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

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Biofuel produced (Billion Liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated energy crops</td>
<td>50.7</td>
</tr>
<tr>
<td>Oil seeds (soy, canola)</td>
<td>1.9</td>
</tr>
<tr>
<td>Crop residue (corn stover, straw)</td>
<td>16.3</td>
</tr>
<tr>
<td>Woody biomass (logging residue only)</td>
<td>10.6</td>
</tr>
<tr>
<td>Corn starch ethanol</td>
<td>56.8</td>
</tr>
</tbody>
</table>

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
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

Future Climate Scenarios

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

Experimental Design: Comparison

Policies (national, regional, local)

Watershed context

Alternative watershed landscape scenarios

Other factors?

Individual stakeholder goals

Economics of alternative crops

Economics of energy crop production

Watershed data (e.g. land use, soils, climate, flow, water quality)
Impacts of corn stover removal at the watershed scale: Wildcat Creek watershed

Nitrate simulation results

Flow Prediction Performance Statistics

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 values (g m\(^{-2}\); mean ± SD) of switchgrass and Miscanthus at the two sites

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

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.

Miscanthus Yield: 22 Mg/ha

Switchgrass Yield: 10 Mg/ha

Kiniry et al., 2011, *Bioenergy Research*
Crop growth in SWAT

- Maximum canopy height
- Canopy height
- Leaf Area Development
- LAI
- Light Interception
- RUE
- Biomass Production
- HI
- Yield
- Optimal development curve
- Shape coefficients
- Maximum rooting depth
- Maximum canopy height
- Nutrient Uptake
- Water Uptake
- Root Biomass Fraction
- Phosphorus Fraction
- Nitrogen Fraction
- fr_{PHU}
- Root Depth
<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant classification</td>
<td>IDC</td>
</tr>
<tr>
<td>Radiation use efficiency (ambient and changing climate)</td>
<td>BIO_E, BIOEHI</td>
</tr>
<tr>
<td>Harvest Index (optimal conditions and lower limit)</td>
<td>HVSTI, WSYF</td>
</tr>
<tr>
<td>Leaf Area Index (max. and min. during dormancy)</td>
<td>BLAI, ALAI_MIN</td>
</tr>
<tr>
<td>Optimal leaf area curve</td>
<td>FRGRW1, LAIMX1, FRGRW2, LAIMX2</td>
</tr>
<tr>
<td>Fraction of growing season when leaf area declines</td>
<td>DLAI</td>
</tr>
<tr>
<td>Maximum canopy height</td>
<td>CHTMX</td>
</tr>
<tr>
<td>Maximum root depth</td>
<td>RDMX</td>
</tr>
<tr>
<td>Optimal temperature</td>
<td>T_OPT</td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>T_BASE</td>
</tr>
<tr>
<td>Fraction of nitrogen or phosphorus in yield</td>
<td>CNYLD, CPYLD</td>
</tr>
<tr>
<td>Nitrogen and phosphorus uptake parameters</td>
<td>PLTNFR(1), PLTNFR(2), PLTNFR(3), PLTPFR(1), PLTPFR(2), PLTPFR(3)</td>
</tr>
<tr>
<td>Minimum value of USLE C factor</td>
<td>USLE_C</td>
</tr>
<tr>
<td>Stomatal conductance (max. and fraction of max.)</td>
<td>GSI, FRGMAX</td>
</tr>
<tr>
<td>Vapor pressure deficit</td>
<td>VPDFR</td>
</tr>
<tr>
<td>Rate of RUE decline from increase in vapor pressure deficit</td>
<td>WAVP</td>
</tr>
<tr>
<td>Elevated CO₂ atmospheric concentration</td>
<td>CO2HI</td>
</tr>
<tr>
<td>Plant residue decomposition coefficient</td>
<td>RSDCO_PL</td>
</tr>
<tr>
<td>Tree-specific parameters</td>
<td>BIO_LEAF, MAT_YRS, BMX_TREES</td>
</tr>
<tr>
<td>Light extinction coefficient</td>
<td>EXT_COEFF</td>
</tr>
</tbody>
</table>
Sensitivity analysis of crop parameters

Switchgrass

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

Miscanthus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TN</th>
<th>TP</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIOE</td>
<td>0.99</td>
<td>1.27</td>
<td>0.98</td>
</tr>
<tr>
<td>BLAI</td>
<td>0.40</td>
<td>0.23</td>
<td>0.36</td>
</tr>
<tr>
<td>FRGW1</td>
<td>0.02</td>
<td>-0.06</td>
<td>-0.01</td>
</tr>
<tr>
<td>FRGW2</td>
<td>-0.10</td>
<td>-0.18</td>
<td>-0.04</td>
</tr>
<tr>
<td>LAIMX1</td>
<td>0.20</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>LAIMX2</td>
<td>-0.23</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>DLAI</td>
<td>-0.06</td>
<td>-0.27</td>
<td>0.23</td>
</tr>
<tr>
<td>CHTMX</td>
<td>0.05</td>
<td>0.16</td>
<td>-0.01</td>
</tr>
<tr>
<td>RTMX</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>T_OPT</td>
<td>0.15</td>
<td>-0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>T_BASE</td>
<td>-0.40</td>
<td>0.54</td>
<td>0.56</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Features</th>
<th>Water Quality Field Station (ACRE)</th>
<th>Northeast Purdue Ag. Center</th>
<th>Throckmorton Purdue Ag. Center</th>
<th>Southeast Purdue Ag. Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil association</td>
<td>Ragsdale-Raub</td>
<td>Morley-Blount-Pewamo</td>
<td>Miami-Russell-Fincastle-Ragsdale</td>
<td>Avonberg-Clermont</td>
</tr>
<tr>
<td>Soil description</td>
<td>Very poorly to somewhat poorly drained, level</td>
<td>Mod. well to very poorly drained up to 12% slope</td>
<td>Well drained to poorly drained, up to 12% slope</td>
<td>Poorly drained, flat, gray silty clay loam with fragipans</td>
</tr>
<tr>
<td>NRCS Land Capability</td>
<td>2, wet</td>
<td>4, erosive</td>
<td>2 to 4, wet, erosive</td>
<td>3, wet</td>
</tr>
<tr>
<td>Parent material</td>
<td>Loess (0.5-1 m) over Wisconsinan glacial till</td>
<td>Calcareous silty clay loam or clay loam glacial till</td>
<td>Loess (&lt;-1 m) over calcareous loam glacial till</td>
<td>Wisconsinan loess over eroded Illinoian till</td>
</tr>
<tr>
<td>Native vegetation</td>
<td>Prairie grasses</td>
<td>Beech, oak, and maple forest</td>
<td>Beech, maple forest</td>
<td>Mainly beech, with some oak, maple</td>
</tr>
<tr>
<td>Representative regions</td>
<td>Tall grass prairie from IN to IA</td>
<td>Rolling non-arable land in the Midwest</td>
<td>Central IN, IL, and OH</td>
<td>Southeast IN to Southern OH, IL</td>
</tr>
<tr>
<td>Drainage mgmt</td>
<td>Depth: 1 m Spacing: 70-120 ft.</td>
<td>None to spacing at 40 to 80 ft.</td>
<td>Depth: 1 m Spacing:70-120 ft.</td>
<td>Depth: 1 m Spacing: 50-80 ft</td>
</tr>
<tr>
<td>Lat./Long.</td>
<td>+40.467/-86.983</td>
<td>+41.133/-85.483</td>
<td>+40.283/-86.900</td>
<td>+39.000/-85.583</td>
</tr>
</tbody>
</table>
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 (CO₂, CH₄ and N₂O) emission from soil.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstressed Leaf Area Development and Light Extinction Coefficient</td>
<td><strong>Leaf Area Index (LAI)</strong> and the <strong>number of accumulated heat units</strong>. Used to quantify leaf area and canopy development during growing season.</td>
</tr>
<tr>
<td>Maximum Crop Height</td>
<td><strong>Canopy height</strong> of non-stressed plants.</td>
</tr>
<tr>
<td>Harvest Index for Optimal Growing Conditions Lower limit of harvest index – highly stressed</td>
<td><strong>Fraction of aboveground biomass</strong> removed in harvest operation.</td>
</tr>
<tr>
<td>Radiation Use Efficiency or Biomass: Energy Ratio</td>
<td><strong>Crop Growth Rate (CGR)</strong> and <strong>Photosynthetically Active Radiation (PAR)</strong>. Amount of biomass produced per unit intercepted solar radiation.</td>
</tr>
<tr>
<td>Nitrogen and Phosphorous uptake</td>
<td><strong>Fraction of nitrogen and phosphorus</strong> in total plant biomass in order to calculate plant nutrient demand throughout growing cycle. Ideally, includes roots as well as aboveground mass.</td>
</tr>
<tr>
<td>Maximum Root Depth (RDMX)</td>
<td><strong>Depth</strong> at which live roots exist. (1 meter soil cores analyzed for live roots at progressive depths.)</td>
</tr>
<tr>
<td>Effective Rooting Depth</td>
<td><strong>Rooting zone</strong> where plant will absorb/uptake the majority of its nutrients.</td>
</tr>
<tr>
<td>Optimal Temperature</td>
<td><strong>Optimal temperature</strong> for leaf development (not plant growth).</td>
</tr>
</tbody>
</table>
Radiation Use Efficiency (RUE)

2009 Switchgrass
\[ y = 1.0814x - 295.93 \]
\[ R^2 = 0.948 \]

2009 Miscanthus
\[ y = 1.8052x - 645.14 \]
\[ R^2 = 0.9705 \]

2010 Switchgrass
\[ y = 1.0688x - 102.64 \]
\[ R^2 = 0.9571 \]

2010 Miscanthus
\[ y = 3.6683x - 1140.5 \]
\[ R^2 = 0.9751 \]
Canopy height

2010

Crop Height (cm)

Plot

Miscanthus

Switchgrass

SWAT Theoretical Documentation, 2005
Root distribution

**Switchgrass**

- **Sampling Date**
  - April '09
  - May '09
  - April '10
  - Dec '10

- **Fine Roots (Mg/ha)**
  - S20
  - S40
  - S60

**Miscanthus**

- **Sampling Date**
  - April '09
  - May '09
  - April '10
  - Dec '10

- **Fine Roots (Mg/ha)**
  - M20
  - M40
  - M60

**Average Distribution**

- **Percentage**
  - 0-20 cm: 74%
  - 20-40 cm: 15%
  - 40-60 cm: 11%

- **Percentage**
  - 0-20 cm: 59%
  - 20-40 cm: 20%
  - 40-60 cm: 21%
Nitrogen uptake

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

% N in crop growth (2010)

- Miscanthus
- Switchgrass

Percent

March April May June July Aug Sept Dec
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
Optimal energy crop selection and placement

**SWAT Model**
- Existing BMP’s
- HRU
- Hydrology
- Crop yield
- Water Quality

**Bio-feedstock scenarios**
- Corn stover
- Switchgrass
- Miscanthus
- BMP

**Bio-feedstock placement optimization**
- Maximization
- Minimization

**Environment impacts**
- Bio-feedstock production

**BMPs**
- No BMP
- Cons. Till
- No Till
- Cons. Till + WASCOB
- No. Till + WASCOB
- Cons. Till + 10m Buffer
- No Till + 10m Buffer
- Cons. Till + WASCOB + 10m Buffer
- No Till + WASCOB + 10m Buffer

$135,000
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](http://engineering.purdue.edu/ecohydrology)
• [engineering.purude.edu/biomasswq](http://engineering.purude.edu/biomasswq)

• Email: [ichaubey@purdue.edu](mailto:ichaubey@purdue.edu)