18.9	21.0	20.9
Org P load (outlet)	kg/ha	1.1	1.4	1.5
TP load (outlet)	kg/ha	1.4	1.7	1.9

- Scenario analysis principles were used to determine key variables, which were (1) the extent to which corn and soybean continue to be maximized vs. a focus on protecting water quality and the environment, and (2) whether bioenergy refineries continue to be large and centralized, necessitating a high percentage of land conversion vs a shift to smaller refineries that could accommodate low percentage of crops (Figure 19). Single crop scenarios that consider planting the entire watershed (all agricultural area) in each candidate feedstock were also included because these will serve as inputs to watershed optimization, and to consider uniform adoption of low rates of stover removal from continuous corn, consistent with contracts that are emerging between farmers and cellulosic biorefineries coming online in the near future. Based on these concepts the project evaluated the following scenarios:
    - Perennial energy crops on marginal lands
    - Corn stover removal– 20%, 30% and 50%, with and without nutrient replacement
    - Perennial bioenergy crops in buffers around corn/soybean areas with different buffer to source area ratios
    - Bioenergy crops in all agricultural areas (100% bioenergy crops in existing agricultural fields)
    - Bioenergy crops in 50% of agricultural area. One scenario with random 50% of agricultural area (will run multiple sampling and report mean of simulations) and one scenario with 50% of agricultural area selected with plausibility criteria of marginal land, high slope area, pasture area, crop productivity, etc.

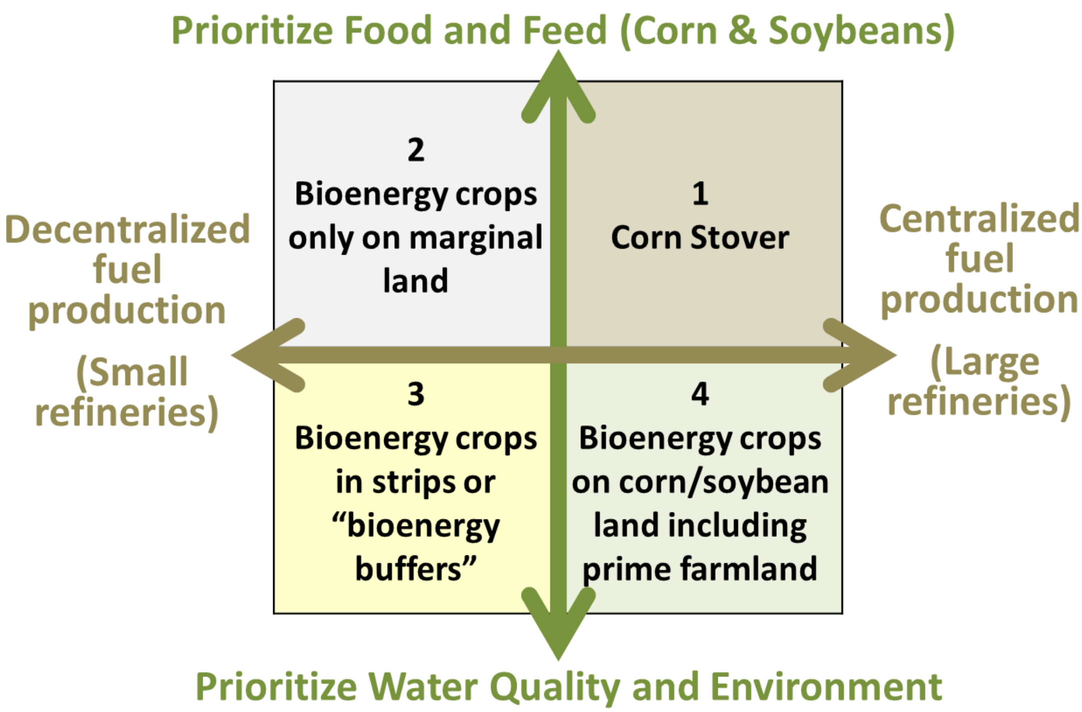

Figure 19 Bioenergy scenario development principle.

- Environmental impacts of 21 bioenergy crop production scenarios were evaluated with measured and projected climate data for both Wildcat Creek and St Joseph River watersheds. The results (Figure 20-Figure 22) showed that

    - Average stream flow, annual peak flow and number of days over threshold reduced with all bioenergy scenarios

    - Energy crop scenarios in general improved water quality with the exceptions of stover removal that increased sediment load at watershed outlet

    - Average annual impacts on hydrology, water quality and sustainability indices with climate change data would be similar to current NCDC weather data

    - Water quality benefits due to land use change are generally greater than the effects of climate change and variability

    - Comparison of scenarios with randomly selected and strategically selected planting area emphasize the opportunity of maximizing bioenergy crop benefits by optimum landscape planning.

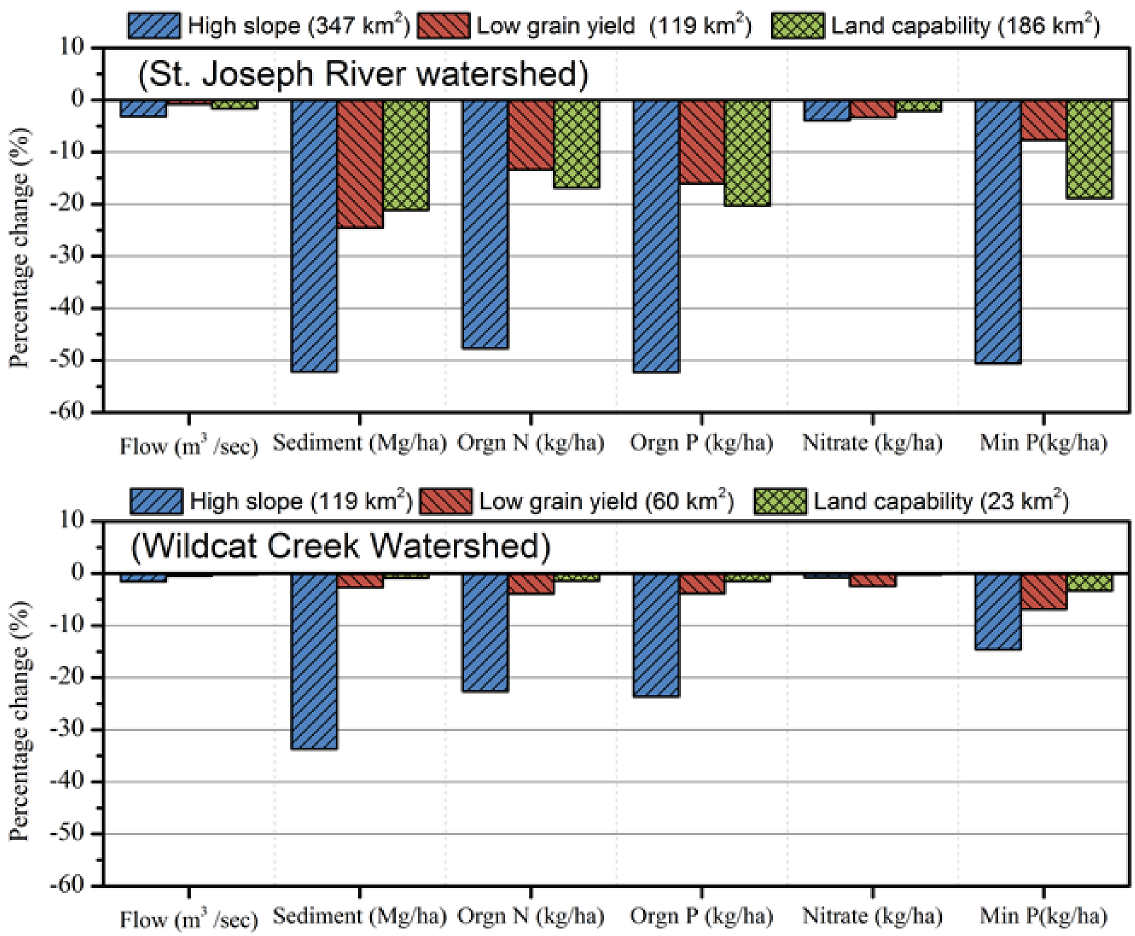

Figure 20. Average annual impact of growing Miscanthus in marginal lands at St Joseph (Top) and Wildcat Creek (Bottom) watersheds. Three Marginal land scenarios were analyzed: environmental (slope>2%), agricultural (corn grain yield <90%ile), and land quality (SSURGO LCC>2).

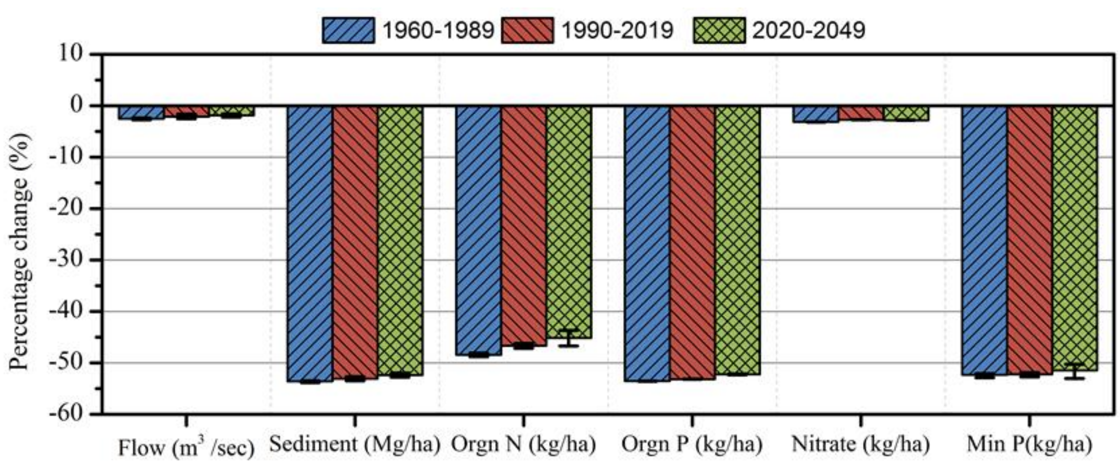

Figure 21. Impact of biofuel scenario (Miscanthus in high slope marginal lands at St. Joseph River watershed) with GCM climate data for three periods: 1960-1989 (Past), 1990-2019 (Present), 2020-2049 (Future). The bars indicate mean percentage change from 9 GCMs and error bars indicates min and max of 9 GCMs.

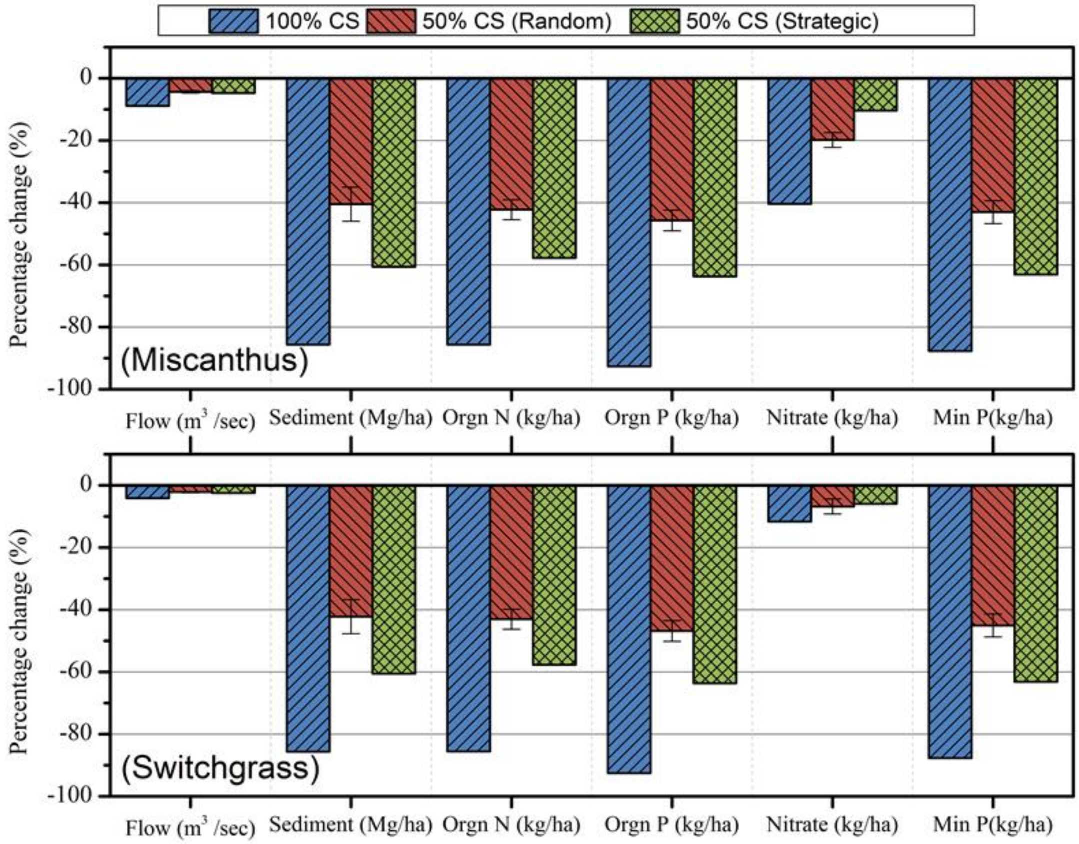

Figure 22. Average annual impacts of growing energy crops in all corn/soybean areas (Blue), randomly selected 50% corn/soybean areas (red) and strategically selected (50%corn/soybean areas) based on area slope at St Joseph River watershed outlet. Error bar for random selection scenario indicates the range of ensemble simulations from100 samples.

- Potential contribution of the marginal lands to produce bioenergy crops and associated hydrologic/water quality impacts was completed using APEX model. Marginal lands of the region (Figure 23) was identified using the land capability classes and land proximity to streams. A manuscript describing results is published in Environmental modelling and software (Feng *et al*., 2015).

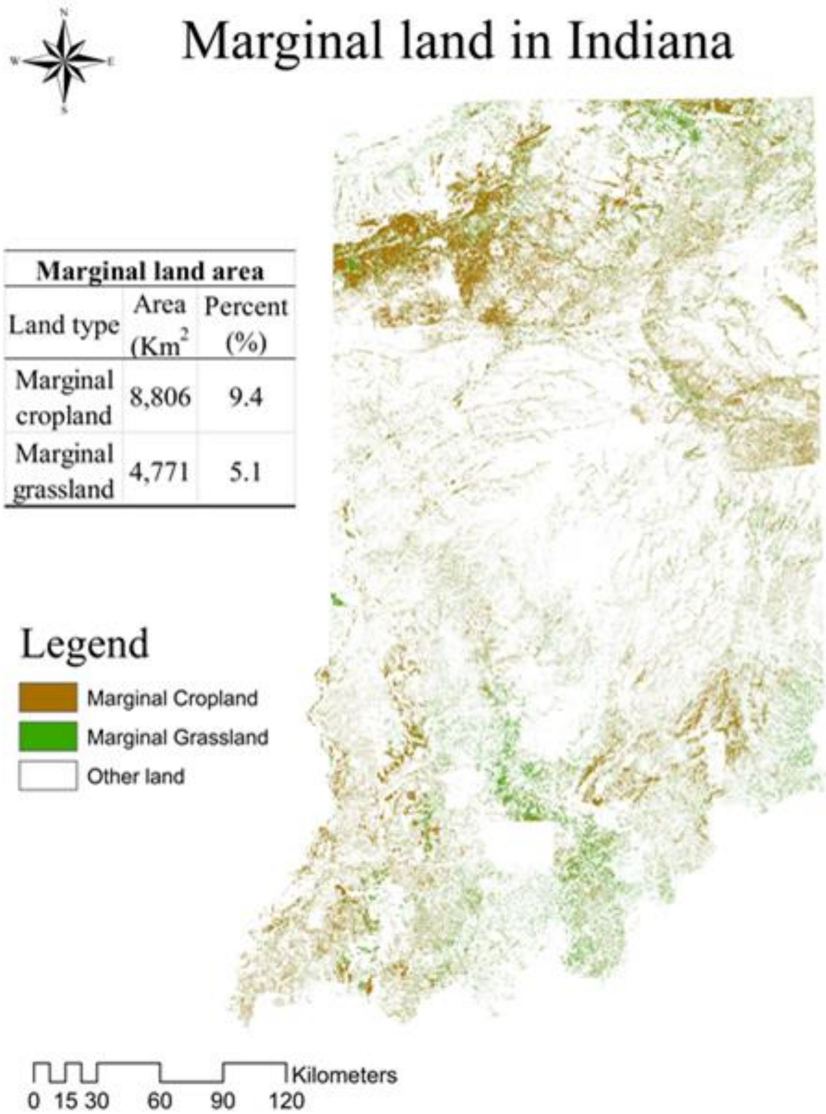

Figure 23 Marginal land map of Indiana. Marginal lands were identified using method discussed in (Feng et al., 2015)

- Marginal land suitability for growth of perennial biofeedstocks is estimated using fuzzy logic based framework for Upper Mississippi River Basin (Feng *et al*., 20XX, in review). Results indicates not all marginal lands are suitable for growing perennial biofeedstocks, 40% of the identified marginal lands in the Upper Mississippi River Basin has poor (LSI 0 to 30) to moderately poor (LSI 30 to 60) suitability for growth of three targeted biofeedstocks (Figure 24).

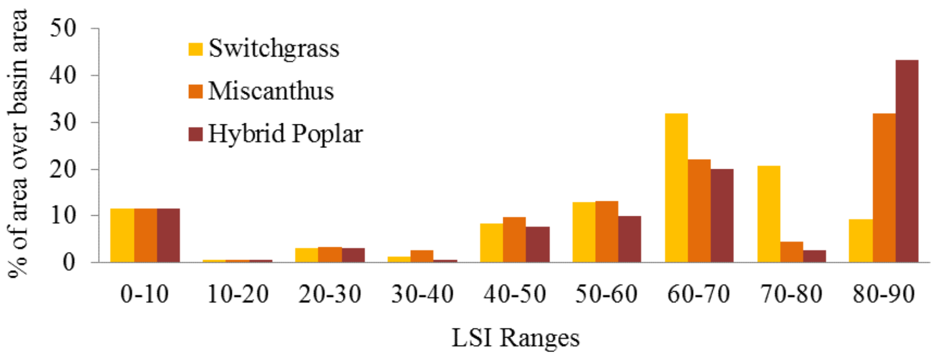

Figure 24 Histogram of areas for each range of Land Suitability Index (LSI) for marginal lands in the Upper Mississippi River Basin (UMRB). The higher the LSI value is, the more marginal land is suitable for growth of these biofeedstocks.

- The effects of landscape scenarios on sustainability metrics were quantified using climate change data for both Wildcat Creek and St. Joseph River basins. Sustainability metrics from bioenergy crop scenarios were compared with a best and worst case scenario (Figure 25). The simulated native prairie landscape is considered as best case scenario and heavily fertilized and tilled corn/soybean rotation is considered as worst case scenario. The comparison indicates bioenergy scenarios sustainability indicators are closer to the native prairie scenario.

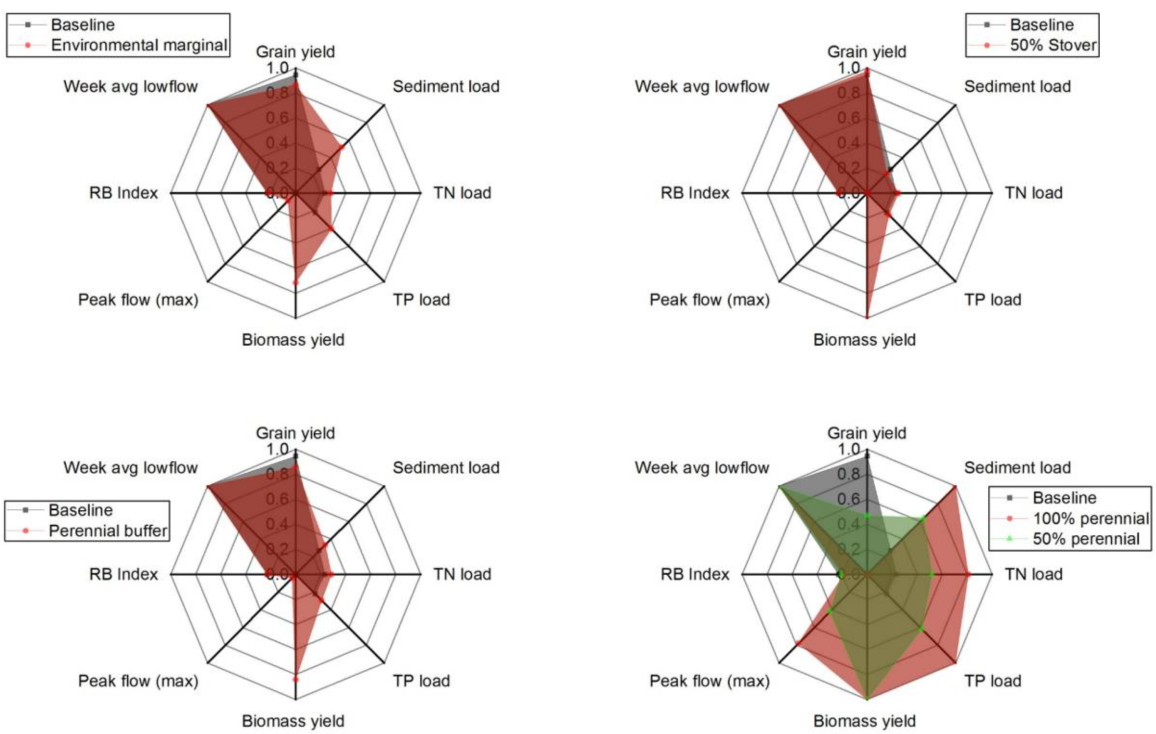

Figure 25. Sustainability indicator comparison of bioenergy scenarios. The indicators are normalized with simulated indicators from native prairie landscape (Best case) and intensively managed corn/soybean (worst case). Value near one and above is good case and near zero and below represents worst case. RB index in figure is not normalized as it is already an index value. Bioenergy scenarios in general is improved sustainability indicators compared to baseline.

- Ecosystem services of futuristic bioenergy based land use change were evaluated with measured weather data (Figure 26) and climate change GCM data (Figure 27). The results indicate the ecosystem services improved with bioenergy crops growing in the watershed. Similar to environmental impact analysis the impacts of land use change on ecosystem services was more dominant than the climate change impacts.

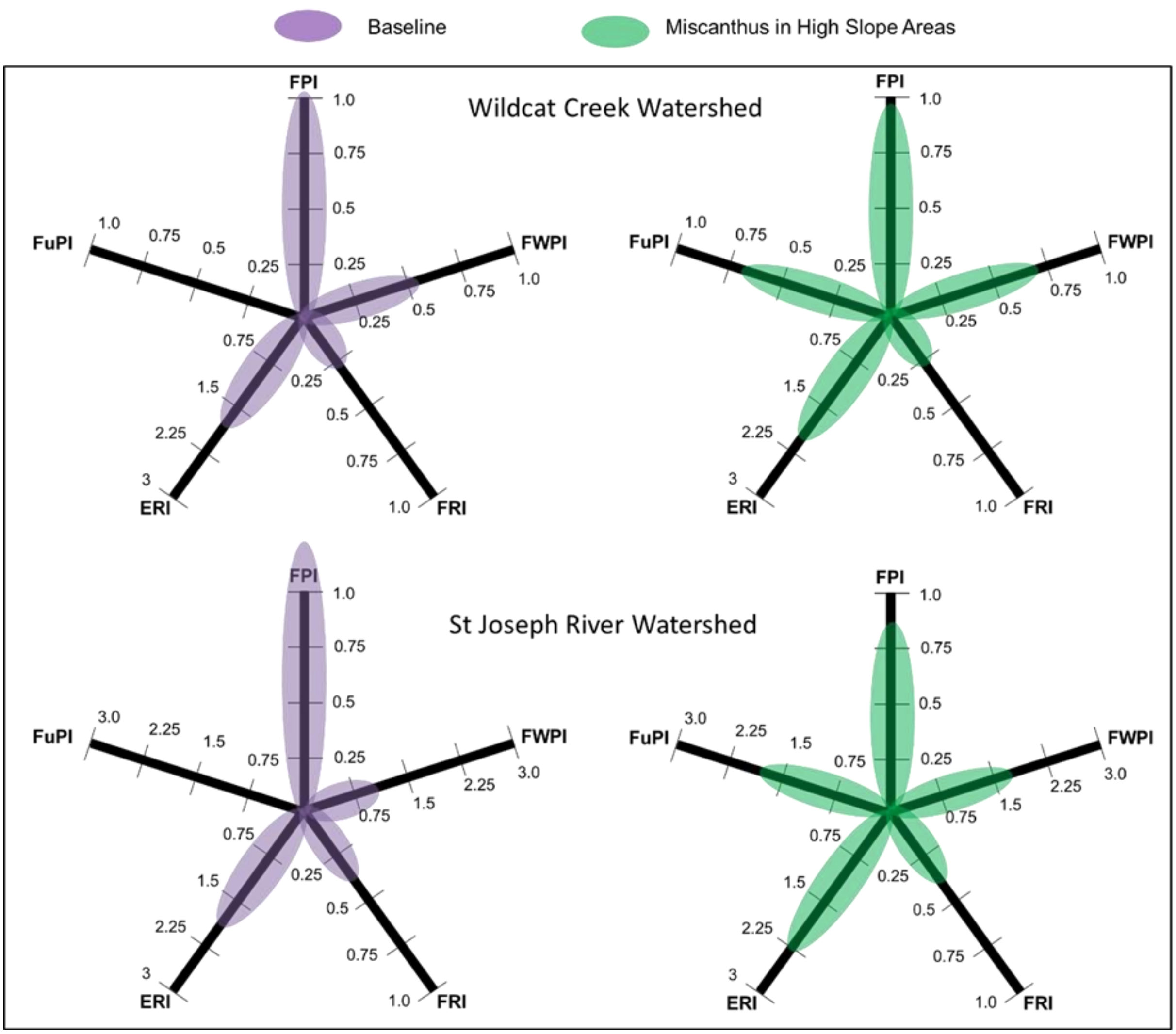

Figure 26. Ecosystem services for base line and Miscanthus in high slope (>2% slope) areas in Wildcat Creek watershed (top) and St Joseph River watershed (bottom). Five ecosystem services were evaluated Fresh water provision (FWPI), food (FPI) and fuel provision (FuPI), erosion regulation (ERI), and flood regulation (FRI).

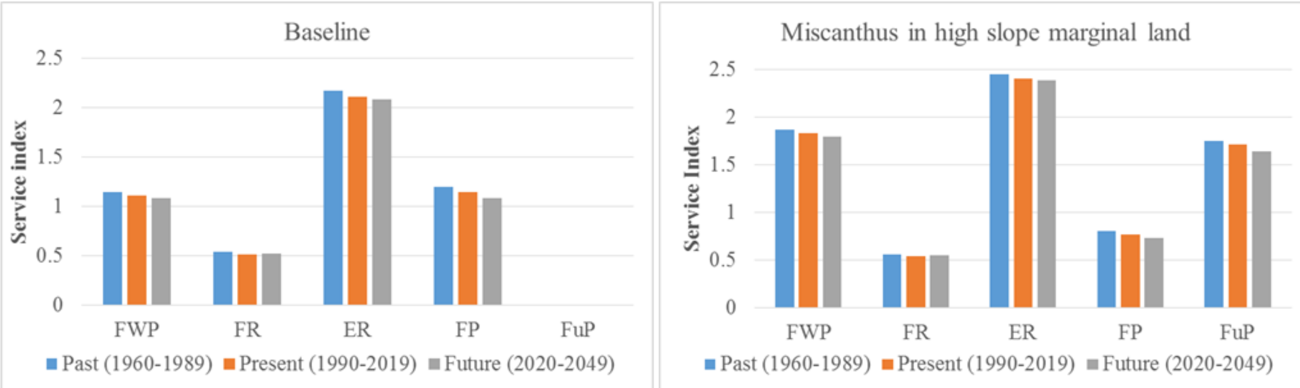

Figure 27 Ecosystem services evaluation with future climate change scenarios. The difference between bars indicate impact of climate change and difference in index between the two figures indicate the impact of bioenergy based landuse change

- Values for fish SSR and RWR were predicted for baseline (i.e., predominantly corn/soybean, C/S) and 25 biofuel cropping scenarios evaluated using the improved SWAT model. Two-way analysis of variance (ANOVA) was used to determine whether predicted values of fish SSR and RWR were different among the scenarios, including baseline conditions. The two factors were biofuel cropping scenario and watershed size as indicated in Figure 28 and Figure 30. Where appropriate, post-hoc Scheffe tests were used to determine significance among scenarios. Tests were considered significant at $\alpha = 0.05$.

  As expected, predicted mean RWRs were significantly different among the sub-basin size classes and increased with increasing size class ($F=5219.5$, $p<0.001$, 4 df) (Figure 28). Predicted mean RWRs were also significantly different among scenarios ($F=29.3$, $p<0.001$, 25 df), and there was no interaction between the two main effects ($F=0.30$, $p>0.99$, 100 df). Post hoc Scheffe tests indicated that RWR means for the 100% C/S *Miscanthus* ($p<0.001$), 100% C/S switchgrass ($p<0.001$), and randomly selected 50% *Miscanthus* C/S replacement ($p=0.025$) scenarios were significantly higher than baseline (Figure 28). The same post hoc tests indicated that predicted mean baseline RWR values were statistically similar to all of the remaining 22 scenarios ($p>0.95$) and that means for these 22 scenarios were all significantly lower than the 100% C/S *Miscanthus* ($p<0.001$) and 100% C/S switchgrass ($p<0.001$) scenarios. Finally, mean RWRs for the randomly selected 50% *Miscanthus* C/S replacement scenario were statistically similar to the 100% C/S switchgrass scenario ($p=0.112$) but significantly lower than the 100% C/S *Miscanthus* ($p<0.001$) scenario. These results suggest that significant increases in RWR mediated by biofuel cropping of perennial grasses can only be achieved via drastic changes in land use from C/S to *Miscanthus* or switchgrass (Figure 28 and Figure 30).

- Similar to mean RWR, predicted mean fish SSR were significantly different among the sub-basin size classes and increased with increasing size class ($F=6350.8$, $p<0.001$, 4 df) (Figure 29). Predicted mean SSRs were also significantly different among scenarios ($F=51.32$, $p<0.001$, 25 df), and there was no interaction between the two main effects ($F=0.65$, $p>0.99$, 100 df). Post hoc Scheffe tests indicated that predicted SSR means for the 100% C/S *Miscanthus* ($p<0.001$), 100% C/S switchgrass ($p<0.001$), randomly selected 50% *Miscanthus* C/S replacement ($p<0.001$), randomly selected 50% switchgrass C/S replacement ($p<0.001$), strategically selected 50% *Miscanthus* C/S replacement ($p=0.001$), and strategically selected 50% switchgrass C/S replacement ($p<0.001$) scenarios were significantly higher than baseline (Figure 30). The same post hoc tests indicated that predicted mean baseline SSR values were statistically similar to all of the remaining 19 scenarios ($p>0.98$), means for these 19 scenarios were all significantly lower than the 100% C/S *Miscanthus* ($p<0.001$) and 100% C/S switchgrass ($p<0.001$) replacement scenarios, and means for the randomly selected 50% *Miscanthus* C/S, randomly selected 50% switchgrass C/S, strategically selected 50% *Miscanthus* C/S, and strategically selected 50% switchgrass C/S replacement scenarios were all significantly lower than the 100% C/S *Miscanthus* ($p<0.001$) and 100% C/S switchgrass ($p<0.001$) replacement scenarios. Finally, mean SSRs for the randomly and strategically selected 50% *Miscanthus* C/S and 50% switchgrass replacement scenarios were significantly higher than the remaining 19 scenarios with the following exceptions: placing *Miscanthus* or switchgrass in environmental marginal land and all marginal land were not significantly different from the randomly and strategically selected 50% *Miscanthus* C/S and 50% switchgrass replacement scenarios ($p>0.08$), and mean SSR values were statistically similar for the 50% corn stover removal, 50% corn stover removal in $<2\%$ slope C/S areas, 10% *Miscanthus* and switchgrass buffers, and strategically selected 50% *Miscanthus* C/S replacement scenarios ($p>0.075$). Like the results presented for RWR, it appears that significant increases in SSR mediated by biofuel cropping of perennial grasses can only be achieved via drastic changes in land use from C/S to *Miscanthus* or switchgrass (Figure 30 and Figure 31).

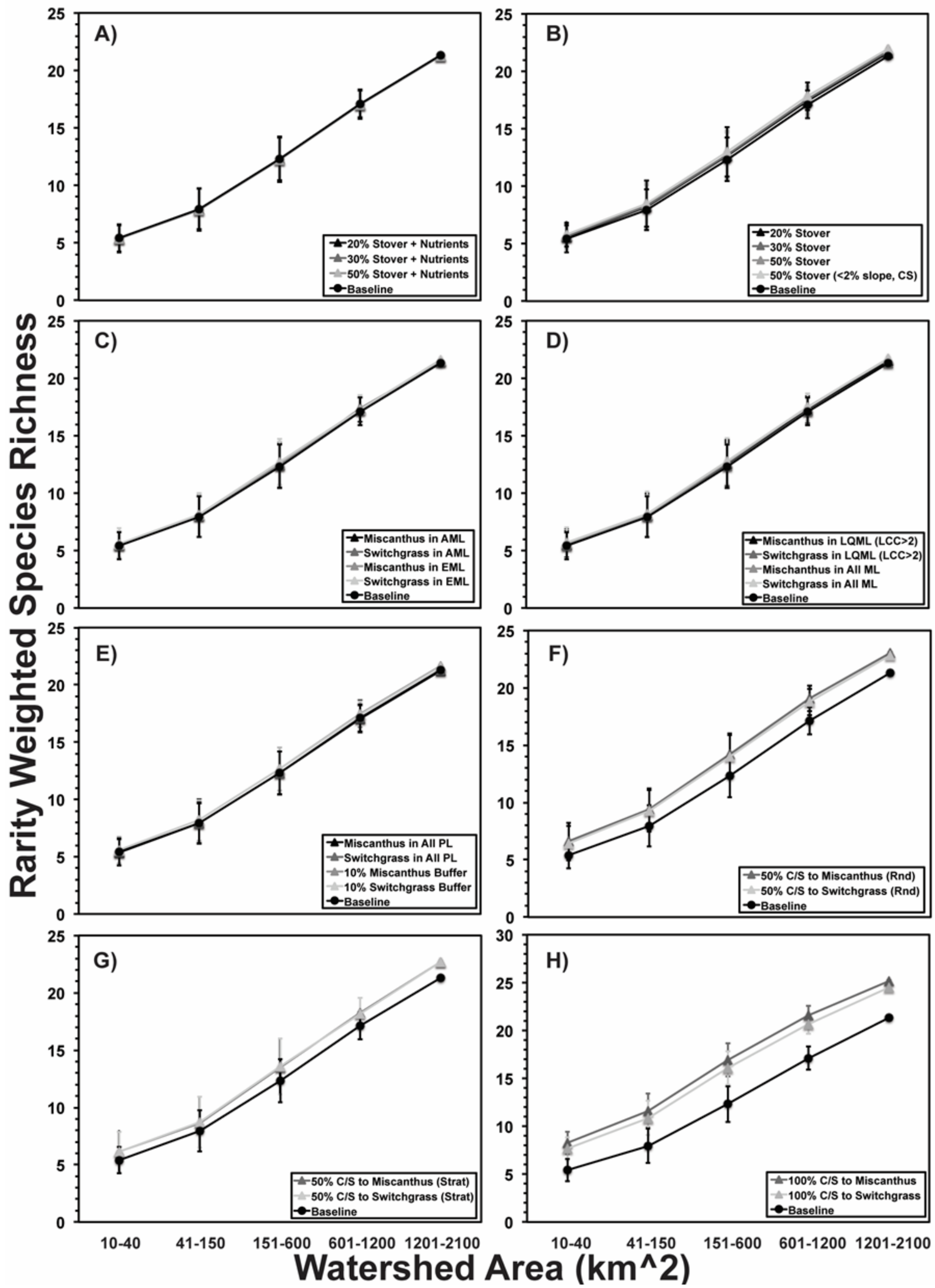

Figure 28 Mean (± 1 standard deviation) fish rarity weighted species richness index (RWR) values for Wildcat Creek watershed, Indiana, stream segments grouped according to watershed size. Values were predicted for baseline (i.e., predominantly corn/soybean, C/S) and 25 biofuel cropping scenarios evaluated using an improved SWAT model. The scenarios are indicated in the figure sublegends according to the following: percentage of corn stover removal A) with and B) without nutrient

replacement, and changing corresponding agricultural land use from baseline to Miscanthus × giganteus (Miscanthus) or upland ecotype Panicum virgatum L. (switchgrass) in C) agricultural marginal land (AML, >5%ile yield) and environmental marginal land (EML, >2% slope), D) land quality marginal lands (LQML, LCC>2) and all marginal lands (ML), E) all pasture lands (PL) and in 10% buffers around C/S, F) 50% of randomly selected baseline C/S, G) 50% of strategically selected baseline C/S, and H) 100% of baseline C/S. Predicted mean RWRs were significantly different among scenarios (ANOVA F=29.3, p<0.001, 25 df), and post hoc Scheffe tests indicated that RWR means for the 100% C/S Miscanthus (p<0.001), 100% C/S switchgrass (p<0.001), and randomly selected 50% Miscanthus C/S replacement (p=0.025) scenarios were significantly higher than baseline. The same post hoc tests indicated that predicted mean baseline RWR values were statistically similar to all of the remaining 22 scenarios (p>0.95) and that means for these 22 scenarios were all significantly lower than the 100% C/S Miscanthus (p<0.001) and 100% C/S switchgrass (p<0.001) scenarios. Finally, mean RWRs for the randomly selected 50% Miscanthus C/S replacement scenario were statistically similar to the 100% C/S switchgrass scenario (p=0.112) but significantly lower than the 100% C/S Miscanthus (p<0.001) scenario.

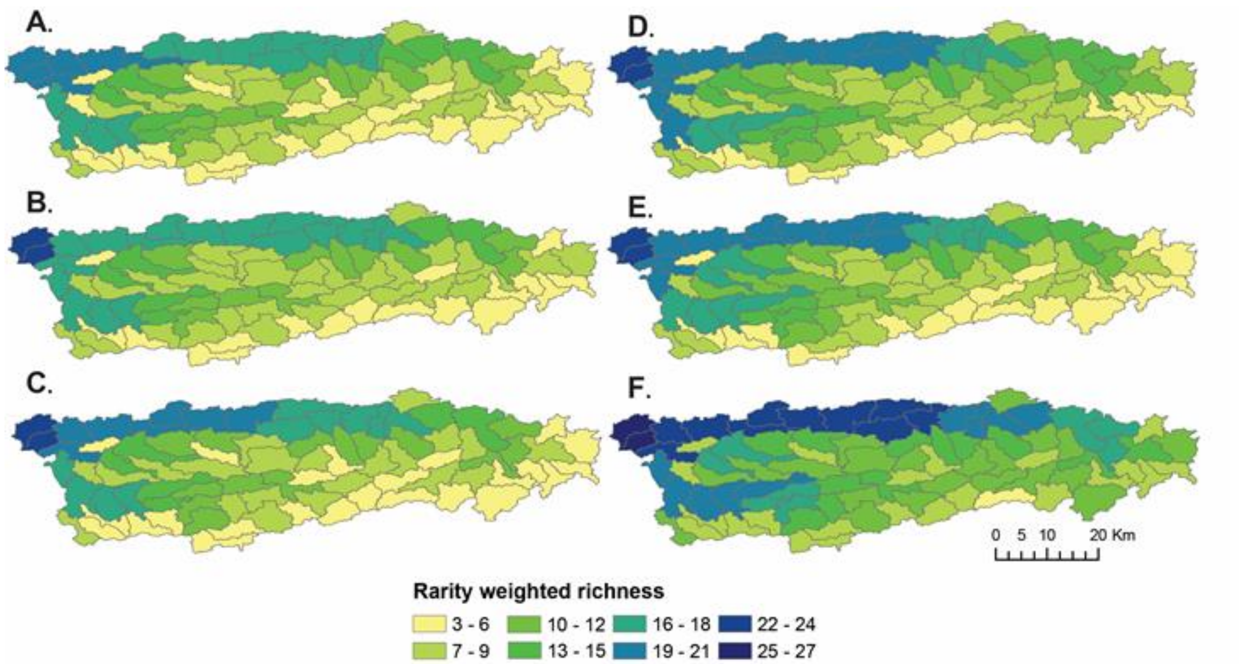

Figure 29 Predicted fish rarity weighted species richness index (RWR) values for Wildcat Creek watershed, Indiana, subwatersheds for six selected scenarios, including: A) baseline (i.e., predominantly corn/soybean, C/S), B) 50% corn stover removal with nutrient replacement, C) 10% Miscanthus × giganteus (Miscanthus) buffers around C/S, D) 50% replacement of randomly selected baseline C/S with Miscanthus, E) 50% replacement of strategically selected baseline C/S with Miscanthus, and H) 100% replacement of baseline C/S with Miscanthus. The selected scenarios are representative of subwatershed conditions for other scenarios according to the statistical results presented in Figure 28.

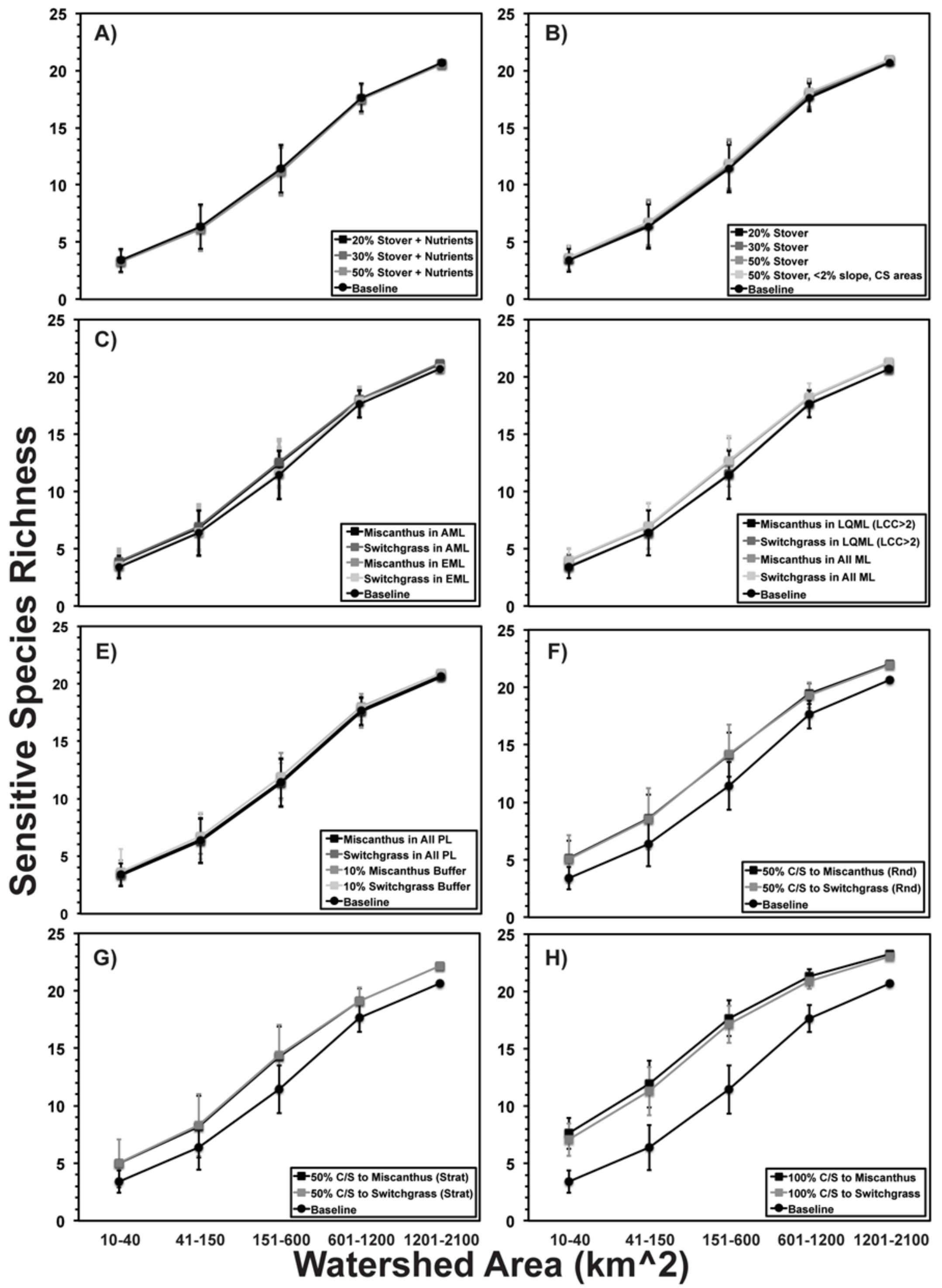

Figure 30 Mean (± 1 standard deviation) fish sensitive species richness (SSR, number of sensitive fish species) values for Wildcat Creek watershed, Indiana, stream segments grouped according to watershed size. Values were predicted for baseline (i.e., predominantly corn/soybean, C/S) and 25 biofuel cropping scenarios evaluated using an improved SWAT model. The scenarios are indicated in the figure sublegends according to the following: percentage of corn stover removal A) with and B) without nutrient replacement, and changing corresponding agricultural land use from baseline to Miscanthus × giganteus

(Miscanthus) or upland ecotype Panicum virgatum L. (switchgrass) in C) agricultural marginal land (AML, >5%ile yield) and environmental marginal land (EML, >2% slope), D) land quality marginal lands (LQML, LCC>2) and all marginal lands (ML), E) all pasture lands (PL) and in 10% buffers around C/S, F) 50% of randomly selected baseline C/S, G) 50% of strategically selected baseline C/S, and H) 100% of baseline C/S. Predicted mean SSRs were significantly different among scenarios (ANOVA F=51.32, p<0.001, 25 df), and post hoc Scheffe tests indicated that SSR means for the 100% C/S Miscanthus (p<0.001), 100% C/S switchgrass (p<0.001), randomly selected 50% Miscanthus C/S replacement (p<0.001), randomly selected 50% switchgrass C/S replacement (p<0.001), strategically selected 50% Miscanthus C/S replacement (p=0.001), and strategically selected 50% switchgrass C/S replacement (p<0.001) scenarios were significantly higher than baseline. The same post hoc tests indicated that predicted mean baseline SSR values were statistically similar to all of the remaining 19 scenarios (p>0.98), means for these 19 scenarios were all significantly lower than the 100% C/S Miscanthus (p<0.001) and 100% C/S switchgrass (p<0.001) replacement scenarios, and means for the randomly selected 50% Miscanthus C/S, randomly selected 50% switchgrass C/S, strategically selected 50% Miscanthus C/S, and strategically selected 50% switchgrass C/S replacement scenarios were all significantly lower than the 100% C/S Miscanthus (p<0.001) and 100% C/S switchgrass (p<0.001) replacement scenarios. Finally, mean SSRs for the randomly and strategically selected 50% Miscanthus C/S and 50% switchgrass replacement scenarios were significantly higher than the remaining 19 scenarios with the following exceptions: placing Miscanthus or switchgrass in EML and all ML were not significantly different from the randomly and strategically selected 50% Miscanthus C/S and 50% switchgrass replacement scenarios (p>0.08), and mean SSR values were statistically similar for the 50% corn stover removal, 50% corn stover removal in <2% slope C/S areas, 10% Miscanthus and switchgrass buffers, and strategically selected 50% Miscanthus C/S replacement scenarios (p>0.075).

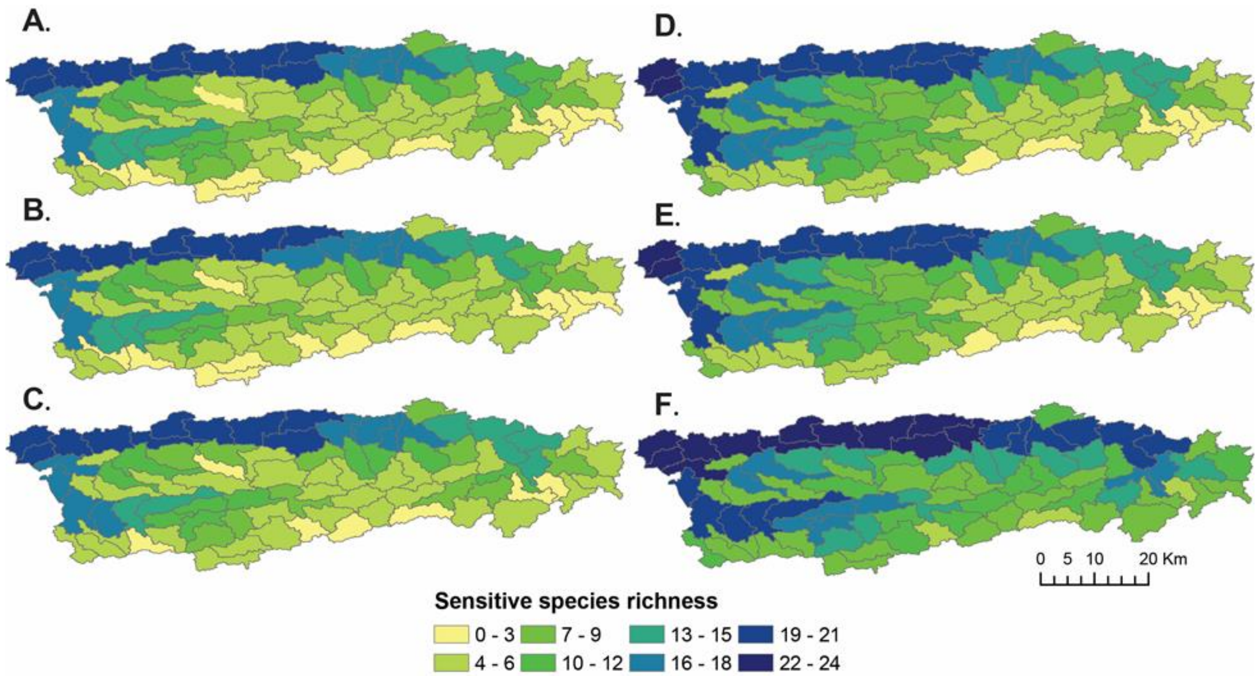

Figure 31 Predicted sensitive species richness (SSR) values for Wildcat Creek watershed, Indiana, subwatersheds for six selected scenarios, including: A) baseline (i.e., predominantly corn/soybean, C/S), B) 50% corn stover removal with nutrient replacement, C) 10% Miscanthus × giganteus (Miscanthus) buffers around C/S, D) 50% replacement of randomly selected baseline C/S with Miscanthus, E) 50% replacement of strategically selected baseline C/S with Miscanthus, and H) 100% replacement of baseline C/S with Miscanthus. The selected scenarios are representative of subwatershed conditions for other scenarios according to the statistical results presented in Figure 30.

Task C: Identify and communicate the optimal selection and placement of energy crops within a watershed for sustainable production

1. **Tasks performed to complete this objective**:

   C.1. Optimize selection and placement of various energy crops in a watershed under single and multi-objective functions, based on economic and ecological criteria.

   C.2. Compare the optimization results with targeting strategies that could be implemented in a watershed (e.g. switchgrass in grassed waterways, vegetated filter strips; hybrid poplar in riparian forest areas; conversion of existing pasture lands into energy crop production).

   C.3. Determine optimal design and implementation strategies for the sustainable production of selected energy crops and other cellulosic feedstock production systems at the watershed scale, and communicate the results.

2. **Actual Accomplishments**:

- We have developed new methods to efficiently optimize land use for bioenergy crop production called Multi-Level Spatial Optimization framework (MLSOPT: Cibin and Chaubey, 2015) (Figure 32).
    - The new method was robust and computationally efficient in identifying optimum solutions.
    - Users can download new optimization framework with example files from https://engineering.purdue.edu/ecohydrology/download.html#MLSOPT
    - This new method for spatial optimization using SWAT was further tested with multi-objective optimization case study to identify optimum stover removal rates from Wildcat Creek watershed with minimum impact of sediment loading (Figure 32, Cibin and Chaubey, 2015).
    - Our results indicate that objective functions in optimization are critical in identifying the sustainable solutions (Figure 33-Figure 35).
    - The optimization results generally had good correlation with the land characteristics (represented by model parameters), (Table 9) indicating that land characteristics could be used a good surrogate to make bioenergy land management decisions.

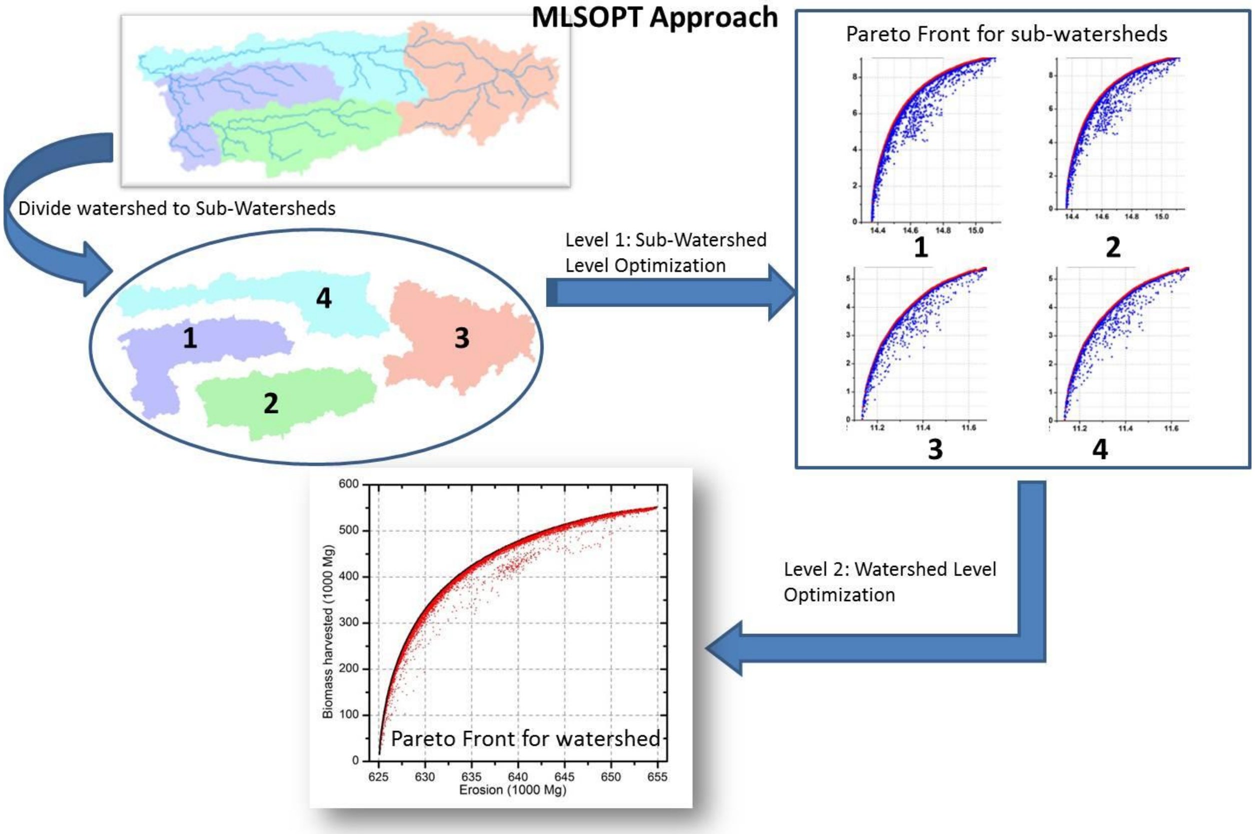

Figure 32. Graphical representation of Multi-Level Spatial Optimization framework (MLSOPT) develop to optimize selection and placement of bioenergy crops and land use in a watershed.

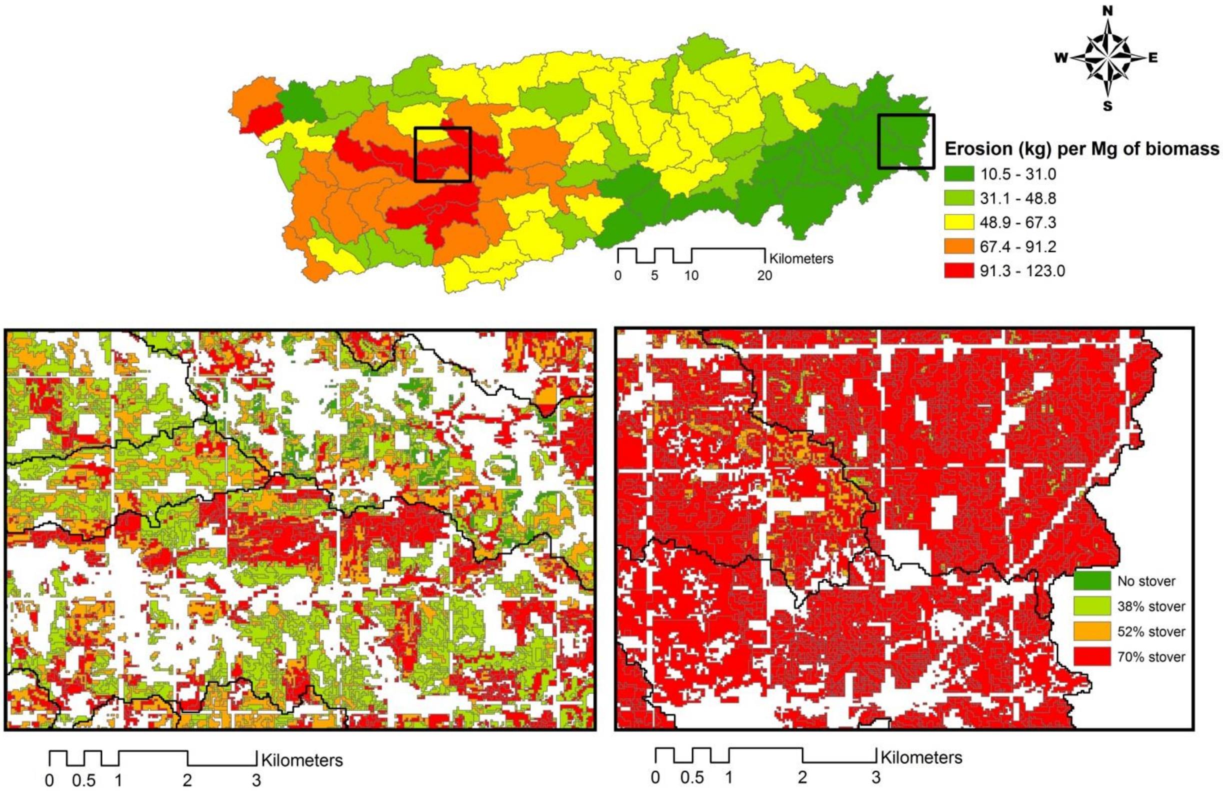

Figure 33. Spatial distribution of optimization result for the watershed. (Top) spatial variability of impact of biomass removal on erosion for sub-basin in watershed. (Bottom) Spatial distribution of stover removal rates with watershed target of 500,000 Mg biomass for high biomass removal sensitive (Left) and low sensitive (Right) region in watershed.

Table 9. Correlation of sub-basin model parameters with biomass harvest sensitivity; erosion (kg) per Mg of biomass harvested.*

Model parameter	Correlation coefficient
Curve number	0.40
Hydrological soil group	0.44
USLE K factor	0.71
USLE P factor	-0.80
USLE LS factor	0.85
Available water capacity (mm)	-0.40
Initial soil moisture(mm)	-0.39
Slope of HRU's	0.85
Slope length of HRU's	-0.80
Overland Manning’s N	0.03
Time of concentration(hr)	-0.74

*Parameters were area weighted at sub-basin level for all corn/soybean HRU’s from which biomass harvested

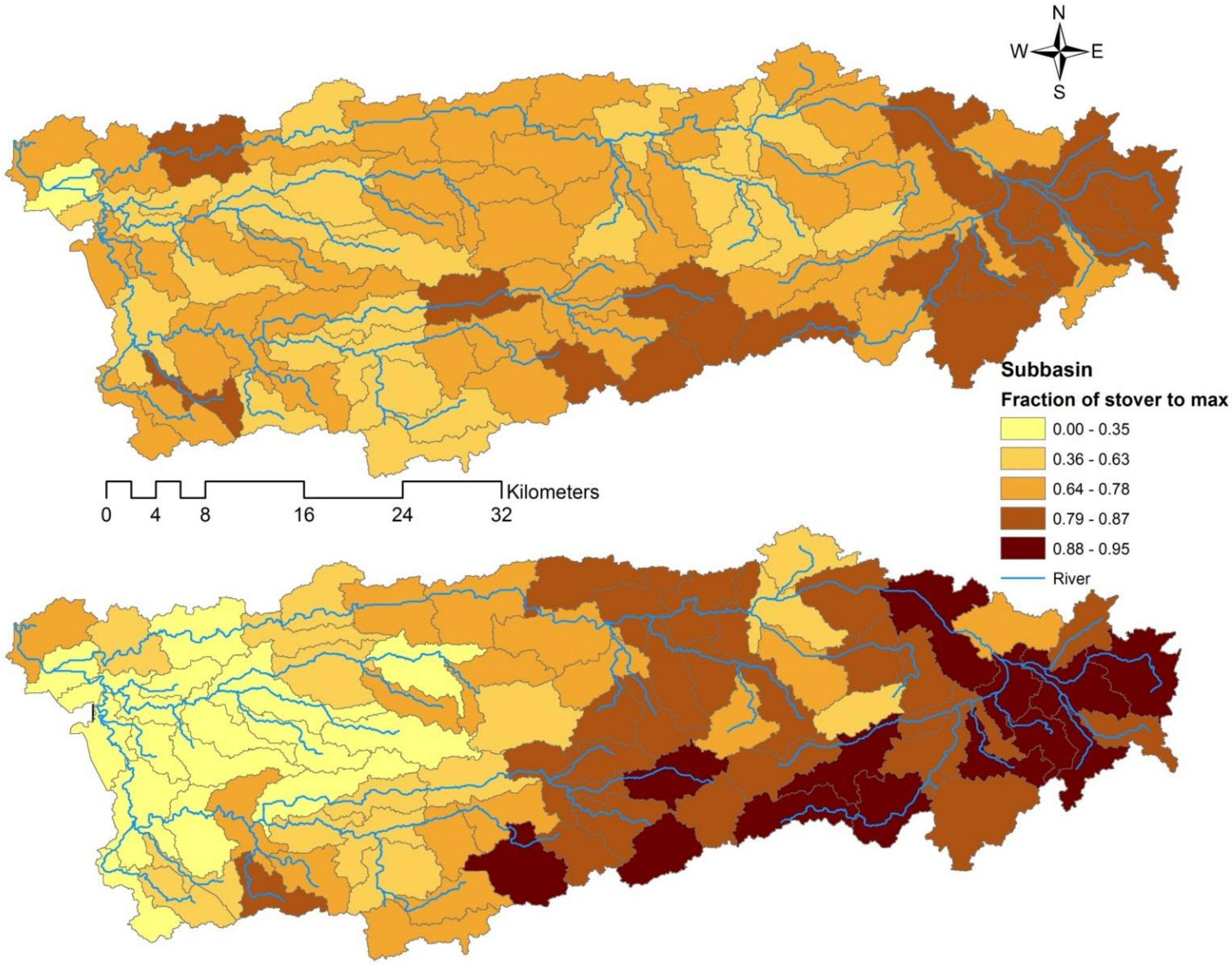

Figure 34. Spatial distribution of corn stover removed at sub-basin level to the maximum possible for optimization with Scenario1 (minimize source level erosion) (Top) and scenario2 (minimize sediment loading at watershed outlet) (Bottom) with watershed target of 800,000 Mg biomass. The different in stover removal spatial distribution between the two scenarios indicate the significance of objective function choice in optimization results. In source level (erosion) based optimization stover removal is distributed across the watershed while in outlet based optimization more stover removed from upstream areas and less stover removal from areas near to watershed outlet.

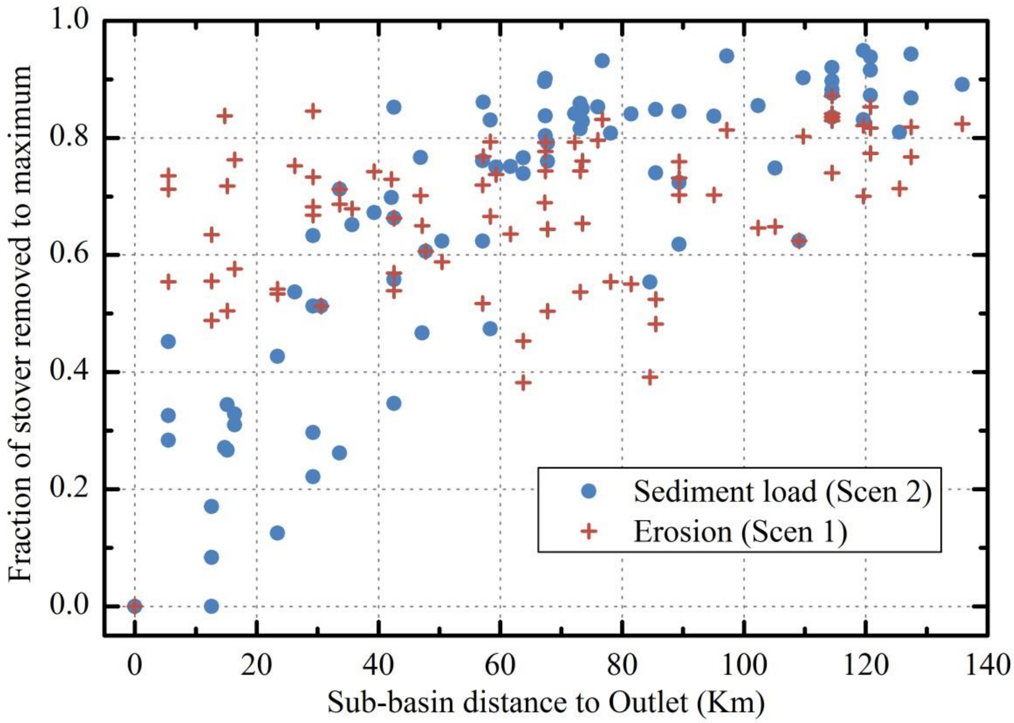

Figure 35. Relationship between fractions of stover removed in sub-basin with distance to outlet for optimization Scenario1 (minimize source level erosion) (red cross) and scenario2 (minimize sediment loading at watershed outlet) (blue dots). Sub-basins in the reach of 40-50 km from watershed outlet were critical areas for scenario 2 and minimum stover removal was estimated from these areas.

- Economic Analysis
  - Feedstock cost of production, transportation costs, and optimization
    - Economic analysis of candidate cellulosic feedstocks in this project began by constructing a farm-gate partial budget—this reflects the *per hectare cost* of growing an individual feedstock, without considering the cost of any other income generating activities on a farm—for each individual feedstock: corn crop residue (corn stover), switchgrass, *Miscanthus* and hybrid poplar. Farm-gate production costs include site preparation (before planting), establishment (planting, fertilization, necessary reseeding in the case of switchgrass), harvest, and on-farm storage of biomass bales. The parameterized and validated SWAT watershed model is used to simulate growing each individual feedstock on every individual land unit based on the farm-gate production costs, and the yield on each unit of land then determines the cost *per metric ton of biomass* harvested, which varies across space. Using the farm-gate production cost together with the simulated biomass yield for each feedstock, we construct a biomass supply curve for each *individual* feedstock in the watershed (see Figure 36).

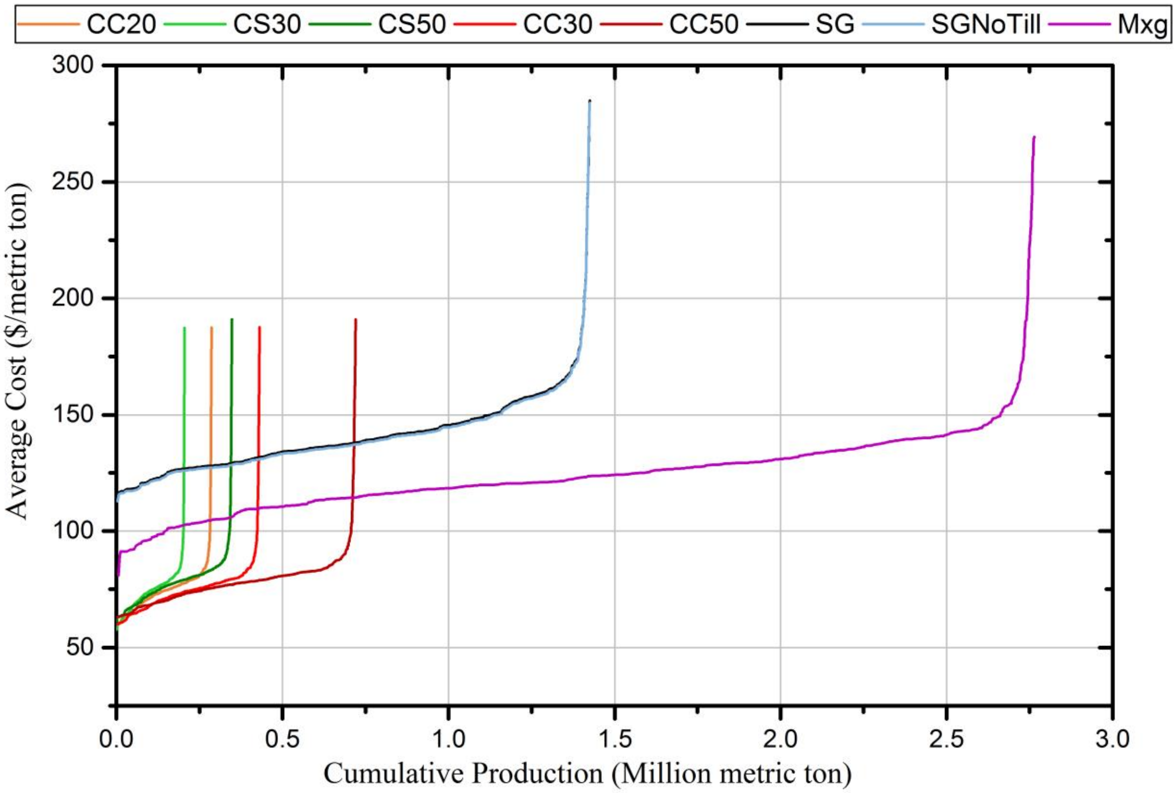

Figure 36 Updated feedstock supply curves for the Wildcat Creek Watershed, Indiana based on estimated 2015 costs of production. [Caption: CC20, CC30 and CC50=continuous corn with 20%, 30% and 50% residue removal; CS30 and CS50= corn-soybean rotation with 30% and 50% corn residue removal; SG=switchgrass; SGNoTill=no-till planted switchgrass; Mxg=miscanthus]

- Transportation costs include loading bales onto trucks at the farm, hauling cost from the farm to the biorefinery, and unloading at the biorefinery. Hauling costs are calculated based on actual road miles (using a road data layer in ArcGIS) between a hypothetical biorefinery location at the center of the watershed and the centroid of each individual land unit (hydrological response unit in the SWAT model) where a feedstock can be grown (see Figure 37).

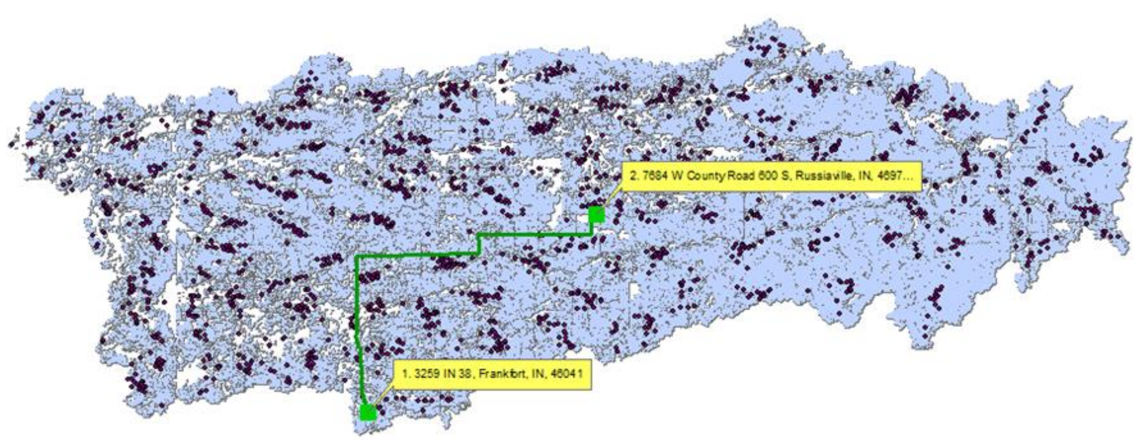

Figure 37 Land units (dots are centroids) and transportation routing from fields (location 1) to a hypothetical biorefinery (location 2)

- Two different types of optimizations were performed. The first was based on supplying a specified amount of total feedstock at the lowest possible cost. This was done based on the total amount of feedstock required to supply the minimum economically feasible size biorefinery based on the prior literature. This entered as a quantity constraint on total metric tons of feedstock required by the hypothetical plant. The economic and environmental metrics used in this study can then be compared for different biomass production requirements, without optimizing for environmental outcomes. The second type of optimization included the same biomass production quantity constraints *and* environmental constraints of 25% and 50% reductions in the total amount of Nitrogen, Phosphorus and sediment delivered to waterways when different feedstocks or mixes of feedstocks are grown in different spatially explicit locations around the watershed. An example of an optimization to supply a large amount of biomass from the watershed for a thermochemical biorefinery is visualized in Figure 38. When pollution constraints are added, the ones that bind vary case by case (Table 10) and the total cost of production implicitly includes pollution abatement costs.

Table 10 Optimization results with biomass production and pollutant level constraints

	25% Reduction Constraint		**50% Reduction Constraint**	
	Thermo-chemical	**Bio-chemical**	**Thermo-chemical**	**Bio-chemical**
Total Cost ($)	141,532,768	94,475,733	161,532,738	145,285,324
Biomass (metric tons)	1,307,074	858,489	1,307,066	1,042,645
TN (% reduction)	25%	25%	50%	50%
TP (% reduction)	25%	25%	63%	80%
Sediment (% reduction)	60%	52%	77%	85%

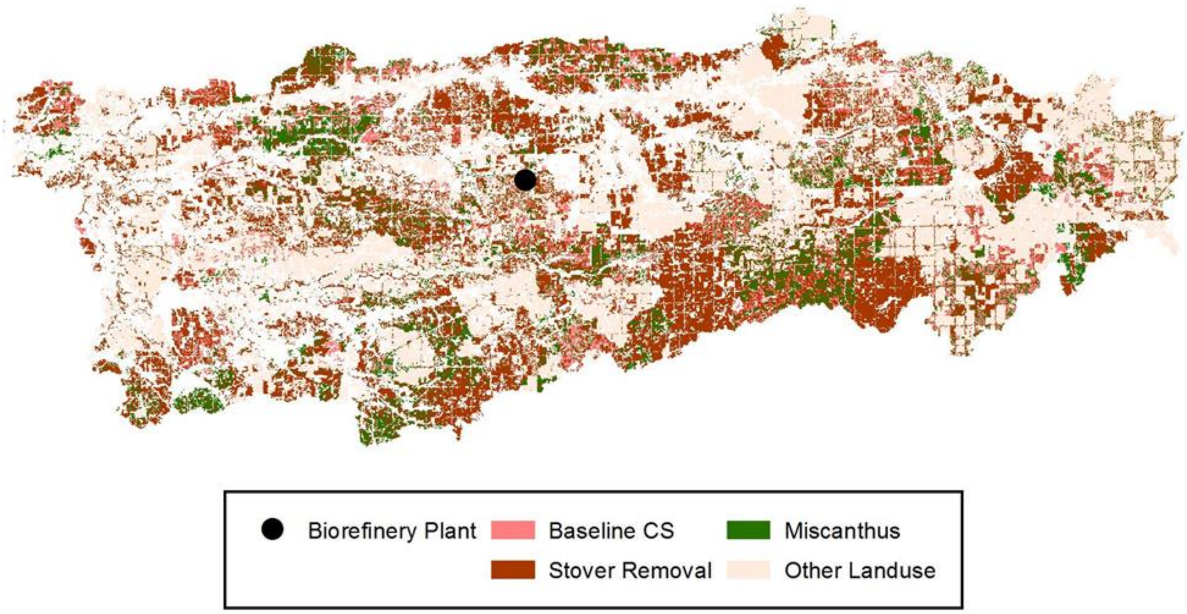

Figure 38 Example optimization results: Cost-minimization to supply a thermochemical refinery in the Wildcat Creek watershed

Land share distributions from different optimization cases are depicted in Figure 38. One noticeable difference among optimization results with different constraints is that much more no-tilled switchgrass is planted when pollutant loading constraints are introduced to the model. With only the production constraint, the cost minimization process selects scenarios that are cheapest but does not take any pollutants into account. Hence CC50 and *Miscanthus* dominate in the first two columns of Figure 39.

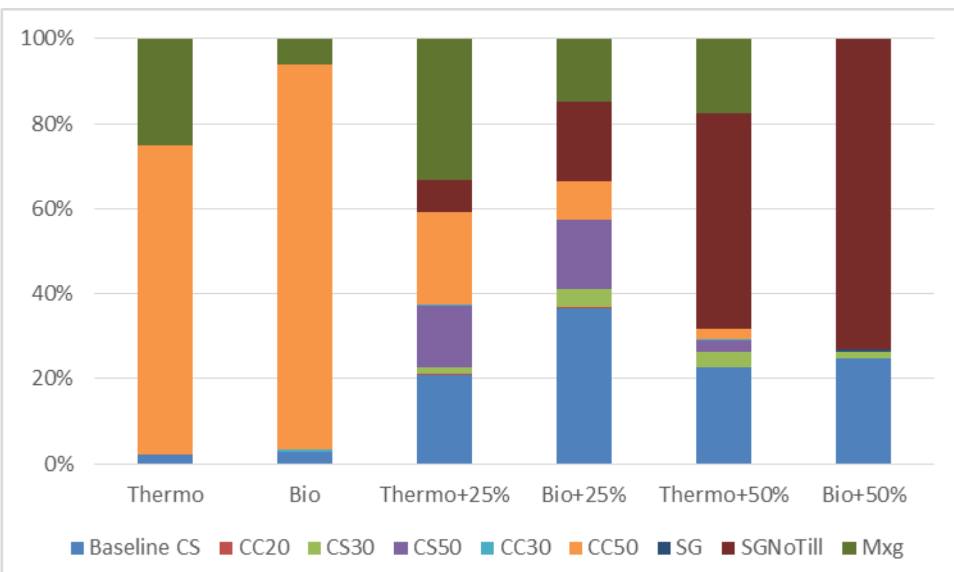

Figure 39 Cost minimizing land shares under different production and pollutant constraints

- One noticeable difference among optimization results with different constraints is that the simulation results indicate that both perennial grass crops are expected to reduce delivery of all three pollutants to the Wildcat Creek, relative to the baseline cropping practices in place today. Stover removal in combination with continuous no-till may be able to improve sediment loss relative to the baseline corn-soybean rotation under the assumed management. The perennial grasses have the highest farm-gate production cost per dry metric of biomass. The opportunity cost of not growing corn and/or soybeans on the high productivity land in the Wildcat Creek watershed cannot be overstated as a determinant of the crop(s) that farmers will choose to plant. If markets for cellulosic feedstocks do eventually emerge, this opportunity cost will ultimately determine if farmers ever choose to grow perennial grasses or woody feedstocks in the eastern Corn Belt. In 2015 in Indiana, this opportunity cost on average quality agricultural land in a corn-soybean rotation is expected to be in the neighborhood of $175 per acre. This means that unless biorefineries are willing to pay prices for switchgrass or *Miscanthus* high enough to generate net revenue per acre greater than or equal to this level, then farmers will not be willing to grow either of these feedstocks and stover is the only realistic feedstock in the watershed.

Table 11 Feedstock Production and Transportation Cost Summaries

Production cost for different scenarios					
		$/acre	**$/ha**	**$/DM ton**	**$/metric ton**
scenario 1	**Baseline CS**	$-	$-	$-	$-
scenario 2	**CCNoTill20 with N replacement**	$51.15	$126.34	$56.74	$62.42
scenario 3	**CSNoTill30 with N replacement**	$36.56	$90.30	$56.74	$62.42
scenario 4	**CSNoTill50 with N replacement**	$65.30	$161.30	$59.76	$65.74
scenario 5	**CCNoTill30 with N replacement**	$76.95	$190.08	$56.74	$62.42
scenario 6	**CCNoTill50 with N replacement**	$135.22	$334.00	$59.65	$65.62
scenario 7	**switchgrass**	$507.58	$1,253.73	$114.85	$126.34
scenario 8	**switchgrass no till**	$504.17	$1,245.30	$114.10	$125.51
scenario 9	***Miscanthus***	$853.64	$2,108.50	$99.66	$109.62
Production + loading/unloading cost					
		$/acre	**$/ha**	**$/DM ton**	**$/metric ton**
scenario 1	**Baseline CS**	$-	$-	$-	$-
scenario 2	**CCNoTill20 with N replacement**	$56.35	$139.19	$62.51	$68.77
scenario 3	**CSNoTill30 with N replacement**	$40.28	$99.48	$62.51	$68.77
scenario 4	**CSNoTill50 with N replacement**	$71.61	$176.87	$65.53	$72.09
scenario 5	**CCNoTill30 with N replacement**	$84.78	$209.41	$62.51	$68.77
scenario 6	**CCNoTill50 with N replacement**	$148.31	$366.32	$65.43	$71.97
scenario 7	**switchgrass**	$540.32	$1,334.60	$122.26	$134.49
scenario 8	**switchgrass no till**	$536.91	$1,326.16	$121.51	$133.66
scenario 9	***Miscanthus***	$917.11	$2,265.25	$107.06	$117.77

Entire watershed costs								
	Collected Biomass Weight (kg/ha)	**metric ton total production**	**Cost $/ha**	**production cost**	**loading-unloading cost**	**hauling cost**	**Total cost**	**Total cost per metric ton**
Baseline CS	0	0	$-	$-	$-	$-	$-	$-
CCNoTill20 with N replacement	2115	306475	$126	$18,308,257	$1,830,521	$1,813,618	$21,952,396	$71.63
CSNoTill30 with N replacement	1512	219048	$90	$13,085,532	$1,308,762	$1,296,749	$15,691,043	$71.63
CSNoTill50 with N replacement	2564	371502	$161	$23,374,077	$2,218,639	$2,197,708	$27,790,423	$74.81
CCNoTill30 with N replacement	3182	461092	$190	$27,544,855	$2,753,227	$2,727,357	$33,025,439	$71.62
CCNoTill50 with N replacement	5318	770681	$334	$48,401,540	$4,600,804	$4,556,210	$57,558,555	$74.69
Switchgrass	10651	1543463	$1,254	$181,681,425	$11,699,516	$11,585,356	$204,966,298	$132.80
Switchgrass no till	10649	1543226	$1,245	$180,460,890	$11,697,704	$11,583,978	$203,742,572	$132.02
Miscanthus	20645	2991663	$2,1090	$305,549,860	$22,675,397	$22,551,770	$350,777,026	$117.25

- A study of the cost of growing hybrid poplar woody biomass for conversion into biofuels was also conducted. Per hectare costs of production are detailed in Table 12. These costs are the basis for calculating the per dry ton biomass price required to break-even (Net Present Value of the investment = $0) growing this woody biomass feedstock. The working paper by McCarty, Sesmero and Gramig, we identified a set of contractual arrangements between biomass growers and a cellulosic biorefinery capable of inducing farmers to grow these crops. This analysis considers a fundamental feature of growing perennial energy crops (switchgrass, *Miscanthus* and woody crops), namely the presence of uncertainty and irreversibility that discourages this type of enterprise. Three specific arrangements are identified from among the set that induces planting. First, we identify the arrangement that maximizes total (farmer plus biorefinery) surplus. Second, we identify the structure that maximizes a farmer's surplus. Finally, we identify the arrangement that maximizes biofuel firm's surplus. Our analysis reveals that incentive systems embedded in contractual arrangements matter, even in the absence of asymmetric information. Our analysis demonstrates that different contractual arrangements result in different welfare outcomes because they have a nonlinear effect on the expectation and volatility of returns from energy crops. In particular, we find that the most efficient policy for inducing growers to enter the market is a fixed payment policy.

  For the case of hybrid poplar tree production, the results suggest that the most efficient contract type to encourage entry is based on a fixed per acre payment. A payment that guarantees average cost is covered will completely eliminate the (option) value of waiting to plant hybrid poplars until a later date. Another interesting result is that a revenue floor (guaranteed base payment) contract does very little to induce farmer planting of woody crops until it gets to very high levels, although it does significantly lower the threshold for leaving the contract at relatively low levels. The asymmetric nature of uncertainty results in conclusions that differ greatly from models without such asymmetry. More specifically, the premium on entry is significantly lower after netting out yield uncertainty for an idle cellulosic biofuels plant. Contracts are not only useful for sharing risk, they also have a very important role to play in perennial crop production. Contracts—especially per acre payment contracts—reduce uncertainty for a grower and allow them to enter production at a fraction of the net revenue required under a performance based contract.

Table 12 White Poplar Cost Sheet

Preparation costs	**Total Cost**	**Price**	**Units**	**Quantity**	**Source**
	Herbicide				
Total kill (Roundup)	$46.21	$4.94	liter	9.4	1
Pre Emergent (Prowl)	$21.49	$9.19	liter	2.3	2
Post Emergent (Fusilade Dx)	$113.15	$32.26	liter	3.5	2
Pesticide cost	$-	$3.04	hectare	0.0	3
Machinery custom hire (herbicide)	$17.30	$17.30	hectare	1.0	3
	Fertilizer				
Nitrogen (raw)	$516.50	$2.30	kg	224.2	4
(N from ESN Polomer coated urea)	$210.60	$0.83	kg	254.7	5
(N from Ammonium Sulfate (AMS)	$305.91	$0.63	kg	482.3	6
K20 (source of potassium)	$-	$-	kg	0.0	3
Lime (spread on field)	$-	$0.02	kg	0.0	7

Machinery custom hire (fertilizer)	$24.71	$24.71	hectare	1.0	3
Strip tillage, machinery cost	$46.23	$46.23	hectare	1.0	8
Planting costs					
Cost of seedlings	$554.65	$0.29	whip	1912.6	9
Cost of planting seedlings	$172.13	$0.09	labor cost	1912.6	10
Replant year 1 seedling cost	$12.90	$0.29	whip	44.5	11
Cost of replanting seedlings yr 1	$4.00	$0.09	labor cost	44.5	11
Replant year 2 seedling cost	$56.61	$0.29	whip	195.2	11
Cost of replanting seedlings yr 1	$17.57	$0.09	labor cost	195.2	11
Yearly management costs					
Labor and management	$49.00	$49.00	hectare	1	3
Crop insurance	$-	$22.24	hectare	0	12
Cutback cost	$-	$49.42	hectare	0	12
Harvesting Costs (w/o labor)					
Feller/Buncher	$328.35	$328.35	hectare	1	12
Skidder	$1,029.34	$1,029.34	hectare	1	12
Total harvesting cost	$1,495.11	$22.05	per dt	67.81	10
Transportation Costs					
Tree farm to factory cost	$387.96	$387.96	hectare	1	13
Opportunity Cost					
CS rotation net rev	$255.75	$255.75	hectare	1	7
Removal Costs					
Stump removal	$741.32	$741.32	hectare	1	12

Table 12 White Poplar Cost Sheet, *Source/Reference list*

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<u>Interagency Collaborations Developed</u>

- We developed interagency collaborations with multiple agencies and universities (see below). These efforts are continuing beyond the life of this project.

    - Iowa State University:
        - We have worked with researchers from the Iowa State University to utilize their datasets for validating improved vegetated filter strip algorithms in the SWAT model (Task A).
        - We have worked with Center for Agriculture and Rural Development (CARD) team to evaluate the potential impacts of bioenergy production in Iowa watersheds and in regional scale. We are in the process of writing a series of four publications from this collaborations.
    - USDA-ARS:
        - We worked with USDA_ARS (National Soil Erosion Research Lab) researchers to utilize field measured tile drain and soil moisture data to validate tile drain routines and soil moisture representation in SWAT model.
        - We have strong collaborations with USDA-ARS (Grassland Soil and Water Research Laboratory) researchers Temple, Texas in SWAT model improvements, testing and validation.

    - Texas A&M University(TAMU): We work very closely with SWAT model development team at TAMU to incorporate model improvements in the release version of the model

    - We are working with the CenUSA project team members to utilize their datasets for model improvements (Award No. 20116800530411, "Sustainable production and Distribution of Bioenergy for the Central US: An Agro-Ecosystem Approach to Sustainable Biofuels Production via the Pyrolysis-Biochar Platform).

<u>Students/post-docs trained on the project</u>

Post-Doctoral Research Associates:

1. **Cibin Raj**, Department of Agricultural & Biological Engineering, Purdue University
2. **Ryan Dierking**, Department of Agronomy, Purdue University
3. **Young Her**, Department of Agricultural & Biological Engineering, Purdue University
4. **Conor S. Keitzer**, Department of Forestry and Natural Resources, Purdue University

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6. **Burks, J. L** Ph.D. Agronomy, Purdue University.
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11. **Trybula, E.** MS. Department of Agricultural and Biological Engineering, Purdue University.
12. **Beugly J.** Ph.D. Department of Forestry and Natural Resources, Purdue University
13. **Ji Tianyun (Helen).** MS. Agricultural Economics, Purdue University
14. **Vester K.** MS. Department of Agricultural and Biological Engineering, Purdue University.

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Feng, Q., Chaubey I., Her Y., Cibin R, Engel B., Volenec J., Wang X. (2015). Hydrologic/water quality impacts and biomass production potential on marginal land. *Environmental Modelling and Software* 72: 230–238. (doi:10.1016/j.envsoft.2015.07.004)

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Appendix A

Publications / Presentations from the Project (Award Number: DE-EE0004396)

Peer Reviewed Journal Articles: Published

1. Wang, R., L.C. Bowling, and K.A. Cherkauer (2016). Estimation of the Effects of climate variability on Crop yield in the Midwest USA. Agricultural and Forest Meteorology, 216, 141–156.

2. Guo, T., B.A. Engel, G. Shao, J.G. Arnold, R. Srinivasan, J.R. Kiniry. Functional Approach to Simulating Short-Rotation Woody Crops in Process-Based Models. Bioenerg. Res. (2015) 8:1598–1613. DOI 10.1007/s12155-015-9615-0

3. Cibin, R., Chaubey, I. Volenec J.J., and Brouder S.M. (2015), Watershed scale impacts of energy crops on hydrology and water quality using improved SWAT model. (GCB bioenergy, *DOI:10.1111/gbb.12307*)

4. Feng, Q., Chaubey I., Her Y., Cibin R, Engel B., Volenec J., Wang X. (2015). Hydrologic/water quality impacts and biomass production potential on marginal land. Environmental Modelling and Software 72: 230–238. (doi:10.1016/j.envsoft.2015.07.004)

5. Boles, C.W., Frankenberger, J.R., Moriasi, D.N. (2015) Tile drainage simulation in SWAT2012: Parameterization and evaluation in an Indiana watershed. Transactions of the American Society of Agricultural and Biological Engineers. (In Press).

6. Her Y, Cibin R, Chaubey I. (2015) Simple parallel computing methods using 'spmd' and 'parfor' for improving efficiency of optimization in hydrologic model applications. Applied Engineering in Agriculture 31(3): 455-468. (doi: 10.13031/aea.31.10905)

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8. Trybula E., Cibin R., Burks J., Chaubey I., Brouder S., Volenec J. (2015). Second generation perennial bioenergy feedstock representation in SWAT: an evidence-based approach for parameter development and model improvement. GCB bioenergy 7(6):1185-1202. DOI: 10.1111/gcbb.12210

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12. Hoque Y M., Cibin R., Hantush M M., Chaubey I., Govindaraju, R.S (2013) How Do Land-Use and Climate Change Affect Watershed Health? A Scenario-Based Analysis. *Water Quality, Exposure and Health* (10.1007/s12403-013-0102-6)

13. Cibin, R., I. Chaubey, and B. Engel. 2012. Simulated watershed scale impacts of corn stover removal for biofuel on hydrology and water quality. *Hydrological Processes*. 26: 1629–1641. DOI: 10.1002/hyp.8280.

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Peer Reviewed Journal Articles: in preparation/review

1. Feng, Q., I. Chaubey, R. Cibin, B. Engel, K.P. Sudheer, and J. Volenec. Simulating establishment period of perennial bioenergy grasses in the SWAT model. *Global Change Biology – Bioenergy. In Review.*

2. Gassman, P.W., A. Valcu, C.L. Kling, Y. Panagopoulos, R. Cibin, I. Chaubey, C.F. Volter, and K.E. Schilling. Assessment of cropping scenarios for the Boone River watershed in North Central Iowa, United States. *J. American Water Resources Association. In Review.*

3. Panagopoulos, Y., P.W. Gassman, C.L. Kling, R. Cibin, and I. Chaubey. Assessment of large-scale bioenergy cropping scenarios for the Upper Mississippi and Ohio-Tennessee River basins. *J. American Water Resources Association. In Review.*

4. Kling, C.L., I. Chaubey, R. Cibin, P.W. Gassman, and Y. Panagopoulos. Policy implications from multi-scale watershed models of biofuel crop adoption across the Corn Belt. *J. American Water Resources Association. In Review.*

5. Cibin R., Chaubey, I., Sudheer K P, White, M.J. and Arnold J.G. (20xx) Improved filter strip representation in SWAT model to simulate energy crop filter strips. *Env. Modelling and Soft. In Review.*

6. Song J, Gramig B, Cibin R, Chaubey I. Economic and environmental constraints on cellulosic biofuel production in an agricultural watershed. *Water Resources Research. In Review.*

7. Feng, Q. I. Chaubey, B. Engel, C. Raj, K.P. Sudheer, and J. Volenec. 2015. Marginal land suitability analysis for switchgrass, miscanthus and hybrid poplar in the Upper Mississippi River Basin (UMRB). *Environmental Science and Technology. In Review.*

8. Boles, C.W., Frankenberger, et al. Simulation of the effects of bioenergy crop cultivation in a small tile-drained watershed. In Review.

9. Cibin R, and Chaubey I, et al (20xx) Watershed scale optimal selection and placement of energy crops for sustainable bioenergy production using multi-objective optimization framework *(Internal Review)*

10. Ruoyu W, Bowling L and Cherkauer K. Exploration of the spatial and temporal variability of corn growth using Landsat imagery *(Under internal review)*

11. McCarty T, Gramig BM and Sesmero JP. Cellulosic Bioenergy Crop Investment under Uncertainty: A Real Options Approach. *(Under internal review).*
12. Wang R, Bowling LC, Cherkauer KA, Cibin R, Her Y, Chaubey I, (20XX) Biophysical and hydrological effects of future climate change including trends in CO2, in the St. Joseph River watershed, Eastern Corn Belt. *(In review).*
13. Wang R, Bowling LC and Cherkauer KA (20XX). Corn response to climate stress detected with satellite-based NDVI time series *(Under internal review).*

Thesis/Dissertation

1. Wang. R. (2016) Investigation of climate variability and climate change impacts on crop yield in the Eastern Corn Belt, USA. Ph.D. Dissertation. Department of Agricultural and Biological Engineering, Purdue University.

2. Feng Q. (2016) Hydrologic and water quality impacts by producing perennial cellulosic bioenergy crops on marginal land. Ph.D. Dissertation. Department of Agricultural and Biological Engineering, Purdue University.

3. Montgomery. A. (2015) Water Quality and Production Potential Effects of Cellulosic Biofuel Crops Grown on Marginal Land. MS Thesis. Department of Agricultural and Biological Engineering, Purdue University.

4. Long. M. (2015) Sustainable Biofuel Feedstock Potential of Sorghum: An Interdisciplinary Approach. Agronomy, Purdue University.

5. Logsdon. R. (2014) Development and Application of Quantitative Methods for Ecosystem Services. Ph.D. Dissertation. Department of Agricultural and Biological Engineering, Purdue University.

6. Burks, J. L (2013). Eco-physiology of three perennial bioenergy systems. . Ph.D. Dissertation. Agronomy, Purdue University.

7. Cibin Raj. (2013) Optimal Land Use Planning on Selection and Placement of Energy Crops for Sustainable Biofuel Production. Ph.D. Dissertation. Department of Agricultural and Biological Engineering, Purdue University.

8. Boles, C.W. (2013). SWAT Model Simulation of Bioenergy Crop Impacts in a Tile-Drained Watershed. MS Thesis. Department of Agricultural and Biological Engineering, Purdue University.

9. Song, J. A. (2013) Spatially Explicit Watershed Scale Optimization of Cellulosic Biofuels Production. M.S Thesis. Department of Agricultural Economics, Purdue University.

10. Feng Q. (2013) Biomass Production and Hydrological/Water Quality Impacts of Perennial Crop Production on Marginal Land. MS Thesis. Department of Agricultural and Biological Engineering, Purdue University.

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Presentations in Various Conferences:

1. Chaubey, I., R. Cibin, J. Frankenberger, J. Volenec, and S. Brouder. 2015. Biofuel-induced land use change impacts on hydrology and water quality. American Geophysical Union. San Francisco, CA. December 18, 2015. (invited)

2. Krishnan, N., R. Cibin, I. Chaubey, and K.P. Sudheer. 2015. Impact of parameter uncertainty in land use planning decisions. Poster presented at the American Geophysical Union Conference. San Francisco, CA. December 18, 2015.

3. Chaubey, I., R. Cibin, J. Frankenberger, J. Volenec, and S. Brouder. 2015. Integrated assessment of bioenergy, land use, and climate change on ecohydrologic response. Joint International Conference of American Society of Agronomy, Crop Science Society of American, and Soil Science Society of America. Minneapolis. November 17.

4. Cibin, R., I. Chaubey, M. Helmers, K.P. Sudheer, M. White. J. Arnold. 2015. Improved physical representation of vegetative filter strips in SWAT. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

5. Feng, Q., I. Chaubey, R. Cibin, B. Engel, K.P. Sudheer, and J. Volenec. 2015. Bioenergy grass production on marginal lands and hydrologic and water quality impacts in the Upper Mississippi River Basin (UMRB). *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

6. Wang R., Bowling, L.C., Cherkauer K.A. (2015) Improve simulation of annual crop sensitivity to climate variability in the Eastern Corn Belt. 2015 International SWAT Conference (Oct. 14 -16) 2015, West Lafayette, IN, USA.

7. Papanagopoulous, Y., P. Gassman, C. Kling, R. Cibin[2], I. Chaubey, J. Arnold. 2015. Assessment of large scale bioenergy cropping scenarios for the Upper Mississippi and Ohio-Tennessee River basins. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

8. Gassman, P., A. Valcu, C. Kling, Y. Panagopoulous, R. Cibin[2], I. Chaubey, J.G. Arnold, C. Wolter, and K. Schilling. 2015. Assessment of bioenergy cropping scenarios for the Boone River watershed in North Central Iowa, United States. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

9. Chaubey, I., R. Cibin[2], S. Brouder, L. Bowling, K. Cherkauer, J. Frankenberger, R. Goforth, B. Gramig, J. Volenec. 2015. How do climate change and bioenergy crop production affect watershed sustainability. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

10. Feng, Q., I. Chaubey, R. Cibin, B. Engel, K.P. Sudheer, J. Volenec. 2015. Simulating establishment period of perennial bioenergy grasses in the SWAT model. *International Soil and Water*

Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.

11. Krishnan, N., R. Cibin, I. Chaubey, and K.P. Sudheer. 2015. Impact of model parametric uncertainty on land use planning decision making. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

12. Song, J., B. Gramig, R. Cibin, and I. Chaubey. 2015. Water quality and cost considerations in the supply of feedstocks for cellulosic biofuels. *International Soil and Water Assessment Tool Conference, West Lafayette, IN. October 14-16, 2015.*

13. Chaubey, I. 2015. Agricultural ecohydrology and watershed management. ASABE Natural Resources and Environmental System Distinguished Scholar Series. New Orleans, LA. July 27. (invited)

14. Cibin, R., I. Chaubey, and B.M. Gramig. 2015. Watershed scale analysis to develop strategies for environmentally sustainable corn stover removal for biofuel production in Indiana. *Paper No. 152190927. ASABE Annual International Conference. New Orleans, LA. July 2015.*

15. Montgomery, A.K., R. Dierking, S. Brouder, I. Chaubey, J. Volenec. 2015. The effects of different biofuel crops and fertilizer rates on subsurface water quality and yield on marginal lands. *Paper No. 152189916. ASABE Annual International Conference. New Orleans, LA. July 2015.*

16. Cibin R, Chaubey I., Trybula E., Volenec J., Brouder S., Arnold J. (2015) SWAT model improvements to simulate bioenergy crops production. International Soil & Water Assessment Tool Conference – Sardinia, Italy June 24-26, 2015.

17. Chaubey I., Cibin R, Frankenberger J., Volenec J., Brouder S., Gassman P., Panagopoulos Y., Kling C., Arnold J. (2015) Application of improved SWAT model for bioenergy production scenarios in Indiana Watersheds. International Soil & Water Assessment Tool Conference – Sardinia, Italy June 24-26, 2015.

18. Gassman P., Valcu A., Kling C., Panagopoulos Y., Cibin R., Chaubey I., Arnold J. (2015) Assessment of Scenarios for the Boone River Watershed in North Central Iowa. International Soil & Water Assessment Tool Conference – Sardinia, Italy June 24-26, 2015.

19. Panagopoulos Y., Gassman P., Kling C., Cibin R., Chaubey I., Arnold J. (2015) Assessment of Large-Scale Scenarios for the Upper Mississippi and Ohio-Tennessee River Basins. International Soil & Water Assessment Tool Conference – Sardinia, Italy June 24-26, 2015.

20. Wang, R., Bowling, L., Cherkauer, K. 2015. “Evaluating the effect of climate change on crop yield in the St. Joseph River Watershed, Eastern Corn Belt". ASABE 1st Climate Change Symposium-Adaptation and Mitigation. Date: May 3 -5, 2015. Location: Chicago, Illinois.

21. Cibin R, R. Logsdon, I Chaubey, K. A. Cherkauer (2015) Ecosystem services evaluation of futuristic bioenergy based land use change and their uncertainty from climate change and variability. ASABE 1st Climate Change Symposium-Adaptation and Mitigation - Chicago, Illinois, May 3-5, 2015, Paper number 152121620, (doi: 10.13031/cc.20152121620)

22. Cibin R., Chaubey, I., Brouder S., Bowling L. C., Cherkauer K., Frankenberger J., Goforth R. R., Gramig B M, Volenec J. (2014). Sustainability analysis of bioenergy based land use change under climate change and variability - AGU Fall Meeting (Dec 15 - 19), San Francisco, California, USA.

23. Chaubey, I., Gramig. B., Cibin R., 2014. Land use Optimization for Sustainable Bioenergy Feedstock Production. BETO Hydrology/Water Quality Modeling Call, DOE webinar (Aug 27).

24. Chaubey, I., Cibin R., Her Y., and Frankenberger J. 2014. Water quality modeling of biofuel land use and land management impacts. ASABE Annual International Meeting (Jul 14 - 16), Montreal, Canada.

25. Cibin R., Chaubey, I., Brouder S., Bowling L.C., Cherkauer K., Frankenberger, J., Volenec, R.R. Goforth .2014. Sustainability analysis of bioenergy production: A Midwest US watershed case study - ASABE Annual International Meeting (Jul 14 - 16), Montreal, Canada.

26. Montgomery A K, R. Wang, S M Brouder, I Chaubey, J Volenec. 2014. Water quality effects of cellulosic biofuel crops grown on marginal land - ASABE Annual International Meeting (Jul 14 - 16), Montreal, Canada.

27. Feng. Q… 2014. Marginal land avaialbility for biomass production in the US. - ASABE Annual International Meeting (Jul 14 - 16), Montreal, Canada.

28. Chaubey, I., Cibin R., Frankenberger J., and Cherkauer K. 2014. Watershed scale environmental and biodiversity sustainability analysis of land use and climate change using SWAT model. Presented at the 2014 International SWAT Conference, July 30 – August 1, 2014. Porto de Galinhas, Brazil.

29. Montgomery, Amanda, Ruoyu Wang, Sylvie Brouder, Indrajeet Chaubey, & Jeff Volenec. "Water quality effects of cellulosic biofuel crops grown on marginal land." Nexus 2014: Water, Food, Climate and Energy Conference. University of North Carolina, Chapel Hill. William and Ida Friday Center, Chapel Hill, NC. 6 Mar 2014.

30. Cibin R., Chaubey, I., Brouder S., Volenec J., and Cherkauer K. (2013). Watershed scale environmental sustainability analysis of biofuel production in changing land use and climate scenarios - AGU Fall Meeting (Dec 9 - 13), San Francisco, California, USA.

31. Ruoyu W., Bowling, L., and Cherkauer K. (2013). Assessing the impact of climate variability and change on crop production in the Midwestern USA – AGU Fall Meeting (Dec 9 - 13), San Francisco, California, USA.

32. Chaubey, I. (2013). Ecohydrologic impacts of land use, land management, and climate change in the Midwest USA. Keynote Address given at the 2013 China-US Annual Workshop on Environmental Health and Green Development. Gatlinburg, TN. November 18-19

33. Long, M.K., J.J. Volenec, and S.M. Brouder. 2013. Theoretical ethanol yield for potential bioenergy sorghum genotypes of differing compositions. Abstract 373-9. Inter. Meeting of the Amer. Soc. Agron.-Crop Sci. Soc. of Amer.-Soil Sci. Soc. of Amer. Nov. 2-6, Tampa, FL. https://scisoc.confex.com/crops/2013am/webprogram/Paper80060.html

34. Purdue University Biomass Production workshop. Throckmorton Purdue Ag Center. Oct. 17, 2013. 60 attendees from Industry and State/Federal agencies.

35. Montgomery, A., R. Wang, S. Brouder, I. Chaubey, and J. Volenec. 2013. Water Quality Effects of Cellulosic Biofuel Crops Grown on Marginal Land. ESE-IGP Symposium. Oct. 17, 2013. Purdue University.

36. Cibin R., Chaubey, I., Sudheer K P, White, M.J. and Arnold J.G. (2013). Optimal Applicability of growing energy crops as BMPs in filter strip areas - ASABE Annual International Meeting (Jul 22 - 24), Kansas City, Missouri, USA.

37. Sharma S, Chaubey, I., Cibin R. (2013). Impact of Bioenergy Crops Expansion on Water Quality in Agricultural Regions of Indiana - ASABE Annual International Meeting (Jul 22 - 24), Kansas City, Missouri, USA.

38. Her Y, Cibin R, and Chaubey I. (2013). Simple parallel computing strategies for parameter calibration and spatial optimization - ASABE Annual International Meeting (Jul 22 - 24), Kansas City, Missouri, USA.

39. Feng .Q, I. Chaubey, Y. Her, X. Wang, C. Boles. (2013) Hydrological/Water quality impacts of perennial crop production on marginal land. ASABE Annual International Meeting (Jul 22 - 24), Kansas City, Missouri, USA.

40. Song J and Gramig BM. (2013) "A Spatially Explicit Watershed Scale Optimization of Cellulosic Biofuels Production." Agricultural and Applied Economics Association Annual Meeting, Washington, DC, USA.

41. Boles, C.M.W. and J. Frankenberger. 2013. Impacts of Tile Drainage on Streamflow and Water Quality Using the New SWAT Drainage Routines. Poster presented at the 56th Annual Conference on Great Lakes Research; Great Lakes Restoration and Resiliency. June 2-6, 2013, West Lafayette, IN.

42. Femeena, P V., Sudheer, K. P., Cibin R, Chaubey, I., Her, Y. (2013). Spatial optimization of cropping pattern in an agricultural watershed for food and biofuel production with minimum downstream pollution. American Geophysical Union Meeting of the Americas, Cancun, Mexico (May 14-17, 2013).

43. Chaubey I., Cibin R, Her Y. Gramig B M. (2013). Is Co-Production of Food and Energy Crops Environmentally Sustainable? A Land Use Optimization Approach- AWRA's 2013 Spring Specialty Conference Agricultural Hydrology and Water Quality II (Mar25-27), St. Louis, MO, USA.

44. Boles, Chelsie, and Jane Frankenberger. 2013. SWAT Model Simulation of Bioenergy Crop Impacts in a Small, Tile-Drained Watershed. Presented at the American Water Resources Association Agricultural Hydrology Conference, St. Louis Missouri, March 25.

45. Chaubey, I. 2013. Bioenergy, landscape changes and ecosystem response: opportunities for sustainable watershed management. Keynote Address given at the 47th Annual Convention of Indian Society of Agricultural Engineers (ISAE) and International Symposium on Bioenergy. Hyderabad, India. January 28-30, 203.

46. Chaubey, I., R. Cibin, Y. Her, and B. Gramig. 2012. Optimizing selection and landscape placement of energy crops. Annual Conference of the American Water resources Association. Jacksonville, FL.

47. Wang, R., L. Bowling, and K. Cherkauer. 2012., "Estimation of Aeration Stress Effects On Crop Yields in Midwest USA." ASA, CSSA, and SSSA International Annual Meetings. Oct. 21-24, 2012, Cincinnati, OH.

48. Trybula, E., I. Chaubey, J. Frankenberger, S.M. Brouder, and J.J. Volenec. 2012. Quantifying ecohydrological impacts of perennial rhizomatous grasses on tile discharge. Abstract 297-9. Inter. Meeting of the Amer. Soc. Agron.-Crop Sci. Soc. of Amer.-Soil Sci. Soc. of Amer. Oct. 21-24. Cincinnati OH.

49. Feng, Q., I. Chaubey, R. Cibin, and Y. Her. 2012. Biomass yield and hydrologic/water quality impacts from switchgrass and Miscanthus on marginal land. Paper no. 121337201, Annual Conference of the ASABE, Dallas, TX.

50. Her, Y. and I. Chaubey. 2012. Impact of the number of parameters and observations on calibration of SWAT. Paper no. 121338438, Annual Conference of the ASABE, Dallas, TX.

51. Cibin, R., I. Chaubey, and B. Engel. 2012. Optimum selection and placement of energy crops at watershed scale: a multi-objective optimization framework for sustainable bioenergy production. Paper no. 121337030, Annual Conference of the ASABE, Dallas, TX.

52. Chaubey, I. 2012. Sustainable watershed management under food, feed, and bioenergy production. Invited talk presented at the Joint China-U.S. Joint Symposium on "Land Use, Ecosystem Services, and Sustainable Development". September 17-19. Shenyang, China.

53. Chaubey, I., J. Volenec, S. Brouder, E. Trybula, J. Burks, and C. Raj. Parameterization of Soil and Water Assessment Tool (SWAT) for energy crop production. OBP Monthly Lab Team Conference. June 4, 2012.

54. Gramig, B.M. "Farmer decision-making and joint economic-ecological outcomes in agro-ecosystem management." Linking Biodiversity and Sustainability Across Natural and Managed Landscapes: Can agriculture and natural communities be complementary? Symposium, Purdue University, April 23, 2012.

55. Chaubey, I. 2012. Environmental management challenges from bioenergy, landscape changes, and ecosystem response: perspectives at global scale. Keynote address at the 46th Annual Conference of the Indian Society of Agricultural Engineers. Pant Nagar, India. February 28, 2012.

56. Brouder, S.M. and J.J. Volenec. 2012. Impact of Climate Change on Crop Nutrient and Water Use Efficiencies: What we know we don't know. Plenary Talk given at the Plant Growth, Nutrition and Environment Interactions Conf., University of Veterinary Medicine, Vienna, Austria. Feb 18 – 21.

57. Volenec, J.J. and S.M. Brouder. 2012. Nutrient Use in Bioenergy Cropping Systems. Poster presented at the Plant Growth, Nutrition and Environment Interactions Conf., University of Veterinary Medicine, Vienna, Austria. Feb 18 – 21.

58. Murphy, P. 2012. Production of dedicated bioenergy crops on marginal lands: what makes sense in 2012?. 25 x '25 Alliance energy panel at the Agricultural Equipment Technology Conference. Louisville, KY. February 13, 2012.

59. Burks, J.L., J.J. Volenec and S.M. Brouder. 2011. Seasonal cycling and partitioning of C and N in perennial bioenergy crops. Abstract ID# 64585. ASA-CSSA-SSSA International Meetings, Oct. 16 to 19, 2011. San Antonio, TX.

60. Chaubey, I. 2011. Sustainability assessment of bioenergy crop production, landscape changes, and ecosystem response. Presented at EPA-ORD, Las Vegas. October 12, 2011.

61. Chaubey, I. 2011. Scaling biomass production from field to watershed. China-US 2011 Joint Symposium on Global Sustainability Issues in Energy, Climate, Water and Environment. Purdue University. September 25-28, 2011.

62. Cibin, R., E. Trybula, I. Chaubey, and B. Engel. 2011. Watershed scale impacts of bioenergy production on hydrology and water quality using SWAT model. American Geophysical Union Conference. December 6-10, 2011. San Francisco, CA.

63. Trybula, E., J. Burks, C. Raj, I. Chaubey, S. Brouder, and J. Volenec. 2011. Parameterization of perennial bioenergy feedstock grasses Miscanthus x giganteus and upland Shawnee switchgrass cultivar in the SWAT model using a multi-disciplinary approach. Annual Ecological Sciences and Engineering Conference, Purdue University. November 9, 2011.

64. Woodson, P., S. Cunningham, P. Murphy, S. Brouder, J. Volenec. 2011. Influence of potassium and phosphorus on yield and composition of switchgrass. In Proceedings of the ASA-CSSA-SSSA Ann. Mtg, San Antonio, TX, Oct. 16 – 19, 2011. http://a-c-s.confex.com/crops/2011am/webprogram/Paper65191.html.

65. Brouder, S.M. 2011. Minimum plant and soil metrics for characterizing Environment (E) x Management (M) impacts on crop performance. Yield Gap Assessment Workshop, Beijing, China, Aug. 31 – Sept. 2.

66. Brouder, S.M. 2011. Impact of climate change on crop nutrient (and water) use efficiencies. China Agricultural University Seminar Day, Beijing, China, Sept. 3.

67. Brouder, S.M. 2011. Comparative Agro-ecological Performance of Perennial and Annual Biomass Systems: Metrics and Data Workflows. China-US 2011 Joint Symposium on Global Sustainability Issues in Energy, Climate, Water and Environment. West Lafayette, IN, Sept. 26 – 29.

68. Cibin R, I. Chaubey, M. Thomas, and B. Engel.2011. Impacts of corn stover removal for biofuel on hydrology/water quality in Indiana. Paper# 1111176, Annual Conference of the American Society of Agricultural and Biological Engineering, Louisville, KY.

69. Cibin R, I. Chaubey, E. Trybula, M. Thomas, and B. Engel. 2011. Watershed scale impacts of energy crops on hydrology and water quality. Paper# 1111177. Annual Conference of the American Society of Agricultural and Biological Engineering, Louisville, KY.

70. Thomas, M.A., B.A. Engel, and I. Chaubey.2011. An Assessment of the Water Quality Impacts of Corn-Silage as a Bioenergy Feedstock for Cellulosic Biofuel Production. Paper# 1111802. Annual Conference of the American Society of Agricultural and Biological Engineering, Louisville, KY.

71. Vester, K., P. Murphy, and I Chaubey. 2011. Production of herbaceous and woody biomass feedstocks on marginal cropland. Poster presented at the 6th Frontiers in Bioenergy Conference; US-Brazil Symposium on Sustainable Bioenergy. May 16-18, 2011, West Lafayette, IN.

72. Werling, C., J. Frankenberger, E. Trybula, I. Chaubey, and B. Gramig. 2011. Identifying Bioenergy Feedstock Scenarios to Inform Sustainability Assessments. Poster presented at the 6th Frontiers in Bioenergy Conference; US-Brazil Symposium on Sustainable Bioenergy. May 16-18, 2011, West Lafayette, IN.

73. Chaubey, I. 2011. Developing watershed management strategies for bioenergy crops. 6th Frontiers

in Bioenergy US-Brazil Symposium on Sustainable Bioenergy. May 16-18, 2011. West Lafayette, IN.

74. Feng, Q., I. Chaubey, J. Volenec, M.M. Kalcic, Y. Gu Her, M.A. Thomas, and C. Raj. 2011. Identification of available marginal land for biofeedstock production in Wildcat Creek watershed. Poster presented at the 6th Frontiers in Bioenergy Conference; US-Brazil Symposium on Sustainable Bioenergy. May 16-18, 2011, West Lafayette, IN.

75. Vester, K., P.T. Murphy, and I. Chaubey. 2011. Production of herbaceous and woody biomass feedstocks on marginal cropland. Poster presented at the 6th Frontiers in Bioenergy Conference; US-Brazil Symposium on Sustainable Bioenergy. May 16-18, 2011, West Lafayette, IN.

76. Volenec, J.J. and S.M. Brouder. 2010. Water-use efficiency in biomass cropping systems. 2nd China-US Workshop on Biotechnology of Bioenergy Plants. Beijing, China. September 19-21.

77. Brouder, S.M., R.F. Turco, and J.J. Volenec. 2010. Nitrogen use efficiency in bioenergy cropping systems. 2nd China-US Workshop on Biotechnology of Bioenergy Plants. Beijing, China. September 19-21.

78. Brouder, S.M., and J.J. Volenec. 2010. Greenhouse gas emissions and pelicans: Ecological accounting in bioenergy cropping systems. China-US 2010 Joint Symp. on Energy, Ecosystem, and Environmental Change. Beijing, China. September 22-24.

79. Volenec, J.J., S.M. Brouder, and R.F. Turco. 2010. Agroecological considerations when growing biomass. China-US 2010 Joint Symp. on Energy, Ecosystem, and Environmental Change. Beijing, China. September 22-24.

80. Brouder, S.M., and J.J. Volenec. 2010 Environmental impacts of using annual crops for biofuel. ASA-CSSA-SSSA International Meetings, Oct. 31 to Nov. 4, 2010. Presentation No. 250-1. http://a-c-s.confex.com/crops/2010am/webprogram/Paper57723.html.

81. Brouder, S.M., and J.J. Volenec. 2010. Grain and dual purpose production: system efficiencies, limitations, and potential. ASA-CSSA-SSSA International Meetings, Oct. 31 to Nov. 4, 2010. Presentation No. 124-2. http://a-c-.confex.com/crops/2010am/webprogram/Paper58277.html.

82. Cherkauer, K. A. and V. Mishra (2011), Observed climate variability and change impacts on agricultural productivity in the Midwestern US, American Meteorological Society (AMS) 91st annual meeting, Seattle, WA, January 25, 2011.