Watershed Scale Optimization to Meet Sustainable Cellulosic Energy Crop Demands

May 22, 2013
Analysis and Sustainability Peer Review

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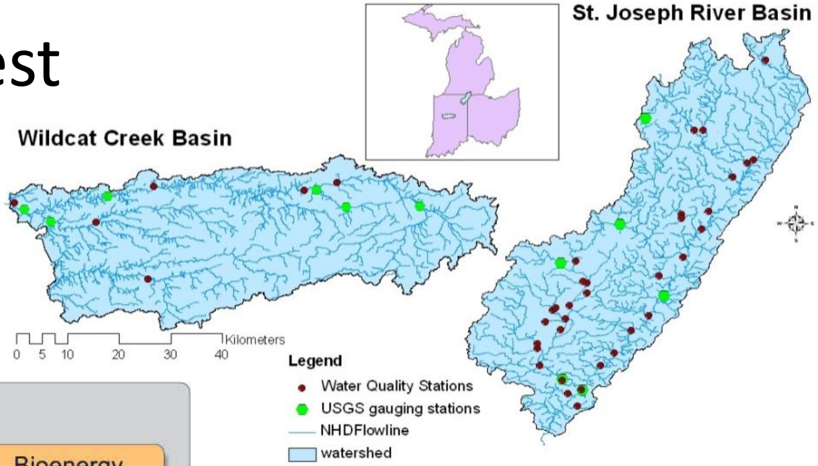
Purdue University

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



Biomass-to-Bioenergy Supply Chain

Feedstock Supply → Biomass Conversion → Bioenergy Distribution → Bioenergy End Use

Enviromental Sustainability

Economic Sustainability

Social Sustainability

OBP Sustainablity Activities

Quad Chart Overview

Timeline

- Start – September 2010
- End – September 2014
- Percent complete – 60%

Budget

Funding FY11 (DOE/Cost share) - $ 440,143/$91,456

Funding FY12 - $448,083/$101,564

Funding FY13 - $343,055/$137,685

Years the project has been funded – 2010-2014

Average annual funding - $497,795

Barriers

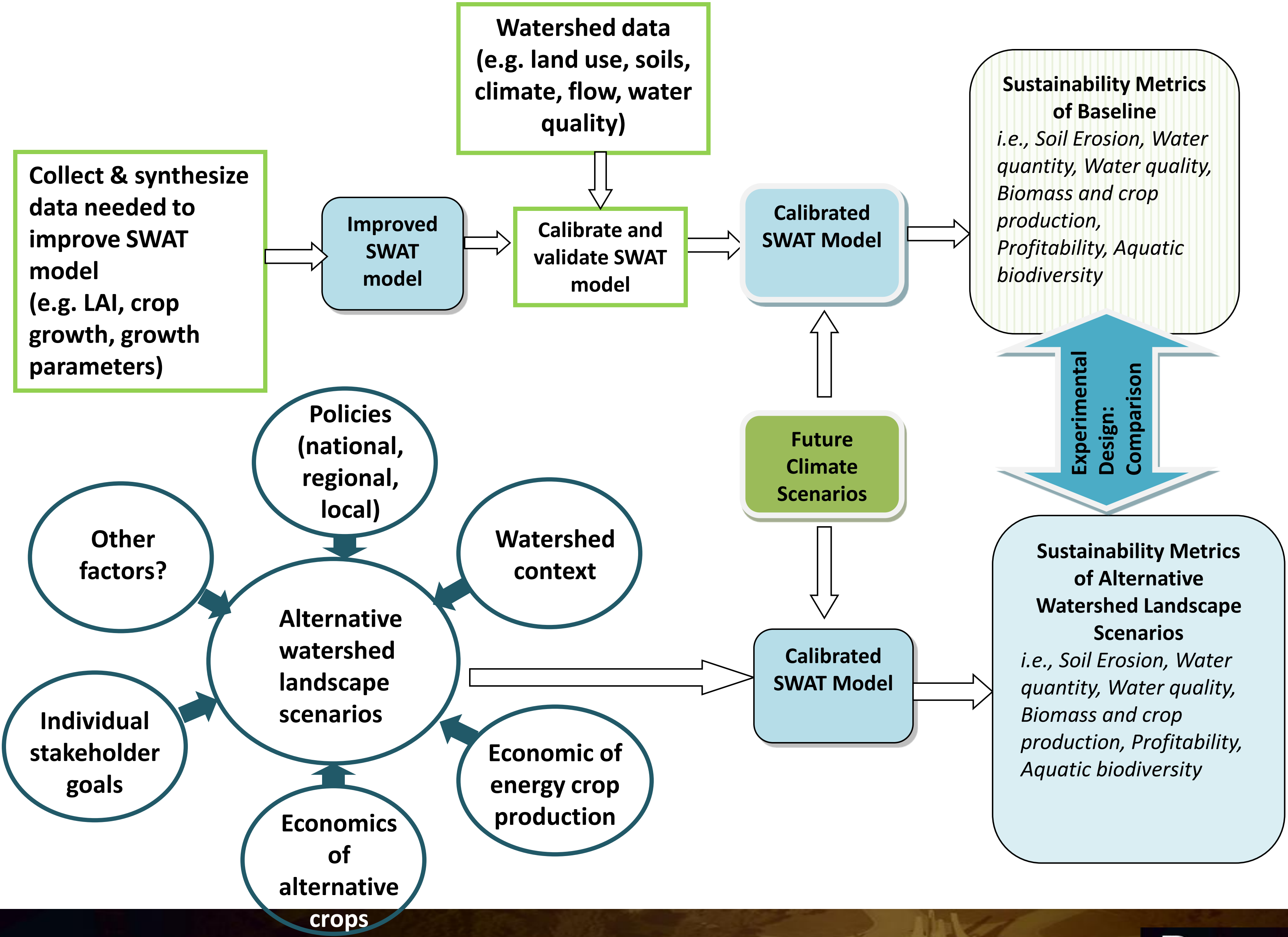
- Barriers addressed
  - St - A. Scientific consensus on bioenergy sustainability
  - St -B. Consistent, defensible message on bioenergy sustainability
  - St-C. Sustainability Data
  - St-D. Sustainability Indicators and methods
  - St-E. Best Practices and Systems

Partners

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

Project Overview

- **Objective 1**: Improve the simulation of cellulosic energy crops, such as *Miscanthus*, switchgrass, and hybrid poplar, in the Soil and Water Assessment Tool (SWAT) model.
- **Objective 2**: 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.
- **Objective 3**: Identify and communicate the optimal selection and placement of energy crops within a watershed for sustainable production.



Collect & synthesize data needed to improve SWAT model (e.g. LAI, crop growth, growth parameters)

Improved SWAT model

Watershed data (e.g. land use, soils, climate, flow, water quality)

Calibrate and validate SWAT model

Calibrated SWAT Model

Sustainability Metrics of Baseline
i.e., Soil Erosion, Water quantity, Water quality, Biomass and crop production, Profitability, Aquatic biodiversity

Experimental Design: Comparison

Future Climate Scenarios

Policies (national, regional, local)

Other factors?

Watershed context

Alternative watershed landscape scenarios

Individual stakeholder goals

Economic of energy crop production

Economics of alternative crops

Calibrated SWAT Model

Sustainability Metrics of Alternative Watershed Landscape Scenarios
i.e., Soil Erosion, Water quantity, Water quality, Biomass and crop production, Profitability, Aquatic biodiversity

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				■				■				■				

Approach: Obj. 1. Improve the simulation of cellulosic energy crops in SWAT model

- ***Overall technical approach***
  - Synthesize available data needed to parameterize the model to simulate landscape impacts of energy crop production and identify data gaps
  - Collect additional data
  - Improve representation and parameterization of new energy crops in the model
  - Validate the model at plot and watershed scales
- Milestones
  - Synthesis of available data (Y1)
  - Collection of new data (Y1-Y3)
  - SWAT code modification (Y1)
  - Model calibration, validation (Y1, cont.)

Approach: Obj. 2. Evaluate sustainability of energy crop scenarios using improved model

- ***Overall technical approach***
  - Parameterize, calibrate, and validate the SWAT model for the watersheds
  - Run the calibrated model with current and future climate scenarios to establish baseline
  - Develop scenarios that represent plausible watershed landscape alternatives, based on scientific assessment and stakeholder input
  - Determine the sustainability of energy crop scenarios through comparison of the baseline to the experimental scenarios
- Milestones

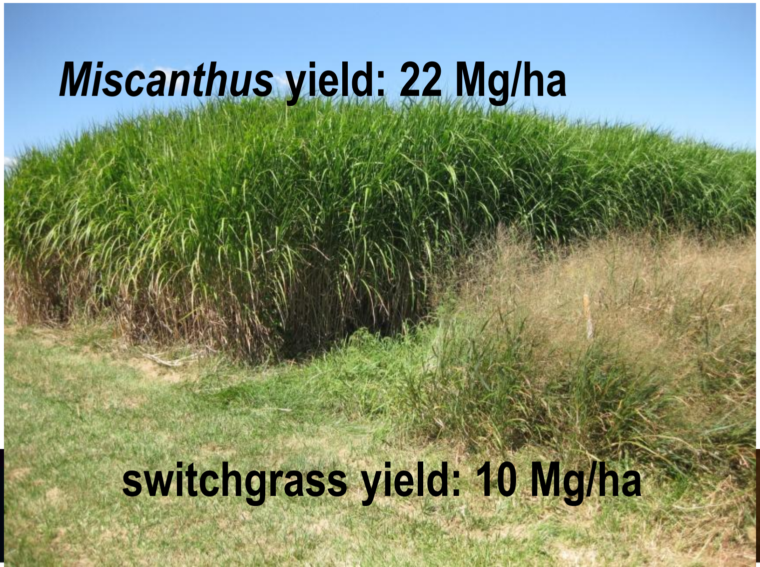
Year 1	**Year 2**	**Year 3**	**Year 4**
• Calibrate model • Climate data sets • Driving forces initial analysis	• Sustainability metrics for baseline • Set of watershed landscape scenarios that represent range of possible land use combinations to be tested	• Break-even analysis of cost of production • Sustainability metrics for initial scenarios	• Evaluate alternative scenarios

Approach: Obj. 3. Identify and communicate results for sustainable energy crop production

- ***Overall technical approach***
  - Optimize selection and placement of various energy crops in a watershed under single and multi-objective functions
  - Compare the optimization results with targeting strategies that could be implemented in a watershed
  - 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
- Milestones
  - Initial optimization (Y3); Final optimization (Y4)
  - Comparison; Workshops and presentations (Y4)
  - Final Report; Presentations, Workshops on optimization method; Synthesis paper in peer-reviewed journal (Y4)

Accomplishment: Synthesized available data needed to parameterize the model

- Biomass, yield, leaf area index, plant nitrogen uptake for *Miscanthus*, switchgrass, and corn – 100% complete
- ***Data gaps identified:*** For *Miscanthus* and switchgrass:
  - Plant P uptake
  - Maximum and effective rooting depth, maximum crop height
  - Harvest index
- Data collected for two years to fill above data gaps

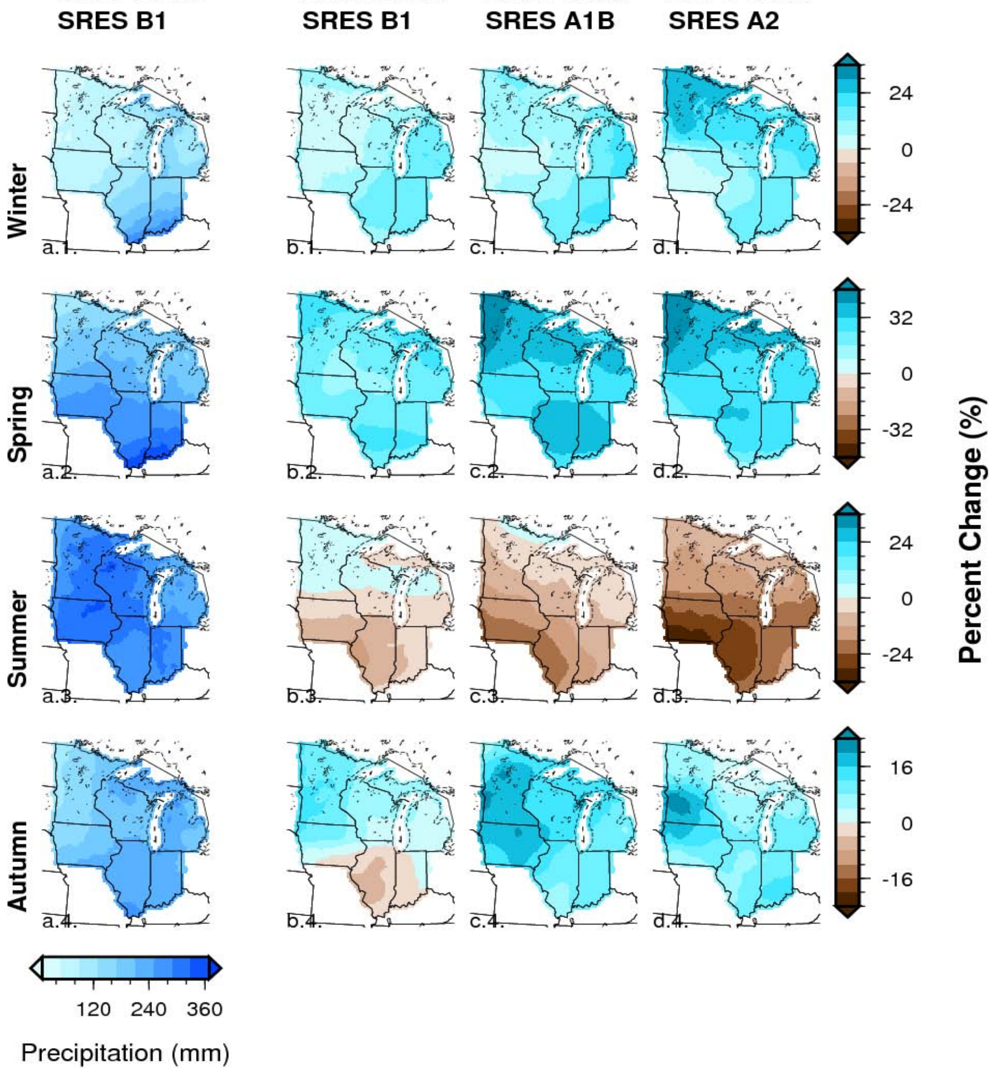


Broad representation from field sites

Features	**Water Quality Field Station (ACRE)**	**Northeast Purdue Ag. Center**	**Throckmorton Purdue Ag. Center**	**Southeast Purdue Ag. Center**
Soil association	Ragsdale-Raub	Morley-Blount-Pewamo	Miami-Russell-Fincastle-Ragsdale	Avonberg-Clermont
Soil description	Very poorly to somewhat poorly drained, level	Mod. well to very poorly drained up to 12% slope	Well drained to poorly drained, up to 12% slope	Poorly drained, flat, gray silty clay loam with fragipans
NRCS Land Capability	2, wet	4, erosive	2 to 4, wet, erosive	3, wet
Parent material	Loess (0.5-1 m) over Wisconsinan glacial till	Calcareous silty clay loam or clay loam glacial till	Loess (<-1 m) over calcareous loam glacial till	Wisconsinan loess over eroded Illinoian till
Native vegetation	Prairie grasses	Beech, oak, and maple forest	Beech, maple forest	Mainly beech, with some oak, maple
Representative regions	Tall grass prairie from IN to IA	Rolling non-arable land in the Midwest	Central IN, IL, and OH	Southeast IN to Southern OH, IL
Drainage mgmt	Depth: 1 m Spacing: 70-120 ft.	None to spacing at 40 to 80 ft.	Depth: 1 m Spacing:70-120 ft.	Depth: 1 m Spacing: 50-80 ft
Lat./Long.	+40.467/-86.983	+41.133/-85.483	+40.283/-86.900	+39.000/-85.583

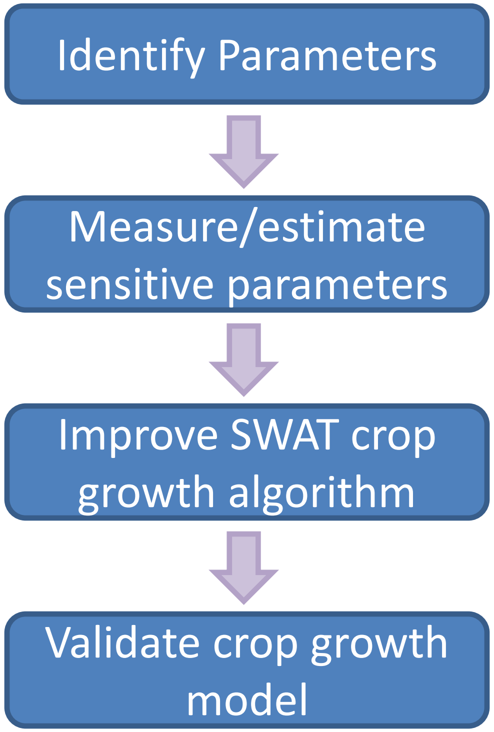
Accomplishment: Generated climate datasets needed for sustainability assessment

- Gridded daily historic climate data available for the region from 1915 through 2009
- Gridded climate projections available from 1950 through 2099
- Region has been getting wetter, with increased precipitation most prevalent in the winter and spring.
- Summer precipitation is projected to stay the same or decrease.



Energy Crops in SWAT

- SWAT requires about 25 crop growth parameters
- *Miscanthus* and upland switchgrass is not in the default crop database of SWAT



Identify Parameters

One at a Time Sensitivity analysis

Measure/estimate sensitive parameters

Data collected from WQFS/TPAC
Biomass, leaf area index, crop height, harvest efficiency

Improve SWAT crop growth algorithm

Check SWAT simulation of perennial grasses and modify if required

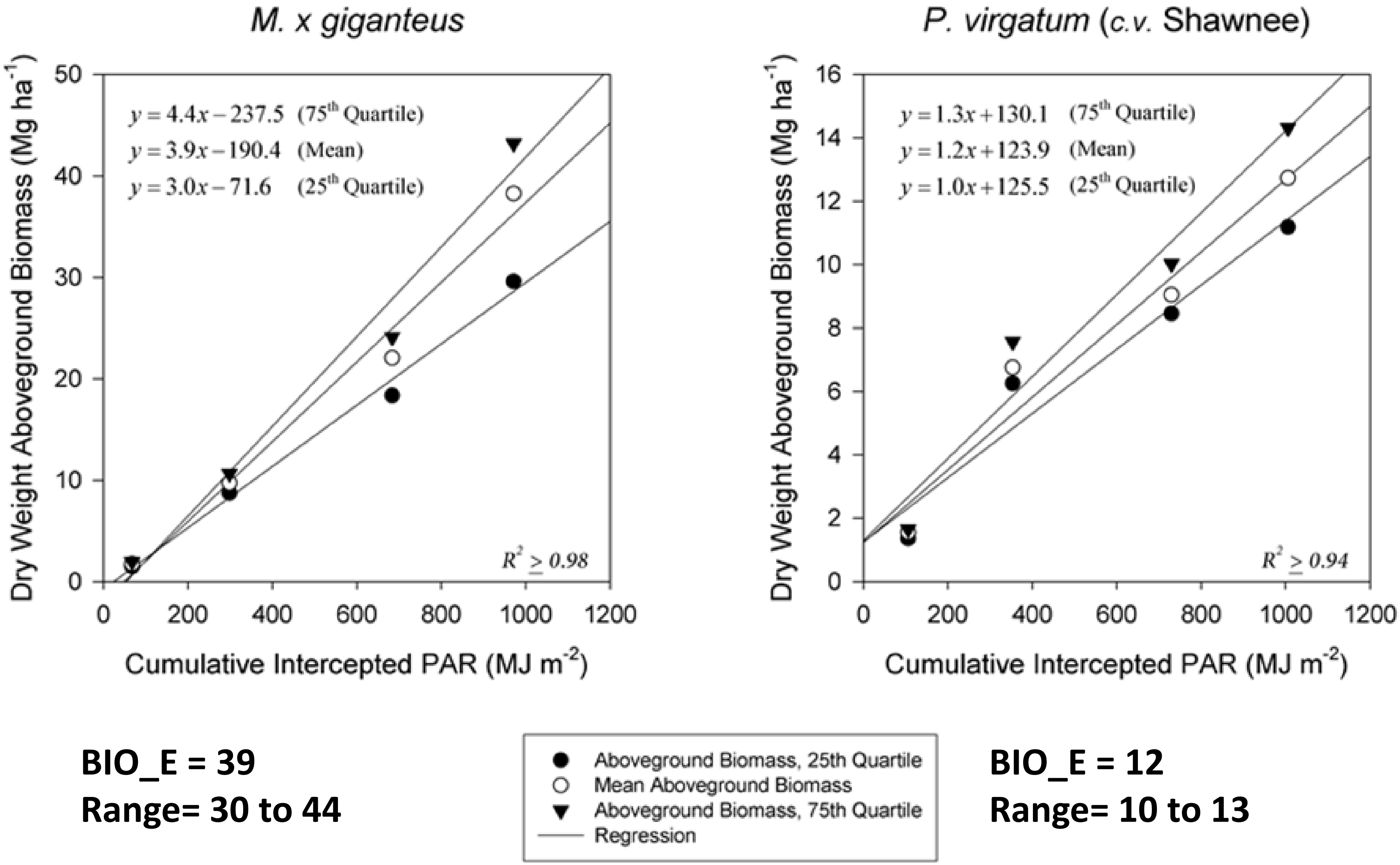
Validate crop growth model

Validate energy crop simulations of SWAT with measured data from WQFS/TPAC

Data Collection WQFS and TPAC

- 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)

Parameter Estimation - RUE



BIO_E = 39
Range= 30 to 44

BIO_E = 12
Range= 10 to 13

Parameter Estimation

	Miscanthus		Shawnee Switchgrass		Alamo Switchgrass
Parameter	**Suggested**	**Range**	**Suggested**	**Range**	**Database value**
T_OPT	25	-	25	-	25
T_BASE	8	7-10	10	8-12	12
BIO_E	39	30-44	12	10-13	47
HVSTI	1	-	1	-	0.9
HEFF	0.7	0.65-0.75	0.75	0.7-0.75	
BLAI	11	10-13	8	-	6
DLAI	1.1	-	1		0.7
EXT_COEFF	0.55	0.45-0.65	0.5	0.4-0.55	0.33
LAIMX1	0.1	-	0.1	-	0.2
LAIMX2	0.85	-	0.85	-	0.95
FRGRW1	0.1	-	0.1	-	0.1
FRGRW2	0.45	-	0.4	-	0.2
PLTNFR(1)	0.0100	0.0097-0.0104	0.0073	0.0066-0.0081	0.035
PLTNFR(2)	0.0065	0.0062-0.0070	0.0068	0.0067-0.0072	0.015
PLTNFR(3)	0.0057	0.0053-0.0060	0.0053	0.0051-0.0055	0.0038
CNYLD	0.0035	0.0034-0.0035	0.0054	0.0053-0.0058	0.0160
PLTPFR(1)	0.0016	0.0016-0.0017	0.0011	0.0010-0.0012	0.0014
PLTPFR(2)	0.0012	0.0010-0.0014	0.0014	0.0013-0.0016	0.001
PLTPFR(3)	0.0009	0.0007-0.0011	0.0012	0.0011-0.0012	0.0007
CPYLD	0.0003	0.0003-0.0004	0.0010	0.0010-0.0011	0.0022
CHTMX	3.5	-	2	-	2.5
RDMX	3	2-4	3	2-4	2.2
WSYF	1	-	1	-	0.9
ALAI_MIN	0	-	0	-	0
USLE_C	Existing Alamo Value		Existing Alamo Value		0.003
VPDFR	Existing Alamo Value		Existing Alamo Value		4
GSI	Existing Alamo Value		Existing Alamo Value		0.005
FRGMAX	Existing Alamo Value		Existing Alamo Value		0.75

Estimated/ Literature

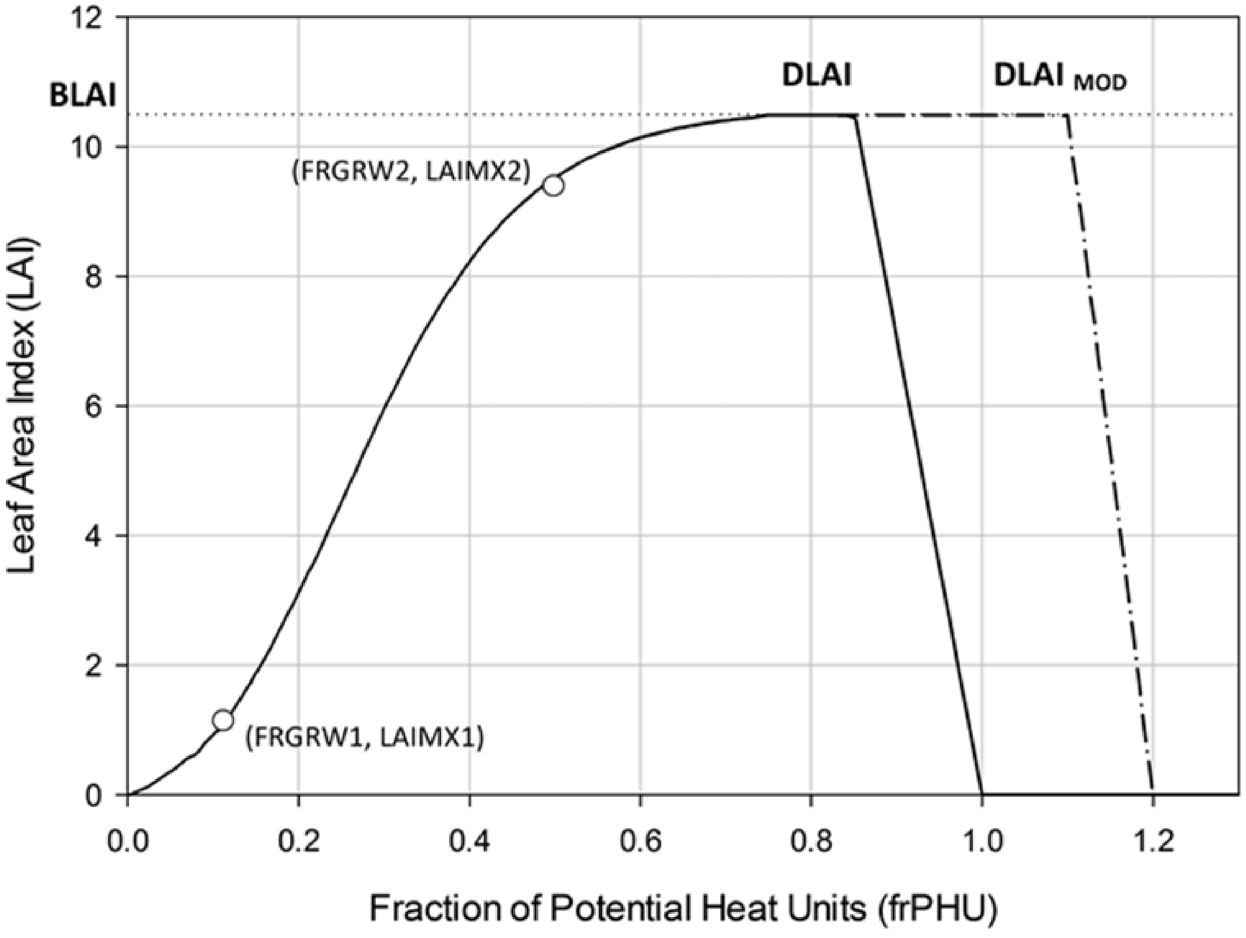
From Measured WQFS Data

From SWAT Database

Crop Growth Algorithm Improvement

- Plant nutrient uptake in stress periods
- Harvest operation representation – Harvest Index (HI) adjustments with water and nutrient stress
- Dead root allocation in harvest operation and dormancy period representation
- LAI after the crop maturity – senescence representation

Crop Growth Algorithm Improvement -LAI



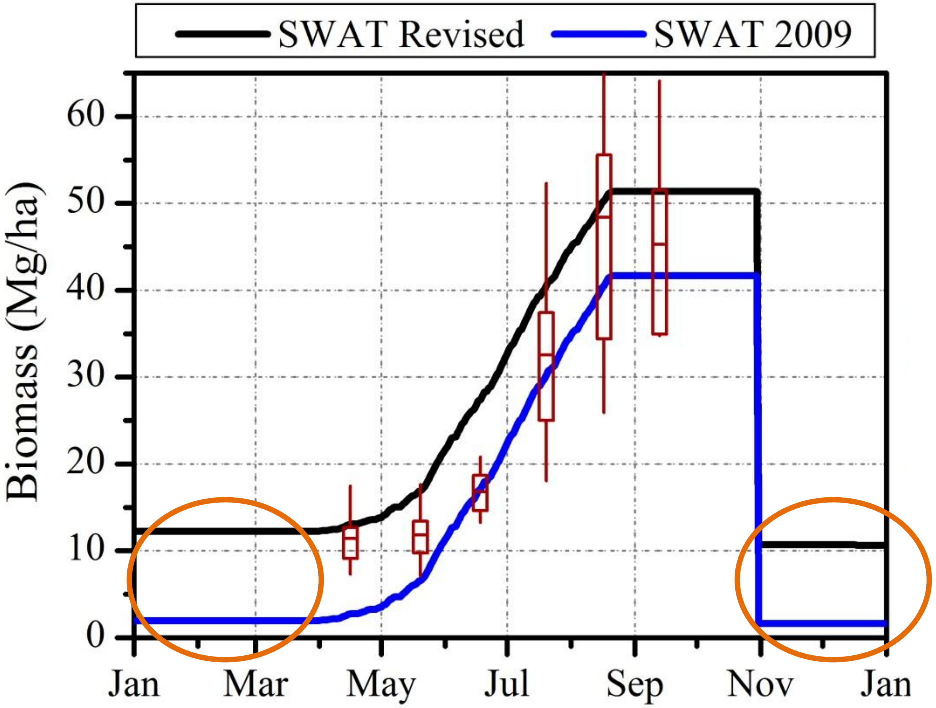
April Sept Nov

October 28, 2011

SWAT Simulation

- One HRU SWAT model
- Soil Data – WQFS
  - SSURGO data
  - WQFS – “Drummer soils”
- Slope : 0.009 m/m
- Weather data – ACRE- iClimate.org
  - Temperature
  - Precipitation
- 2004 – 2010 , 7 years simulation, 3 years model warm-up

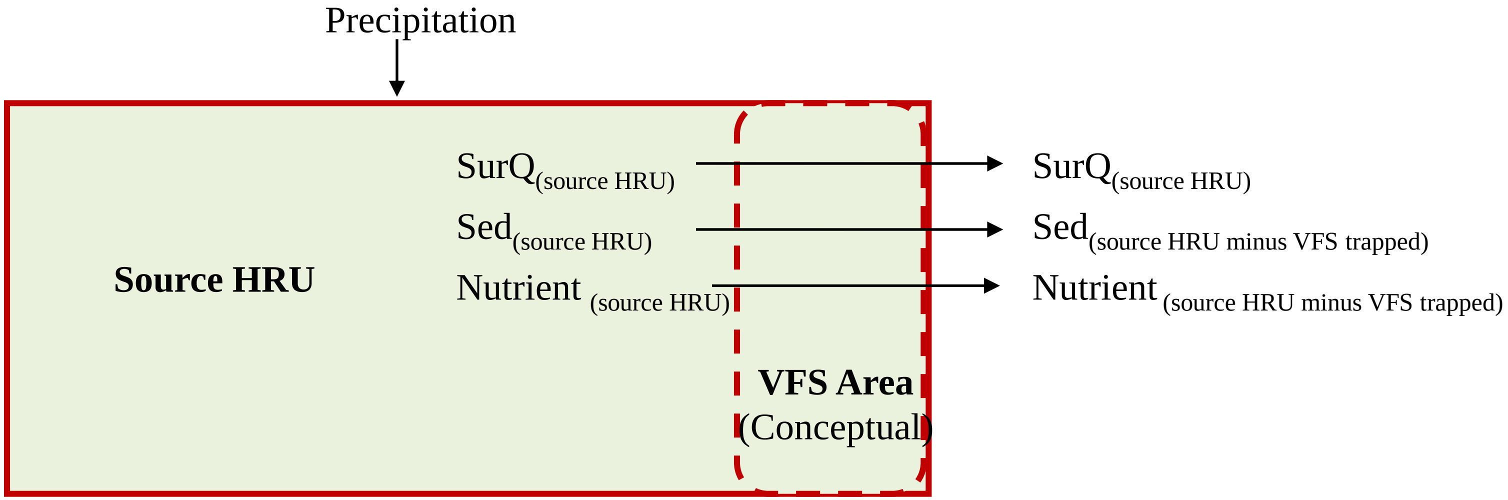
Energy Crop Simulation -SWAT



- Nutrients stored in below ground biomass not considered
- About 100 kg N/ha & 30 kg P/ha stored

- Affect nutrient uptake process
- water quality estimations impacted

SWAT- VFS Enhancement



Precipitation

Source HRU

$\text{SurQ}_{\text{(source HRU)}}$

$\text{Sed}_{\text{(source HRU)}}$

$\text{Nutrient}_{\text{(source HRU)}}$

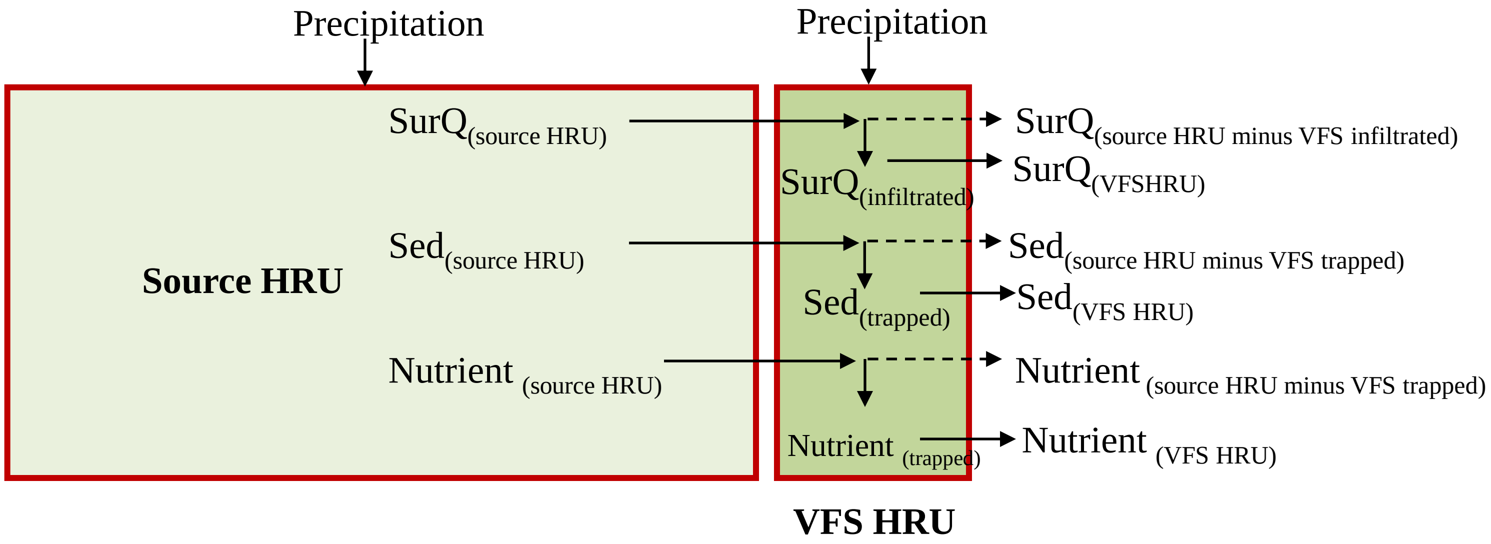
VFS Area
(Conceptual)

$\text{SurQ}_{\text{(source HRU)}}$

$\text{Sed}_{\text{(source HRU minus VFS trapped)}}$

$\text{Nutrient}_{\text{(source HRU minus VFS trapped)}}$

Biomass yield- 6.3 Mg/ha



Precipitation

Precipitation

Source HRU

$\text{SurQ}_{\text{(source HRU)}}$

$\text{Sed}_{\text{(source HRU)}}$

$\text{Nutrient}_{\text{(source HRU)}}$

$\text{SurQ}_{\text{(infiltrated)}}$

$\text{Sed}_{\text{(trapped)}}$

$\text{Nutrient}_{\text{(trapped)}}$

VFS HRU

$\text{SurQ}_{\text{(source HRU minus VFS infiltrated)}}$

$\text{SurQ}_{\text{(VFSHRU)}}$

$\text{Sed}_{\text{(source HRU minus VFS trapped)}}$

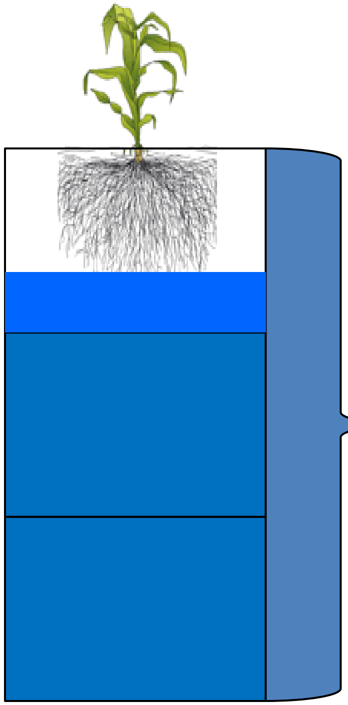
$\text{Sed}_{\text{(VFS HRU)}}$

$\text{Nutrient}_{\text{(source HRU minus VFS trapped)}}$

$\text{Nutrient}_{\text{(VFS HRU)}}$

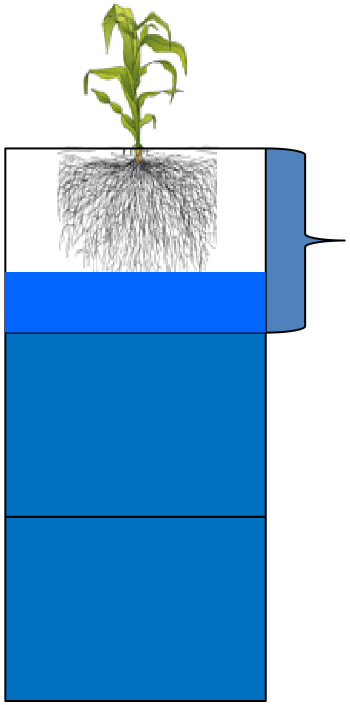
Aeration stress calculation (Layer)

Original algorithm



Aeration stress was calculated from the whole soil profile

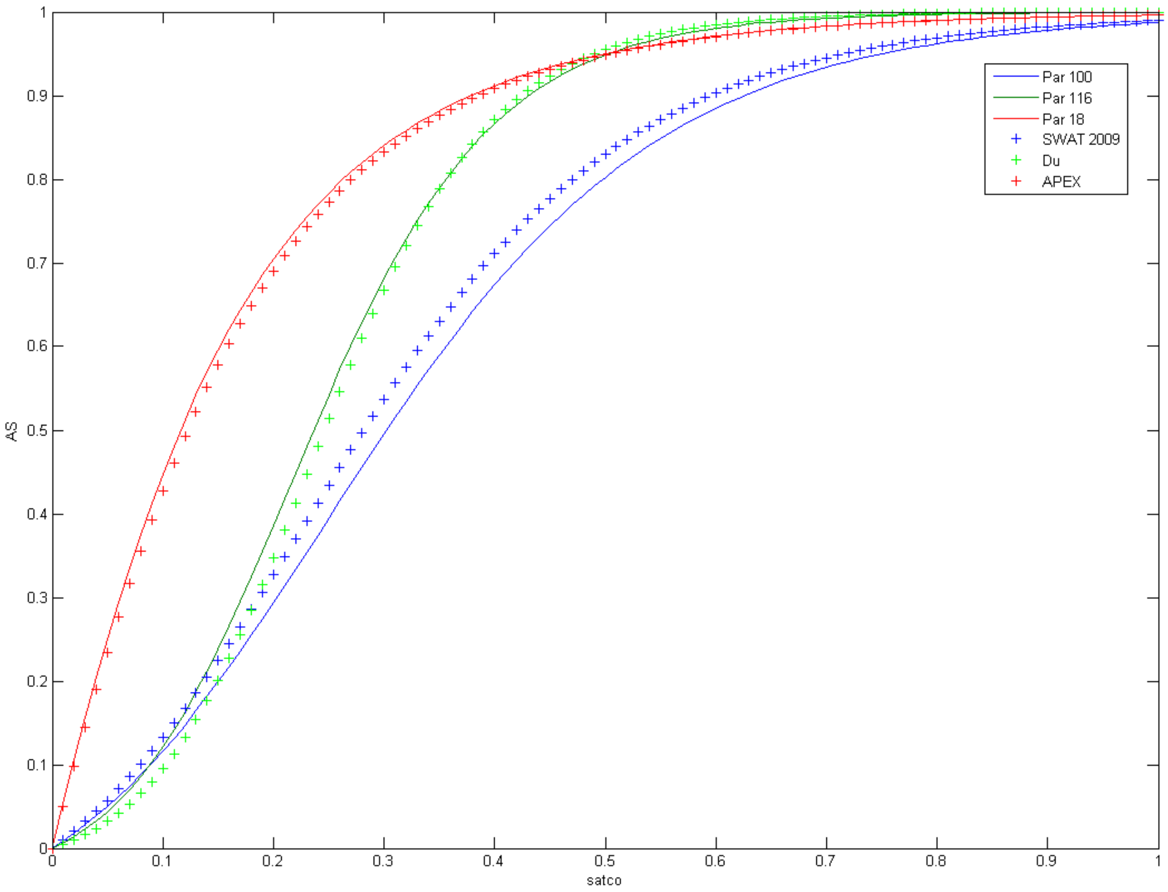
Modified algorithm



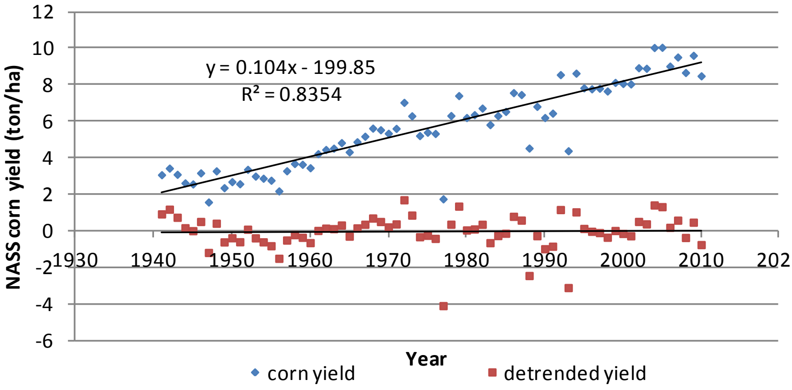
Aeration stress is calculated from layers directly related to root depth

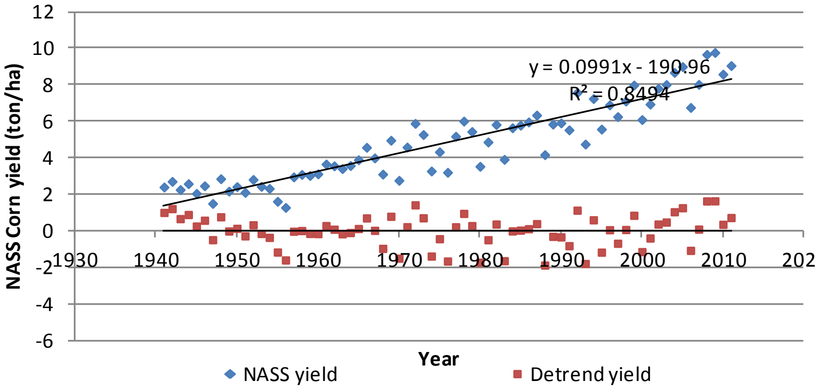
Modified aeration stress algorithm is more appropriate for early growing stage of plant, when root depth is not deep.

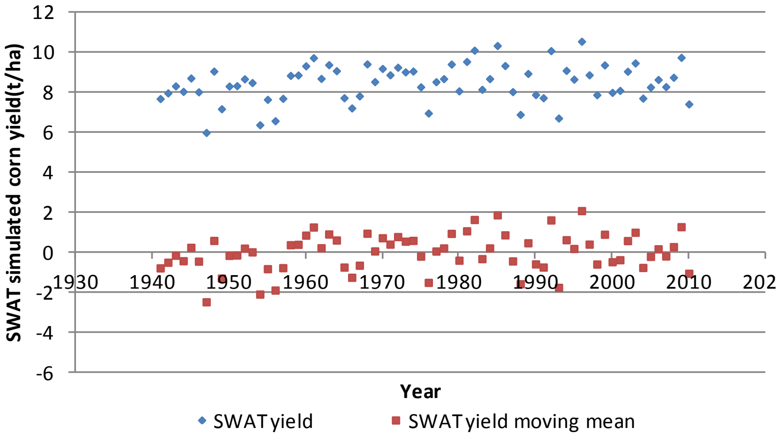
Aeration stress (S-curve)

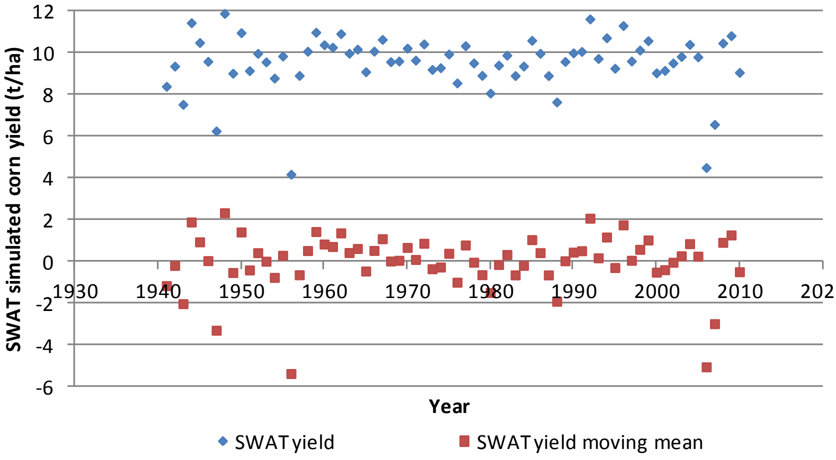


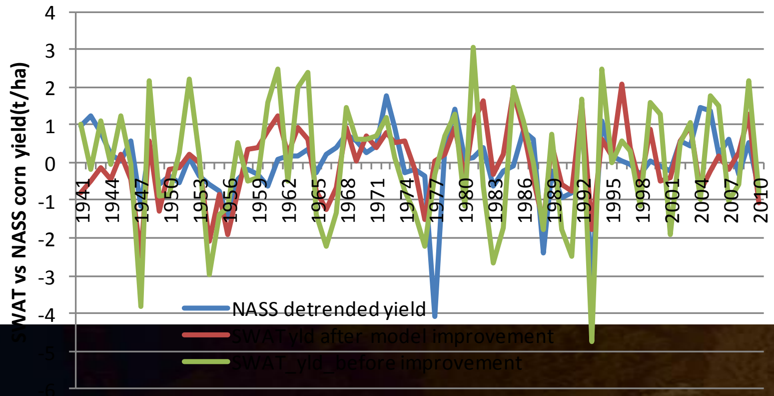
S-curve groups recreate 3 popular aeration stress algorithms very well

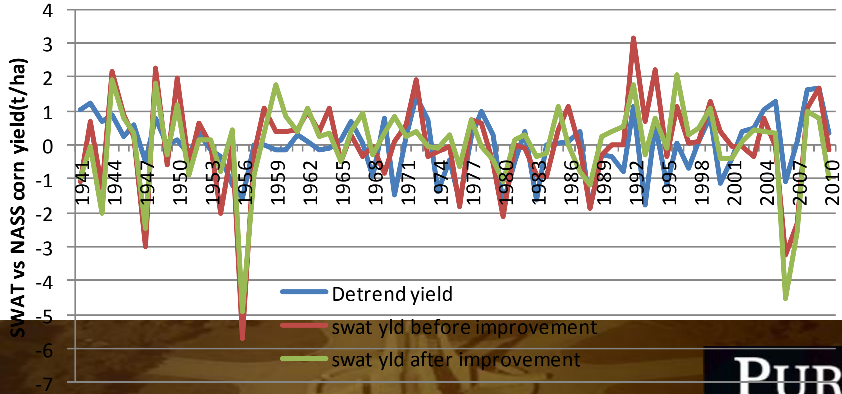

Detrended corn yield in Boone, IA


Detrended corn yield in Woodbury, IA


Mean removed SWAT corn yield in Boone, IA


Mean removed SWAT corn yield in Woodbury, IA





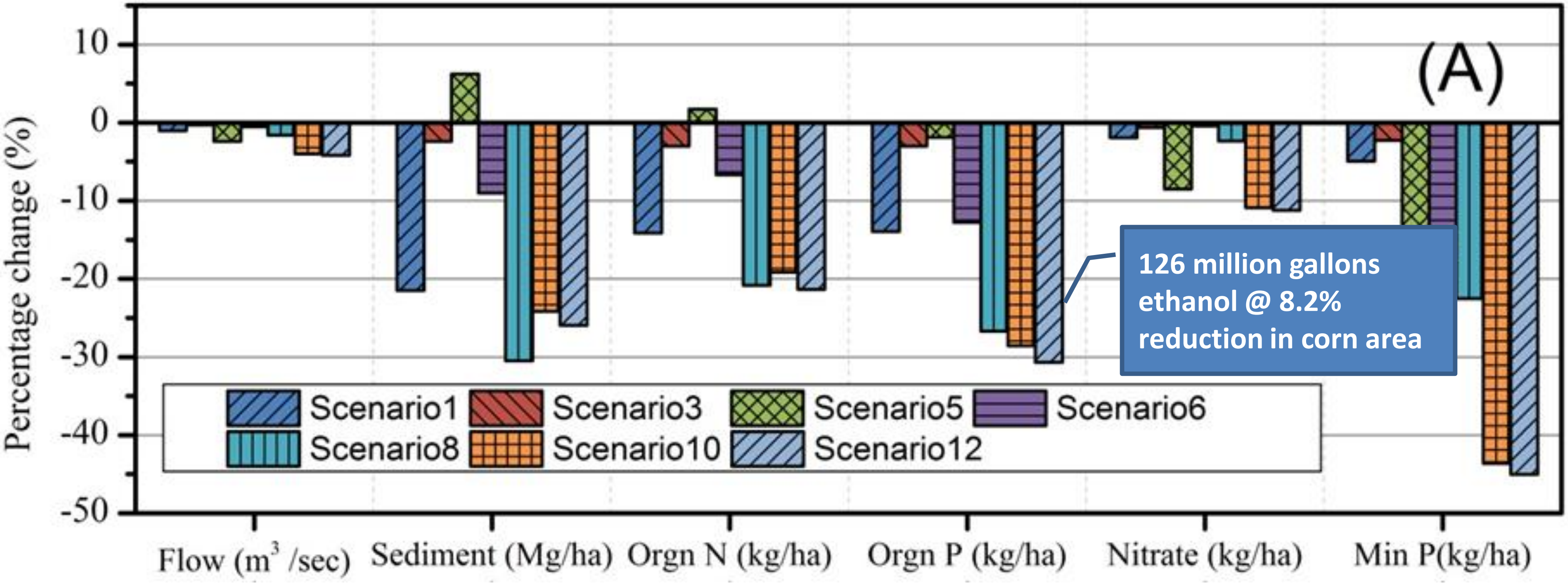
Accomplishment: Developed appropriate indicators of bioenergy crop impacts

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

Impacts of Bioenergy Scenarios

- Corn stover – 38%, 52% and 70% (Cibin et al., 2012)
- Cellulosic energy crops
  - *Miscanthus* and Switchgrass
  - Energy crops in high slope : >2% slope (Scenario 1-2)
  - Energy crops in agricultural marginal land: < 5 percentile yield (Scen 3-4)
  - Energy crops in Pasture areas (Scenario 6-7)
  - Crop residues –corn stover 70% (Scenario 5)
- Combinations of these scenarios (Scenario 8-13)
- 15 years (1995-2009) average annual impacts compared with baseline scenario

Impacts of Bioenergy Scenarios - *Miscanthus*



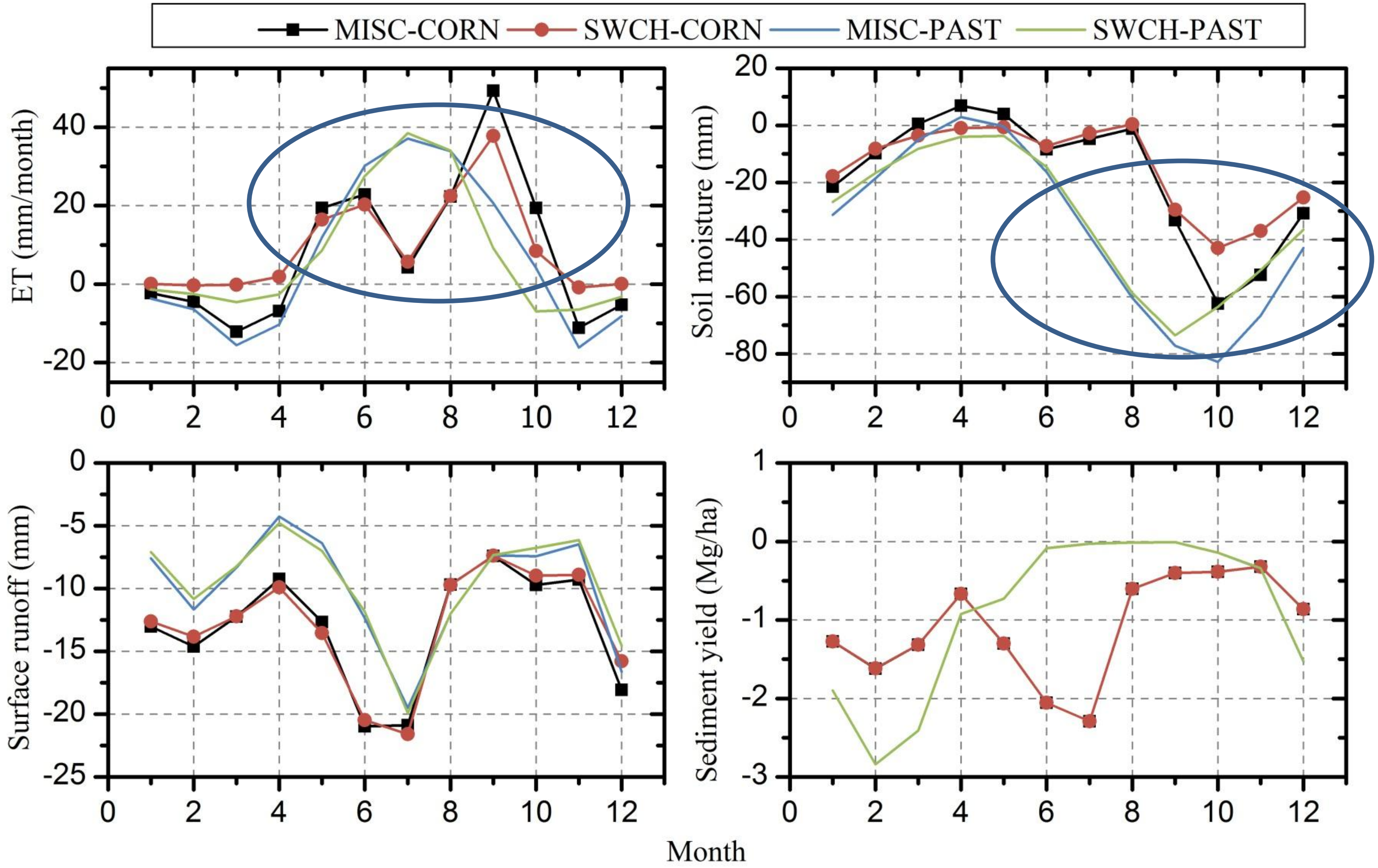
126 million gallons ethanol @ 8.2% reduction in corn area

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

Scenario6: Pasture Scenario8: >2% slope + Pasture

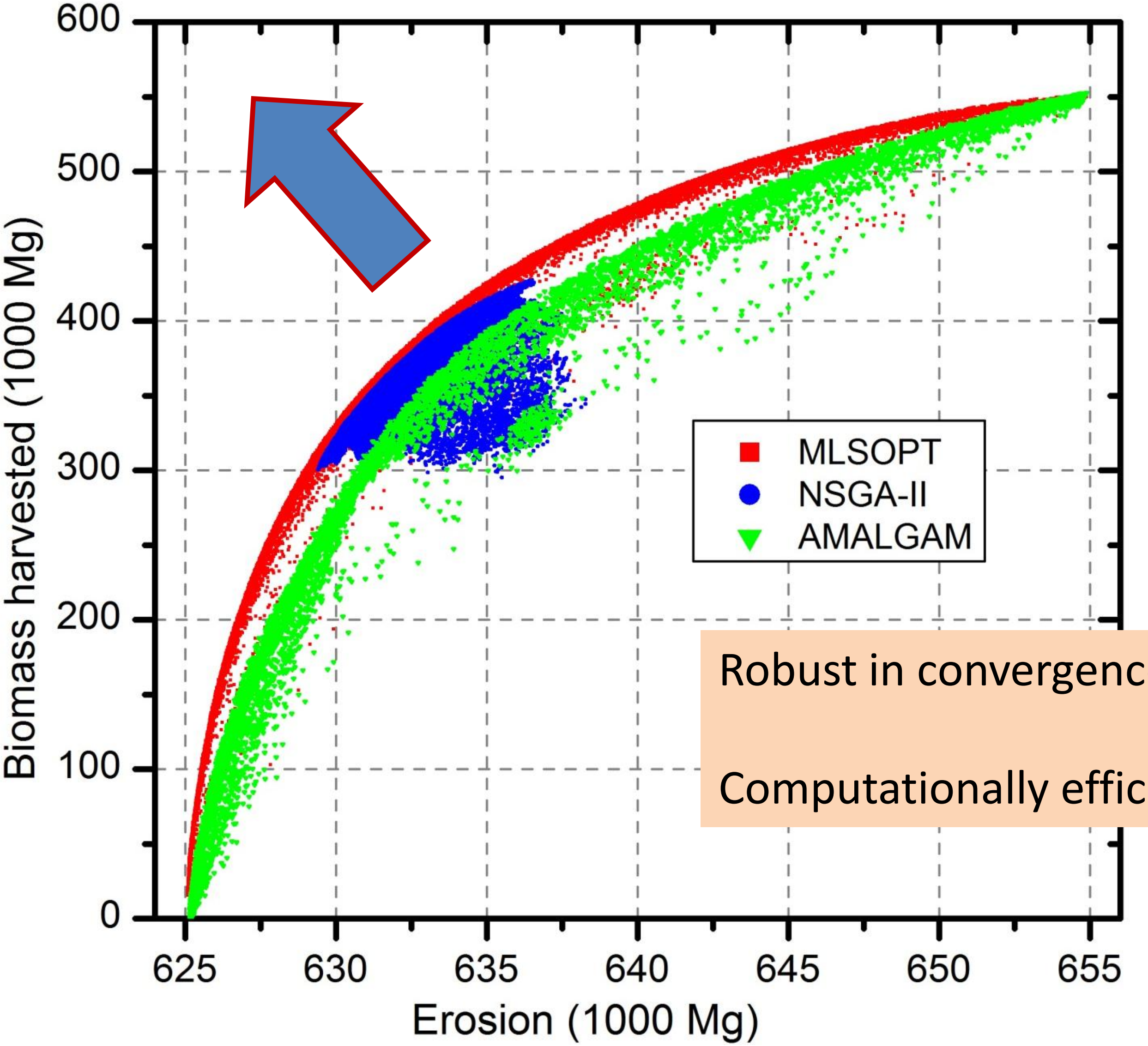
Scenario 10: Stover 70% + >2% slope + Pasture Scenario 12 : All

Impacts on Hydrology –Monthly One HRU



Corn/Pasture converted to *Miscanthus*/switchgrass – Relative change

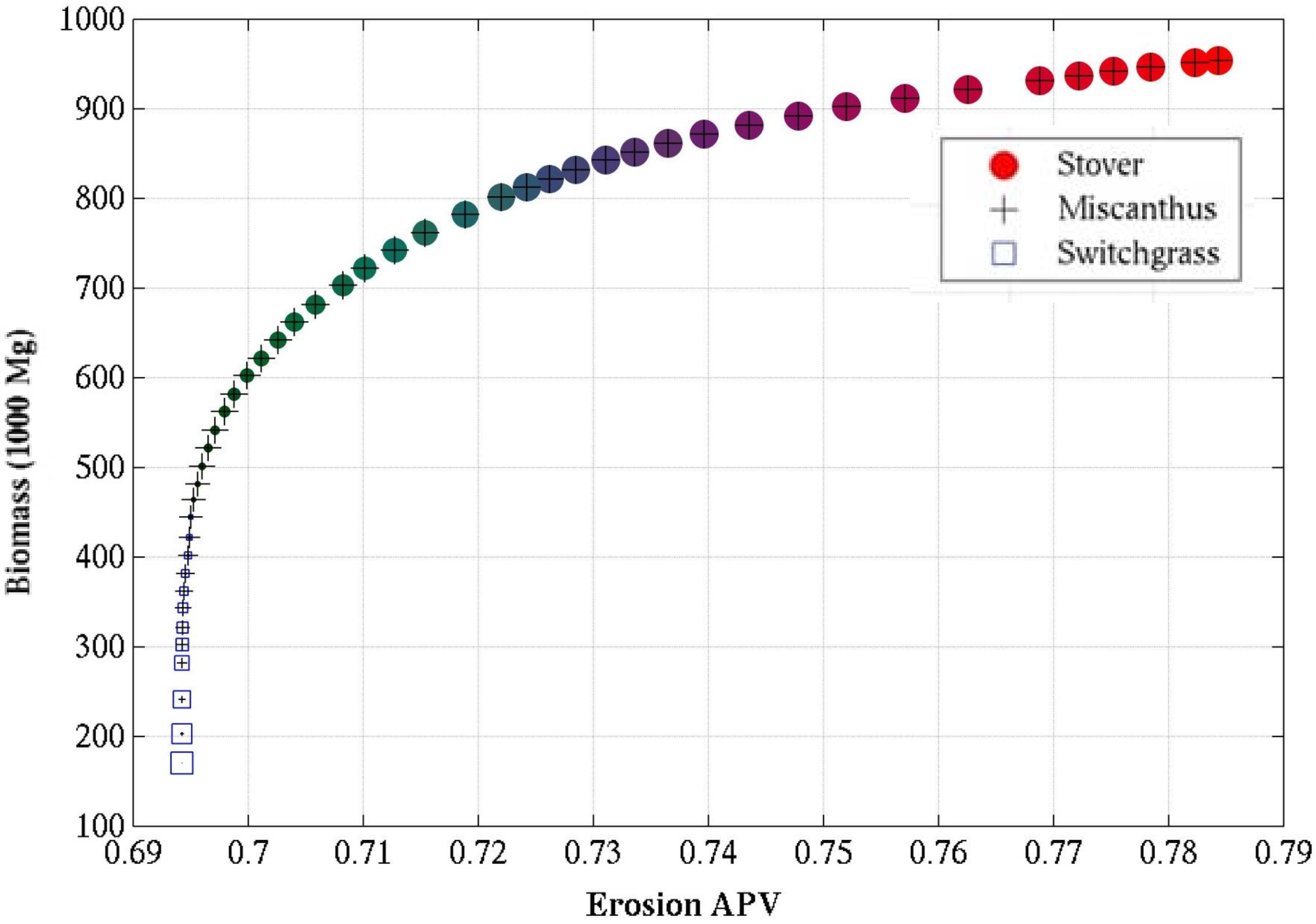
Development of new optimization methods



Robust in convergence and search space

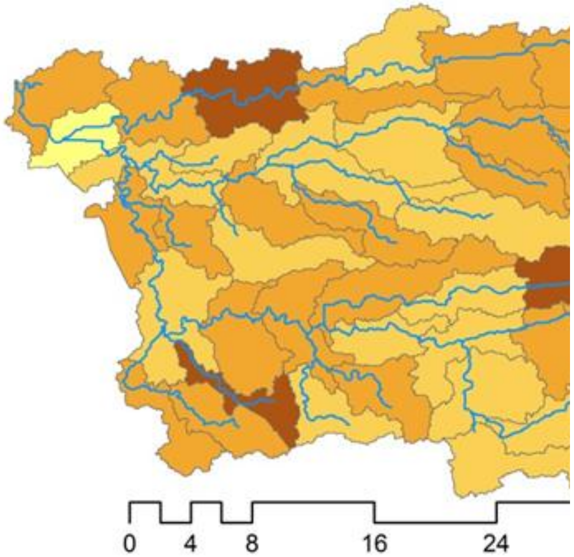
Computationally efficient : ~20 times

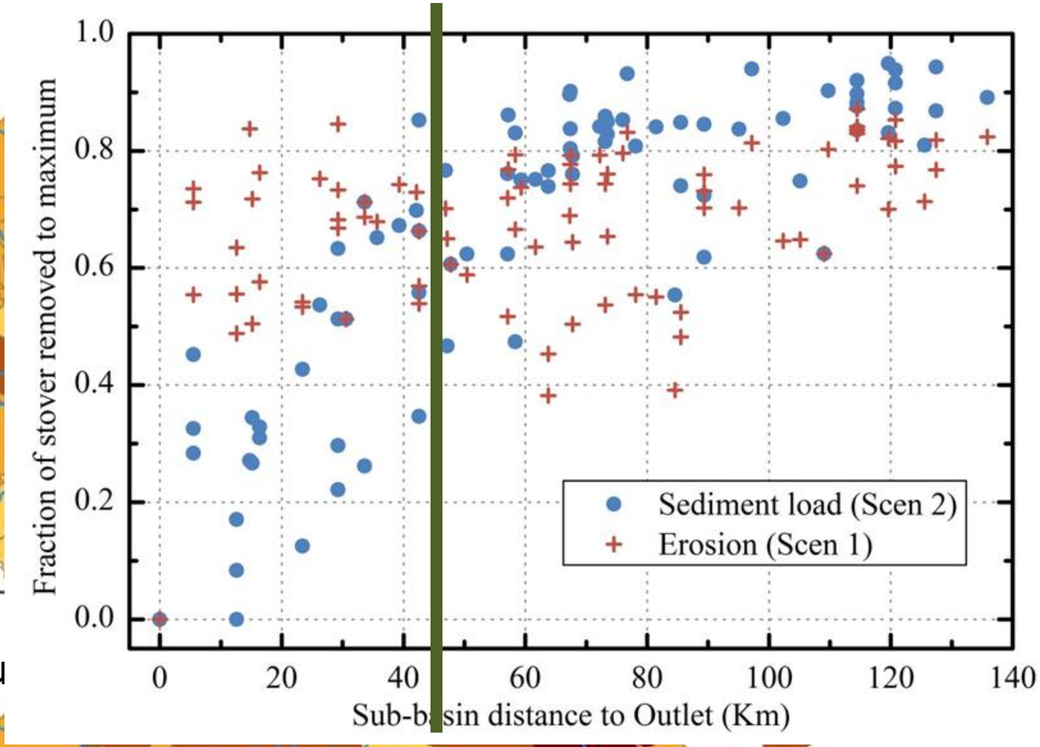
Optimal Placement - Results



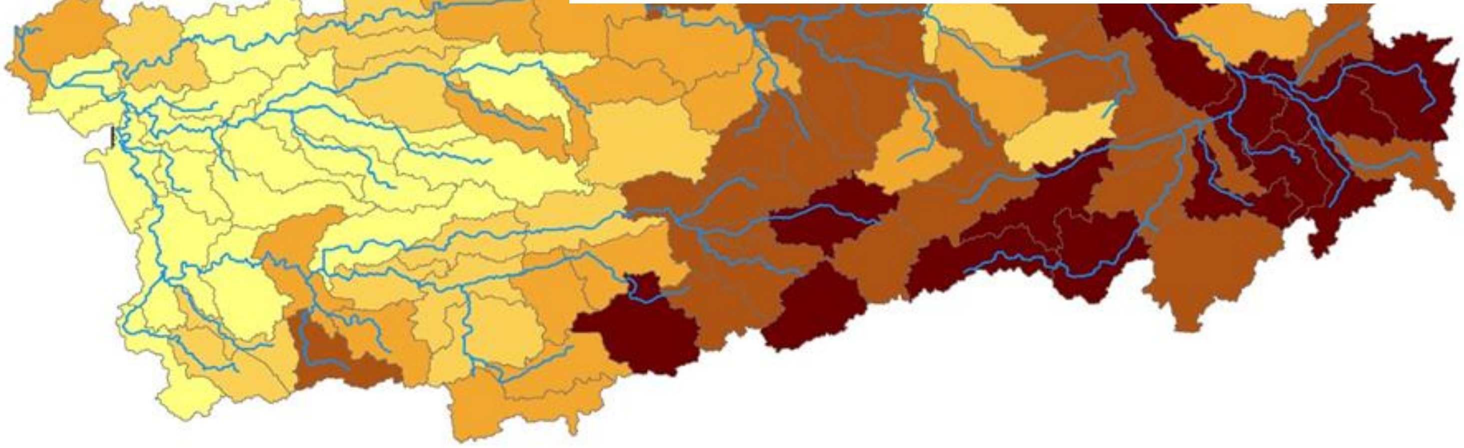
Optimization results

Scenario 1 – Source Level



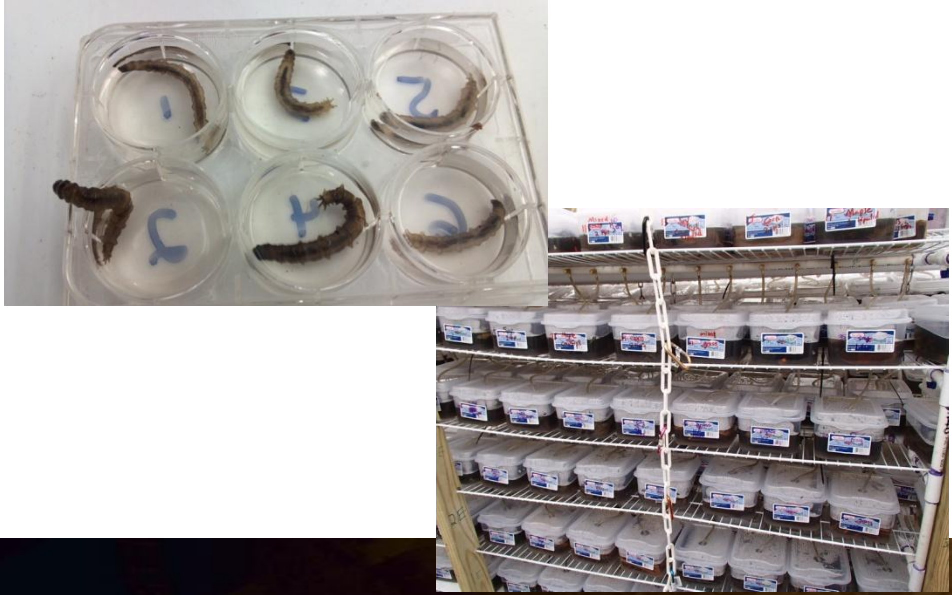


Scenario 2 – Watershed Ou



Aquatic Ecosystem Impacts

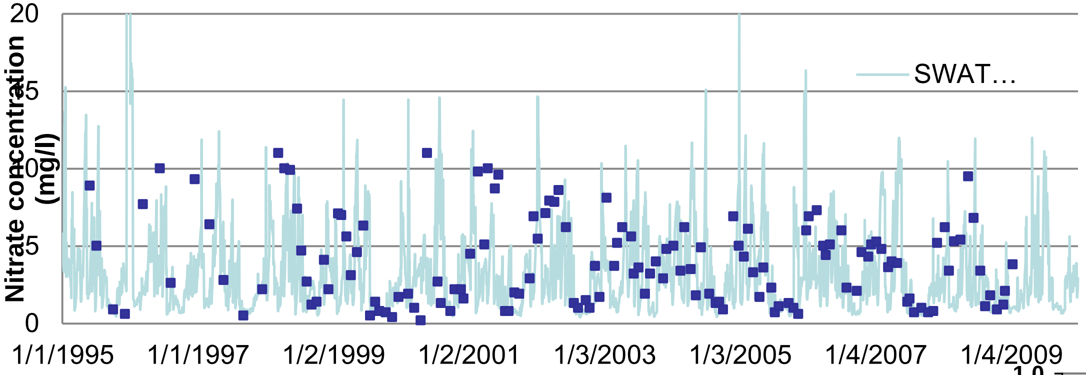
- The energy base of small streams is generally provided from leaves that blow or fall into the stream
- There is evidence to suggest that leaf-feeding insect larvae (*Tipula* sp.) are less able to process Miscanthus leaves and exhibit higher growth when leaf diversity is higher.
- Shifts in production to favor only Miscanthus could drastically change energy flow in stream ecosystems.



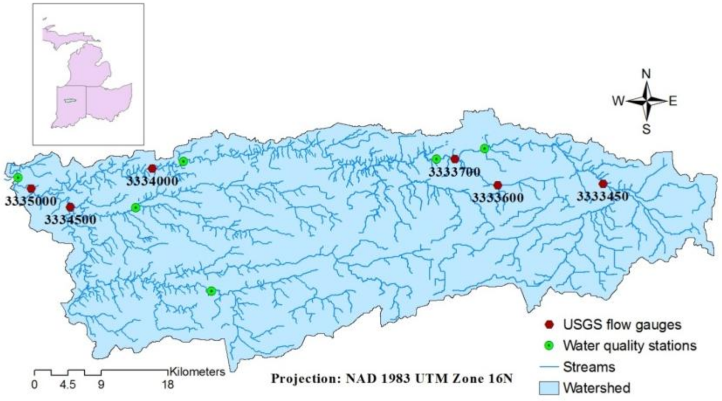
Accomplishment: Following Slides are needed

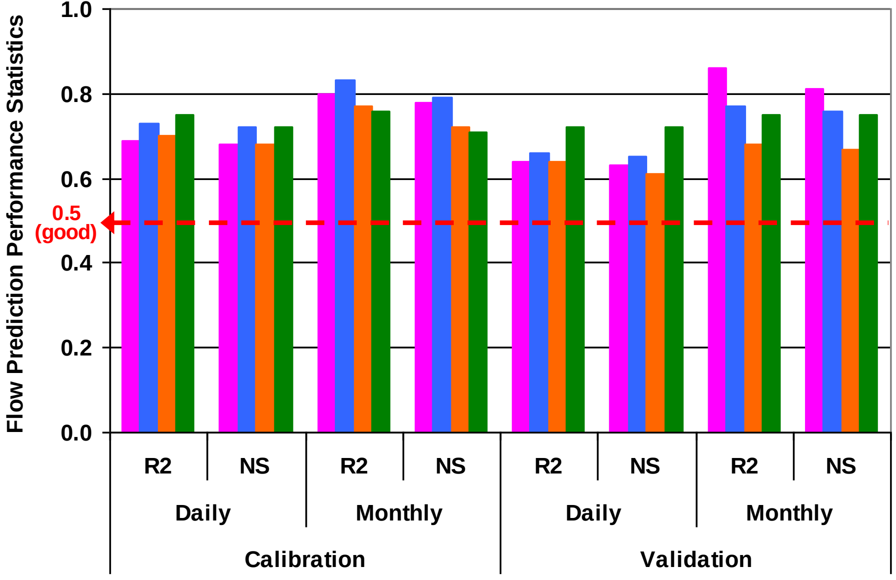
- **Please limit to 2 slides or less**
  - **Results on excess water stress – Laura/Keith?**
  - **Scenario development – Jane, Ben?**
  - **Cost functions, economic analysis – Ben**
  - **Aquatic ecosystem impacts – Reuben**

Accomplishment: SWAT model calibrated for Wildcat Creek and St. Joseph River watersheds



Nitrate simulation results





SWAT performance for flow simulation

Accomplishment: Developed detailed plan for stakeholder focus groups

- Plans submitted to Institutional Review Board on Human Subjects
- Conducted informal feedback session with approximately 40 stakeholders who participated in the Indiana Biomass Energy Working Group meeting on January 10, 2011

3 - 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 will be 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 optimization will be 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 will 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
Set standards / 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

4 - 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

Future Work

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Summary: This project is designed to support MYPP sustainability goals

- **Sustainability of biofeedstock production** in terms of soil erosion, water availability, water quality, biomass production, profitability, and aquatic biodiversity will be evaluated.
- Current and future scenarios evaluated using **feedback from a diverse array of stakeholders**
- Will contribute to **systemic assessment** of sustainability that can be used to make informed production decisions
- **SWAT model improvements** will enable similar assessments in other geographic regions
- Project **leverages** multiple projects funded to the multi-disciplinary research team at Purdue

Additional Slides

Publications/Presentations

- Thomas, M.A., B.A. Engel and I. Chaubey. 2010. Multiple corn-stover removal rates for cellulosic biofuels and long-term water quality impacts. *Journal of Soil and Water Conservation. In Review.*
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.