Quantifying Energy and Environmental Effects of Biofuels

Presentation to the Biomass Research and Development Technical Advisory Committee

August 27, 2015

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Biofuel life cycle system boundary example: switchgrass to ethanol
Biofuel life cycle analysis addresses key biofuel sustainability questions

- Does producing biofuels consume more energy than the fuel contains?
- What quantity of fossil fuels are consumed to make biofuels?
- Over their lifecycle, do biofuels emit or sequester carbon on net? If they emit carbon, do they emit less carbon than fossil fuels?
- How water intensive are biofuels to produce?
- What amount of air pollutants are emitted over the course of a biofuel’s life cycle?
- Which life-cycle stages contribute the most to GHG emissions and other impacts?
- How do biofuel co-products share the energy and emissions burdens of the biofuels?
- What indirect effects are associated with biofuels and how can they be quantified?
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- GREET and its documents are available at Argonne’s website at http://greet.es.anl.gov
- There are over 23,000 GREET registered users worldwide
GREET Transportation Applications

- GREET includes more than 100 fuel production pathways
  - Petroleum fuels: conventional crude and oil sands
  - Natural gas: conventional gas and shale gas
  - Coal: to various liquid fuels
  - \( \text{H}_2 \) and electricity production from different feedstocks
  - Renewable fuels: corn, sugarcane, cellulosic biomass, oil crops, algae, biogas

- Ground transportation
  - Conventional gasoline and diesel vehicles
  - Hybrid electric vehicles and plug-in hybrid electric vehicles
  - Battery electric vehicles
  - Fuel cell vehicles

- Aviation transportation
  - Passenger and freight transportation
  - Various alternative fuels blending with petroleum jet fuels

- Rail transportation

- Marine transportation
  - Ocean transportation
  - Inland water transportation
GREET includes many biofuel production pathways

- Ethanol via fermentation from
  - Corn
  - Sugarcane
  - Sorghum (grain, juice, cane)
  - Cellulosic biomass
    - Crop residues
    - Dedicated energy plants: switchgrass, miscanthus, willow, poplar
    - Forest residues

- Soybeans, other oil seeds, and corn oil to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet and marine fuel

- Cellulosic biomass via gasification to
  - Fischer-Tropsch diesel
  - Fischer-Tropsch jet fuel
  - Hydrogen

- Cellulosic biomass via pyrolysis to
  - Renewable gasoline
  - Renewable diesel
  - Renewable jet fuel

- Renewable natural gas from
  - Landfill gas
  - Anaerobic digestion of animal wastes, municipal solid waste, and other feedstocks

- Corn to butanol

- Soybeans and other oil seeds
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet and marine fuel

- Algae to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet and marine fuel

- Ethanol to jet fuel
Feedstock production

- Harvesting equipment fuel consumption
- Fertilizer application
- Nitrogen fertilizer conversion to $\text{N}_2\text{O}$
- Storage technique
- Transportation to biorefinery
- Soil organic carbon changes resulting from land management change
- Carbon stock changes as a result of land use change
**Life cycle analysis must take into account technology advancements**

**Examples: Corn farming and corn ethanol plants**

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Wang M. et al., 2011, *Biomass and Bioenergy*
Does harvesting corn stover as a biofuel feedstock reduce soil organic carbon (SOC) and increase CO$_2$ emissions?

- 100% residue removal?
  - “we are not aware of any management practices for corn grain production that prescribe 100% stover removal.” (Robertson et al., 2014 *NCC*)

- SOC trend
  - “…almost universally predict stable or increasing SOC with full residue retention under no-till management in Midwest soils”.
    (Robertson et al., 2014 *NCC*)

- Time horizon
  - 5-10 (Liska 2014), or
  - >20, even 100 years (“dilutes the average annual carbon emissions”). (Bentsen et al., 2014 *NCC*)
    (Sheehan et al., 2014 *NCC*)

How do practices such as manure application and cover crops influence SOC and overall GHG emissions?
SOC change rates for LCAs should be based on a time horizon of 20 to 30 years in most cases.

Soil carbon sequestration rate (t C ha\(^{-1}\) yr\(^{-1}\))

**Legend:**

- **Initial land state:**
  - Cropland (C)
  - Grassland (G)
  - Forest (F)

- **Final land state:**
  - Corn (C)
  - Switchgrass (S)
  - Miscanthus (M)
  - Poplar (P)
  - Willow (W)

Qin et al., *GCB Bioenergy*, 2015
Critical LCA issues for woody bioenergy

- Current debate on carbon neutrality and biomass additionality for biofuels

- Carbon cycle dynamics over time
  - Carbon absorption from forest growth model
  - Above- and below-ground biomass after harvest

- Forest carbon sinks and sources
  - Validity of carbon neutrality assumption for different forest types and different woody feedstock types
  - Discounting over time of carbon sinks and sources

- Counterfactual scenarios

Credit: National Renewable Energy Laboratory
How carbon neutral is biofuel combustion?

annual crop uptakes atmospheric carbon

conversion to fuel

vehicles combust fuel and emit CO₂

Carbon cycle is fast

<table>
<thead>
<tr>
<th>GHG Emissions</th>
<th>petroleum-derived</th>
<th>bio-derived</th>
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</thead>
<tbody>
<tr>
<td>Well-to-Pump</td>
<td></td>
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<tr>
<td>Pump-to-Wheel</td>
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<tr>
<td>Biogenic CO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well-to-Wheel</td>
<td></td>
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</tbody>
</table>

CO₂
How carbon neutral is biofuel combustion?

trees uptake and store atmospheric carbon

conversion to fuel

vehicles combust fuel and emit CO$_2$

GHG Emissions

- Well-to-Pump
- Pump-to-Wheel
- Biogenic CO$_2$
- Well-to-Wheel

petroleum-derived

bio-derived

Is there a reduction?
Land-Use Change Overview

ΔAgricultural Land

Increased domestic acreage to grow biofuel

ΔCrop Exports

Domestic

Change in land type areas:
- Forest
- Pasture
- Cropland
- Cropland/Pasture

International

Change in land type areas:
- Forest
- Cropland
- Grassland
- Pasture
- Cropland/Pasture

Changes in above- and below-ground soil carbon, foregone sequestration

GHG Emissions
Estimating land-use change GHG emissions incorporates results from several models and data sets.

Data and calculations are contained within GREET module: Carbon Calculator for Land Use Change from Biofuels Production (CCLUB).
Estimates of LUC GHG emissions for corn-to-ethanol pathway

Critical factors for LUC GHG emissions:

- Economic models are used for global simulations
- Crop yields: exist cropland vs. new cropland; global yield differences and potentials
- Available land types: cropland, grassland, forestland, wetland, etc.
- Price elasticities
  - Crop yield response to price
  - Food demand response to price
- Animal feed modeling
- Soil organic carbon changes from land conversions
GTAP modifications to reflect historical land use patterns improve LUC estimates

Assess land allocation patterns and agricultural land use in period 1990-2010.

Unique elasticity assigned to each category

Low land transition
Intermediate land transition
High land transition

Conversion cost: \( C_P \)
Conversion cost: \( C_F \)

Pastureland
Cropland
Forest

\[ C_F > C_P \]

GTAP modeling improvements reduce anticipated LUC GHG emissions associated with corn ethanol

<table>
<thead>
<tr>
<th>Ease of Land Conversion</th>
<th>Forest Conversion Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>Equal to Pasture</td>
</tr>
<tr>
<td>Tuned</td>
<td>Greater than Pasture</td>
</tr>
</tbody>
</table>

### LUC GHG Emissions (g CO₂e/MJ)

- **US Grassland**
- **US Cropland-Pasture**
- **US Forest**
- **US Young Forest-Shrub**
- **Intl Forest**
- **Intl Grassland**
- **Intl Cropland-Pasture**
- **Net**
Biofuel water use accounting

Surface and ground water

Production of electricity and other fuels and chemicals

Cooling, Process water, Steam

Rainfall

Irrigation

Discharge wastewater

Feedstock production

Feedstock transport

Biofuel production

Biofuel transport

Biofuel utilization
Detailed water life-cycle analysis of fuel pathways

Irrigation dominates for biofuels
Agricultural chemicals (limestone mining) non-negligible
Natural gas/SMR have lower water impact
Biomass combustion was identified to be a key contributor to black carbon emissions (g/mi in FFVs)

CS: Corn stover; SC: sugarcane; SS: Sweet sorghum; FR: Forest residue; SB: Soybean; RG: Renewable gasoline; FTD: Fischer-Tropsch diesel; RD: Renewable diesel; FCEV: Fuel cell electric vehicle
Black and organic carbon significantly influence sugarcane and cellulosic ethanol, but minimally affect fossil- and electricity-powered vehicle systems.
Evaluation of air pollutants emitted over a biofuel’s life cycle

- During farming influenced by type of farming equipment, sulfur level of fuel
- During conversion, electricity grid will influence emissions as will process chemistry
- At the biorefinery, combustion equipment will also influence emissions
- Combustion emissions depend on process fuel and type of equipment
- Pollution control regulations influence expected changes in air pollution from combustion equipment and farming equipment over time
Co-Product Methods: Benefits and Issues

- **Displacement method**
  - Data intensive: need detailed understanding of the displaced product sector
  - Dynamic results: subject to change based on economic and market modifications

- **Allocation methods: based on mass, energy, or market revenue**
  - Easy to use
  - Frequent updates not required for mature industry, e.g. petroleum refineries
  - Mass based allocation: not applicable for certain cases
  - Energy based allocation: results not entirely accurate, when coproducts are used in non-fuel applications
  - Market revenue based allocation: subject to price variation

- **Process energy use approach**
  - Detailed engineering analysis is needed
  - Upstream burdens still need allocation based on mass, energy, or market revenue
Corn ethanol-corn oil biodiesel system is a case study in choosing a co-product allocation technique
Co-product allocation choice influences life-cycle GHG emissions of both fuels
CO₂ intensity of petroleum refinery products differ depending on level of processing

Elgowainy et al. *Environmental Science and Technology*, 2014
Forman et al. *Environmental Science and Technology*, 2014
## Gasoline Well-to-Wheel GHG emissions: grams/MJ

![Bar chart showing the breakdown of gasoline emissions by stage of production and consumption.](chart)

### Oil sand land disturbance GHG (Yeh et al. 2014)

- **Pay-as-you –go**
  - 3.4-3.4 g/MJ for surface mining
  - 1.8-2.8 g/MJ for in-situ

- **Amortization**
  - 1.9 g/MJ for surface mining
  - 0.56-0.89 g/MJ for in-situ

<table>
<thead>
<tr>
<th>Stage</th>
<th>Conventional Crude</th>
<th>Mining SCO (53%)</th>
<th>Mining Dilbit (4%)</th>
<th>In-Situ SCO (8%)</th>
<th>In-Situ Dilbit (35%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery</td>
<td>4.1</td>
<td>20</td>
<td>7.0</td>
<td>24</td>
<td>13</td>
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<td>Land Disturbance</td>
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<td>1.9</td>
<td>1.5</td>
<td>0.70</td>
<td>0.56</td>
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<tr>
<td>Refining</td>
<td>15</td>
<td>18</td>
<td>17</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Transport. &amp; Distribution</td>
<td>2.3</td>
<td>3.7</td>
<td>3.9</td>
<td>3.7</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>Total Well-to-Pump</strong></td>
<td><strong>21</strong></td>
<td><strong>44</strong></td>
<td><strong>29</strong></td>
<td><strong>47</strong></td>
<td><strong>36</strong></td>
</tr>
</tbody>
</table>
Overview of life-cycle GHG emissions of selected biofuels
Emissions breakout for different biofuels

Corn ethanol, 62 g CO₂e/MJ
Including DGS credit: -14 g CO₂e/MJ
- Fertilizer production: 16%
- Fertilizer N₂O: 10%
- Farming, harvest, collection, storage: 21%
- Fuel production: 43%
- Transportation and Distribution: 4%
- Fuel combustion, including biogenic emissions credit: 5%
- Land-use Change: 1%

Corn stover ethanol, 14 g CO₂e/MJ
Including electricity (-18 g/MJ) and LUC (-1 g/MJ) credits
- Fertilizer production: 12%
- Fertilizer N₂O: 24%
- Farming, harvest, collection, storage: 51%
- Fuel production: 12%
- Transportation and Distribution: 1%
- Fuel combustion, including biogenic emissions credit: 24%

Pyrolysis gasoline from Forest Residue, g 27 CO₂e/MJ
- Farming, harvest, collection, storage: 12%
- Fuel production: 4%
- Transportation and Distribution: 82%
- Fuel combustion, including biogenic emissions credit: 2%

Renewable gasoline via IDL, g 15 CO₂e/MJ
- Fertilizer production: 13%
- Fertilizer N₂O: 3%
- Farming, harvest, collection, storage: 8%
- Fuel production: 45%
- Transportation and Distribution: 9%
- Fuel combustion, including biogenic emissions credit: 22%
Externalities: an undeveloped area of analysis

- Feedstock production can offer environmental services including reduced nitrogen run-off
- Additional air, water, and soil quality issues merit further exploration and are likely to be spatially- and feedstock-dependent
- Fossil fuel externalities and indirect effects – double standard?
  - Catastrophic events
  - Biodiversity and other influences on ecosystems where drilling occurs
- Existing tools could quantify externality effects on life-cycle metrics, but data availability is likely limited
Biofuel and petroleum-derived fuel LCA areas for development

- Carbon neutrality of woody feedstocks
- Improved accounting of biofuel life-cycle air emissions
- Better accounting for soil chemistry changes that influence GHG emissions from soils
- Advances in conversion processes and feedstock production
- Spatial-temporal resolution
- Land-use change effects beyond C stock (albedo, surface water, etc.)
- Improved handling and quantification of indirect effects and externalities
Acknowledgements

This study was supported by the Bioenergy Technologies Office of the Energy Efficiency and Renewable Energy Office of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357. We acknowledge Kristen Johnson, Alicia Lindauer, and Zia Haq for their support and guidance.

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