# Watershed scale sustainability analysis of land use and climate changes using SWAT model

**Indrajeet Chaubey**
**Cibin Raj, Jane Frankenberger, Keith Cherkauer**

Purdue University

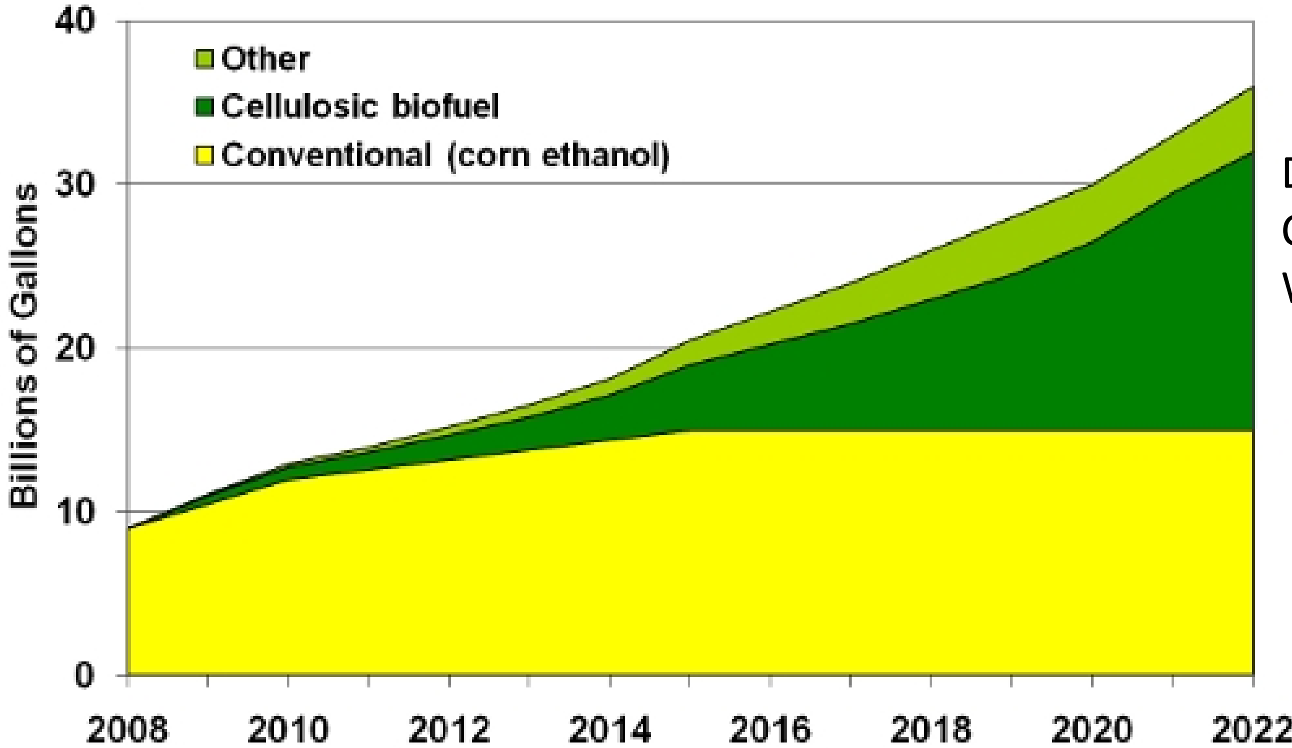
July 31, 2014
SWAT International Conference

Funding: US Department of Energy, Office of Biomass Program

# Increased demand for food and fuel will drive global-scale land use changes

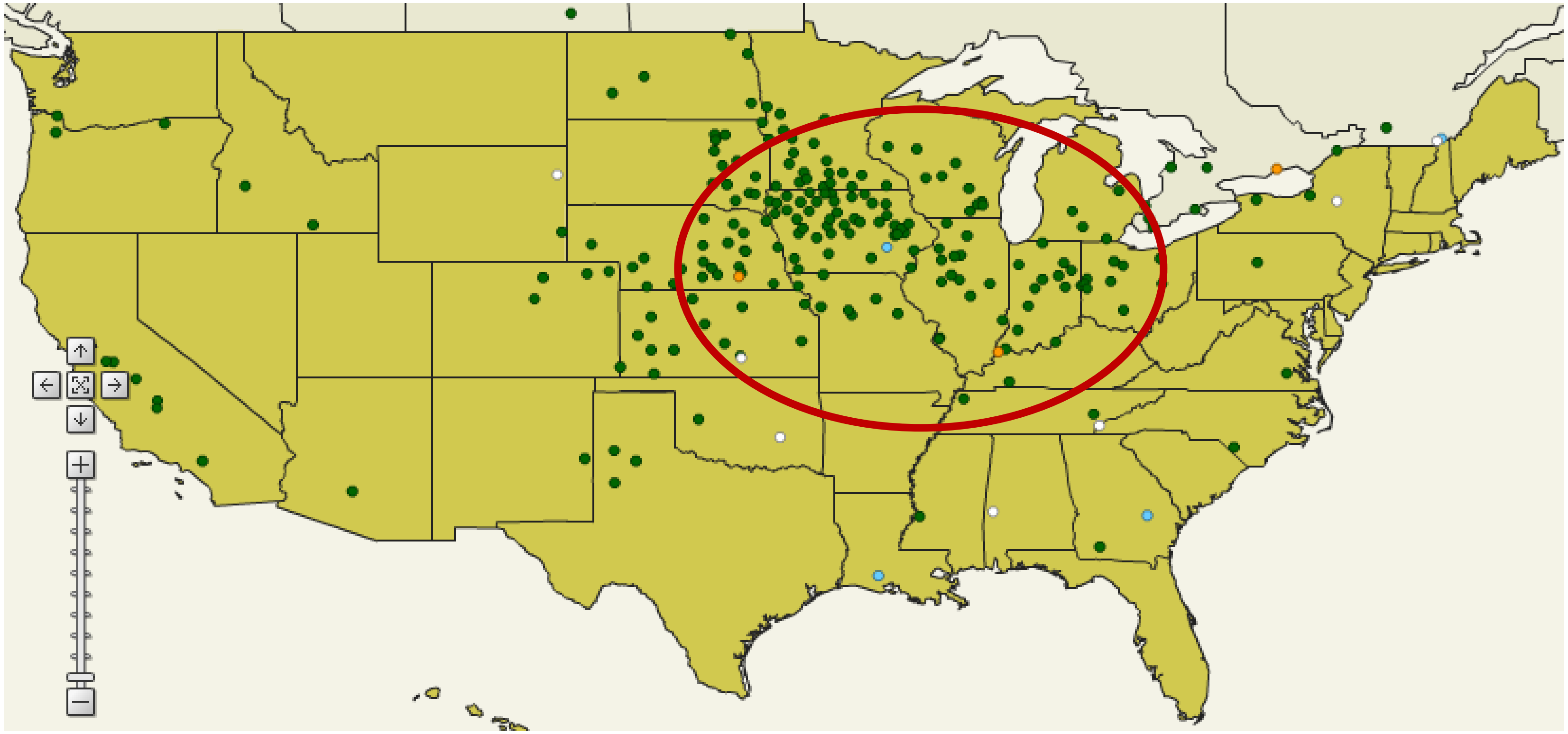
- Rising energy cost is increasing interest in alternative sources for energy production.
- Bioenergy produced from annual and perennial feedstock has emerged as a viable option.
- The U.S.A. Energy Independence and Security Act (EISA) of 2007:
  - 136 billion liters of biofuel by 2022.
  - Cellulosic ethanol and advanced biofuels: 79 billion liters
- However, unintended hydrologic/water quality consequences from large scale bioenergy production must be carefully evaluated.

# Introduction




Dedicated Energy Crops : 65%
Crop Residues : 20%
Woody Biomass : 15%

# Ethanol power plants in US, 2010



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

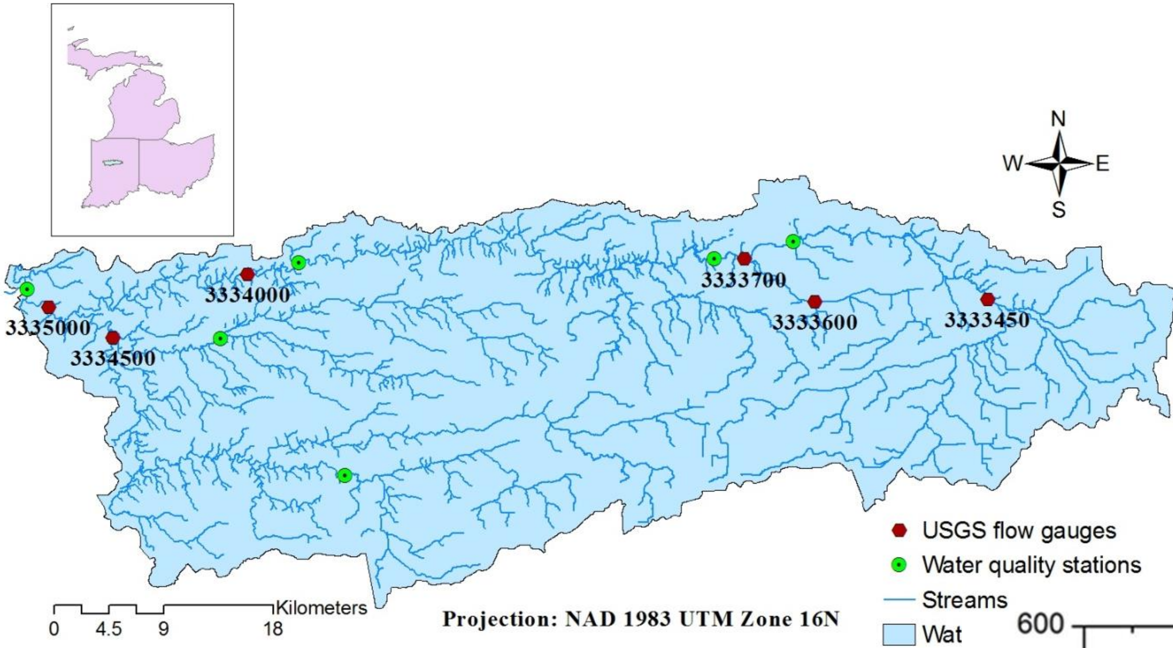
# Research goal

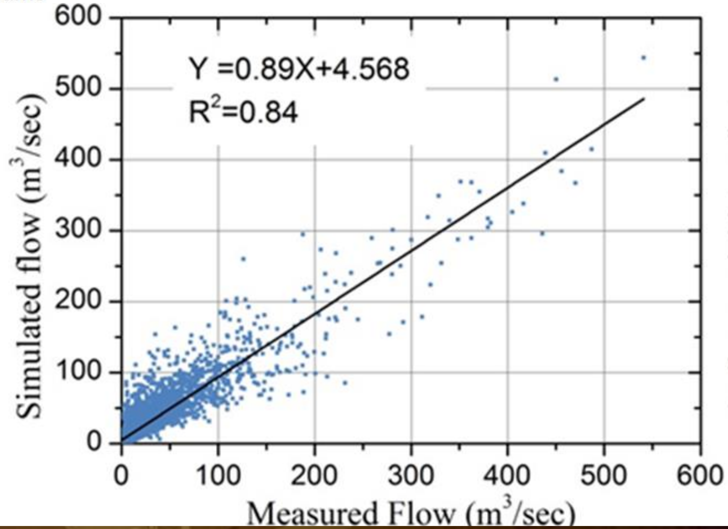
Evaluate environmental sustainability of various plausible land and crop management options for biofuel production under changing climate scenarios

# Research Highlights

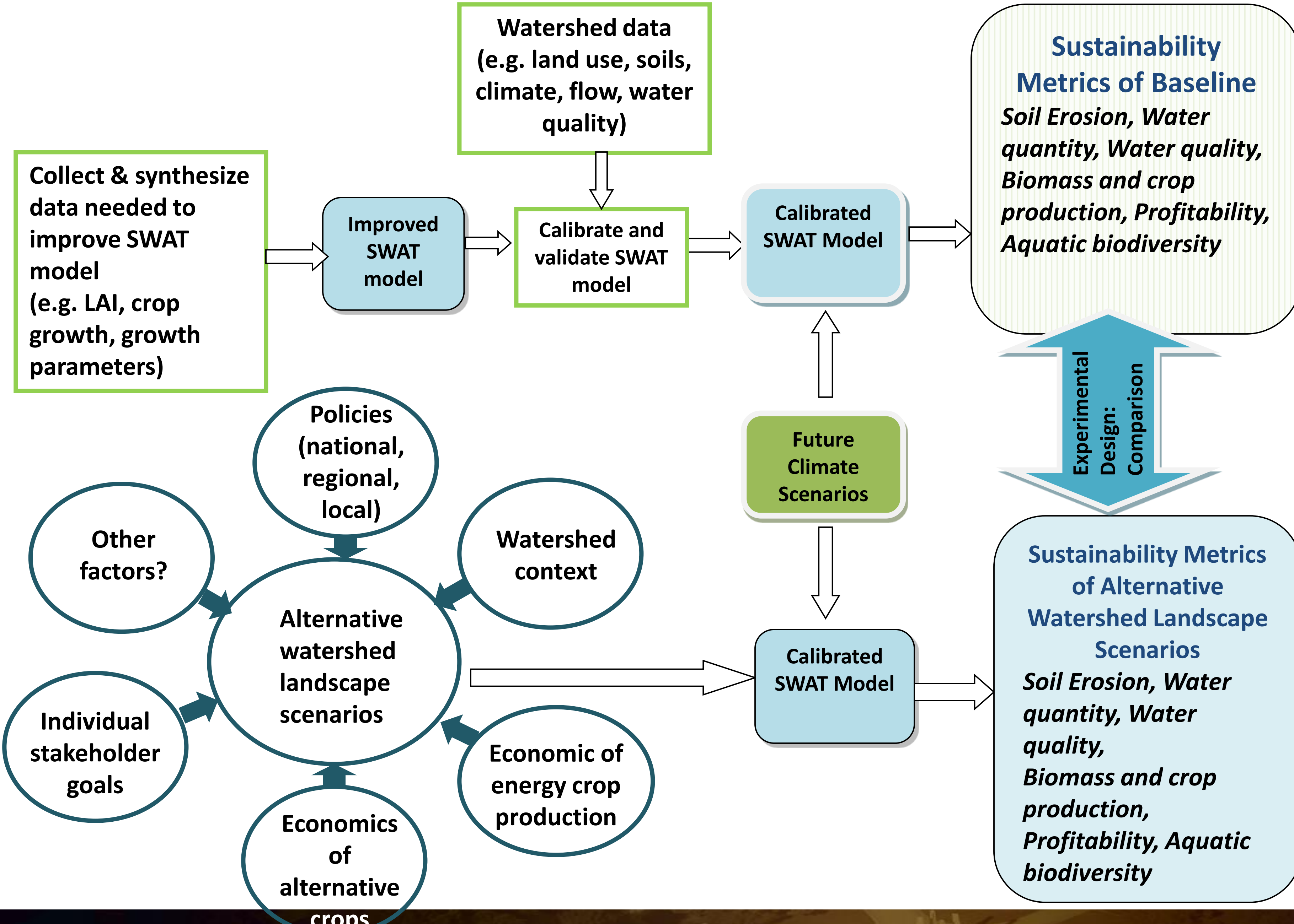
- Energy crops (*Miscanthus* and switchgrass) parameterized with field data
- An improved SWAT model used to simulate impacts of perennial energy crop production on hydrology, water quality and environmental sustainability
  - Trybula et al. 2014. Global Change Biology-Bioenergy, doi 10.1111/gcbb.12210

# Study Area– Wildcat Creek Watershed




- North-Central Indiana
- Area – 2,045 km$^2$
- Agricultural watershed: 70% Corn /soyb
- Calibrated with basin level parameters


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
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
Soil Erosion, Water quantity, Water quality, Biomass and crop production, Profitability, Aquatic biodiversity

# Methodology: Energy crop scenarios

- Thirteen energy crop scenarios were developed with *Miscanthus,* switchgrass and corn stover removal
- Energy crop scenarios
  - 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)
- Average annual impacts were compared

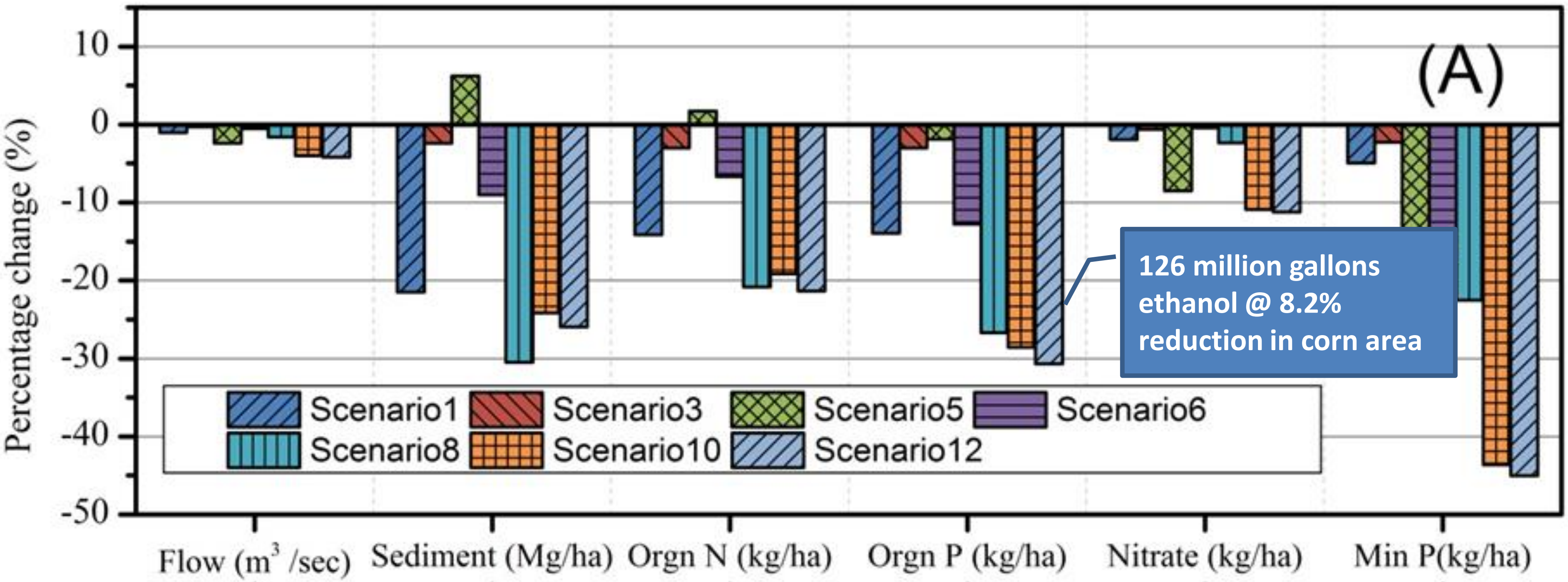
# Methodology: Sustainability Indicators

| | Category | Indicator | Unit | Indicator for |
|---|---|---|---|---|
| 1 | **Soil erosion** and its impact on long-term **productivity** | Erosion | Mg/ha/year | soil loss and productivity |
| 2 | | Total nitrogen | Kg-N/ha | soil loss and productivity |
| 3 | | Extractable Phosphorus | Kg-P/ha | soil loss and productivity |
| 4 | **Water quantity**, including High-flow frequency, Streamflow distribution, Streamflow variability, Low flows, and Groundwater recharge | Annual maxima and peaks and exceedances over threshold | $m^3$/sec | High flow |
| 5 | | Runoff index | - | Stream flow distribution |
| 6 | | Richards-Baker Flashiness Index | - | Variability |
| 7 | | 7 day average low flow for year | $m^3$/sec | Low flow |
| 8 | | Water Stress Index (WSI) | | Consumptive water use |
| 9 | **Water quality**, including suspended sediment, nitrogen (nitrate, TKN, total), phosphorus (dissolved and total), pesticides | Sediment load or sediment concentration | Mg/ha/year | Suspended sediment |
| 10 | | Nitrate and total nitrogen | Kg-N/ha | Nitrogen loading |
| 11 | | Organic phosphorus and total phosphorus | Kg-P/ha | Phosphorus loading |
| 12 | **Biomass and crop production** | Total biomass and harvested yield | t/ha | crop production |
| 13 | **Profitability** | Break-even feedstock price | | |
| 14 | **Aquatic biodiversity** | | | |

# Methodology: Climate Change

- Precipitation and temperature from **nine climate model simulations**: 3 models (GFDL CM2.0.1, UKMO HadCM3 3.1 and NCAR PCM 1.3) for each of three future emission scenarios (A1B, A2, B1)
- Bias corrected and statistically downscaled with resolution of 1/8$^{o}$
- climate data from 1950-2050: 10 years model warm up, **1960-1989(Past), 1990-2019 (present), and 2020-2049 (future)**

# Impacts of Bioenergy Scenarios - *Miscanthus*




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

# Sustainability Indicators of Energy crop scenarios

14 years, 1996-2009, NCDC weather data, calibrated model, ***Miscanthus*** scenarios

| | Unit | Baseline | Scenario 1 | Scenario 5 | Scenario 12 |
|---|---|---|---|---|---|
| Erosion | Mg/ha | 2.5 | 1.9 | 2.8 | 2.1 |
| Final Org N (Init=13140) | kg/ha | 12574 | 12582 | 12564 | 12572 |
| Final Nitrate (Init=64) | kg/ha | 57 | 55 | 49 | 46 |
| Final Org P (Init=1610) | kg/ha | 1533 | 1532 | 1526 | 1524 |
| Final Min P (Init=287) | kg/ha | 416 | 403 | 423 | 400 |
| Avg of Annual Peak flow | $m^3$/sec | 284 | 280 | 280 | 271 |
| Days over threshold | Days >300 m3/sec | 18 | 17 | 17 | 14 |
| Runoff Index | - | 0.653 | 0.637 | 0.662 | 0.634 |
| R-B Index | - | 0.253 | 0.247 | 0.254 | 0.244 |
| 7day Avg low flow | - | 0 | 0 | 0 | 0 |
| Water Stress index | - | 0.604 | 0.608 | 0.612 | 0.620 |
| Sediment load (outlet) | Mg/ha | 1.07 | 0.82 | 1.15 | 0.87 |
| Nitrate load (outlet) | kg/ha | 10.8 | 10.6 | 10.0 | 9.8 |
| TN load (outlet) | kg/ha | 19.4 | 18.0 | 18.9 | 17.2 |
| Org P load (outlet) | kg/ha | 1.4 | 1.2 | 1.4 | 1.1 |
| TP load (outlet) | kg/ha | 1.6 | 1.4 | 1.6 | 1.3 |

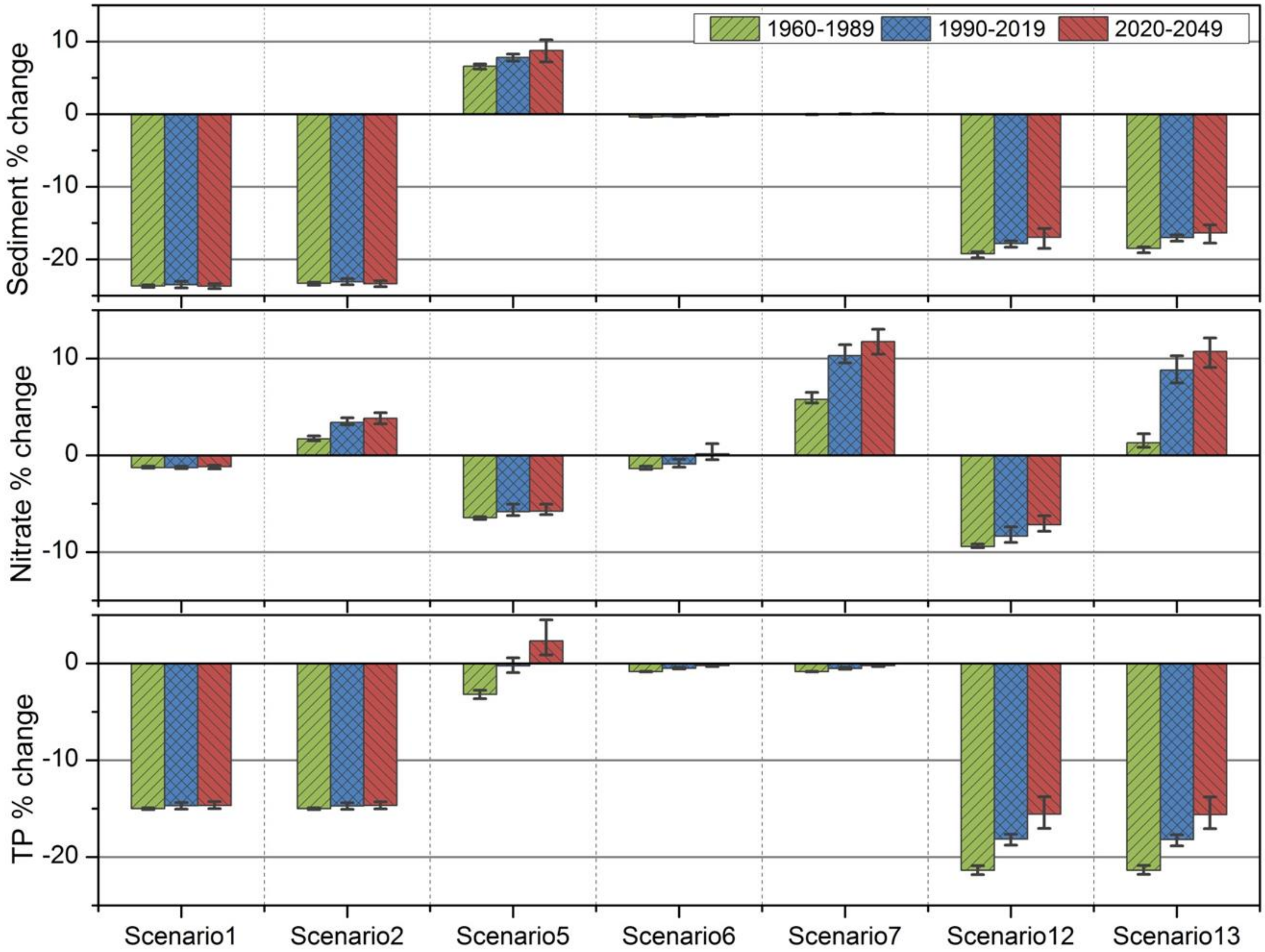
# Climate change scenarios

Sustainable indicators of the **baseline scenario** with GCM data; 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 |

# Climate change + biofuel scenarios

The bars indicate mean percentage change from 9 GCMs and error bars indicates min and max of 9 GCMs.



# Conclusions

- 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 exceptions of stover removal that increased sediment load and switchgrass replacing pasture that increased nitrate 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 is generally greater than the effects of climate change variability