Comparison of Biofuel Systems (COBS): Productivity and Environmental Impacts

Projects 2007-F-01 and 2007-F-02

Project Investigators: Matt Liebman, Robert Horton, Michael Thompson, Matt Helmers, Richard Cruse, Thomas Sauer, and Rob Anex
Generously funded by
ConocoPhillips Company

Iowa State University
College of Agriculture and Life Sciences
Leopold Center for Sustainable Agriculture
Plant Sciences Institute
Agronomy Department
Comparison of Biofuel Systems (COBS)

Six treatments, four replicate blocks, no tillage
• Corn/soybean rotation (grain), both entry points
• Continuous corn (grain and stover), +/- rye cover crop
• Multi-species reconstructed prairie, +/- fertilizer

ISU South Reynolds Farm
Boone Co., IA, August 2009
Each of the 24 plots is 27 m x 61 m
Photo courtesy of T. Schultz
Comparison of Biofuel Systems: COBS

Our working hypotheses

• Diverse mixtures of perennial plants can produce nearly as much biomass as conventionally managed corn, but with greater economic and energetic efficiency.

• Diverse perennial mixtures used for feedstock production can
  – emit fewer nutrients to drainage water,
  – sequester more carbon, and
  – reduce greenhouse gas emissions relative to corn- and soybean-based cropping systems.

• Cover crops can reduce nutrient losses from corn production systems.
Multiple Performance Criteria

- Fossil fuel replacement
  - Liebman, Anex

- Soil carbon storage
  - Thompson, Liebman

- Greenhouse gas emissions
  - Horton, Sauer

- Environmental quality (water quality, biodiversity)
  - Helmers, Liebman
## Comparison of Biofuel Systems: COBS

<table>
<thead>
<tr>
<th>Soil</th>
<th>Air</th>
<th>Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient dynamics (N, P)</td>
<td>CO₂ emissions</td>
<td>Plant productivity</td>
</tr>
<tr>
<td>Soil organic matter</td>
<td>N₂O emissions</td>
<td>Resource use efficiency</td>
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<tr>
<td>maintenance and production</td>
<td></td>
<td>Nutrient dynamics</td>
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<tr>
<td>Carbon sequestration</td>
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<td>Root growth and decay</td>
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<td>Biomass composition</td>
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<tr>
<td>Water</td>
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<tr>
<td>Dissolved carbon</td>
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<td>Dissolved phosphate</td>
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<tr>
<td>Nitrate and ammonium</td>
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</tr>
</tbody>
</table>
Comparison of Biofuel Systems: COBS

**Soil**
- Nutrient dynamics (N, P)
- Soil organic matter maintenance and production
- Carbon sequestration

**Air**
- CO₂ emissions
- N₂O emissions

**Water**
- Dissolved carbon
- Dissolved phosphate
- Nitrate and ammonium

**Crops**
- Plant productivity
- Resource use efficiency
- Nutrient dynamics
- Root growth and decay
- Biomass composition
COBS 2009 Aboveground Biomass

<table>
<thead>
<tr>
<th>Treatment</th>
<th>DOY 95% biomass</th>
<th>Date 95% biomass</th>
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<tbody>
<tr>
<td>Continuous corn</td>
<td>262</td>
<td>19 Sept</td>
</tr>
<tr>
<td>Continuous corn + rye</td>
<td>262</td>
<td>19 Sept</td>
</tr>
<tr>
<td>Prairie</td>
<td>227</td>
<td>15 Aug</td>
</tr>
<tr>
<td>Fertilized prairie</td>
<td>212</td>
<td>31 July</td>
</tr>
</tbody>
</table>
COBS 2010 Aboveground Biomass

- Continuous corn
- Continuous corn + rye
- Prairie
- Fertilized prairie

Biomass (g/m²)

Day of year
2009 Above- & Belowground Biomass

- **Grain**
- **Biomass**
- **Rye**
- **Residue**
- **60-100cm**
- **30-60cm**
- **0-30cm**

Biomass (Mg/ha)
Estimated Ethanol Yield, 2009

- C2: Corn grain
- CC: Nongrain biomass
- CCW: Nongrain biomass
- P: Nongrain biomass
- PF: Nongrain biomass

Lethanol/ha

- C2: 5000
- CC: 3000
- CCW: 5000
- P: 4000
- PF: 4000
# C:N ratios for roots to 1-m depth

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2008</th>
<th>2009</th>
<th>SE for 2009</th>
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</thead>
<tbody>
<tr>
<td>Prairie, unfertilized</td>
<td>35</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>Prairie, fertilized</td>
<td>35</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Soybean following corn</td>
<td>26</td>
<td>21</td>
<td>1</td>
</tr>
<tr>
<td>Continuous corn <em>with</em> rye cover crop</td>
<td>23</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Continuous corn <em>without</em> rye cover crop</td>
<td>23</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>Corn following soybean</td>
<td>27</td>
<td>26</td>
<td>1</td>
</tr>
</tbody>
</table>
COBS: Root Growth in 2010

Mg Biomass ha$^{-1}$ to 30 cm

- Continuous Corn
- Fertilized Prairie
- Prairie
Comparison of Biofuel Systems: COBS

**Soil**
- Nutrient dynamics (N, P)
- Soil organic matter maintenance and production
- Carbon sequestration

**Water**
- Dissolved carbon
- Dissolved phosphate
- Nitrate and ammonium

**Air**
- CO₂ emissions
- N₂O emissions

**Crops**
- Plant productivity
- Resource use efficiency
- Nutrient dynamics
- Root growth and decay
- Biomass composition
Carbon Dioxide Emissions From the Cropping Systems

Three-season values of CO₂ emissions among the cropping system treatments

<table>
<thead>
<tr>
<th>Descriptive Statistic</th>
<th>Cropping System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continuous Corn</td>
</tr>
<tr>
<td></td>
<td>Continuous Corn with Cover Crop</td>
</tr>
<tr>
<td></td>
<td>Corn/ Soybean Rotation</td>
</tr>
<tr>
<td></td>
<td>Prairie Fertilized</td>
</tr>
<tr>
<td></td>
<td>Prairie Unfertilized</td>
</tr>
<tr>
<td>Mean(^a)</td>
<td>2.8(^b)</td>
</tr>
<tr>
<td>Sum(^a)</td>
<td>122</td>
</tr>
<tr>
<td>CV (%)</td>
<td>40</td>
</tr>
</tbody>
</table>

\(^a\) Values are in µmol CO₂ m⁻² s⁻¹ (1 µmol CO₂ m⁻² s⁻¹ = 26 g CO₂ ha⁻¹ min⁻¹)

\(^b\) Soil-CO₂ emissions were measured weekly.
**Soil**
- Nutrient dynamics (N, P)
- Soil organic matter maintenance and production
- Carbon sequestration

**Air**
- CO\(_2\) emissions
- N\(_2\)O emissions

**Water**
- Dissolved carbon
- Dissolved phosphate
- Nitrate and ammonium

**Crops**
- Plant productivity
- Resource use efficiency
- Nutrient dynamics
- Root growth and decay
- Biomass composition
## Comparison of Biofuel Systems: COBS

### Soil
- Nutrient dynamics (N, P)
- Soil organic matter maintenance and production
- Carbon sequestration

### Air
- \( \text{CO}_2 \) emissions
- \( \text{N}_2\text{O} \) emissions

### Water
- Dissolved carbon
- Dissolved phosphate
- Nitrate and ammonium

### Crops
- Plant productivity
- Resource use efficiency
- Nutrient dynamics
- Root growth and decay
- Biomass composition
Drainage Water Monitoring and Sampling

- Monitor volume of subsurface drainage to assess treatment effects on drainage volume
- Collect flow-proportional water samples for nitrate-nitrogen, orthophosphate, and dissolved organic carbon
Drainage Water Quantity and Quality (Nitrate-N) – 2009 & 2010
Tradeoffs Among Cropping Systems

- Corn systems are more productive aboveground.
- Prairie systems require few inputs and little management.
- Prairie systems have more biodiversity, larger root systems, more belowground C, but greater CO$_2$ emissions.
- Prairie systems lose very little N in drainage water, even when fertilized.
- Prairie and row crop systems are not mutually exclusive at a landscape scale.
Carbon Accounting and Credits in Biofuel Cropping Systems

Michael Thompson and Matt Liebman
Agronomy Department, ISU

With the collaboration of
Rob Anex
University of Wisconsin
Biobased Industry Center Research Priority

• Mechanisms for carbon measurement, carbon accounting, and credit allocation and evaluation of land use changes and offsets
The stocks of soil carbon vary across the landscape today.
We need to make **local and regional predictions** about how those stocks will change as biofuel crops are placed on the landscape.

- To decrease risk for parties who contract for local soil carbon storage
- To provide policy makers with regional predictions about the impacts of alternative policies
- To target incentives to increase biomass production and soil carbon storage without decreasing food production
Objectives of Modeling Project

• To improve model predictions of the impact of widespread adoption of biofuel feedstock production on regional terrestrial carbon stocks.

• To identify the most sensitive local-scale measurements that are needed to model the impacts of land-use change associated with biofuel crop production.
Approach

There are four tasks in this project.

1. Simulate long-term carbon budgets for four biofuel cropping systems (local scale)

2. Simulate *regional* carbon sequestration outcomes for various adoption scenarios

3. Identify model parameters that have the largest impact on predicted carbon sequestration and biomass production

4. Improve regional predictions of carbon storage and biomass production by calibrating models with COBS data
Carbon Dynamics Models

- **CENTURY**
  Natural Resource Ecology Laboratory, Colorado State University

- **ROTH C**
  Rothamsted Experimental Station, UK

- **EPIC (Environmental Policy Impact Climate Model)**
  USDA (ARS + NRCS)
DAYCENT Simulation Model

Temporal scale
- Daily time step

Spatial scale
- Rooting depth

Predictions of
- Crop growth
- Crop yield
- Water movement
- Soil organic C dynamics
- Soil N dynamics
Possible Model Sensitivities

• Distribution of belowground biomass (carbon) and nutrients (nitrogen) in deeply rooted perennials
• Decomposition rate constants for belowground biomass of diverse perennial mixtures (to 1 m depth)
• Distribution of soil carbon in slow and passive pools
• Level of annual stover harvest
Example of sensitivity analysis

IMPACT OF STOVER HARVEST ON SOIL ORGANIC CARBON

Soil Organic Carbon (g m⁻²)

Year

1701 1726 1751 1776 1801 1826 1851 1876 1901 1926 1951 1976 2001

- 0% Harvest
- 50% Harvest
- 90% Harvest
1. Compare long-term carbon budgets for biofuel cropping systems

- First, use measured, site-specific soil characteristics and simulated local climate patterns to run the DAYCENT model for the cropping systems at the COBS research site over a 30-year simulation period
- Compare long-term predictions of carbon accounting for these diverse biofuel production systems
Measured Soil Properties

- Horizon (or layer) thicknesses (cm)
- Bulk density
- Sand, silt, and clay contents
- Water-holding capacity
- Wilting point
- pH
- Organic C content
2. Simulate carbon sequestration outcomes

- *Second*, use public databases for *climate* patterns, *soil* properties, and *land-use* patterns to simulate carbon sequestration (or loss) outcomes for widespread, regional (north central Iowa) adoption of biofuel cropping systems for the 30-year period.
Databases

• Climate patterns: Iowa Environmental Mesonet

• Soil properties: NRCS Soil Survey Geographic Database (SSURGO): County-level

• Land-use patterns: National Agricultural Statistics Service
3. Sensitivity Analysis

- Third, identify processes and measurable parameters that most affect the carbon-budget predictions of DAYCENT specifically for biofuel cropping systems.

- Use the COBS team’s measurements of
  - soil carbon pools
  - plant productivity
  - nutrient dynamics
  - root growth and decay
  - greenhouse gas emissions

at the research site (2008 – 2010) to calibrate those most sensitive model processes and re-run the model over the 30-year simulation period runs to predict impact of land use change on carbon balances.
4. Regional predictions of widespread feedstock production

• **Rank feedstock cropping systems** for their ability to produce biomass and store carbon at a regional scale (comparing a range of possible scenarios for land use change)

• Examples of scenarios to compare:
  – A - Grow perennials only on >C-slope soils and riparian zones and maintain corn grain production on prime soils
  – B - Grow perennial biomass crops on any soils within 25-mile radius of processing plants

• Essential data for *allocating* carbon credits and structuring incentives in regional and national policy
Workplan and Schedule

• Post-doctoral researcher to parameterize and run the models as outlined
• The four tasks: About 10 weeks each
• Final weeks: Summarize results and prepare technical and non-technical reports
<table>
<thead>
<tr>
<th>Operation</th>
<th>By crop</th>
</tr>
</thead>
</table>
| Annual seeding        | Winter rye = 10/31/08 & 11/6/09  
                        | Corn = 5/7-8/09 (Agrigold 6325 VT3 – 104-day)  
                        | Soybean = 5/8/09 (Pioneer 92M53)                                                              |
| Nitrogen application  | Corn = split application (75 lb N/acre at seeding – UAN, remaining as needed after LSNT – UAN)  
                        | Corn = 125 lb N/acre  
                        | Continuous corn = 150 lb N/acre  
                        | Continuous corn with rye = 195 lb N/acre  
                        | Fertilized prairie = 75 lb N/acre on 4/17/09 (ammonium nitrate)  
                        | Soybean and prairie = no nitrogen fertilizer                                                |
| Herbicide application | Corn = glyphosate (C = 5/29/09; CC & CCW = 5/29/09 & 6/23/09)  
                        | Soybean = glyphosate (6/4/09 & 7/1/09)                                                      |
| Harvest               | Soybean = 10/13/09  
                        | Prairie = 10/19/09 (8” cut height)  
                        | Corn grain = 10/21/09  
                        | Corn stover = 11/3-6/09 (stalks shredded, raked, and bailed)                              |
## Plot Layouts

### Comparison of Biofuel Systems (COBS)

<table>
<thead>
<tr>
<th>2-year System (conventional cash grain)</th>
<th>Continuous Prairie System</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2-S2  Corn - soybean rotation</td>
<td>P  Continuous prairie unfertilized system</td>
</tr>
<tr>
<td>S2-C2  Soybean - corn rotation</td>
<td>PF Continuous prairie fertilized system</td>
</tr>
</tbody>
</table>

**Continuous Corn System**

- CC: Continuous corn w/ stover removal
- CCW: Continuous corn w/ stover removal and winter cover crop

### Grid Layout

- **North**
  - CCW  CC  C2-S2  S2-C2  PF  P
  - C2-S2  PF  CCW  P  CC  S2-C2

- **West**
  - P  C2-S2  S2-C2  CC  CCW  PF
  - S2-C2  CCW  P  PF  C2-S2  CC

13 acres fescue

### South

- 90' (36 row s)

### Complementary Experiment

- SG  Switchgrass
- SG  Corn
- SG  Corn
- SG  Switchgrass
- Corn
- Corn
- Corn
# ISU Faculty Team

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Position and ISU Department</th>
<th>Project Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rob Anex</td>
<td>Associate Professor, <em>Agricultural and Biosystems Engineering</em></td>
<td>Life cycle analyses: (1) energy return on investment, (2) fossil fuel displacement, and (3) environmental impacts</td>
</tr>
<tr>
<td>Rick Cruse</td>
<td>Director, Iowa Water Center and Professor, <em>Agronomy</em></td>
<td>Management of soil resources: Fertility and structural characterizations</td>
</tr>
<tr>
<td>Matt Helmers</td>
<td>Extension Agricultural Engineer and Associate Professor, <em>Agricultural and Biosystems Engineering</em></td>
<td>Nutrient (nitrogen and phosphorus) leaching through soil; water quality assessments</td>
</tr>
<tr>
<td>Emily Heaton</td>
<td>Assistant Professor, <em>Agronomy</em></td>
<td>Bioenergy from switchgrass; N dynamics in biomass crops</td>
</tr>
<tr>
<td>Kirsten Hofmockel</td>
<td>Assistant Professor, <em>Ecology, Evolution, and Organismal Biology</em></td>
<td>Microbial decomposition of root residues; microbial regulation of nitrogen dynamics</td>
</tr>
<tr>
<td>Bob Horton</td>
<td>Curtiss Distinguished Professor of Agriculture and Life Sciences, <em>Agronomy</em></td>
<td>CO₂ and N₂O emissions, water and heat transport</td>
</tr>
<tr>
<td>Matt Liebman</td>
<td>Wallace Chair for Sustainable Agriculture and Professor, <em>Agronomy</em></td>
<td>Above- and below-ground biomass production and carbon sequestration</td>
</tr>
<tr>
<td>Fernando Miguez</td>
<td>Assistant Professor, <em>Agronomy</em></td>
<td>Modeling of crop and soil processes</td>
</tr>
<tr>
<td>Michael Thompson</td>
<td>Pioneer Professor of Agronomy, <em>Agronomy</em></td>
<td>Decomposition of roots; composition of organic matter in soil</td>
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# Professional and Student Team

<table>
<thead>
<tr>
<th>Personnel</th>
<th>ISU Department</th>
<th>Primary Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dave Sundberg</td>
<td>Agronomy</td>
<td>Site and crop management: Planting, fertilization, harvest, soil sampling</td>
</tr>
<tr>
<td>Toby Ewing</td>
<td>Agronomy</td>
<td>Field sensors of temperature and water</td>
</tr>
<tr>
<td>Carl Pederson</td>
<td>Agricultural and Biosystems Engineering</td>
<td>Installation and maintenance of water sampling equipment</td>
</tr>
<tr>
<td>Teresita Chua</td>
<td>Agronomy</td>
<td>Soil sampling and characterization</td>
</tr>
<tr>
<td>Meghann Jarchow</td>
<td>Agronomy</td>
<td>Aboveground crop dynamics</td>
</tr>
<tr>
<td>Ranae Dietzel</td>
<td>Agronomy</td>
<td>Root abundance and distribution</td>
</tr>
<tr>
<td>Jacob Prater</td>
<td>Agronomy</td>
<td>Temperature and moisture sensing, saturated hydraulic conductivity measurements, soil sampling</td>
</tr>
<tr>
<td>Dedrick Davis</td>
<td>Agronomy</td>
<td>Temperature and moisture sensing, saturated hydraulic conductivity measurements, soil sampling</td>
</tr>
<tr>
<td>Xinhua Xiao</td>
<td>Agronomy</td>
<td>Temperature, moisture, and CO₂ sensing equipment</td>
</tr>
<tr>
<td>Aaron Daigh</td>
<td>Agronomy</td>
<td>CO₂ and N₂O emissions from soil; soil temperature and moisture measurements; drainage events</td>
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<tr>
<td>Fritzie Rivas</td>
<td>Agronomy</td>
<td>Composition of plant tissue and soil organic matter</td>
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<tr>
<td></td>
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<td>Many undergraduate student assistants</td>
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