Biofuels: The Land Use and Environmental Implications of Addressing Transportation and Energy Problems

Dedication to Lee Schipper

October 17, 2011
UCLA Conference, Arrowhead Lake
Outline:

• Biofuels and policy context for decarbonizing transportation
• Global consequences of biofuels → LUC, ILUC
• Life Cycle Assessment (LCA) of lignocellulosic biofuel conversion technologies
  • Models; uncertainty
  • Focus: GHG environmental impacts
• Better biomass and biofuels:
  • perennial grasses, ag. residues, winter crops,
  • pyrolysis bio-oil, higher alcohols, algae bio-oils
Introduction and Background

• A 2004 paper outlined a strategy for reducing GHG emissions from different economic sectors by 1 gigaton each, a “wedge analysis”


• The Gigaton Throwdown Project

  • Launched by venture capitalists in clean tech industry

  • What is the capital cost of investment to achieve a 1 gigaton reduction in GHG emissions by 2020?

• Biofuels are one avenue for achieving this “wedge” in the transportation sector

Spatari, Tomkins, Kammen, 2009
Policy Context:

- Since 2004, low carbon and renewable fuel policies in development around the world
  - LCFS (California, North-east states, Ontario), RFS (US)
  - Reduce GHGs relative to baseline gasoline $\sim 93 \text{ gCO}_2\text{e/MJ}$
- Biofuels compatible, attractive strategy for reducing transportation’s carbon intensity
  - Feedstocks today: corn (ethanol), soybean (diesel)
    - Mingles energy with food markets
- Recent research on adverse “land-based” impacts of biofuels:
  - Direct and indirect CO$_2$ from land use change (LUC)
  - Other sustainability risks: water, biodiversity, food security
- Need a robust life cycle assessment tool to estimate complete fuel cycle GHG emissions + consequences
Land use change (LUC) may cause large GHG emissions

U.S. corn/soybean farmers sell land to developers, land is now developed

Soy farmers everywhere use more inputs to increase yields

U.S. soybean exports go down and world soybean prices rise

Additional land in Brazil (for instance) is put into soy production

Indirect LUC emissions

Indirect process emissions

Direct process emissions: Change in CO2 flux on land

Unobservable variables!

Potentially large global land carbon debt!

From M. O'Hare, UC Berkeley; Searchinger et al., 2008, 10.1126/science.1151861
### Sustainability issues:

<table>
<thead>
<tr>
<th>Ecological</th>
<th>Socio-economic</th>
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<tbody>
<tr>
<td>Water use</td>
<td>Food and energy security</td>
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<td>Water pollution</td>
<td>Land tenure</td>
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<td>Organic pollutants</td>
<td>Net Employment</td>
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<td>Agro-chemicals</td>
<td>Income distribution</td>
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<td>Biodiversity</td>
<td>Wages</td>
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<td>Soil erosion</td>
<td>Working conditions</td>
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<td>Fertilizer use</td>
<td>Child labor</td>
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<td>GMOs</td>
<td>Social responsibility</td>
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<tr>
<td>GHGs/energy input</td>
<td>Competitiveness</td>
</tr>
<tr>
<td>Harvesting practices</td>
<td>Culture - Traditional way of life</td>
</tr>
</tbody>
</table>

1Direct + Indirect  
Scale: Regional, national, global

Spatari, O'Hare et al. 2008
**LCFS/RFS: Fuel Cycle Model**

- **Fuel cycle**
  - Feedstock Production
  - Ethanol Conversion
  - Vehicle Operation

- **Feedstocks:**
  - Winter barley
  - Chemicals, Enzymes, Nutrients
  - Co-products: CO2, protein meal, hulls (energy recovery)
  - Denaturant (2% gasoline)

- **Technologies:**
  - Dry grind process
  - Sugar generation
  - Fermentation
  - Co-product crediting

- **Vehicle:**
  - Ethanol-fueled vehicle (E92)
  - Compare with baseline gasoline vehicle (96 g CO2e/MJ)

**Vehicle use**

+ Indirect consequences

- Blending with gasoline
- Vehicle operation
Policy Context:

• Since 2004, low carbon and renewable fuel policies in development around the world
  • LCFS (California, North-east states, Ontario), RFS (US)
• Biofuels compatible, attractive strategy for reducing transportation’s carbon intensity
• New research on adverse “land-based” impacts of biofuels:
  – Direct and indirect CO$_2$ from land use change (LUC)
  – Other sustainability risks: water, biodiversity, food security
• Need a robust life cycle assessment tool to estimate complete fuel cycle GHG emissions + consequences
Methods

• LCA methods used to estimate C-intensity of biofuels

• Established process-based and EIO-LCA methods not equipped to estimate “market-mediated” LUC effects
  
  • Need new tools: Consequential LCA (CLCA)
  
  • Example: Price response via CGE or PE models

• Circumvent iLUC effects by selecting lignocellulosic feedstocks that do not compete for arable land and use “sustainable” fractions:
  
  • Ag. Residue, MSW, forest/mill waste, novel technologies (e.g., algae)
Key challenges with CLCA (1)

- Completeness: what are the “full” consequences of a decision (e.g., implementing the Renewable Fuel Standard) in the uncertain future with all its dynamics?
  - 1st order consequences: directly associated with the physical flows
  - 2nd order consequences: caused by equilibrium shifts controlled by price mechanisms
  - Other rebound effects

- Data availability and uncertainties
  - E.g., what will be the marginal electricity mix for future biorefineries? (varies by time horizon, available resources, cost, technologies, capacities, etc.)

References:
Key challenges with CLCA (2)

• Modeling tools
  - Commonly used tools:
    - Macro-economic and/or econometrical models, e.g.,
      1) Partial equilibrium (PE) models
      2) Computable general equilibrium (CGE) models
    - Agent-based models
    - System Dynamics models
    - Scenarios

From: Zhang, Y. National Renewable Energy Laboratory (NREL)
Ethanol: Energy and Environment

- Energy security: compared to gasoline, corn ethanol:
  - Significantly reduces petroleum use (~95%), moderately lowers (13%) fossil energy use (Farrell et al. 2006);
- Many increased risks related to LUC

Time Effects Uncertainty

Plevin et al 2010 O’Hare et al 2009 Mullins et al 2010
Direct GHG Emissions – biofuels versus conventional & unconventional oil

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Yield (PJ/ha)</th>
<th>GHG Emissions per Disturbed Area (t CO₂e/ha)</th>
<th>GHG Emissions per Energy Output (g CO₂e/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil Fuel</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>California oil</td>
<td>0.79 (0.48–2.6)</td>
<td>73 (59–117)</td>
<td>0.09 (0.02–0.25)</td>
</tr>
<tr>
<td>Alberta oil</td>
<td>0.55 (0.33–1.8)</td>
<td>157 (74–313)</td>
<td>0.13 (0.03–0.35)</td>
</tr>
<tr>
<td>Oil sands - surface mining</td>
<td>0.33 (0.16–0.69)</td>
<td></td>
<td>0.47 (0.12–1.98)</td>
</tr>
<tr>
<td>Oil sands - in situ</td>
<td>0.20 (0.092–0.40)</td>
<td></td>
<td>0.78 (0.20–3.39)</td>
</tr>
<tr>
<td><strong>Biofuel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palm biodiesel (Indonesia/Malaysia)</td>
<td>0.0062</td>
<td>702 ± 183</td>
<td>113 ± 30</td>
</tr>
<tr>
<td>Palm biodiesel (Indonesia/Malaysia)</td>
<td>0.0062</td>
<td>3452 ± 1294</td>
<td>557 ± 209</td>
</tr>
<tr>
<td>Soybean biodiesel (Brazil)</td>
<td>0.0009</td>
<td>737 ± 75</td>
<td>819 ± 83</td>
</tr>
<tr>
<td>Sugar cane (Brazil)</td>
<td>0.0059</td>
<td>165 ± 58</td>
<td>28 ± 10</td>
</tr>
<tr>
<td>Soybean biodiesel (Brazil)</td>
<td>0.0009</td>
<td>85 ± 42</td>
<td>94 ± 47</td>
</tr>
<tr>
<td>Corn ethanol (US)</td>
<td>0.0038</td>
<td>134 ± 33</td>
<td>35 ± 9</td>
</tr>
<tr>
<td>Corn ethanol (US)</td>
<td>0.0038</td>
<td>69 ± 24</td>
<td>18 ± 6</td>
</tr>
</tbody>
</table>

Peatland conversion

Yeh et al. 2010, Environ. Sci. Tech. 44: 8766-8772
Better Biomass & Biofuels

• LCA methods used to estimate C-intensity of biofuels

• Established process-based and EIO-LCA methods not equipped to estimate “market-mediated” LUC effects
  • Example: Price response via CGE or PE models

• Minimize iLUC effects by selecting lignocellulosic feedstocks that do not compete for arable land and use “sustainable” fractions:
  • Ag. Residue, MSW, forest/mill waste, novel technologies (e.g., algae)
Bioenergy Production Pathways

Clarke et al., 2009
W. Barley – Spatial/temporal system boundaries

Counties in the DelMarVa region within 100-mi radius of Osage biorefinery; conversion to E98: ~38 g CO$_2$e/MJ

Significant Chesapeake Bay watersheds

Data sources: USDA (2010); NRCS (2011)
Uncertainty in LC GHG emissions (with LUC vs. without LUC)

DA = dilute acid pretreatment followed by simultaneous saccharification and cofermentation (SSCF)

AFEX = ammonia fiber explosion pretreatment followed by SSCF

Spatari and MacLean (2010), Environ. Sci. Technol. 44: 8773-8780
Better Biofuels? Lignocellulosic biomass

- LCA models show reduction in GHG intensity of ag. residue and energy crops on marginal lands

- Lignocellulosic ethanol is still under development!
  - No competitive technologies at commerical-scale
  - Key technological challenge for R&D is enhancing individual processes AND overall *integration*
  - Demonstration scale projects

- Development of other infrastructure compatible fuels show promise but need further research
  - Upgraded pyrolysis bio-oil + biochar
  - Higher alcohols
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