Improving the simulation of biofuel crop sustainability assessment using SWAT model

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Background

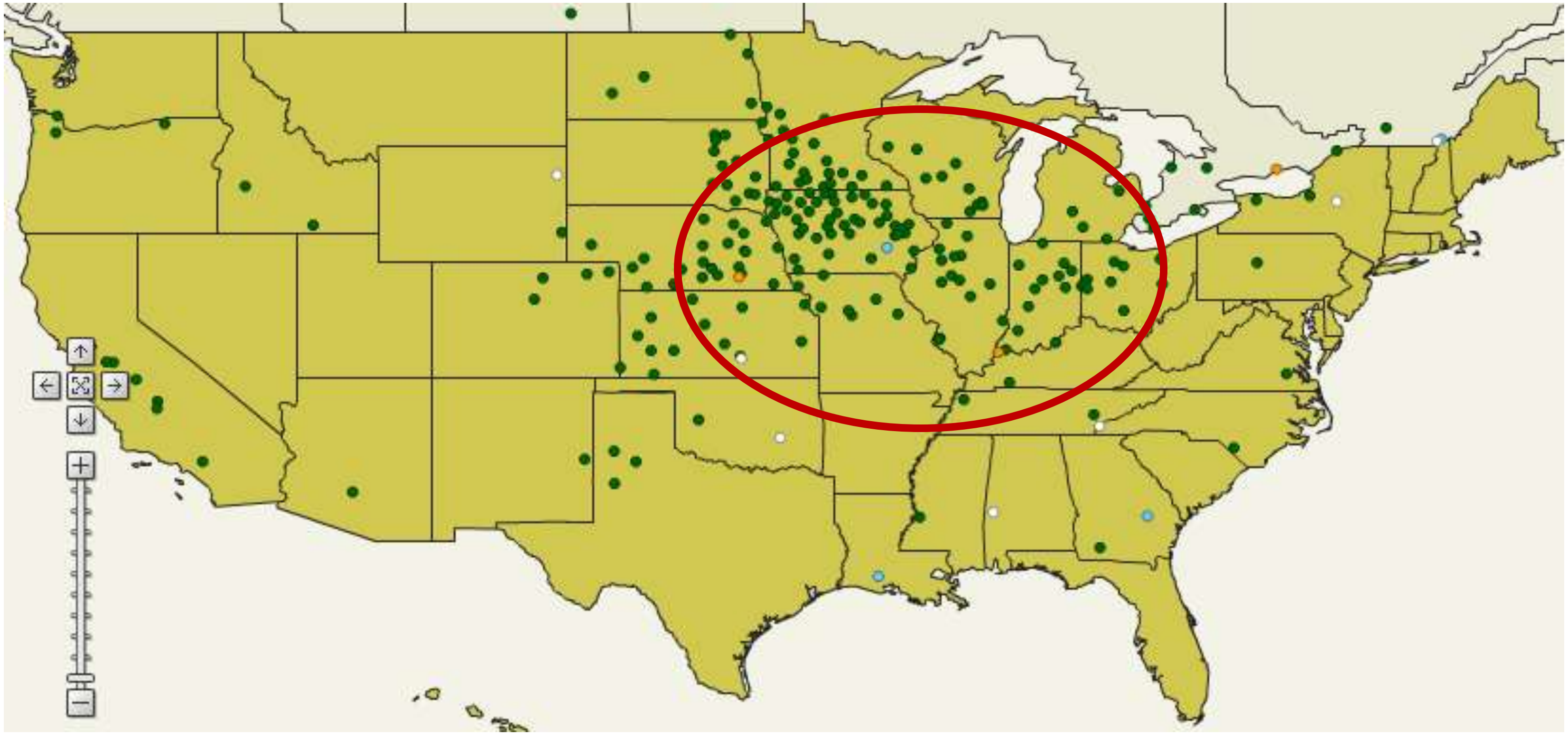
- The Energy Independence and Security Act (EISA) of 2007:
  - Renewable Fuels Standards (RFS):
    136 billion liters of biofuel by 2022.
  - Cellulosic ethanol and advanced biofuels: 79.5 billion liters
- EISA Section 204 mandates US Environmental Protection Agency, US Department of Agriculture (USDA), and Department of Energy (DOE):
  - Report to Congress the current as well as future environmental and resources conservation impacts of biofuel production
  - Both USDA and DOE have started major initiatives to evaluate ecosystem sustainability of biofeedstock production

Feedstock sources to meet production goals

Feedstock	Biofuel produced (Billion Liters)
Dedicated energy crops	50.7
Oil seeds (soy, canola)	1.9
Crop residue (corn stover, straw)	16.3
Woody biomass (logging residue only)	10.6
Corn starch ethanol	56.8

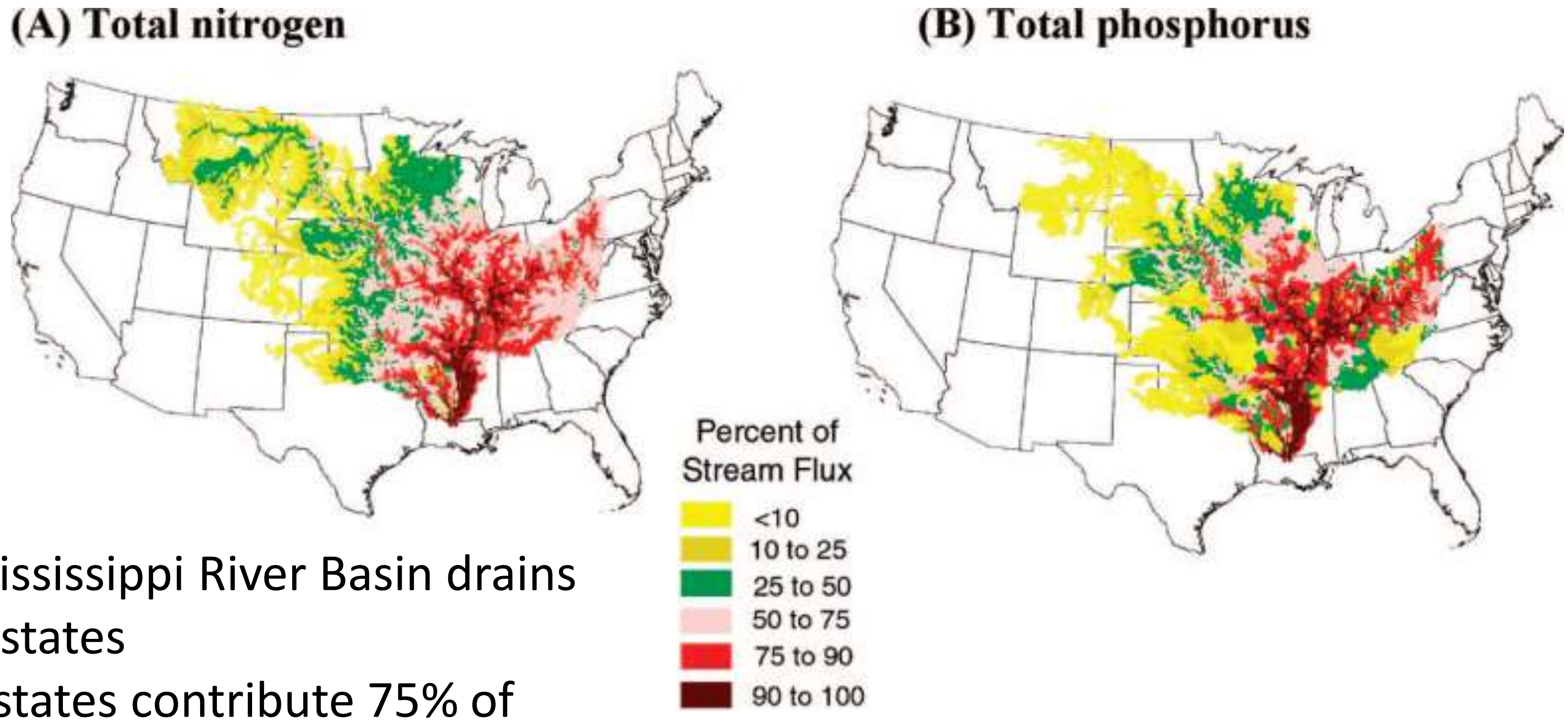
Source: USDA Biofuels strategic production report, June 23, 2010

Ethanol power plants in US, 2010



Source: http://www.ethanolproducer.com/plantmap/

Nutrient transport in Mississippi River Basin



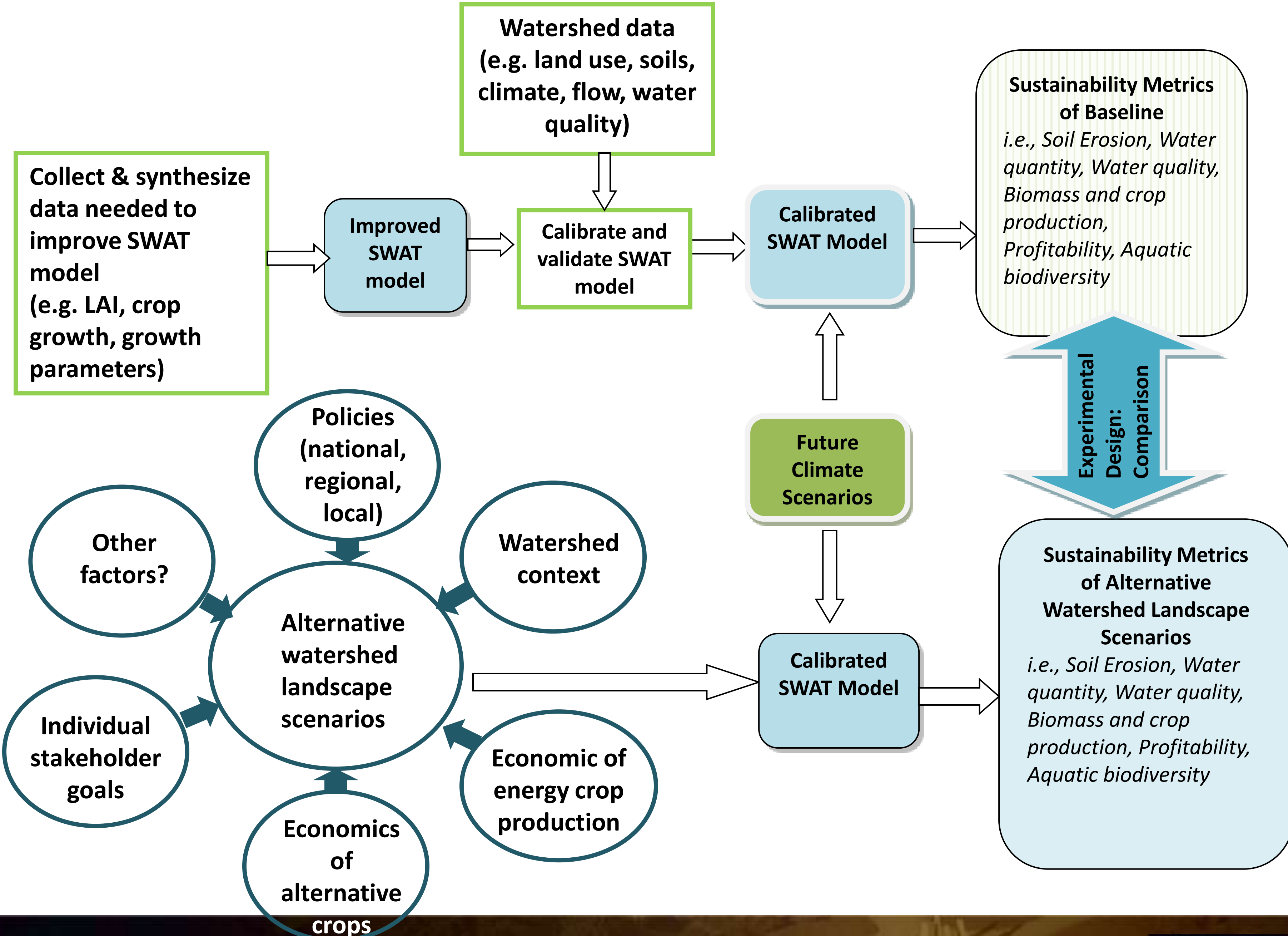
- Mississippi River Basin drains 31 states
- 9 states contribute 75% of total N and P
- However, these states account for only 33% of MARB Area
- 86% of N comes from corn/soybean areas

Source: Alexander et al., 2008

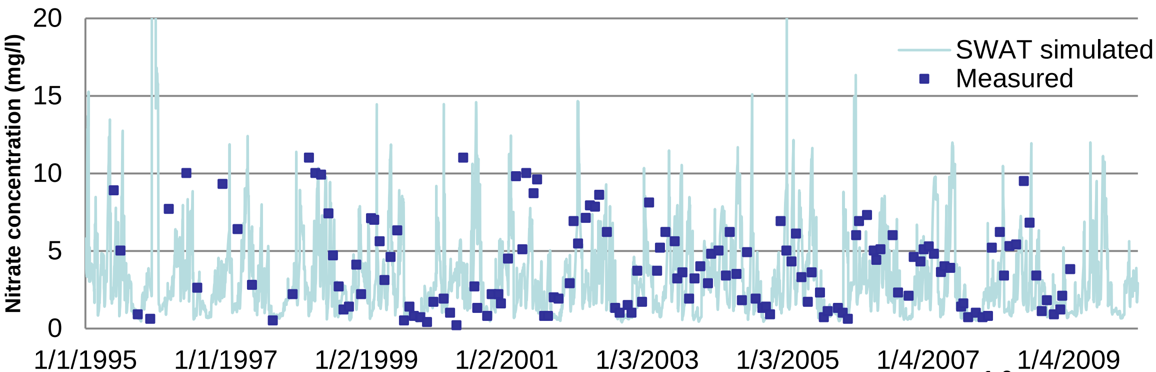
Key Questions

- What are the environmental impacts of various biofeedstock production systems to meet cellulosic ethanol demands?
  - Corn Stover
  - Switch grass
  - *Miscanthus*
  - Mixed grasses
  - Fast growing trees (e.g. hybrid poplar)

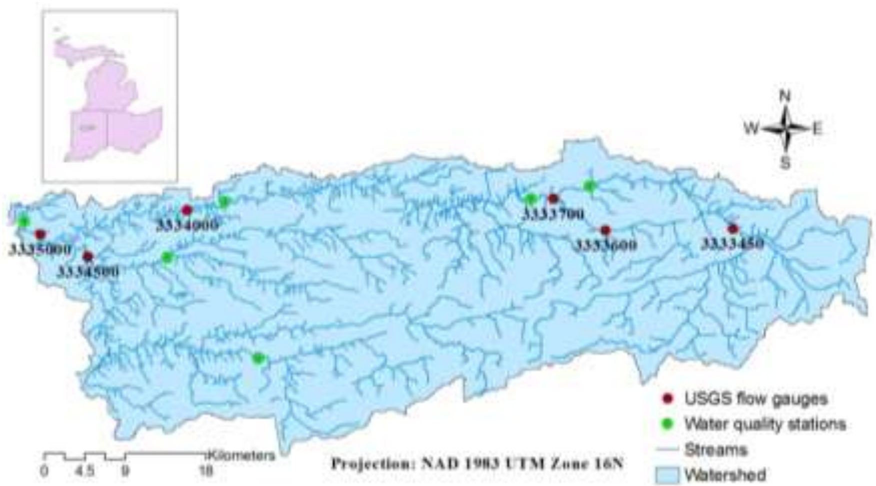
- What modifications are needed in current generation of watershed models to adequately represent current and future biofeedstock scenarios?
  - Various levels of biomass removal
  - New crops, varieties
  - Crop failures

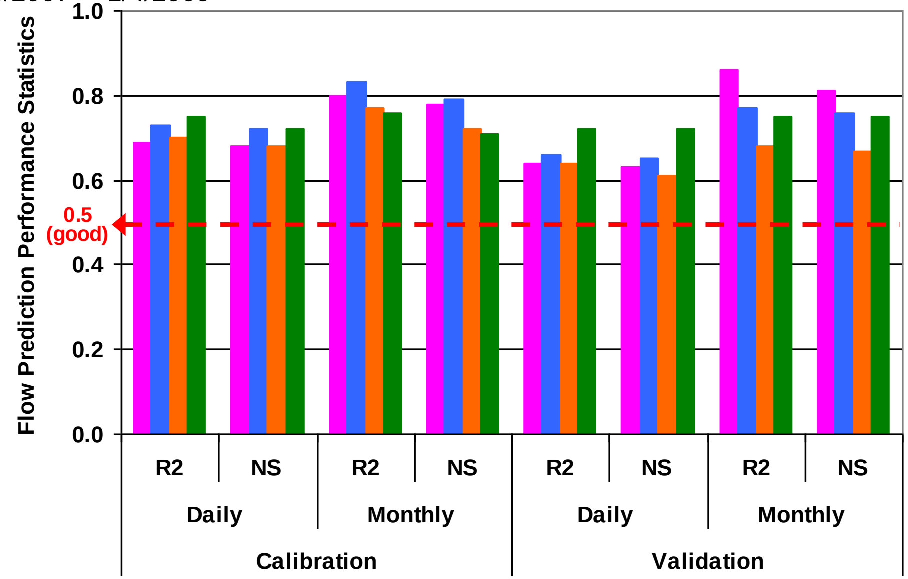

Watershed data
(e.g. land use, soils, climate, flow, water quality)
Collect & synthesize data needed to improve SWAT model
(e.g. LAI, crop growth, growth parameters)
Improved SWAT model
Calibrate and validate SWAT model
Calibrated SWAT Model
Sustainability Metrics of Baseline
i.e., Soil Erosion, Water 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

Impacts of corn stover removal at the watershed scale: Wildcat Creek watershed



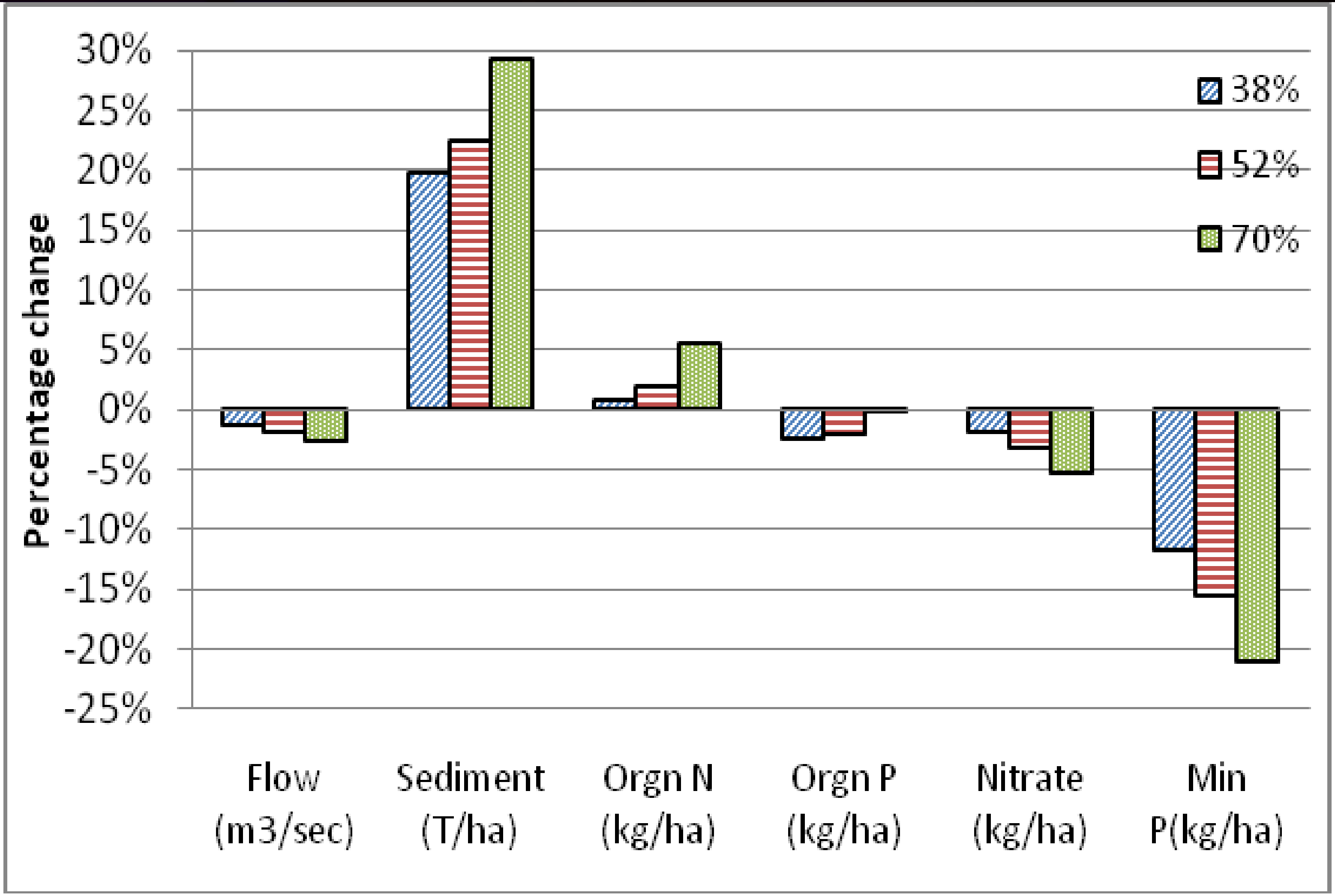
Nitrate simulation results





SWAT performance for flow simulation

Watershed response to residue removal



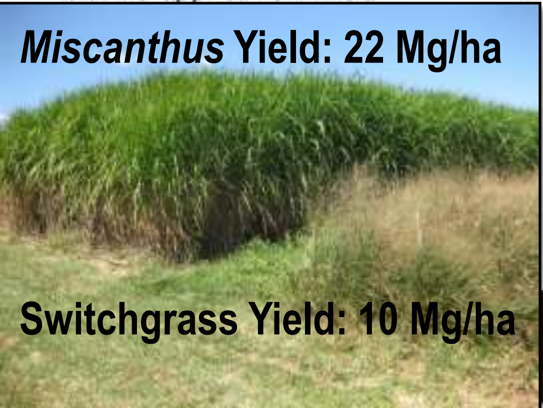
Cibin, Chaubey & Engel. 2011. Hydrologic Processes (in review)

Perennial crop variability

Table 4 Final dry weight v alues (g m^{-2}; mean ± SD) of switchgrass and Miscanthus at the two sites

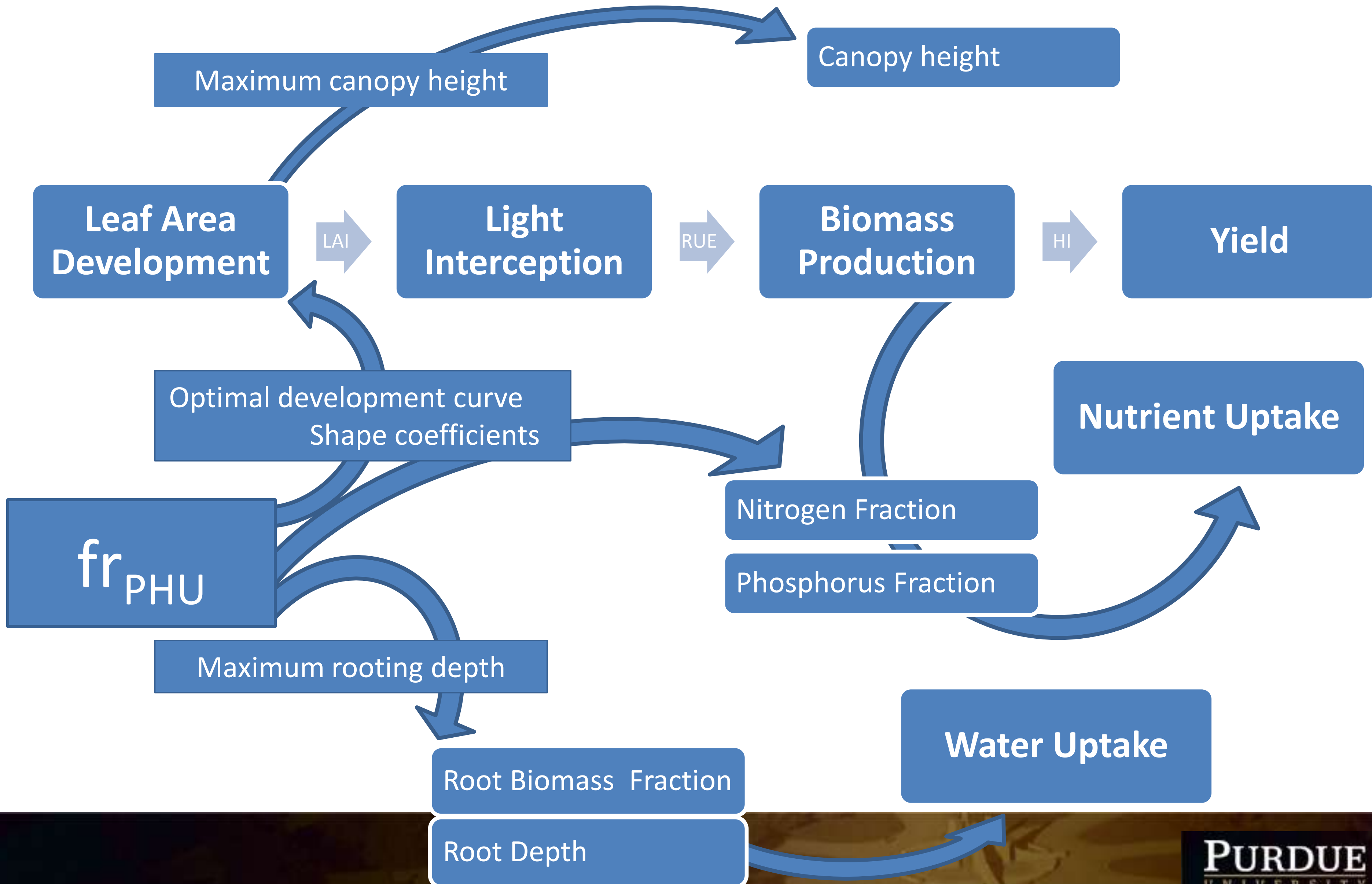
	2008	2009	2010	Mean
Elsberry, MO				
Switchgrass				
Cave-in-Rock	1,230±601	1,032±139		1,131
Kanlow	1,684±936	1,310±208		1,497
Alamo	2,044±956	1,412±197		1,738
Miscanthus				
M. × *giganteus*	2,945±1,476	2,549±922		2,747
Gustine, TX				
Alamo switchgrass				
Irrigated	1,028±413	2,949±219	1,900±625	1,959
Non-irrigated	517±289	1,729±543	481±139	909
Miscanthus				
Irrigated	1,080±409	2,386±243	1,430±625	1,632
Non-irrigated	197±78	1,003±259	155±88	452

At Gustine, the irrigated treatment received dairy waste water through a center pivot irrigation system while the non-irrigated treatment only received rain, with no applied fertilizers



Kiniry et al., 2011, *Bioenergy Research*

Crop growth in SWAT



Parameters in crop.dat

Description	Parameter
Plant classification	IDC
Radiation use efficiency (ambient and changing climate)	BIO_E, BIOEHI
Harvest Index (optimal conditions and lower limit)	HVSTI, WSYF
Leaf Area Index (max. and min. during dormancy)	BLAI, ALAI_MIN
Optimal leaf area curve	FRGRW1, LAIMX1, FRGRW2, LAIMX2
Fraction of growing season when leaf area declines	DLAI
Maximum canopy height	CHTMX
Maximum root depth	RDMX
Optimal temperature	T_OPT
Minimum temperature	T_BASE
Fraction of nitrogen or phosphorus in yield	CNYLD, CPYLD
Nitrogen and phosphorus uptake parameters	PLTNFR(1), PLTNFR(2), PLTNFR(3), PLTPFR(1), PLTPFR(2), PLTPFR(3)
Minimum value of USLE C factor	USLE_C
Stomatal conductance (max. and fraction of max.)	GSI, FRGMAX
Vapor pressure deficit	VPDFR
Rate of RUE decline from increase in vapor pressure deficit	WAVP
Elevated CO_2 atmospheric concentration	CO2HI
Plant residue decomposition coefficient	RSDCO_PL
Tree-specific parameters	BIO_LEAF, MAT_YRS, BMX_TREES
Light extinction coefficient	EXT_COEFF

Sensitivity analysis of crop parameters

Switchgrass

Parameter	TN	TP	Biomass
BIOE	0.17	0.85	**0.98**
BLAI	**0.30**	-0.02	0.33
FRGW1	0.25	-0.05	-0.03
FRGW2	0.27	-0.10	-0.04
LAIMX1	-0.01	0.10	0.02
LAIMX2	-0.23	0.29	0.11
DLAI	-0.19	-0.17	0.22
CHTMX	0.02	0.10	-0.02
RTMX	0.00	0.00	0.00
T_OPT	-0.22	0.07	-0.20
T_BASE	-0.40	**1.16**	0.83

Miscanthus

Parameter	TN	TP	Biomass
BIOE	**0.99**	**1.27**	**0.98**
BLAI	0.40	0.23	0.36
FRGW1	0.02	-0.06	-0.01
FRGW2	-0.10	-0.18	-0.04
LAIMX1	0.20	0.01	0.00
LAIMX2	-0.23	0.29	0.11
DLAI	-0.06	-0.27	0.23
CHTMX	0.05	0.16	-0.01
RTMX	0.00	0.00	0.00
T_OPT	0.15	-0.04	0.06
T_BASE	-0.40	0.54	0.56

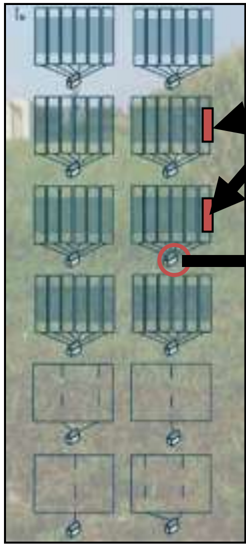
- OAT sensitivity analysis
- ±10% change
- Relative sensitivity (Sr)

$$S_r = \frac{Y_2 - Y_1}{X_2 - X_1}\left(\frac{X}{Y}\right)$$

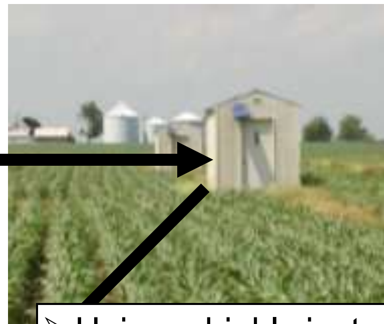
Field sites characterization for crop data collection

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

Collaborative data collection for improved parameters



Field Scale Drainage Lysimeters



Purdue University Water Quality Field Station (WQFS)

- Unique, highly instrumented, in-field laboratory
- Integrated studies of agricultural productivity and environmental impacts
- Team approach: Agronomy, Physiology, Breeding & Genetics, Ecology, Soil Science, Economics, Sociology, Agric. Engineering, Modeling, Life Cycle Analysis

Cropping treatments

Low-input prairie
Maize-soybean rotation
Continuous maize
Continuous maize w/ residue removal
Miscanthus
Switchgrass
High yielding, high sugar sorghum
Manure applications (spring vs. fall)

Opportunity

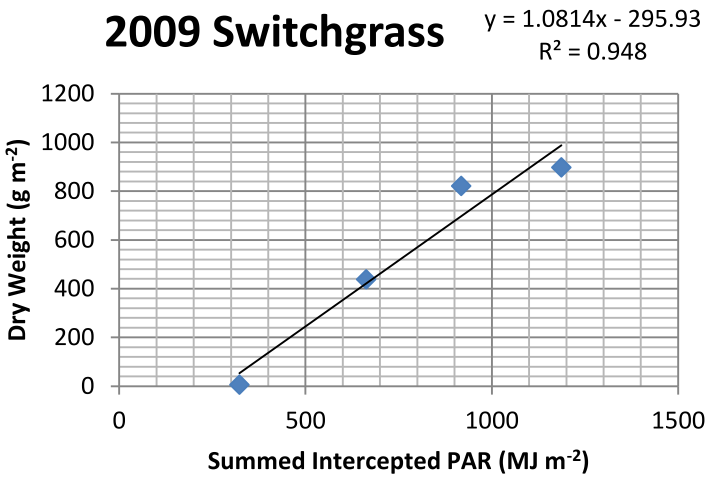
Targeted measurements coincide with model crop growth parameter development.

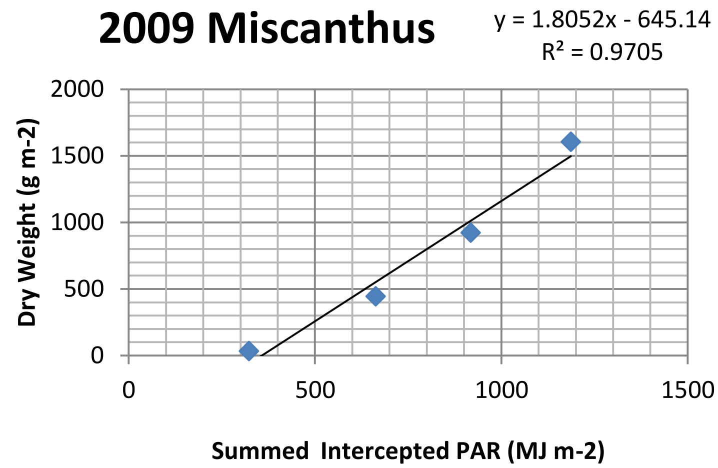
WQFS Research Capabilities: Biomass and grain yields, Biomass composition, Radiation, Water and N use efficiencies of cropping systems in the context of 1) Nutrient (C and N) losses to surface waters in tile drainage water, and 2) Greenhouse gas (CO_2, CH_4 and N_2O) emission from soil.

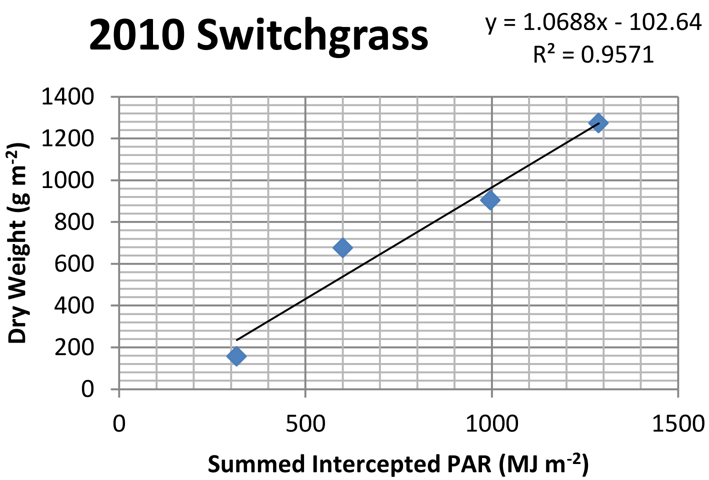
Measurements and parameters

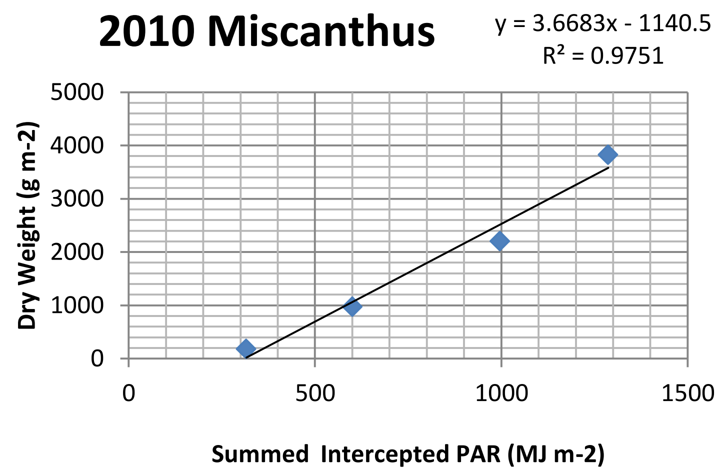
Parameter	**Measurement Description**
Unstressed Leaf Area Development and Light Extinction Coefficient	**Leaf Area Index** (LAI) and the **number of accumulated heat units**. Used to quantify leaf area and canopy development during growing season
Maximum Crop Height	**Canopy height** of non-stressed plants.
Harvest Index for Optimal Growing Conditions Lower limit of harvest index – highly stressed	**Fraction of aboveground biomass removed in harvest operation**.
Radiation Use Efficiency or Biomass: Energy Ratio *Independent of growth stage.*	**Crop Growth Rate** (CGR) and **Photosynthetically Active Radiation** (PAR). Amount of biomass produced per unit intercepted solar radiation.
Nitrogen and Phosphorous uptake	**Fraction of nitrogen and phosphorus in total plant biomass** in order to calculate plant nutrient demand throughout growing cycle. Ideally, includes roots as well as aboveground mass.
Maximum Root Depth (RDMX)	**Depth** at which live roots exist. (1 meter soil cores analyzed for live roots at progressive depths.)
Effective Rooting Depth	**Rooting zone** where plant will absorb/uptake the majority of its nutrients.
Optimal Temperature	**Optimal temperature** for leaf development (not plant growth)

Radiation Use Efficiency (RUE)

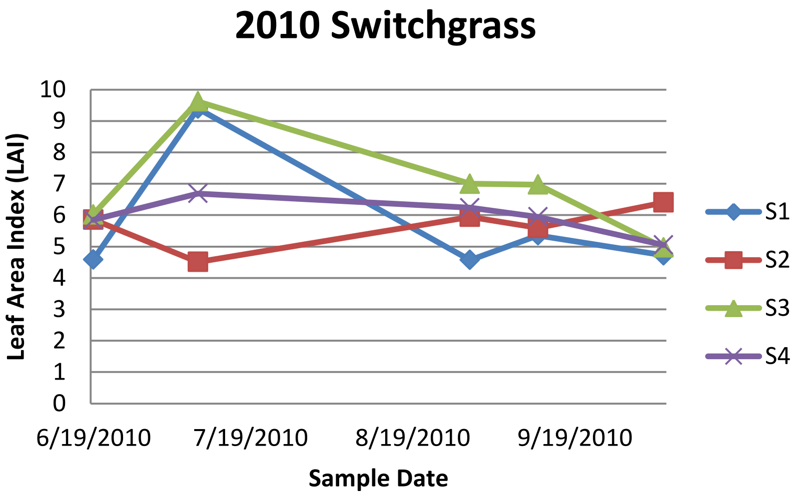


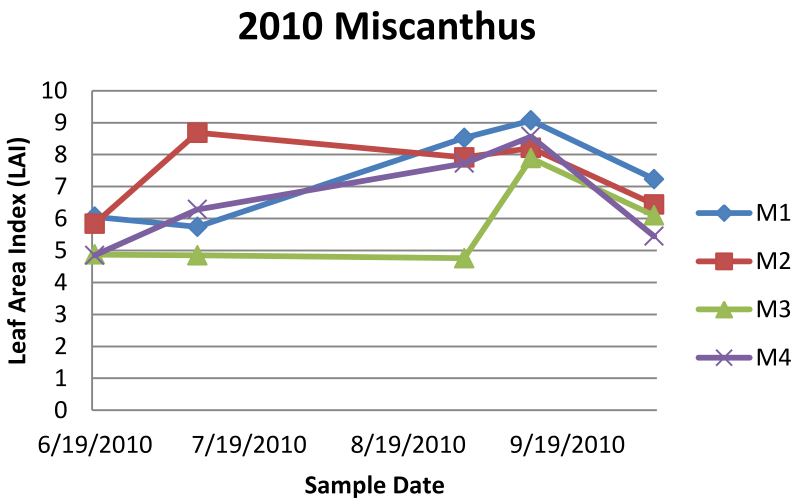




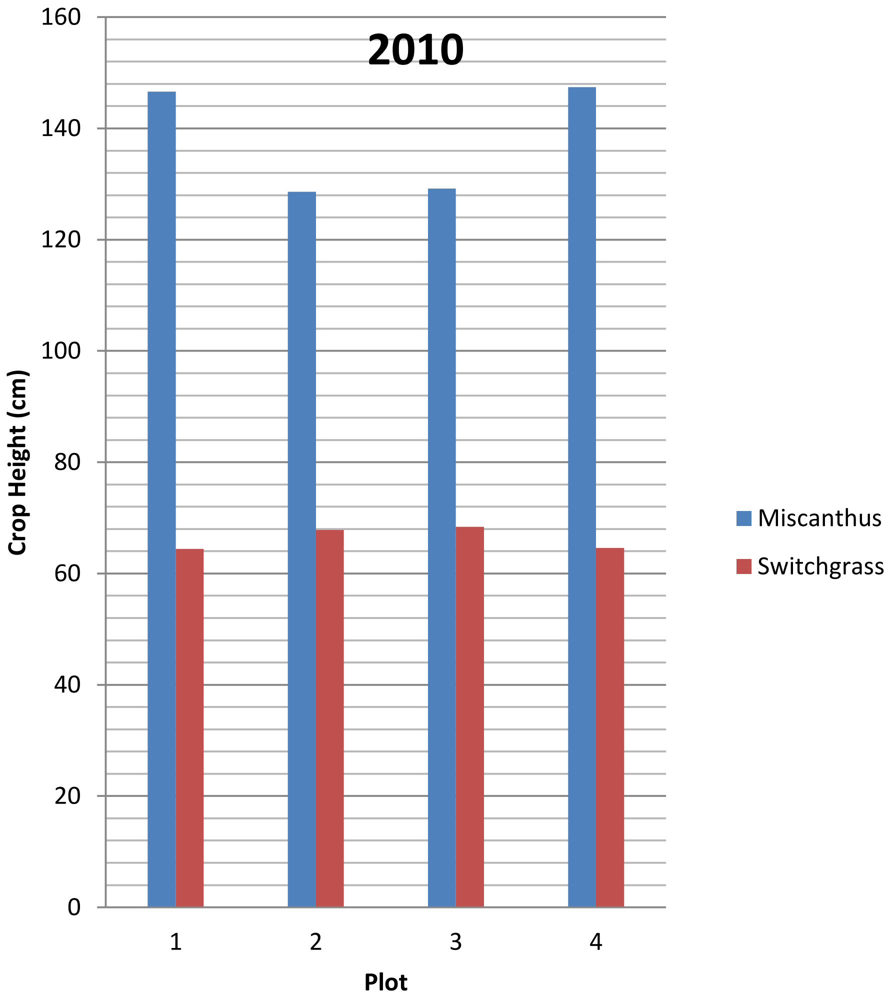


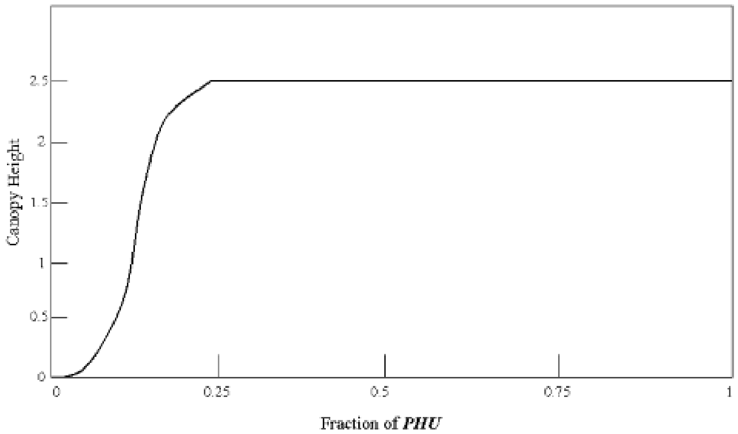
Leaf area index (LAI)





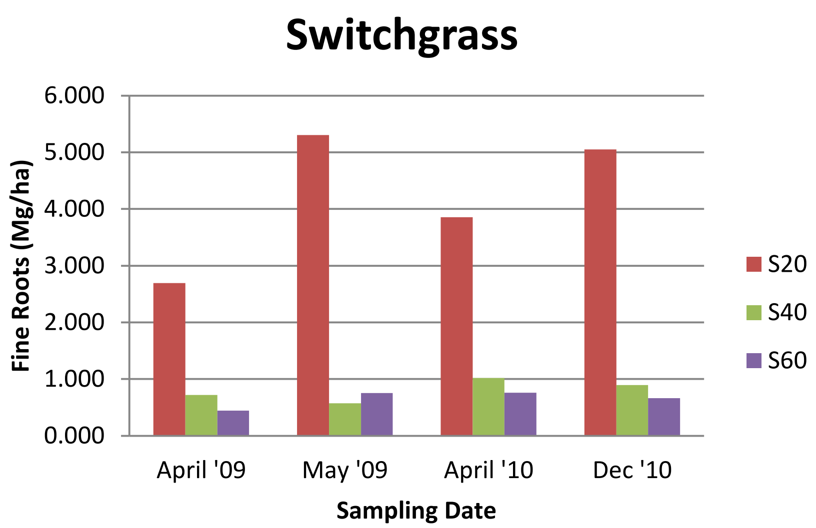
Canopy height

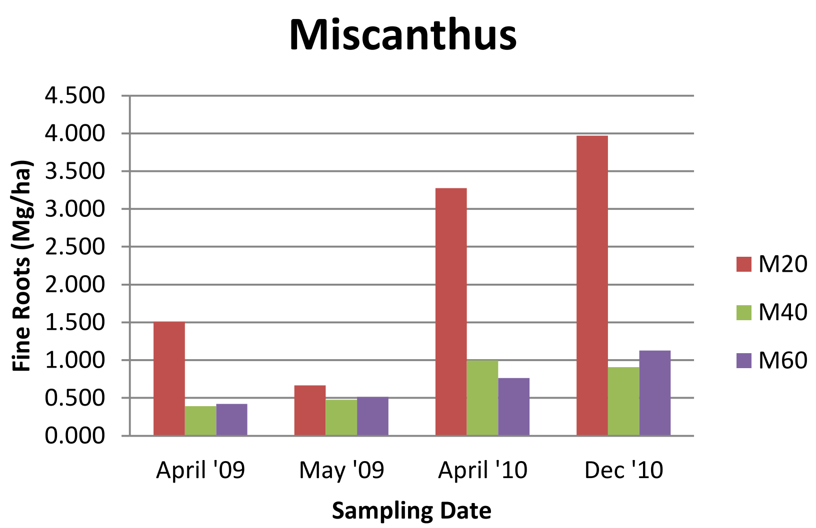


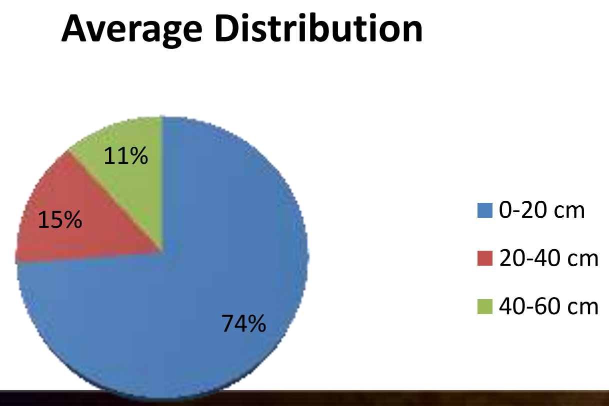


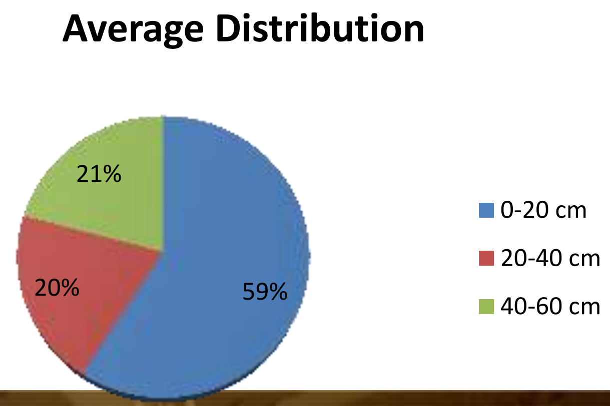
SWAT Theoretical Documentation, 2005

Root distribution

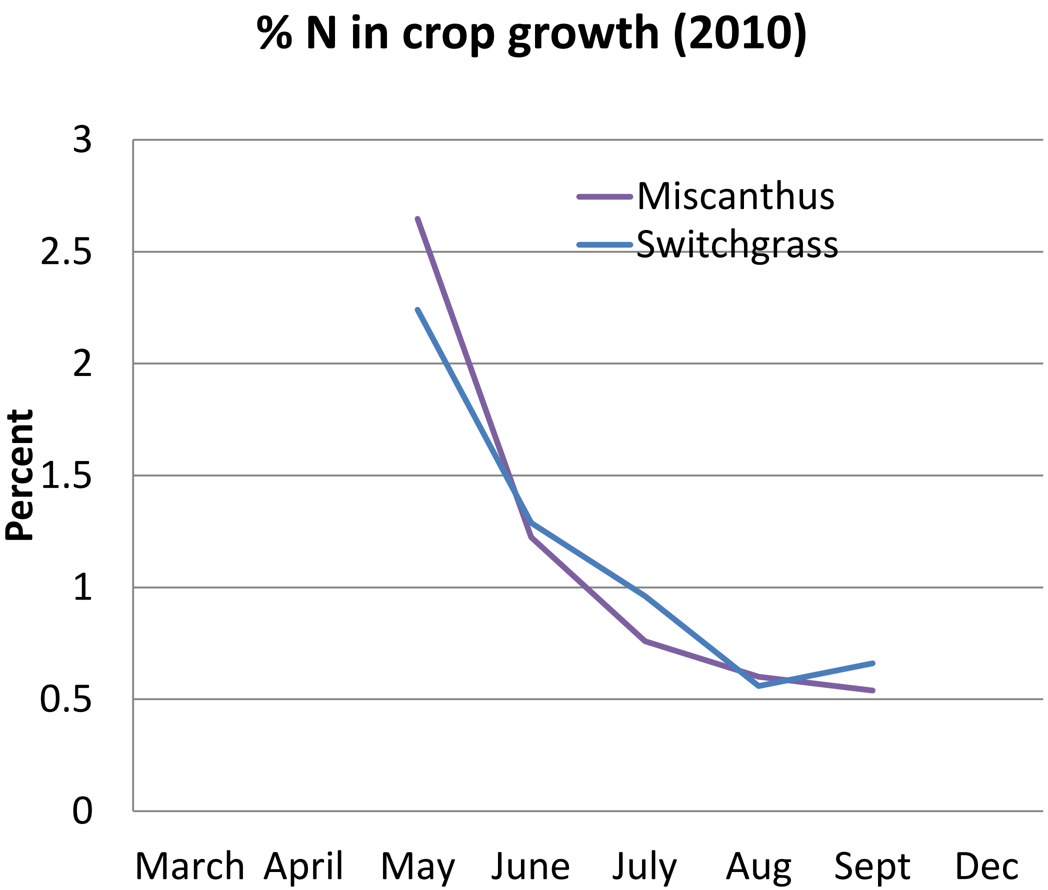








Nitrogen uptake



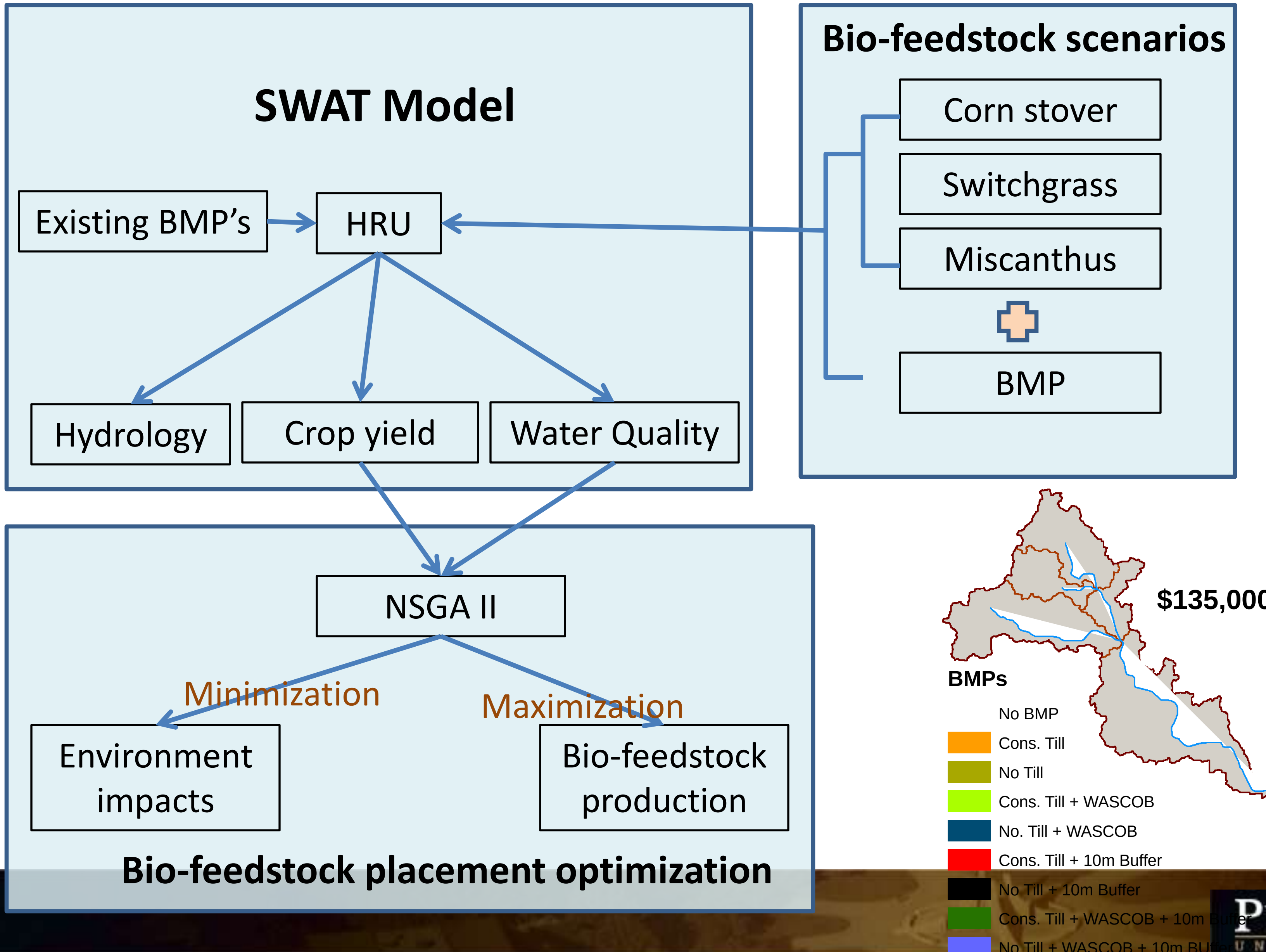
- Nitrogen and Phosphorus data for 2009, 2010
- N and P fractions at different growth stages will be derived
- P Analysis in Progress

Energy crops as BMP

- As riparian area, vegetative filter strip and grassed waterways
- Improve SWAT model BMP algorithms to include crop growth in BMP area
- Validate crop growth and BMP performance
- Impacts of target placement of energy crops as BMP's
- A manual for energy crop representation in SWAT similar to BMP representation manual

NRCS stock photos

Optimal energy crop selection and placement



Summary

- **Sustainability of biofeedstock production** in terms of soil erosion, water availability, water quality, biomass production, profitability, and aquatic biodiversity
- SWAT model will play a significant role in evaluating **systemic assessment** of sustainability that can be used to make informed production decisions
- However, **SWAT model improvements** are needed to evaluate many of the potential production scenarios
- **Multi-disciplinary** team approach needed to collect data and make model improvements

For additional information visit various project web-sites…

- engineering.purdue.edu/ecohydrology
- engineering.purude.edu/biomasswq

- Email: ichaubey@purdue.edu