GREET Life-Cycle Analysis of Biofuels

March 24, 2015
Analysis and Sustainability

Michael Wang, Jennifer B. Dunn
Argonne National Laboratory
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anaerobic digestion</td>
</tr>
<tr>
<td>AEO</td>
<td>Annual Energy Outlook</td>
</tr>
<tr>
<td>AEZ</td>
<td>Agricultural Ecological Zone</td>
</tr>
<tr>
<td>AGE</td>
<td>Air emissions, greenhouse gas emissions, energy consumption</td>
</tr>
<tr>
<td>ALU</td>
<td>Algal lipid upgrading</td>
</tr>
<tr>
<td>AHTL</td>
<td>Algal hydrothermal liquefaction</td>
</tr>
<tr>
<td>BD</td>
<td>Biodiesel</td>
</tr>
<tr>
<td>BETO</td>
<td>Bioenergy Technologies Office</td>
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<tr>
<td>BEV</td>
<td>Battery electric vehicle</td>
</tr>
<tr>
<td>CARB</td>
<td>California Air Resources Board</td>
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<tr>
<td>CHG</td>
<td>Catalytic hydrothermal gasification</td>
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<tr>
<td>CCLUB</td>
<td>Carbon Calculator for Land Use Change from Biofuel Production</td>
</tr>
<tr>
<td>CS</td>
<td>Corn stover</td>
</tr>
<tr>
<td>DGS</td>
<td>Distillers’ grains solubles</td>
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<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>FCEV</td>
<td>Fuel cell electric vehicle</td>
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<tr>
<td>FR</td>
<td>Forest residue</td>
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<tr>
<td>FTD</td>
<td>Fischer Tropsch Diesel</td>
</tr>
<tr>
<td>FN</td>
<td>Fuel gas/natural gas</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal year</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse gases, Regulated Emissions, and Energy use in Transportation</td>
</tr>
<tr>
<td>GTAP</td>
<td>Global Trade Analysis Project</td>
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<tr>
<td>GV</td>
<td>Gasoline vehicle</td>
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<tr>
<td>HTL</td>
<td>Hydrothermal liquefaction</td>
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<tr>
<td>LCA</td>
<td>Life cycle analysis</td>
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<tr>
<td>PM</td>
<td>Particulate matter</td>
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<td>PTW</td>
<td>Pump-to-wheels</td>
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<tr>
<td>RA</td>
<td>Resource assessment</td>
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<tr>
<td>SCO</td>
<td>Synthetic crude oil</td>
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<td>SOC</td>
<td>Soil organic carbon</td>
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<tr>
<td>SOT</td>
<td>State of technology</td>
</tr>
<tr>
<td>WTP</td>
<td>Well-to-pump</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-wheels</td>
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</table>
Goal statement

- Develop a life-cycle analysis (LCA) model that supports BETO Sustainability and Strategic Analysis by quantifying energy and environmental impacts of biofuels
  - Energy security
  - Greenhouse gas (GHG) emissions
  - Air pollutant emissions
  - Water consumption

- Conduct LCAs and disseminate LCA results
  - Provide LCA results to agencies and industries for R&D and policy decision making
  - Examine critical issues affecting biofuel LCA results and biofuel sustainability
**Quad chart overview**

### Timeline

- Project start date: FY2007
- Project end date: Annual
- Percent complete: On schedule

### Barriers

**Barriers addressed**

- At-B: limitations of analytical tools and capabilities for system-level analysis
- At-A: lack of comparable, transparent, and reproducible analysis
- St-F: systems approach to bioenergy sustainability

### Budget

<table>
<thead>
<tr>
<th>Total Costs FY 10 –FY 12</th>
<th>FY 13 Costs</th>
<th>FY 14 Costs</th>
<th>Total Planned Funding (FY 15-Project End Date)</th>
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<tbody>
<tr>
<td>DOE Funded</td>
<td>$3.8 M</td>
<td>$1.3 M</td>
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<td></td>
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<td>$3.6 M</td>
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</tbody>
</table>

### Partners

**In-kind**

- NREL, ORNL, PNNL, INL, MIT, Purdue
- Other agencies (FAA, EPA, USDA, DOD-DLA-Energy, CARB)
- Industry stakeholders (energy companies, biofuel producers/tech developers, auto companies)
- Research institutions and NGOs

**Supported**

- U. of IL at Chicago and at Urbana-Champaign, U. of WI Madison, UC Davis, Stanford
- ERG, Great Plains Institute
Project overview

- Develop GREET™ LCA model to address energy and environmental impacts of biofuels and conventional fuels
  - Advance LCA methodologies especially to deal with technology uncertainties, LCA system boundary, co-products, indirect effects, etc.
  - Develop extensive, reliable data for LCAs of biofuel and petroleum fuel pathways
  - Maintain model openness and transparency and provide tool training

- Conduct LCAs of key biofuel production pathways
  - Update existing biofuel pathways in GREET
  - Examine emerging LCA issues and add new biofuel pathways to GREET
  - Publish biofuel LCA studies and review/evaluate relevant studies

- Interact with stakeholders (researchers, agencies, industries) to provide LCA results and to improve LCAs
**GREET overview**

- Several DOE programs have supported GREET development since 1995
- A publicly available LCA tool for consistently examining life-cycle energy and emissions of vehicle/fuel systems
  - Available for free download at greet.es.anl.gov
  - Fuel types include petroleum fuels, NG-based fuels, hydrogen, electricity, and many biofuel types
  - End use transportation applications
    - Over 85 on-road vehicle/fuel systems (conventional tech., hybrids, plug-in hybrids, battery electric vehicles, fuel cell vehicles)
    - Marine transportation, air transportation, and rail transportation

**GREET produces results for**

- Greenhouse gas emissions (CO$_2$e of CO$_2$, CH$_4$, N$_2$O, black carbon)
- Criteria pollutant emissions (VOC, CO, NO$_x$, SO$_x$, PM$_{2.5}$, and PM$_{10}$); separated into total and urban emissions
- Energy use by total energy, fossil energy, petroleum energy
- Water consumption

- Biofuels have been an important fuels group in GREET development and applications
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

- Soybeans and other oil seeds
  - 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

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

- Ethanol to jet fuel
Approach, data sources, and key issues with GREET LCA

- **Approach:** build LCA modeling capacity with the GREET model
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Maintain openness and transparency of LCAs by making GREET publicly available

- **Data Sources**
  - Open literature and results from other researchers
  - Simulations with models such as Aspen Plus for fuel production and Argonne Autonomie and EPA MOVES models for vehicle operation
  - Fuel producers and technology developers for fuels and automakers and system components producers for vehicles
  - Baseline technologies and energy systems: EIA AEO projections, EPA eGrid for electric systems, etc.
  - Consideration of effects of regulations already adopted by agencies
GREET biofuel LCA system boundary example: switchgrass to ethanol
Approach: project management

- Annual plan determined via discussions with BETO
- Multi-step quality control process
  - Internally,
    - First researcher conducts initial analysis/calculations
    - Second researcher checks and verifies initial analysis/calculations
    - A team reviews and documents analysis and results
  - External experts review results/publications
- Community engagement for data availability, representativeness, and reliability
- Feedback through external interactions and communication
  - Interact with agencies, industry, researchers, and others to identify key issues and exchange data
  - Communicate via peer-reviewed publications, presentations, and public outreach for broad dissemination of LCA results
- Project progress and deliverables
  - Tracking through monthly and quarterly written reports, quarterly conference calls with sponsor to track milestone completion
  - Biweekly internal team meetings to review technical progress and gain feedback
Critical success factors of GREET development and applications

- Critical LCA issues need to be addressed with science and thoroughness
  - LCA system boundary: determined by LCA scope and broad policy context
  - Methods for co-products in biofuel LCAs: need to address broad issues (e.g., food and fuels; synergy of different energy products)
  - LCA output attributes should be relevant to energy and environmental concerns

- LCA models should address technology advancements and technical variability and uncertainties
  - Temporal and spatial variations in data should be accommodated in LCAs to reflect
    - Technology advancement over time
    - Geographic differences
  - Technical variability of pathway parameters are addressed with stochastic simulations in GREET
  - Technical uncertainties are addressed with scenario analysis and a variety of technology paths for a given supply chain

- Reliable data and transparent models/analyses are key to success of LCA including GREET
  - GREET and its publications are fully accessible at its website
  - Community can conduct detailed computations with GREET and provide detailed critiques
**Key accomplishments**

1. GREET model development
2. Stakeholder engagement
3. Refined analysis of baseline petroleum fuels
4. Expansion of GREET to include black carbon emissions
5. Expansion of GREET to include life-cycle water consumption
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There are more than 23,000 registered GREET users globally.

- Geographically, 71% in North America, 14% in Europe, 9% in Asia
- 51% in academia and research, 23% in industry, 8% in governments
Modular user interface and structured database

- Provides efficient and standardized LCA model and database sharing
- Minimizes time to add new data or update from Argonne’s data server

Example: Update land-use change GHG emissions using CCLUB module (Excel)
Online presence and support for GREET

http://greet.es.anl.gov/greet/

A fresh design for GREET life cycle analysis tool

GREET 2013 provides the user with an easy to use and fully graphical toolbox to perform life cycle analysis simulations of alternative transportation fuels and vehicle technologies in a matter of a few clicks. This new tool includes the data of the GREET model, a fast algorithm for processing it and an interactive user interface. The interface allows faster development using graphical representation of each element in the model, and drag & drop editing approach to add and modify data.

DOWNLOAD AND INSTALL NEW GREET PLATFORM

- Explore major features
  Interactive ways to solve LCA studies
- Differences between versions
  Details about what has changed in this new release and changelog
- Documentation
  Available documentation for the software
- API for developers
  Documentation for the GREET API
- Available modules for GREET
  Lists the available modules for GREET
- Contact the GREET team
  Questions regarding the use of the software or assumption in the data
- FAQ
  Frequently asked questions

GREET Model Tutorial Videos

Video #1: Introduction

GREET users per version

- GREET.net
- Excel Series Fuel Cycle
- Excel Series Vehicle Cycle
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Argonne participates in key stakeholder groups, provides analyses of emerging reports and issues

- Co-chair LCA Subgroup of International Civil Aviation Organization’s Alternative Fuel Task Force to develop LCA methodology and assimilate LCA results of renewable jet fuels
- Participate in ISO 248 Committee to develop sustainability standard for bioenergy
- Member of the US-China Advanced Biofuel Working Group to examine biofuel sustainability in US and China
- Provide analyses and comments on emerging reports/issues

Comments on

Ethanol’s Broken Promise by the Environmental Working Group (May 2014)

Michael Wang1, Jennifer B. Dunn2, Steffen Mueller3, Zhangcai Qin4, Wally Tyner5, and Barry Goodwin6

June 9, 2014

1 Energy Systems Division, Argonne National Laboratory
2 Energy Resource Center, University of Illinois at Urbana-Champaign
3 Purdue University College of Agriculture
4 North Carolina State University Department of Agricultural and Biological Engineering

Summary

In their recent report1, the Environmental Working Group concludes that the economies of scale and environmental benefits of corn ethanol are greater than those of other biofuels.

Response to “Biofuels from crop residue can reduce soil carbon and increase CO2 emissions”

Jennifer B. Dunn, Zhangcai Qin, Michael Wang

Energy Systems Division, Argonne National Laboratory

In their recent paper1, Liska et al. examine the potential for corn stover removal from corn fields to offset CO2 emissions from other sources. However, when all life-cycle consequences are considered, the benefits of stover removal are much higher than previously thought.

Comments on

Avoiding Bioenergy Competition for Food Crops and Land by Searchinger and Heimlich

By Michael Wang and Jennifer B. Dunn

Systems Assessment Group
Energy Systems Division
Argonne National Laboratory

February 16, 2015

The report by Searchinger and Heimlich expresses concern that bioenergy cannot contribute significantly to the fuel supply for the transportation and power sectors without compromising food security.
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Petroleum refinery CO$_2$ intensity was modeled with 43 U.S. refineries (~70% U.S. refining capacity)

Elgowainy et al. *Environmental Science and Technology*, 2014
Forman et al. *Environmental Science and Technology*, 2014
Argonne addressed GHG emissions of oil sands

**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></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>
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<tbody>
<tr>
<td>Recovery</td>
<td>4.1</td>
<td>20</td>
<td>7.0</td>
<td>24</td>
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<td>Land Disturbance</td>
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<td>1.9</td>
<td>1.5</td>
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<td>18</td>
<td>17</td>
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<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>
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<tr>
<td>Total Well-to-Pump</td>
<td>21</td>
<td>44</td>
<td>29</td>
<td>47</td>
<td>36</td>
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</tbody>
</table>
Key accomplishments

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Black and organic carbon significantly influence sugarcane and cellulosic ethanol, but minimally affect fossil- and electricity-powered vehicle systems.

Fossil- and electricity-powered vehicle systems

Biofuel-powered vehicle systems

BC emissions from biomass (and diesel) combustion are a major contributor to stover and sugarcane ethanol.
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Biofuel water use accounting

In GREET, net withdrawal from surface and ground water is considered, while water from rainfall is not.
Detailed water life-cycle analysis of fuel pathways

Irrigation dominates for biofuels
Agricultural chemicals (limestone mining) non-negligible
Hydropower pervades all pathways
Natural gas/SMR have lower water impact

For biofuels, data sources and approach build on WBS 4.2.1.10, incorporate analysis directly into GREET with most recent data.
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Algae: Ways to Achieve GHG Targets in ALU and AHTL Pathways

R&D Guidance from LCA:

- Must achieve productivity *at low mixing energy*. All 4 seasons must be considered.
  - Energy use must be reported with productivity data
  - Harvest at or above ~0.5 g/L
- Establish CHG or immediate return of AD digestate to ponds to avoid CH$_4$ & N$_2$O
- Must demonstrate a low energy primary harvest. (Huge water movement).
## Algae: Examined pathways with Improved Economics

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>MFSP ($2011/GGE)</th>
<th>Seasons</th>
<th>Productivity (g/m²/d)</th>
<th>Total Fuel cycle</th>
<th>Total Infrastructure</th>
<th>Total</th>
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<tbody>
<tr>
<td>Baseline ALU</td>
<td>FY12</td>
<td>$20.79</td>
<td>3</td>
<td>15.5</td>
<td>67500</td>
<td>8300</td>
<td>75800</td>
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<td>National Scale HTL</td>
<td>FY13</td>
<td>$11.34</td>
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<td>14.6</td>
<td>40100</td>
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<td>HTL design case</td>
<td>FY14</td>
<td>$4.49</td>
<td>4</td>
<td>30</td>
<td>35700</td>
<td>1700</td>
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<td>$4.35</td>
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<td>30</td>
<td>34900</td>
<td>2100</td>
<td>37000</td>
</tr>
</tbody>
</table>

MFSP - Minimum fuel selling price  
GGE - Gallons of gasoline equivalent  
WTW GHG - Well to wheels (whole lifecycle) greenhouse gas emissions

The TEA / LCA / RA collaboration guides BETO’s system integration and design

- Algae project metrics
  - Approximately 1.5 FTE
  - 3 journal articles and 3 conference presentations in 2 yrs
  - Principal is co-leading system integration in an Algal Biomass Yield collaboration
Key technical accomplishments

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Argonne supply chain sustainability analysis for BETO key pathways

Collaborative effort with input from
- Idaho National Laboratory: feedstock logistics
SCSA identifies GHG drivers for BETO priority pathways

FY13 analyses
- Corn stover to ethanol via fermentation
- Southern pine to ethanol via gasification
- Hybrid poplar to renewable gasoline and diesel by fast pyrolysis
BETO MYPP includes FY14 SCSA results by citing the SCSA report

Separately, Algae HTL SCSA in FY14 shows 65% reduction compared to low-sulfur diesel
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Corn ethanol plant co-production - ethanol, DGS, and corn oil: three co-product treatment scenarios

Scenario I

Scenario II

Share energy burden of corn ethanol production with ethanol and DGS

Scenario III

Burden free
The three co-product treatment scenarios result in different WTW GHG emissions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WTW GHG Emissions (g CO₂ e/MJ)</th>
<th>Ethanol</th>
<th>Corn Oil</th>
<th>Biodiesel</th>
</tr>
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<tbody>
<tr>
<td>Scenario I</td>
<td>61</td>
<td>61</td>
<td>None*</td>
<td></td>
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<tr>
<td>Scenario II</td>
<td>46</td>
<td>46</td>
<td>45</td>
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<tr>
<td>Scenario III</td>
<td>61</td>
<td>61</td>
<td>10</td>
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<tr>
<td>CA Air Resources Board**</td>
<td>60</td>
<td>60</td>
<td>34</td>
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</tbody>
</table>

* Biodiesel GHG credit is fully assigned to ethanol, thus no biodiesel volume to avoid double counting.

** CARB values are tentative and for comparison only, the final values from CARB may be subject to change.
Life-cycle GHG emissions of gasoline from fast pyrolysis is lower when biochar is used as a soil amendment

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Selection of bioproducts was based on a high-level market analysis
Bioproducts uniformly showed reductions compared to their fossil-derived counterparts.
**Key technical accomplishments**

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Carbon stock implications of land-use change is a key issue in biofuel life cycle analysis

Soil organic carbon (SOC) modeling improvements and expansions
- Modeling is at county-level
- Poplar and willow added as feedstocks
- User selects 30-cm or 100-cm soil depth results
SOC change rates for LCAs should be based on a time horizon of 20 to 30 years in most cases

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

- Current debate on carbon neutrality and biomass additionality for biofuels
- Composition of different types of woody feedstocks
- Carbon cycle dynamics over time
  - Carbon absorption from forest growth model
  - Above- and below-ground biomass after harvest
- Carbon sinks and sources of forests
  - 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: Elaine Oneil, CORRIM
Relevance of GREET development and applications

- GREET is an integral part of BETO’s Sustainability and Strategic Analysis mission
  - Develop a consistent model to advance understanding of biofuel sustainability
  - Produce high-quality, consistent, peer-reviewed analyses
  - Outreach and engage agencies and stakeholders with LCA results to promote clean, efficient biofuels and biofuel production

- Sustainability criteria are critical for BETO in technology/pathway down-selection; analysis with GREET quantifies and clarifies:
  - Energy security benefits of biofuels
  - GHG emission reduction potentials of biofuels
  - Air pollutant effects of biofuels
  - Water consumption
  - Identification of key energy and environmental sources and mitigation measures for adverse effects

- Supply chain analysis is an important area of BETO efforts
  - GREET provides a platform to integrate life cycle stages of biofuel pathways and TEA results to address their overall energy and environmental benefits

- Sustaining program funding to GREET by BETO (and other EERE programs) results in an open, transparent LCA tool for consistent comparisons among fuels and in continuing advances in LCAs
Future work

GREET model development and LCAs
- Analyze carbon dynamics of woody feedstocks including pine, fir, forest residue, willow, poplar to address concerns of carbon neutrality and biomass additionality
- Analyze air emissions for biofuel pathways in collaboration with NREL on feedstock production and conversion
- Examine additional farming practices such as manure application and cover crops to mitigate possible SOC loss from crop residual removal
- Continue to expand key GREET modules, including pretreatment, catalyst, bioproducts
- Add heavy-duty vehicles, detailed refinery model at process unit level into GREET.net

GREET LCA applications
- Carry out Supply Chain Sustainability Analysis for BETO priority pathways
- Upgrade and update the Bioeconomy AGE model to estimate economy-wide biofuel benefits
- Apply GREET approach and data to Billion Ton Study Sustainability Chapter in collaboration with other laboratories
**Summary**

- GREET is a widely-accepted LCA tool that industry, agencies, and academia use to assess life-cycle energy and environmental metrics of biofuels. These users apply the model for a range of purposes including developing R&D strategies, identifying energy/environmental issues and solutions, and developing/evaluating biofuel policies.

- GREET and supporting technical documentation are publicly available, enabling users to examine critical issues, develop their own analyses, and provide critical feedback to Argonne LCA research.

- Argonne develops publications and presentations that address key issues in biofuel sustainability and disseminate LCA results in the national and international debate of biofuel sustainability.

- Argonne is developing applications of GREET that address biofuel sustainability at an economy-wide level, expanding GREET application beyond per-fuel-level analysis.

- Argonne develops LCA results for BETO priority pathways through collaboration with NREL, INL, and PNNL, laboratories that develop TEAs for feedstock logistics and conversion technologies. BETO uses the resulting supply chain sustainability analyses to select biofuel technology options and guide R&D.
Additional Slides
Selected comments from BETO 2013 GREET review and ANL responses

Apply GREET LCA results to inform policy
We engage in the dissemination of GREET LCA results and biofuel LCA key issues through stakeholder engagement, publications, and public speaking. We continue to seek engagement with a diverse stakeholder base that can include policy makers and their staff.

Consider data repository development distinct from Excel modeling that can incorporate input from external users
We continue to explore transparent and clear ways to display data in GREET, which is a significant database of the material and energy intensity of biofuel pathways. We will continue to make GREET serve that role and function as an LCA model. While GREET is designed for users to incorporate their own data, we have a vigorous process to choose GREET default data for data representation and reliability because, as GREET developers, we shoulder the responsibility for the model’s data quality.

Expand beyond Excel platform relying on software engineering expertise and maintaining transparency
In our development of the .net platform, our team of software engineers is striving to retain transparency while optimizing ease of use. We continue to solicit feedback from users of GREET.net to improve it.
Peer Reviewed Journal Articles and Book Chapters


• M.C. Johnson and E Frank, “Energy consumption during the manufacture of nutrients for algae cultivation.” 2014 *Algal Research* 2: 426-436


Selected Technical Reports (http://greet.es.anl.gov/publications)


Additional Technical Memoranda at http://greet.es.anl.gov/publications
Selected presentations


- Z Wang, JB Dunn, J Han, M Wang, How Does Biochar Application to Soil Influence Life-Cycle GHG Emissions of Biofuels Generated from Pyrolysis? 2013 American Society of Agri. and Biological Engineers Annual Meeting, Kansas City, Missouri, July 21-24, 2013


- MQ Wang, Key Issues for GREET Transportation Fuel LCA, CRC Workshop on Life Cycle Analysis of Transportation Fuels, Argonne, IL, Oct. 16-17, 2013


- MQ Wang, Biofuel Life Cycle Analysis Results, HEI SCET Workshop, Chicago, Dec. 5, 2013


- MQ Wang, Life-Cycle Greenhouse Gas Emissions of Corn Ethanol with the GREET Model, EESI Congressional Briefing, Washington, DC, Sept. 18, 2014


- JB Dunn, F Adom, NF Sather, Bioproduct Life Cycle Analysis: Key Results and Methodological Issues." LCA XIV, San Francisco, Calif., Oct. 6-8 2014
Backup Slides
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
The marine module contains well-to-hull and per energy functional unit results

- Bio-based marine fuels offer GHG reductions
- Transit in international waters largest contributor to well-to-hull emissions.

- Vessel types:
  - Bulk Container
  - Large Container
  - Crude Carrier

- Regions
  - Atlantic
  - Pacific
  - Great Lakes
  - Gulf of Mexico