Biofuels and Agricultural Sustainability

Cellulosic Biofuels
and Ecosystem Services

G. Philip Robertson
W.K. Kellogg Biological Station and
Dept. of Crop and Soil Sciences
Michigan State University

robertson@kbs.msu.edu
Legislated Biofuel Goals

  - 22% of transportation fuel mix in 2022
    - 36 billion gallons ethanol
      - 15 billion gallons of grain-based ethanol
      - 16-21 billion gallons of cellulosic ethanol

- **European Union**
  - 20% renewable energy by 2020
  - 10% of transport fuels by 2020
## Corn Grain Ethanol - Current Status

<table>
<thead>
<tr>
<th>Year</th>
<th>Existing Plants</th>
<th>Capacity bgal yr</th>
<th>New Plants</th>
<th>Production bgal yr</th>
<th>Capacity bgal yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>109</td>
<td>5.3</td>
<td>65</td>
<td>4.8</td>
<td>9.1</td>
</tr>
<tr>
<td>2007</td>
<td>135</td>
<td>7.3</td>
<td>76</td>
<td>6.4</td>
<td>13.5</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td>9.1&lt;sup&gt;est&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td>15&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>


Legislated Biofuel Goals

  22% of transportation fuel mix in 2022
    - 36 billion gallons ethanol
      - 15 billion gallons of grain-based ethanol
      - 16-21 billion gallons of cellulosic ethanol
Ethanol Production from cellulose

1. Biomass Production and Delivery
   Biomass is harvested, delivered to the biorefinery, and ground into particles.

2. Pretreatment
   Pulverized biomass is pretreated with heat and chemicals to make cellulose accessible to enzymes.

3. Cellulose Hydrolysis
   Enzymes are added to break down cellulose chains into sugars.

4. Sugar Fermentation
   Microbes ferment sugars into ethanol and other biofuels.

5. Biofuel Processing
   Biofuels are extracted from the fermentation tank and prepared for distribution.

DOE; http://genomics.energy.gov
A diversity of production systems

Low Diversity
- Corn
- Corn-Soybean-Canola

High Diversity
- Restored prairie
- Early successional
- Poplar trees
- Native grasses
- Switchgrass
- Miscanthus
Legislated Biofuel Goals

  - 22% of transportation fuel mix in 2022
    - 36 billion gallons ethanol
      - 15 billion gallons of grain-based ethanol
      - 21 billion gallons of cellulosic ethanol

- **2008 Farm Bill**
  - $1.01 / gallon subsidy for cellulosic ethanol
  - $45 / ton of cellulosic feedstock
### How much cellulosic biomass is needed?

<table>
<thead>
<tr>
<th>Time period</th>
<th>EtOH</th>
<th>Biomass required¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today (2007)</td>
<td>0 bgal</td>
<td>0</td>
</tr>
<tr>
<td>Tomorrow (2022)²</td>
<td>21 bgal</td>
<td>266 MMT</td>
</tr>
<tr>
<td>Future (2050)³</td>
<td>80 bgal</td>
<td>1,013 MMT</td>
</tr>
</tbody>
</table>

¹ 0.3 L ethanol / kg biomass  
³ USEPA, NRDC 2050 scenarios

**Compare to**

- 110 x 10⁶ MT corn stover of 196 x 10⁶ MT available⁴  
- 106 x10⁶ MT industrial wood waste⁵

**Leaving**

- ~800 MMT to be grown

---

⁴ Graham et al. 2007 Agron J 99:1-11  
⁵ Perlack et al. 2005 Technical feasibility of a billion-ton annual supply. DOE.
How much land?

- Land Requirements for $800 \times 10^6$ MT biomass
  - Switchgrass today\(^1\) at 8 (6-9) MT/ha = $100 \times 10^6$ ha

- Compare to
  - $180 \times 10^6$ ha cropland
  - $240 \times 10^6$ ha range, grasslands
  - $15 \times 10^6$ ha CRP

\(^1\) Schmer et al. 2008 *PNAS* 105:464-468
Elements of Biofuel Sustainability

• Economic
  ✓ Profitable

• Environmental
  ✓ Carbon negative (climate stabilizing)
  ✓ Nutrient, water conservative
  ✓ Biodiversity benefits

• Social
  ✓ Food, energy security
  ✓ Rural community health
A traditional framework for understanding biofuel systems

Cropping System

System Structure
- Crop species / varieties
- Insect pests & predators
- Pathogens & vectors
- Landscape elements

System Function
- Primary productivity
- Carbon flow
- Nutrient storage and transformations
- Greenhouse gas fluxes
- Ethanol conversion
- Feedstock pretreatment

Disturbance

Managed
- Crop selection
- Rotation frequency
- Cover crops and tillage
- Harvest timing & intensity
- Pretreatment location

Unmanaged
- Disease & pest outbreaks
- Extreme weather (drought, flooding, hail)

Outputs

- Fuel, food, fiber
- Nitrate, phosphorus, soil exports
- Pesticides, greenhouse gases

Robertson et al., in prep; After S. Collins et al. 2007
A traditional framework for understanding biofuel systems

Disturbance

Managed
Crop selection
Rotation frequency
Cover crops and tillage
Harvest timing & intensity
Pretreatment location

Unmanaged
Disease & pest outbreaks
Extreme weather (drought, flooding, hail)

Cropping System

System Structure
Crop species / varieties
Insect pests & predators
Pathogens & vectors
Landscape elements

System Function
Primary productivity
Carbon flow
Nutrient storage and transformations
Greenhouse gas fluxes
Ethanol conversion
Feedstock pretreatment

Ecosystem Services

Provisioning (e.g. feedstock)
Regulating (e.g. climate stabilization)
Supporting (e.g. soil maintenance)
Cultural (e.g. wildlife amenities)

Robertson et al., in prep; After S. Collins et al. 2007
A Socio-Ecological Framework for Biofuel Systems

Social System
- **Human Behavior**
  - Farmer decisions & actions
  - Refiner decisions & actions
  - Consumer preference
  - Regulations & incentives
  - Markets
  - Technology

- **Human Outcomes**
  - Quality of life
  - Economic vitality
  - Values
  - Perceptions & knowledge
  - Community health

Cropping System
- **System Structure**
  - Crop species / varieties
  - Insect pests & predators
  - Pathogens & vectors
  - Landscape elements

- **System Function**
  - Primary productivity
  - Carbon flow
  - Nutrient storage and transformations
  - Greenhouse gas fluxes
  - Ethanol conversion
  - Feedstock pretreatment

Disturbance
- **Managed**
  - Crop selection
  - Rotation frequency
  - Cover crops and tillage
  - Harvest timing & intensity
  - Pretreatment location

- **Unmanaged**
  - Disease & pest outbreaks
  - Extreme weather (drought, flooding, hail)

Ecosystem Services
- Provisioning (e.g. feedstock)
- Regulating (e.g. climate stabilization)
- Supporting (e.g. soil maintenance)
- Cultural (e.g. wildlife amenities)

Robertson et al., in prep; After S. Collins et al. 2007
Managing for multiple services is crucial for meeting societal expectation for biofuel crops.

**Stackable Services?**

**Provisioning Services**
- Cellulosic feedstocks
- Food and forage production
- Surface and ground water

**Regulating Services**
- CO₂ Stabilization
- Pest and disease suppression
- Soil nutrient delivery

**Cultural services**
- Recreational opportunities
- Aesthetic attributes
- Cultural and heritage amenities

**Corollary:** There will be tradeoffs....

After Millennium Ecosystem Assessment 2005
## Tradeoffs: Multiple environmental benefits from a uniform subsidy

<table>
<thead>
<tr>
<th>Benefit gained</th>
<th>Benefit Targeted</th>
<th>Carbon</th>
<th>Erosion</th>
<th>N Runoff</th>
<th>N Leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon*</td>
<td></td>
<td>3.2</td>
<td>0.8</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Erosion*</td>
<td></td>
<td>7.4</td>
<td>40.5</td>
<td>14.1</td>
<td>9.7</td>
</tr>
<tr>
<td>N Runoff**</td>
<td></td>
<td>2.8</td>
<td>5.1</td>
<td>11.7</td>
<td>2.8</td>
</tr>
<tr>
<td>N Leaching**</td>
<td></td>
<td>10.0</td>
<td>6.4</td>
<td>5.6</td>
<td>30.6</td>
</tr>
</tbody>
</table>

*Values expressed in million tons

**Values expressed in thousand tons

Source: Feng et al. 2007; *Climatic Change*
Complex Tradeoffs: $N_2O$ flux vs. crop yield

$N_2O$ fluxes increase with crop yield but mainly at N-fertilizer rates greater than yield response

Major Potential Sources of Global Warming Impact (CO$_2$e) in Biofuel Cropping Systems

- **Farm Operations**
  - Fuel use
  - Fertilizer, pesticides
  - Lime (CaCO$_3$)
- **Soil carbon change**
- **N$_2$O flux**
- **CH$_4$ oxidation**
- **Post-harvest transport**
- **Fuel Production (CO$_2$ offset)**
Nitrous Oxide

Global Anthropogenic Sources

- Industry
- Agriculture
- Cattle & Feedlots
- Biomass burning
- Agricultural soils

Total Annual Impact 1.2 Pg $C_{\text{equiv}}$ (compare to fossil fuel loading = 4.1 Pg C)

Source IPCC 2001, 2007; Prinn 2004; Robertson 2004
## Global Warming Potential (GWP) Biogenic Gases

<table>
<thead>
<tr>
<th></th>
<th>Lifetime yr</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20 yr</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>variable</td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>12</td>
<td>62</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>114</td>
<td>275</td>
</tr>
</tbody>
</table>

Source: IPCC 2002; 2007
### KBS Long-Term Ecological Research (LTER) Site

<table>
<thead>
<tr>
<th>Ecosystem Type</th>
<th>Management Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Grain Crops (Corn - Soybean - Wheat)</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional tillage</td>
<td>High</td>
</tr>
<tr>
<td>No-till</td>
<td></td>
</tr>
<tr>
<td>Low-input with legume cover</td>
<td></td>
</tr>
<tr>
<td>Organic with legume cover</td>
<td></td>
</tr>
<tr>
<td><strong>Perennial Biomass Crops</strong></td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td></td>
</tr>
<tr>
<td>Poplar trees</td>
<td></td>
</tr>
<tr>
<td><strong>Unmanaged Communities</strong></td>
<td></td>
</tr>
<tr>
<td>Early successional old field</td>
<td>Low</td>
</tr>
<tr>
<td>Mid successional old field</td>
<td></td>
</tr>
<tr>
<td>Late successional forest</td>
<td></td>
</tr>
</tbody>
</table>
Nitrous Oxide Fluxes at KBS (1992-2007)

Robertson et al. 2000; Grandy et al. 2006 JEQ; and Parr et al. in prep.
# GWP Impact for Field Crop Activities

<table>
<thead>
<tr>
<th></th>
<th>Farming</th>
<th>N\textsubscript{2}O</th>
<th>CH\textsubscript{4}</th>
<th>Soil C (\Delta)</th>
<th>Fuel Offset (farm gate)</th>
<th>Transport</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional grain/stover</td>
<td>46</td>
<td>56</td>
<td>-1.5</td>
<td>0</td>
<td>-641</td>
<td>13</td>
<td>-527</td>
</tr>
</tbody>
</table>

- **N\textsubscript{2}O** is the largest source of CO\textsubscript{2}e
- Soil carbon is at equilibrium (no annual change)
- Includes 50% of corn stover

All values = g CO\textsubscript{2} m\textsuperscript{-2} y\textsuperscript{-1} for 1992-2007
# GWP Impact for Field Crop Activities

<table>
<thead>
<tr>
<th></th>
<th>Farming</th>
<th>N₂O</th>
<th>CH₄</th>
<th>Soil C ∆</th>
<th>Fuel Offset (farm gate)</th>
<th>Transport</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional grain/stover</td>
<td>46</td>
<td>56</td>
<td>-1.5</td>
<td>0</td>
<td>-641</td>
<td>13</td>
<td>-527</td>
</tr>
<tr>
<td>No-till grain/stover</td>
<td>45</td>
<td>60</td>
<td>-1.8</td>
<td>-66</td>
<td>-606</td>
<td>12</td>
<td>-557</td>
</tr>
</tbody>
</table>

- No change in N₂O
- Soil carbon gain; offsets N₂O
- Greater overall mitigation

All values = g CO₂ m⁻² y⁻¹ for 1992-2007
# GWP Impact for Field Crop Activities

<table>
<thead>
<tr>
<th></th>
<th>Farming</th>
<th>( \text{N}_2\text{O} )</th>
<th>( \text{CH}_4 )</th>
<th>Soil C Δ</th>
<th>Fuel Offset (farm gate)</th>
<th>Transport</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional grain/stover</td>
<td>46</td>
<td>56</td>
<td>-1.5</td>
<td>0</td>
<td>-641</td>
<td>13</td>
<td>-527</td>
</tr>
<tr>
<td>No-till grain/stover</td>
<td>45</td>
<td>60</td>
<td>-1.8</td>
<td>-66</td>
<td>-606</td>
<td>12</td>
<td>-557</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>31</td>
<td>56</td>
<td>-2.2</td>
<td>-186</td>
<td>-539</td>
<td>11</td>
<td>-618</td>
</tr>
</tbody>
</table>

Lower farming cost (no fertilizer)

Greater soil C gain

All values = g CO\(_2\) m\(^{-2}\) y\(^{-1}\) for 1992-2007
## GWP Impact for Field Crop Activities

<table>
<thead>
<tr>
<th></th>
<th>Farming</th>
<th>$\text{N}_2\text{O}$</th>
<th>$\text{CH}_4$</th>
<th>Soil C $\Delta$</th>
<th>Fuel Offset (farm gate)</th>
<th>Transport</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional grain/stover</td>
<td>46</td>
<td>56</td>
<td>-1.5</td>
<td>0</td>
<td>-641</td>
<td>13</td>
<td>-527</td>
</tr>
<tr>
<td>No-till grain/stover</td>
<td>45</td>
<td>60</td>
<td>-1.8</td>
<td>-66</td>
<td>-606</td>
<td>12</td>
<td>-557</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>31</td>
<td>56</td>
<td>-2.2</td>
<td>-186</td>
<td>-539</td>
<td>11</td>
<td>-618</td>
</tr>
<tr>
<td>Early succession</td>
<td>3</td>
<td>22</td>
<td>-2.2</td>
<td>-339</td>
<td>-300</td>
<td>6</td>
<td>-610</td>
</tr>
</tbody>
</table>

- **Little farming cost** (harvest only)
- **Large $\text{N}_2\text{O}$ drop**
- **Large SOC gain**
- **Less biomass**
- **Same net**
Fertilized successional yields are similar to on-farm switchgrass yields.
Global Warming Impact – KBS Field Crops

Annual Crops

- Conventional
- No-till
- Cover cropped

Perennial Crops

- Alfalfa
- Early successional

Source of Impact:
- Farming
- \( \text{N}_2\text{O} \)
- Transport
- \( \text{CH}_4 \)
- Fuel
- Soil C

Missing: Indirect Land Use Costs
Other services: Nitrate Conservation

Nitrate Loss 1996-2007

Nitrate Leached Cumulative (kg NO$_3$-N ha$^{-1}$)

- Conventional
- No Till
- Low Input
- Organic
- Alfalfa
- Poplars
- Successional
- Mid Successional
- Forest

Annual Crops

Perennials

Source: Syswerda, et al. in prep.
Other services: Biodiversity

*Darwin, C. 1881. The formation of vegetable mould, through the action of worms, with observations on their habits.*

Other services: Biodiversity

Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes

Predators save soybean farmers $13-79 \text{ acre}^{-1} \text{ yr}^{-1}$ in reduced pesticide applications and yield loss

Increased corn in the landscape reduces key predators and biocontrol services in soybean

Costing producers $58 – 671 \text{ M yr}^{-1}$ in forgone biocontrol services

(based on actual 2006-07 increase in corn in MI, MN, IA, WI)

Landis et al. 2008 PNAS 105:20552.
Conclusions: What do we know?

1. Land requirements are substantial (ca. 75-100 M ha US)
2. Outcomes that provide multiple benefits (ecosystem services) are possible
3. Best outcomes will depend on
   - Choice of crops (e.g. annual vs. perennial)
   - Management practices (residue return, fertilization rate, harvest intensity and timing, irrigation…)
   - Location – prior crop history
4. We know what’s needed
   - Comprehensive science understanding at systems level, using a framework that includes human interactions
   - Willingness to incentivize environmental performance
Bird species with legal protection in Michigan that were observed to breed in 2008 biofuel stands (n=30)

<table>
<thead>
<tr>
<th></th>
<th>Corn</th>
<th>Switchgrass</th>
<th>Prairie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern harrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(special concern)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dickcissel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(threatened)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Henslow’s sparrow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(threatened)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasshopper sparrow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(special concern)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(B. Robertson, D. Schemske, D. Landis 2009, unpubl.)
Geographic Distribution of Biomass Crops

Bird diversity and biofuel production systems

Number of bird species

- nesting
- foraging use only

- corn
- switchgrass
- prairie
Historical Soil Carbon Loss from Cropping Systems

• locally 40-60% of original C lost after 40-60 years of cultivation in North America

• globally 54 Pg C from an original 222 Pg C (about 25%)

• potential for recovering 0.3 – 0.5 Pg C y\(^{-1}\)
  – Increasing C inputs (crop residues, cover crops)
  – Slowing decomposition (no-till)