Watershed Scale Optimization to Meet Sustainable Cellulosic Energy Crop Demands

March 23, 2015

Analysis and Sustainability Peer Review

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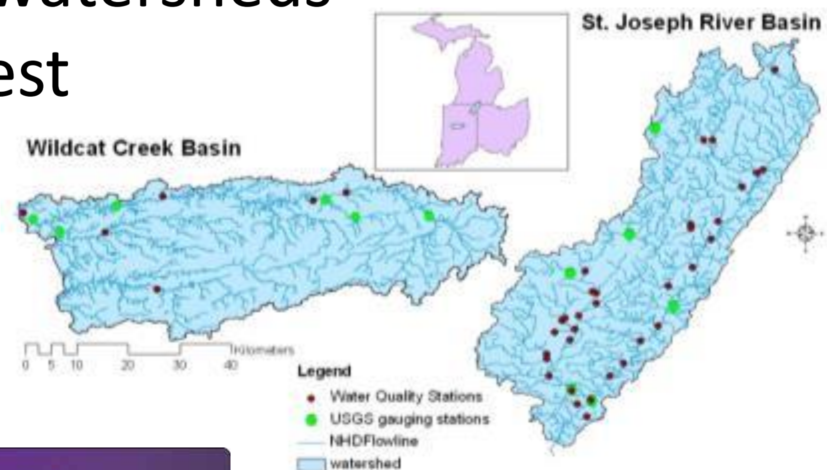
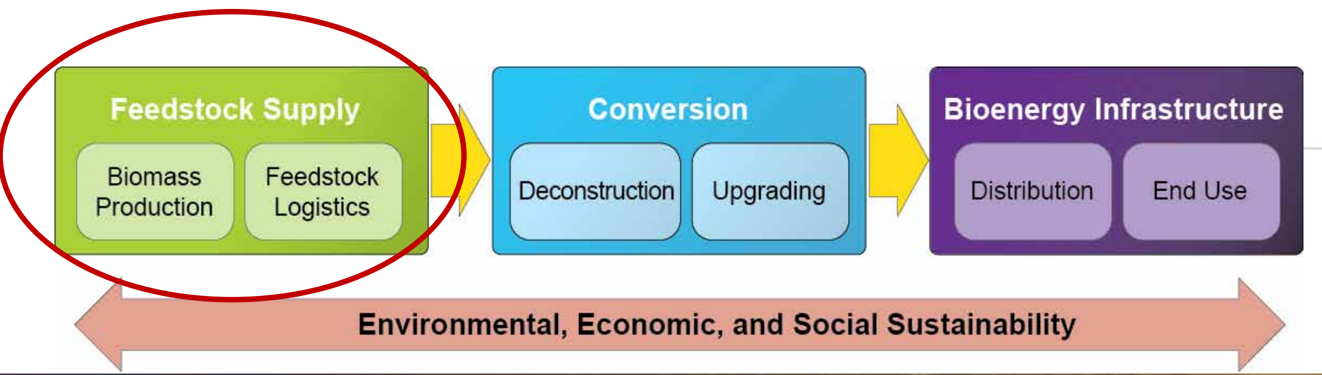
Purdue University

Goal Statement

- Overall goal is to conduct a watershed-scale sustainability assessment of multiple energy crops and removal of crop residues
- Assessment conducted in two watersheds representative of Upper Midwest
  - Wildcat Creek watershed
  - St. Joseph River watershed





Quad Chart Overview

Timeline

- Start – September 2010
- End – September 2015
- Percent complete – 85%

Budget

Years the project has been funded – 2010-2014

Average annual funding - $497,795

Barriers

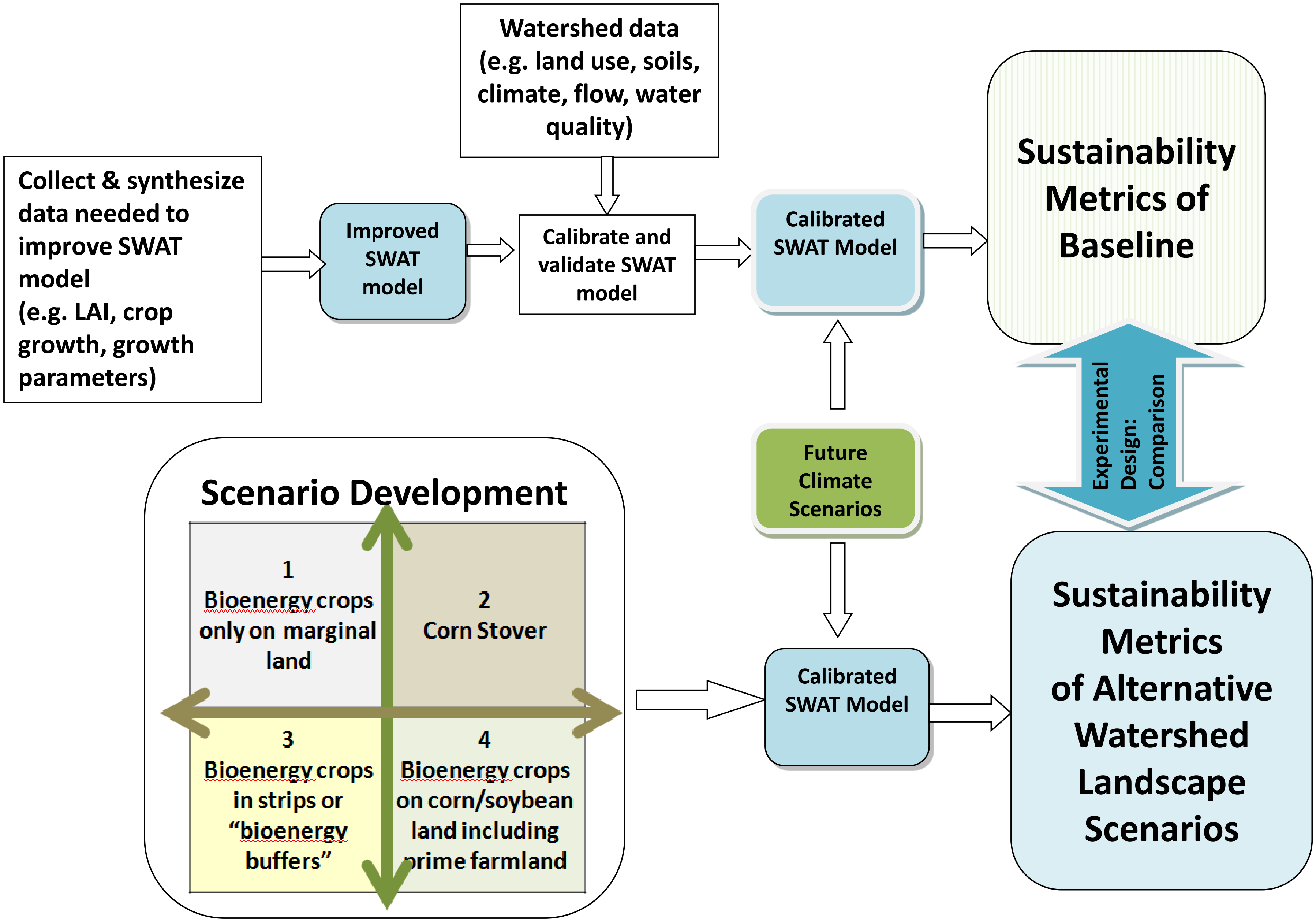
- Barriers addressed
  - Ft-B. Production
  - St - A. Scientific consensus on bioenergy sustainability
  - St -B. Consistent, defensible message on bioenergy sustainability
  - St-C. Sustainability Data
  - St-D. Sustainability Indicators and methods
  - St-E. Best Practices and Systems

Partners

Purdue University; Mendel Bioenergy Seeds; St. Joseph River Watershed Initiative; The Nature Conservancy; US EPA - Region 5

Project Overview

- **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.


Watershed data (e.g. land use, soils, climate, flow, water quality)
Collect & synthesize data needed to improve SWAT model (e.g. LAI, crop growth, growth parameters)
Improved SWAT model
Calibrate and validate SWAT model
Calibrated SWAT Model
Sustainability Metrics of Baseline
Experimental Design: Comparison
Future Climate Scenarios
Scenario Development
1 Bioenergy crops only on marginal land
2 Corn Stover
3 Bioenergy crops in strips or "bioenergy buffers"
4 Bioenergy crops on corn/soybean land including prime farmland
Calibrated SWAT Model
Sustainability Metrics of Alternative Watershed Landscape Scenarios

Technical Accomplishments/ Progress/Results (Task A)

- Existing data were synthesized and data gaps identified
- **4275 plot-years** of bioenergy crops have been monitored
- Using the data collected, we improved the SWAT model ability to simulate:
  - Bioenergy crop growth
  - Removal of corn stover
  - Simulation of woody biomass for energy crops (e.g. poplar)
  - Production of energy crops in buffer strips/riparian areas
  - Biotic and abiotic impact of excess moisture and drought
  - Climate change impacts using user-input CO_2 time series
  - Hydrologic/water quality impacts

Data Collected to Improve Biophysical Models

- Emergence dates (daily observations)
- Daily temperature (^{o}C)
- Daily solar radiation (x0.5 determined PAR)
- Total biomass (Monthly destructive sampling)
  - Top growth, stem base, rhizome, root
- Leaf Area Index (Decagon AccuPAR LP-80)
- Canopy height measurement (m)
- Tissue Nitrogen or phosphorus
- Annual yield: Biomass removed at harvest (g/m^2)
- Field residue after harvest (g/m^2)
- Root distribution to 60 cm (percent)

Biomass System Yield Interacted with Location

	Biomass Yield, kg DM/ha		
Biomass System	TPAC	NEPAC	SEPAC
Switchgrass	10157	1349	1523
Miscanthus	16759	8809	9049
Big Bluestem – indiangrass mix	4610	3018	1085

Miscanthus grew at all three locations, but thrived in the better soils at the TPAC location. Switchgrass and the big bluestem-indiangrass prairie mix did not survive in the landfill overburden at the SEPAC location, and each performed similarly at TPAC and NEPAC.

In 2013, Biomass Composition was Fairly Consistent Across Location

	Cellulose, g/kg DM			Lignin, g/kg DM		
Biomass System	TPAC	NEPAC	SEPAC	TPAC	NEPAC	SEPAC
Switchgrass	377	394	*	87	80	*
Miscanthus	388	448	372	86	94	88
Big Bluestem – indiangrass mix	377	365	*	61	49	*

*no sample available for analysis

Miscanthus had high concentrations of cellulose and lignin. The big bluestem-indiangrass mixture tended to have low concentrations of cellulose and lignin compared to the other systems. Switchgrass composition was generally intermediate between the other systems.

TPAC – Throckmorten Purdue Ag. Center; NEPAC – Northeast Purdue Agriculture Center; SEPAC – Southeast Purdue Ag. Center

Genotype x Environment x Mgmt Interactions Complicate Yield (kg/ha) Predictions From Field to Landscape

Very Low Yield-No N Response

Biomass Species	N Fertilizer kg/ha	Location 1 SEPAC	Location 2 NEPAC	Location 3 TPAC
Maize (Well-studied Agro-ecosystem)	0	700	3361	11479
	50	173	4792	14063
	100	1548	2804	15705
	150	110	9544	14581
	200	195	8053	16896
Photoperiod-sensitive Sorghum (Understudied Biomass System)	0	9501	2746	23100
	50	8934	6702	22253
	100	10143	7468	23861
	150	12695	8974	23827
	200	14593	13081	23519

High Yield ~50% Increase Due To N

Very High Yield-No N Response

Need to understand the biophysical basis for the GxExM;

Water Flow and Water Composition in Agro-ecosystems

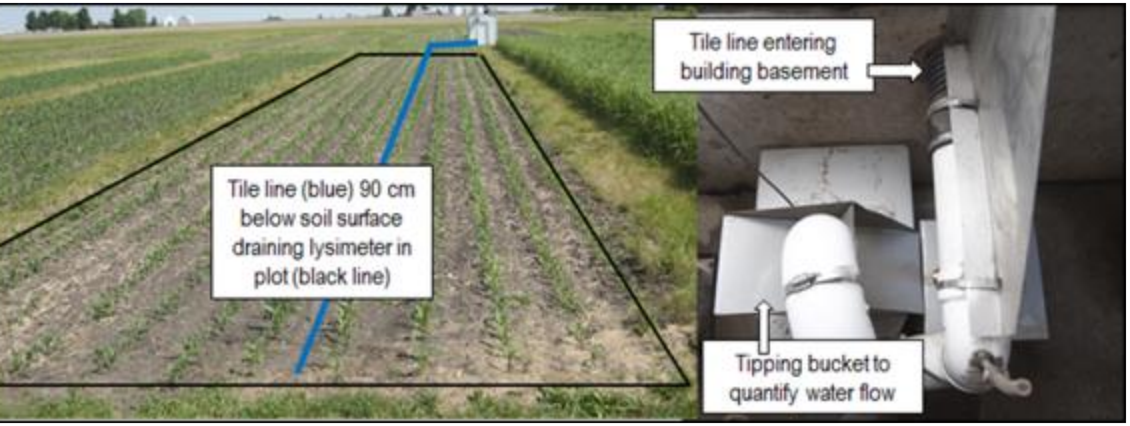
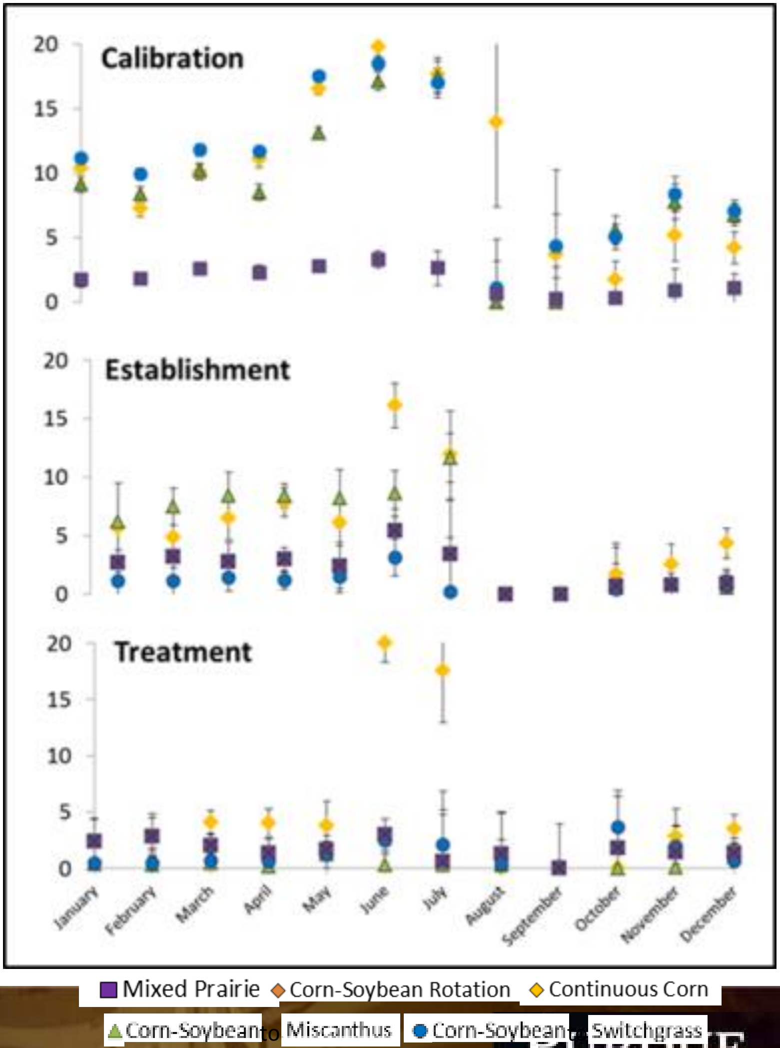


Figure 1. Photo of one of 48 plots (outlined in black) at the Water Quality Field Station (left). A 10 x 30-m lysimeter with impermeable side walls is located in the center of the plot. A 10-cm-diam tile (blue line) drains water from the lysimeter to a basement under an adjacent building. The tile enters the building basement where a calibrated tipping-bucket system is used to measure water volume and a flow-proportional sub-sample is captured for laboratory analysis (right photo).

Average monthly tile drain nitrate conc. by cropping system. Establishment of *Miscanthus* and switchgrass decreased nitrate concentrations to values observed in long-term mixed prairie plots within three years.



Perennial grasses had lower sediment losses

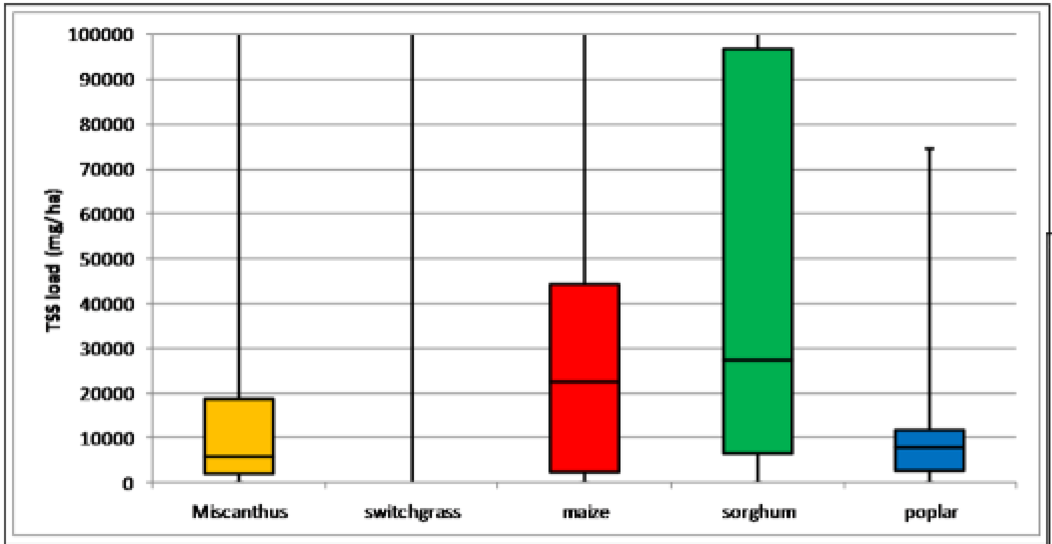


Figure 10. Total suspended solids in surface runoff as an effect of crops in TPAC east plots. One replicate, no statistical significance.

- Greater loss of soil following rain events from poplar, maize, and sorghum.
- Consistently low level of erosion from *Miscanthus* and switchgrass plots.

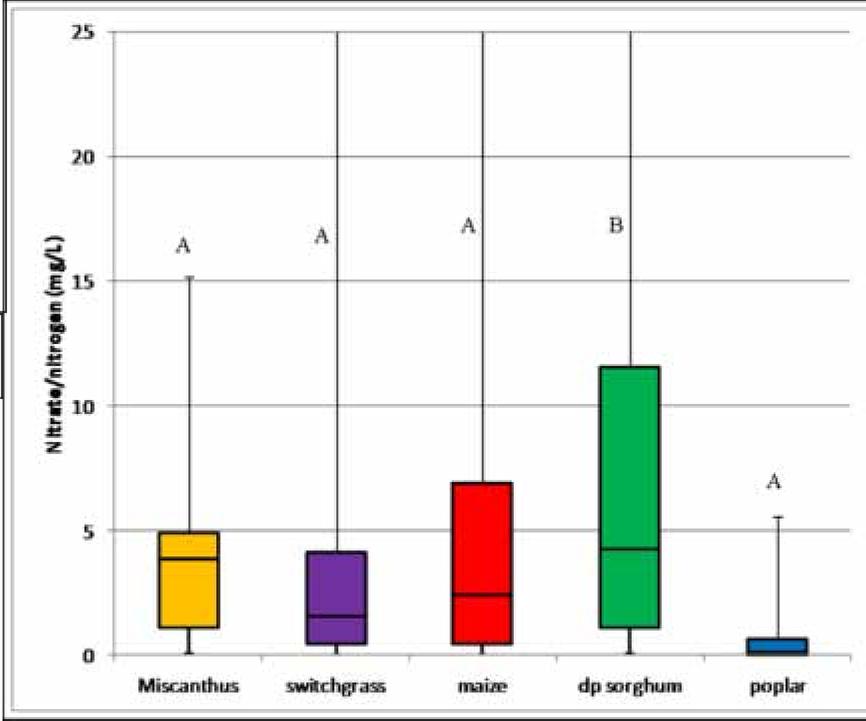


Figure 4. Effects of crop on subsurface nitrate-nitrogen loss in TPAC east plots. Means with different letters are significantly different (Tukey's HSD, $p<0.05$).

GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2014), doi: 10.1111/gcbb.12210

Perennial rhizomatous grasses as bioenergy feedstock in SWAT: parameter development and model improvement

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Abstract

The Soil and Water Assessment Tool (SWAT) is increasingly used to quantify hydrologic and water quality impacts of bioenergy production, but crop-growth parameters for candidate perennial rhizomatous grasses

- Improved SWAT model validated with data collected
- Our model improvements are now incorporated in the official SWAT model
- SWAT code (Version 612): (http://swat.tamu.edu/software/swat-model/

SWAT Model Simulations with Improved Model (from Trybula et al., 2014)

	Evapo-Transp. (mm)	Surface Runoff (mm)	Soil Erosion (Mg/ha)	Organic N loss (kg/ha)	Organic P loss (kg/ha)	Nitrate loss (kg/ha)	Min P loss (kg/ha)
Maize	702	202	4.454	27.96	3.435	30.46	1.141
Alamo SG	610	61	0.021	0.14	0.017	18.39	0.028
Shawnee SG	786	39	0.010	0.07	0.009	14.59	0.020
Miscanthus	845	33	0.009	0.06	0.007	8.20	0.022

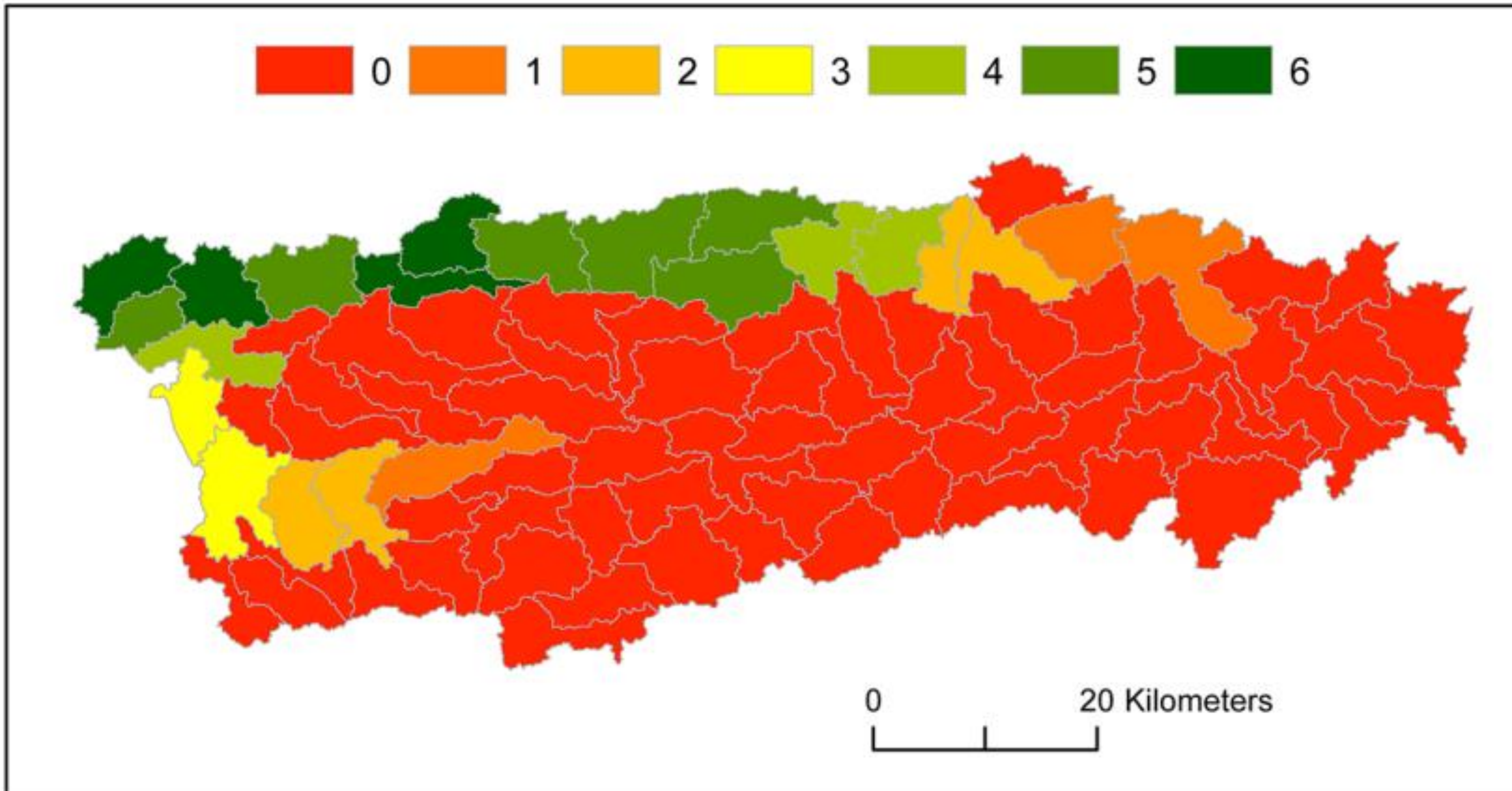
Notable Differences Between SG Cultivars

Notable Differences Between SG Cultivars & Miscanthus

Additional Model Improvements

- Woody bioenergy crops representation in SWAT
  - Model outputs are improved due to new algorithms and parameterization
- Soil moisture representation in SWAT
  - Better simulation of bioclimate stress effects on annual yield and inter-annual variability
- VFS representation SWAT model to simulate energy crop production in VFS areas
  - Improved model simulates biomass growth in VFS
  - Improvements tested with measured data fromfrom Iowa (Helmers et al. 2012, J. Environ. Qual. 41)

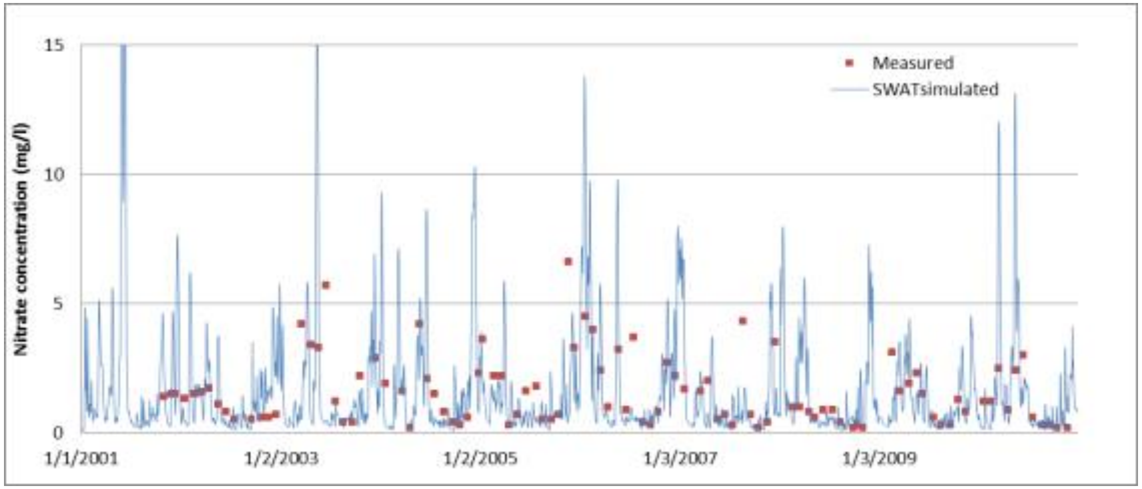
We Have Developed a Model to Predict Number of Sensitive Fish Species

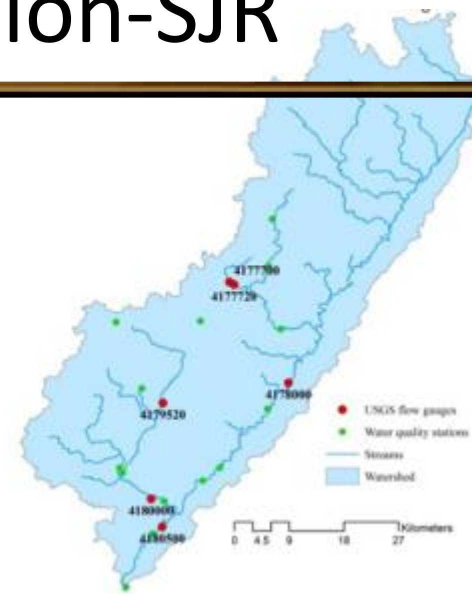


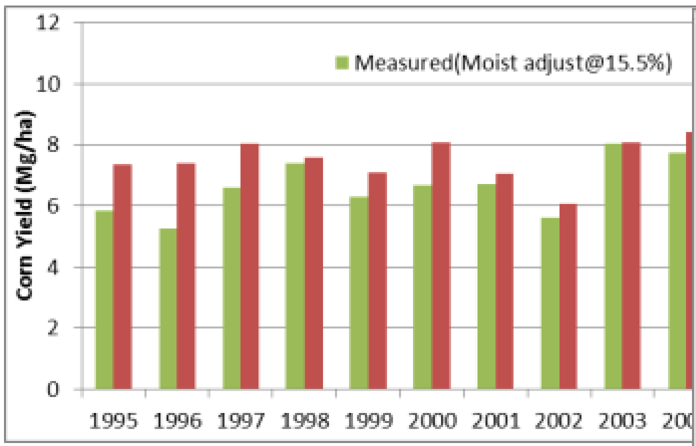
Technical Accomplishments/ Progress/Results (Task B)

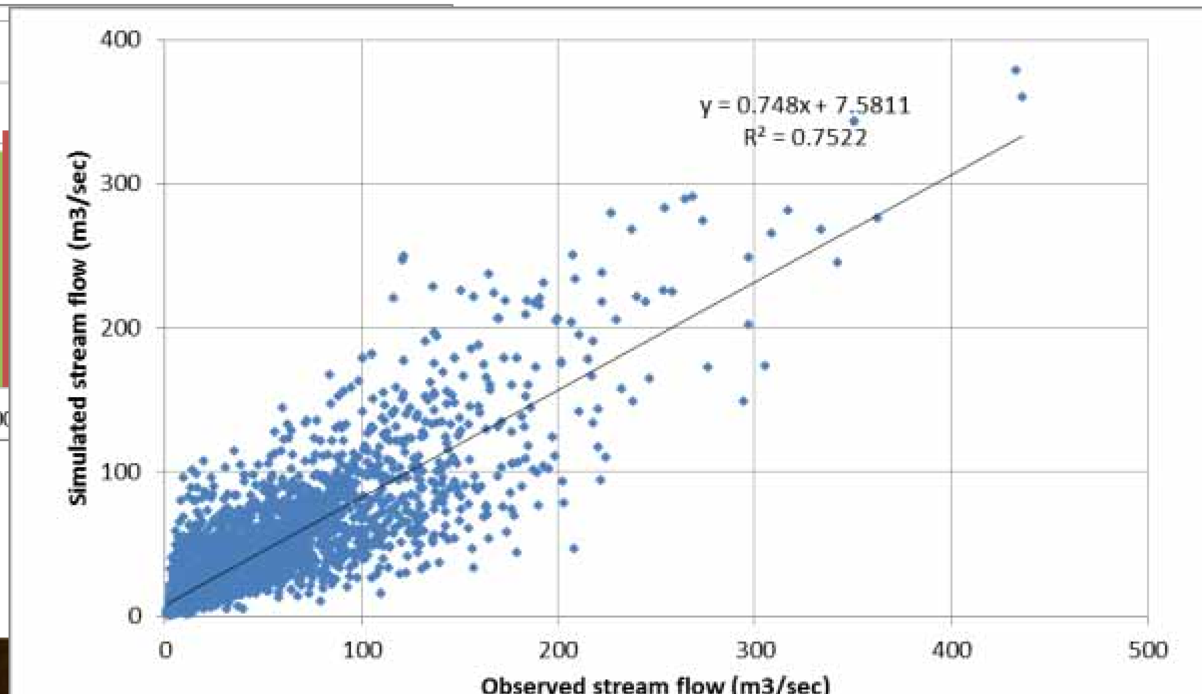
- Model developed and calibrated for Wildcat creek (WCC) and St. Joseph River (SJR) watershed
- Established baseline for both watershed using measured weather data and future climate projections
- Plausible bioenergy crop production scenarios developed
- Sustainability indicators of bioenergy scenarios were evaluated
- (Ongoing) Investigating food/fuel provision and environmental impacts of replacing corn/soybeans with biofuel crops in lands not ideal for row crop

SWAT Model – Calibration/Validation-SJR









Task B.1

Accomplishment: Developed Appropriate Indicators of Bioenergy Crop Impacts

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			

Baseline Scenario Established – Future climate

- Future climate was simulated with 9 climate model simulations:
- 3 models
  - GFDL CM2.0.1,
  - UKMO HadCM3 3.1
  - NCAR PCM 1.3

for each of

- 3 future emission scenarios (A1B, A2, B1)

	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

Sustainablility indicators of the baseline scenario with GCM data for three 30-year simulations; average values from 9 GCM model simulations are provided

Scenario Development Principles

Prioritize Food and Feed (Corn & Soybeans)

Decentralized fuel production

(Small refineries)

2 **Bioenergy crops only on marginal land**	**1** **Corn Stover**
3 **Bioenergy crops in strips or “bioenergy buffers”**	**4** **Bioenergy crops on corn/soybean land including prime farmland**

Centralized fuel production

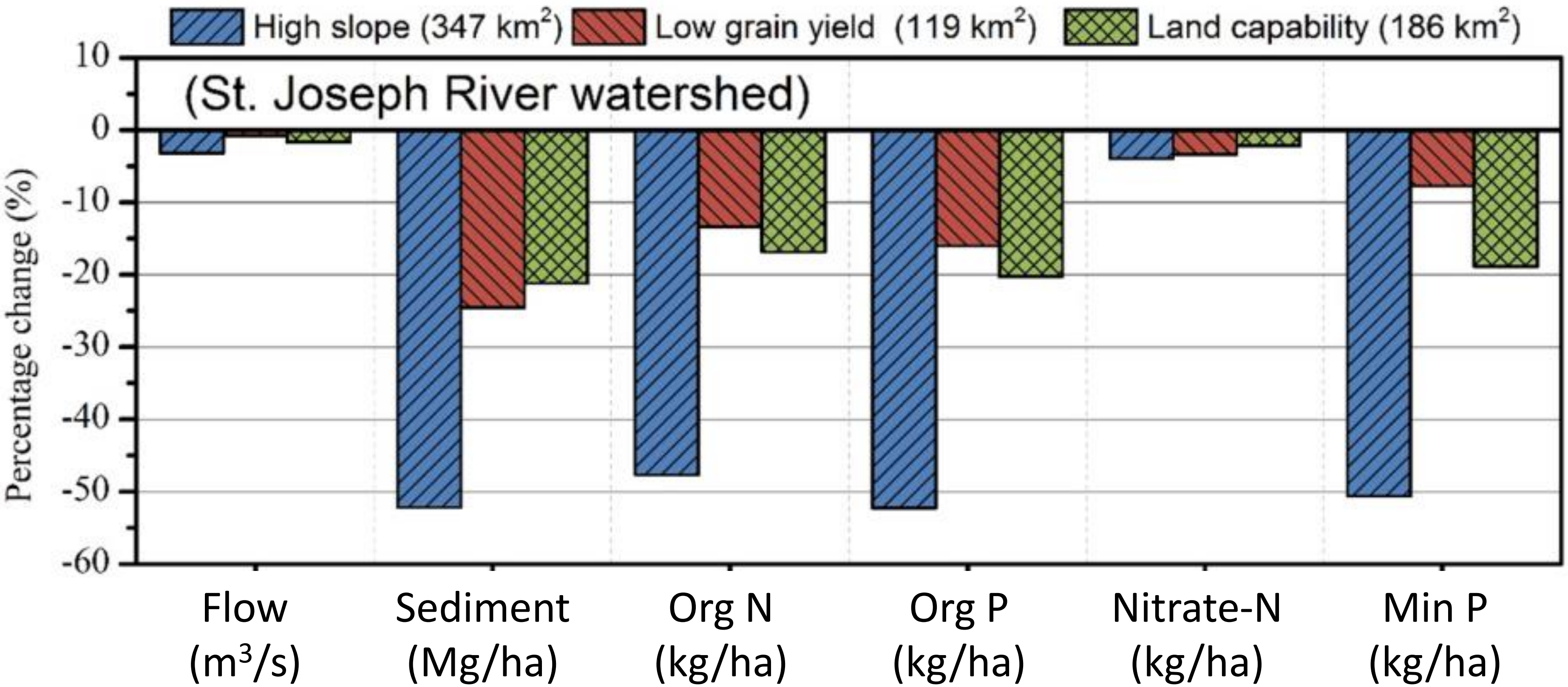
(Large refineries)

Prioritize Water Quality and Environment

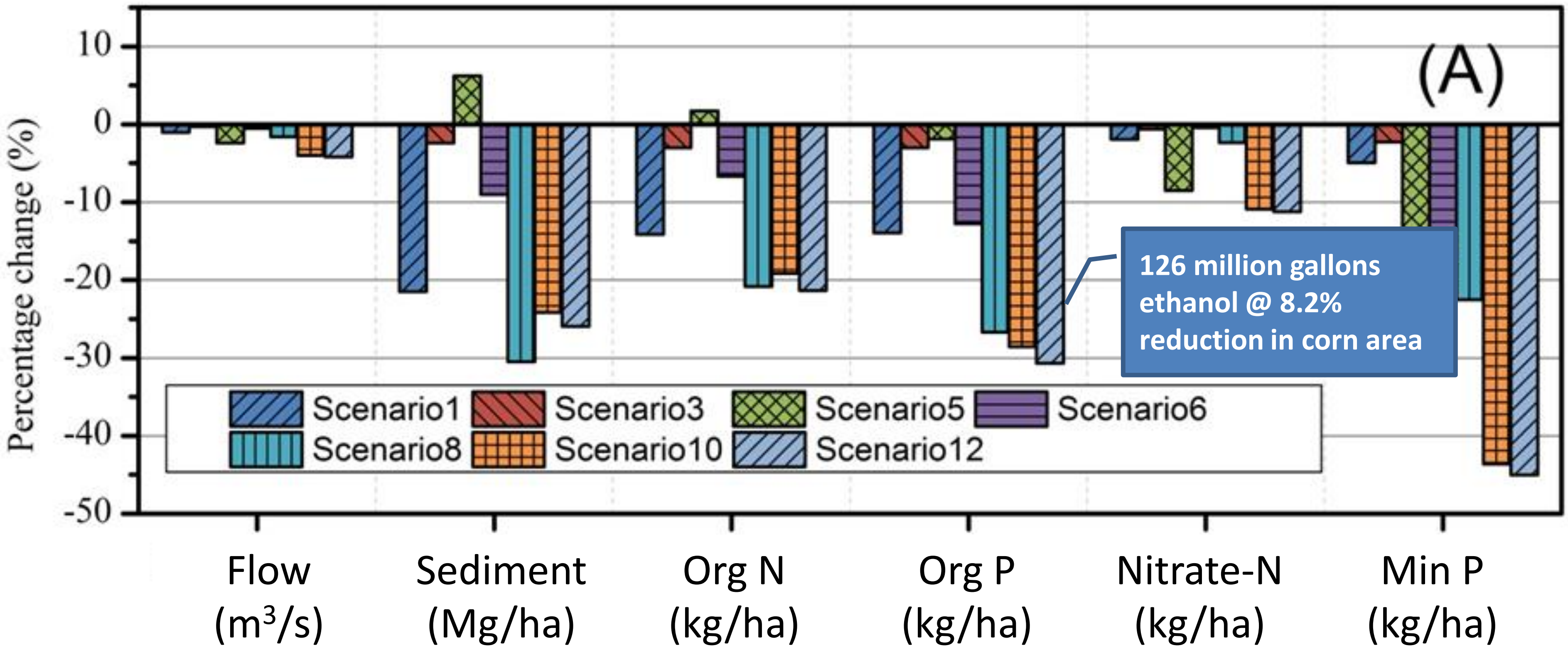
Bioenergy Scenarios

1. Corn stover removal– 20%, 30% and 50% (consistent with contracts that are emerging between farmers and cellulosic biorefineries), with and without nutrient replacement
2. Perennial bioenergy crops on marginal lands – environmental (>2% slope), agricultural (low grain yield), land quality (LCC>2)
3. Perennial bioenergy crops in buffers around corn/soybeans
4. Bioenergy crops in all agricultural areas
    - 100% of watershed
    - 50% of watershed, randomly selected
    - 50% of watershed, selected with plausibility criteria of marginal land, high slope area, pasture area, crop productivity etc.

Miscanthus Grown on Marginal Lands Improves Water Quality



Most of the Bioenergy Crop Production Scenarios Improve Water Quality



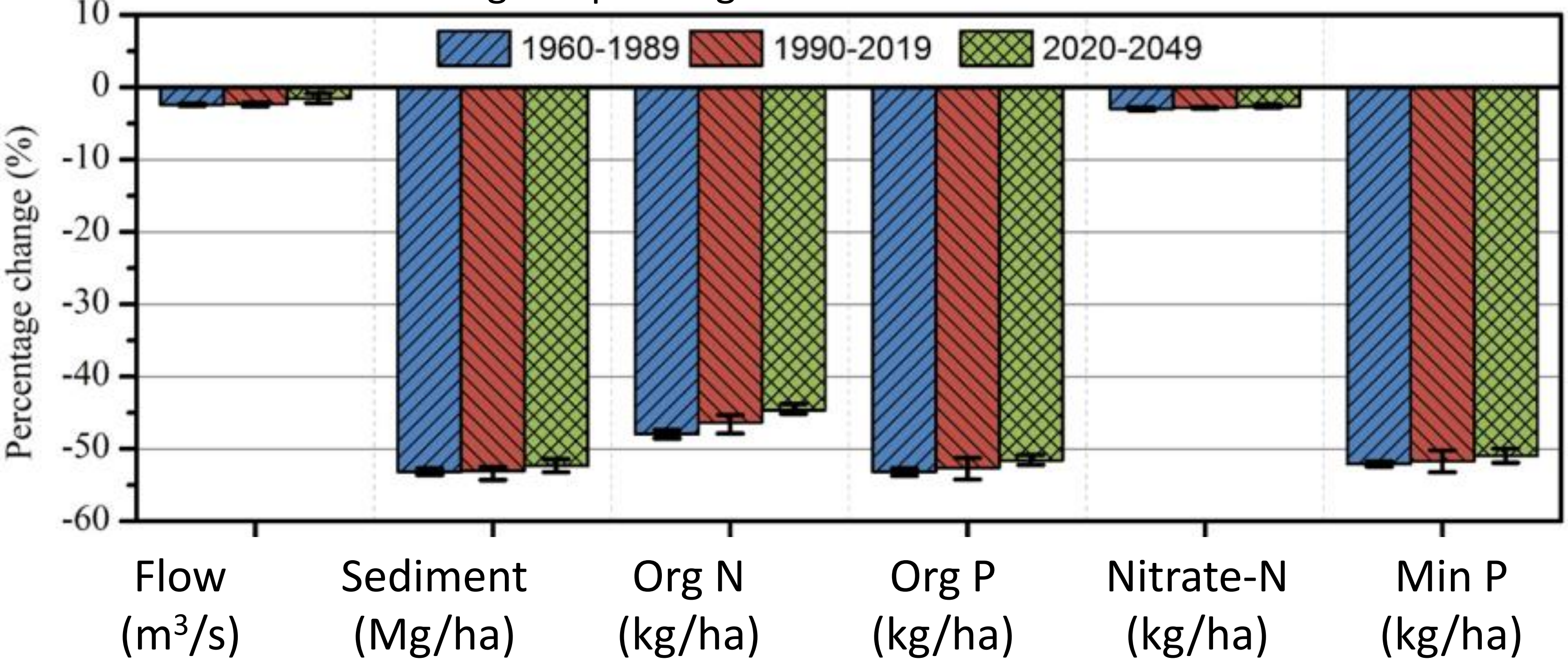
Scenario1: >2% slope Scenario3: <5%ile yield Scenario 5: Stover 70%

Scenario6: Pasture Scenario8: >2% slope + Pasture

Scenario 10: Stover 70% + >2% slope + Pasture Scenario 12 : All

Environmental impacts of energy crop scenarios with climate change

Miscanthus in high slope marginal land- SJR



- Results that are similar under all climate periods and GCMs (error bars) show that water quality benefits due to **land use change** is generally greater than the effects of **climate change variability.**

Technical Accomplishments/ Progress/Results (Task C)

- Developed efficient optimization methods
- Economic analysis conducted: Feedstock cost of production, transportation costs, and optimization
- Various optimization based scenarios developed and evaluated
- (On-going) 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)

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Economic Analysis of Cellulosic Bioenergy Crops: How the Pieces Fit Together

Data

Climate and environment

- Precipitation, temperature
- Soils
- Water flow
- Water quality: N, P, Sediment

Agronomic

- Yields
- Management: tillage, fertility, etc.

Literature

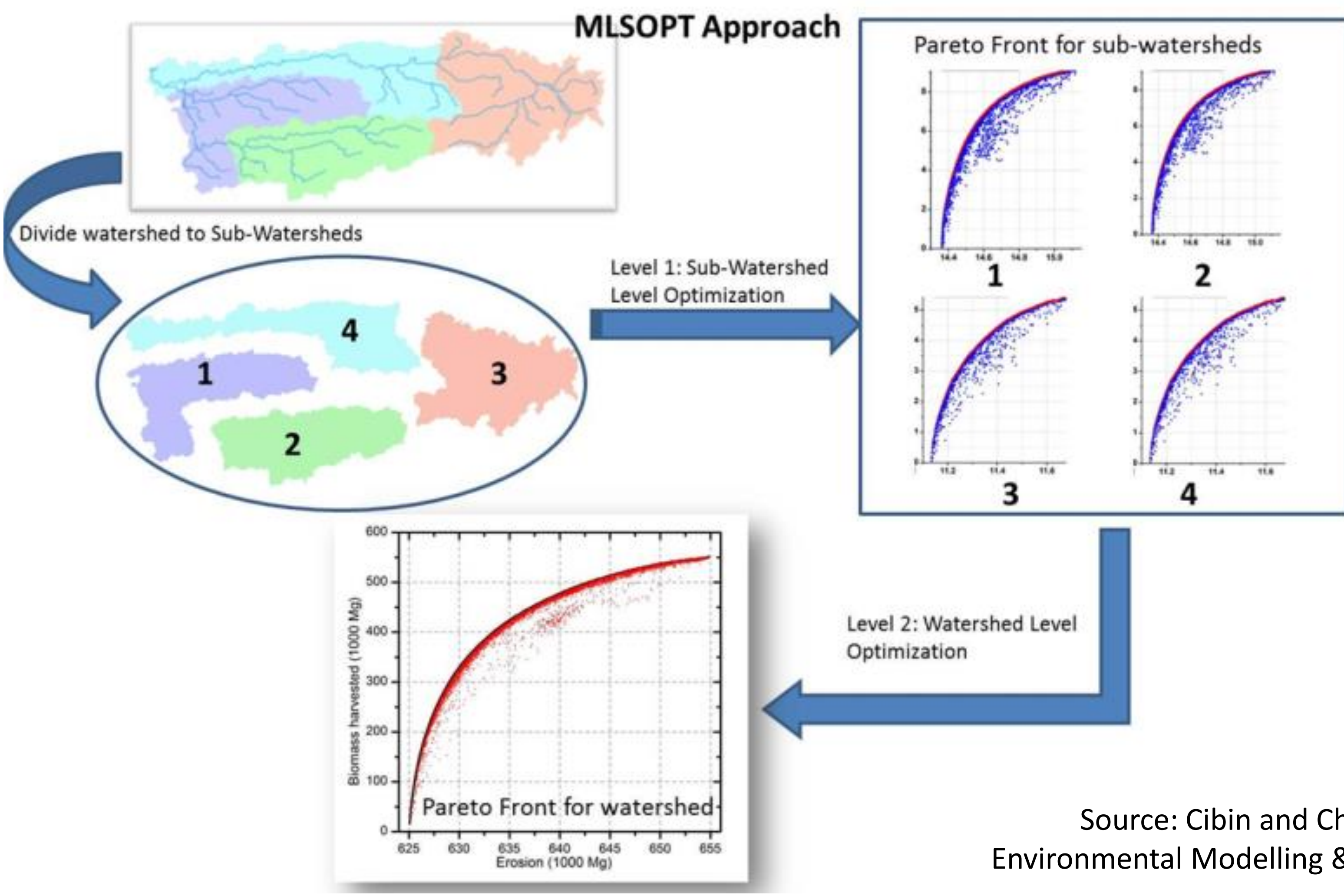
- Input costs
- Transport and logistics costs

SWAT model

Economic Budgets

Watershed Optimization

Efficient Optimization Method Developed- MLSOPT



Source: Cibin and Chaubey. 2015, Environmental Modelling & Software 66

MLSOPT was 20 times more computationally efficient in solving source area based optimization and 3 times more computationally efficient for watershed outlet based optimization

Loading, Unloading and Hauling Costs

Activity	Time (hrs)	Hourly Wage ($/hr)	Corn ($/bale)	SG & Mxg ($/bale)	Source
Loading			1.15	1.15	Petrolia (2008)
Unloading			1.15	1.15	
Truck Wait	1.329	19.68	0.87	0.87	Thompson & Tyner (2014)
Oversize Permit			0.02	0.02	Author's Estimate
Total			3.45	3.45	2014 dollars

Hauling cost	$0.21 per bale, per loaded mile (includes cost of the return trip)	Iowa State University, 2014

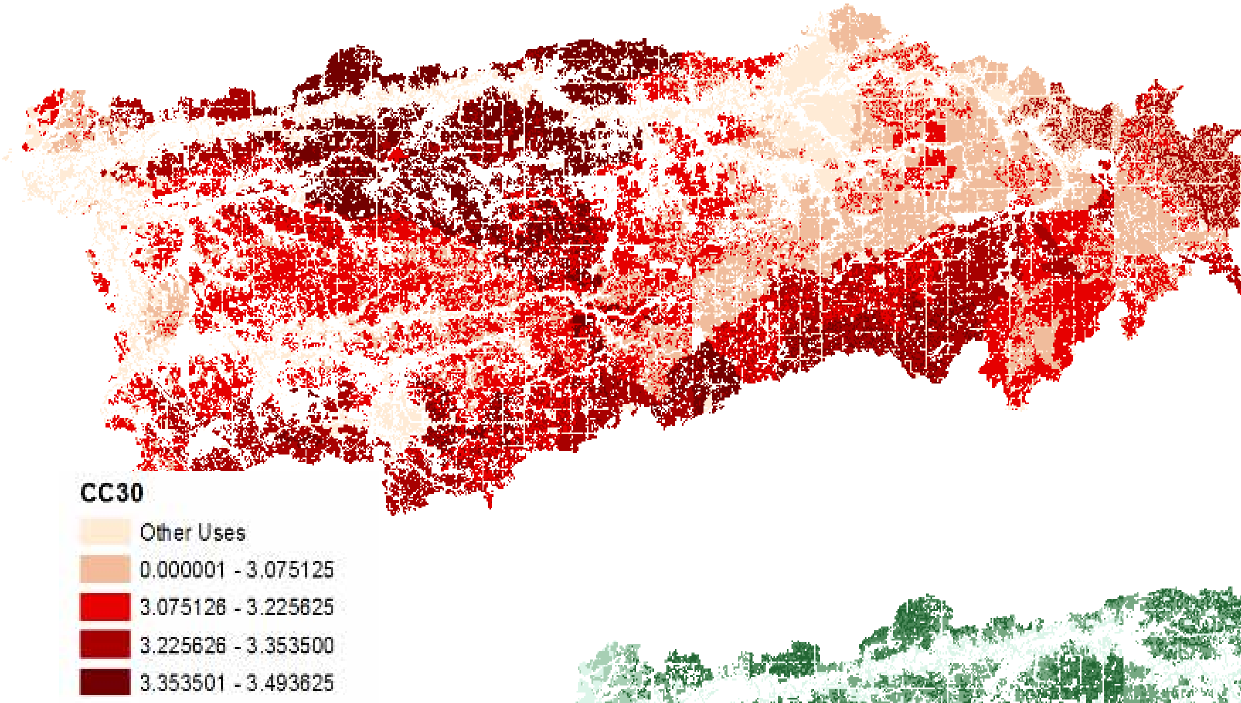
Farm Gate to Bio-refinery Gate Production and Transportation Costs

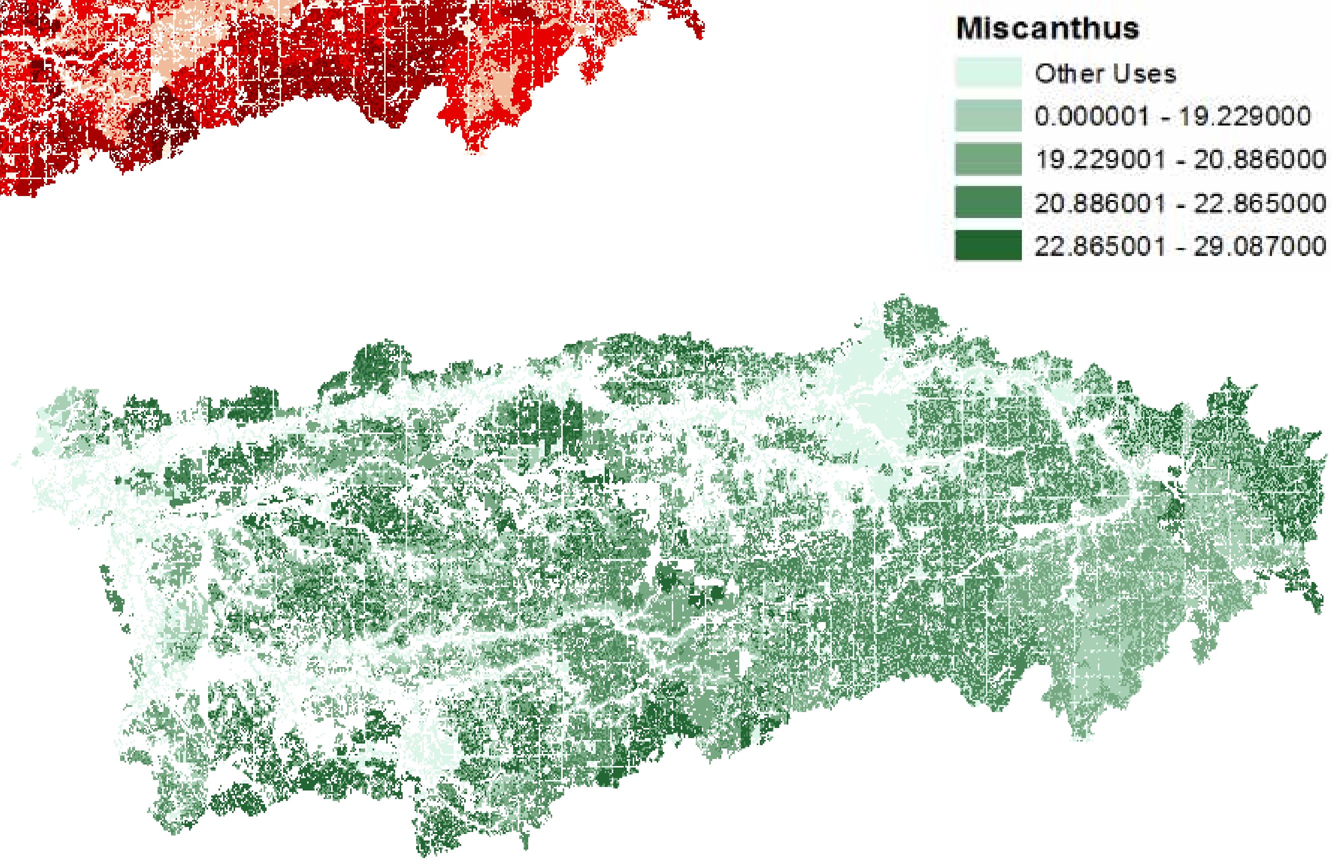
Scenario	Cropping system	Unit Production Cost ($/ha)	Total Watershed Production ($)	Total Loading + Unloading ($)	Total Hauling ($)	Total Cost ($)
1	Baseline: Corn-Soy (CS)	0	0	0	0	0
2	Continuous Corn, 20% removal (CC20)	126.34	18,308,257	1,830,521	1,813,618	21,952,396
3	CS30	90.30	13,085,532	1,308,762	1,296,749	15,691,043
4	CS50	161.30	23,374,077	2,218,639	2,197,708	27,790,423
5	CC30	190.08	27,544,855	2,753,227	2,727,357	33,025,439
6	CC50	334.00	48,401,540	4,600,804	4,556,210	57,558,555
7	Switchgrass	1,253.73	181,681,425	11,699,516	11,585,356	204,966,297
8	Switchgrass, No-Till planted	1,245.30	180,460,890	11,697,704	11,583,978	203,742,572
9	Miscanthus	2,108.50	305,549,860	22,675,397	22,551,770	350,777,026

Simulated Biomass Yield Results from SWAT

	Biomass Yield (dry metric ton/ha)	Total Production (metric tons)
Baseline CS	0	0
CC20	2.11	306,475
CS30	3.02	219,048
CS50	5.13	371,502
CC30	3.18	461,092
CC50	5.32	770,681
Switchgrass	10.65	1,543,463
SwitchgrassNoTill	10.65	1,543,226
Miscanthus	20.64	2,991,663

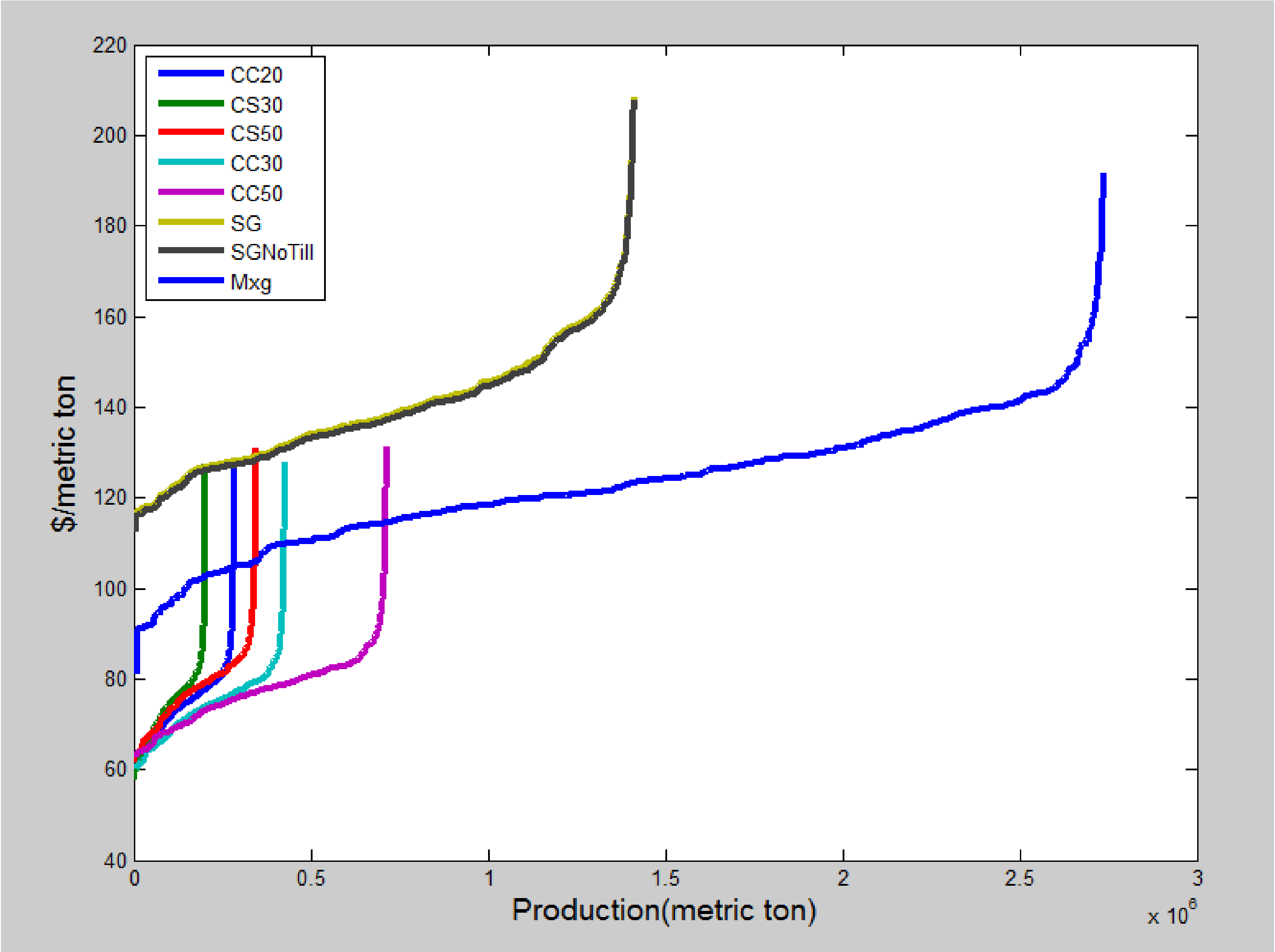
Yield Variation in the Watershed: CC30 and *Miscanthus*





Task C. 1

Supply Curves for 8 Biomass Production Scenarios in the Wildcat Creek Watershed



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Simulated Pollutant Loadings for Each Crop

Scenario	Sediment (metric ton/ha)	Total Sediment (metric tons)	N (kg/ha)	Total N (kg)	P (kg/ha)	Total P (kg)
Baseline CS	2.76	400,258	36.24	5,252,363	3.87	560,299
CC20	2.09	303,221	60.69	8,795,061	7.13	1,032,836
CS30	2.27	328,430	35.58	5,156,636	6.93	1,004,513
CS50	2.34	338,534	35.53	5,148,937	7.04	1,019,666
CC30	2.11	306,293	59.35	8,601,283	7.18	1,040,536
CC50	2.20	319,269	55.39	8,026,275	7.29	1,056,324
Switchgrass	0.01	1,616	16.22	2,351,037	0.09	12,641
Switchgrass, No-Till	0.01	1,616	16.22	2,350,941	0.10	14,630
Miscanthus	0.01	1,433	10.32	1,494,803	0.06	8,411

Fuelshed Size and Total Cost for Each Scenario

Scenario	Land Needed (ha)	% of Watershed Size	Fuelshed Size (mile)	Total Cost ($)	Total Cost Relative to Mxg	Hauling distance where indifferent btw scenario and Mxg (miles)
CC20	618,032	426.48%	49.13	101,457,030	67.76%	13.8
CS30	864,702	596.70%	58.12	104,304,849	69.66%	9.9
CS50	509,852	351.83%	44.63	104,184,183	69.58%	15.6
CC30	410,787	283.47%	40.06	98,579,902	65.84%	20.8
CC50	245,771	169.60%	30.98	99,710,291	66.59%	32.4
Switchgrass	122,718	84.68%	21.89	172,575,412	115.26%	-18.7
Switchgrass, No-Till Establishment	122,737	84.70%	21.90	171,565,987	114.58%	-17.7
Miscanthus	63,313	43.69%	15.73	149,732,780	100.00%	0

Knowledge Dissemination

- Peer Reviewed Journal Articles (Published) : 8
- Peer Reviewed Journal Articles (in preparation/review) : 9
- Thesis/Dissertation (completed) : 5
- Thesis/Dissertation (ongoing) : 5
- Presentations in Various Meetings, Workshops, and Conferences: 61
- Data will be published with a persistent DOI number at the Purdue University Research Repository (https://purr.purdue.edu/).

Future Work

- Complete all tasks by 09/30/2015
- Publish results in peer-reviewed journals
- Continue to disseminate results to various stakeholder groups
- Final report

Additional Slides

4 - Relevance

MYPP Goal/Objective	Project Contribution	Output Application
Identify sustainability indicators for climate, water, and land use by 2012	Sustainability indicators and targets for water and land use in terms of water quantity, quality, biomass and crop production, profitability, and aquatic biodiversity	Method developed to quantify sustainability using these indicators
Identify metrics and set baselines for soil quality and air quality by 2013	Sustainability indicators and targets for soil quality in terms of soil erosion	Method developed are used to quantify sustainability using soil erosion as an indicator
Analyze systemic sustainability	Multi-objective optimization using SWAT model and alternative objective functions	SWAT model improvements and results are discussed with stakeholders
Develop and evaluate best practices based on monitoring, field data and modeling results.	Comparison of baseline and future scenarios under current and climate change conditions	Baseline and future scenario results are be discussed with different stakeholder groups
Compare practices with empirical data to support continuous improvement in sustainability.	Model performance evaluated using data collected at plot and watershed scales	SWAT Model improved based on data collected and stakeholder needs
Promote adoption of best practices	Best biomass production scenarios identified and communicated	Sustainable practices will be communicated through publications, presentations through various outlets, and project reports

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5 - Critical Success Factors

Achieving successful project results:

- Developing parameters and code modification that simulate bioenergy crops throughout their life cycle

- Developing scenarios representing the full range of potential implementation of bioenergy crops in the landscape

Commercial viability

- Estimated farm-level break-even cost of production for each cellulosic feedstock as a crucial measure of farmer willingness-to-accept payment to supply biomass, and thus the minimum price required by farmers to supply biomass to refineries

- Comparison of cost of production differences between prime and marginal cropland

Project milestones and timeline

	Quarter															
Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.1: Synthesize available data	■	■														
1.2: Collect data not yet available		■	■	■	■	■	■	■								
1.3: Improve energy crop representation in SWAT	■	■	■	■												
1.4: Validate SWAT crop production functions				■	■	■	■	■								
2.1: Parameterize, calibrate, and validate the SWAT model	■	■	■													
2.2: Run simulations w/ climate scenarios to establish baseline	■	■	■	■	■	■	■	■								
2.3: Develop scenarios	■	■	■	■	■	■	■	■								
2.4: Determine the sustainability of energy crop scenarios									■	■	■	■	■	■	■	■
3.1: Optimize selection and placement of various energy crops					■	■	■	■	■	■	■	■	■	■	■	■
3.2: Compare the optimization results with targeting strategies	■	■	■	■	■	■	■	■								
3.3: Communicate results				■				■				■	■	■	■	■
Peer Review Meeting with Go/No-Go decision				■				■				■				