Land Use Change Impacts by Cultivation Location: A Geographic Life Cycle Assessment of Biofuels from Wastewater Algae

Marie-Odile P. Fortier,¹ Griffin W. Roberts,² Dr. Belinda S.M. Sturm,¹ Dr. Susan M. Stagg-Williams²

1. Civil, Environmental & Architectural Engineering, University of Kansas
2. Chemical and Petroleum Engineering, University of Kansas
Introduction

- The outcome of a biofuel life cycle assessment (LCA) depends on location-specific factors which influence algal productivity and direct land use change impacts.
  - The net life cycle greenhouse gas (LC-GHG) emissions from changing potentially available land around wastewater treatment plants (WWTPs) to algal ponds are unknown.

- Four prior algal biofuel LCAs have noted the land area requirement for feedstock production, but none have determined the direct land use change (LUC) impacts of algal cultivation.
Selected features of this LCA study:

- Municipal wastewater effluent as media for algal cultivation
- Hydrothermal liquefaction instead of lipid extraction
- Accounts for ranges of possible parameter values

Builds upon our prior LCA model in order to:

- Integrate geographically specific variables for algae biofuel feedstock production
- Include climate change impacts of direct land use change
## LCA Framework

<table>
<thead>
<tr>
<th>Scope</th>
<th>The scope of this LCA is “well-to-wake.” The processes are modeled with SimaPro 7.3.3.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Unit</td>
<td>1 GJ of jet fuel</td>
</tr>
</tbody>
</table>
| System Boundaries | • Infrastructure, construction, and labor are not included.  
                     • **Direct land use change impacts** are included. |
| Impact Assessment | EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2 (TRACI 2) |
| Sensitivity Analyses | Performed for each case using ranges of parameter values |
| Monte Carlo Analyses | 10,000 runs of each case using Python code developed for this LCA model |

### Diagram

- **WWTP**
  - Land Use Change Impacts
  - Algae Production at WWTP
  - Algae Harvesting
  - Algae Dewatering
  - HTL Reaction
- **Refinery**
  - Transport to Refinery
  - Upgrading Processes
  - Transport to Airport
  - Combustion in Jet Engine
LCA Framework

Level II Ecoregions assessed:

<table>
<thead>
<tr>
<th>Level II Ecoregion</th>
<th>Number of WWTPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Highlands</td>
<td>254</td>
</tr>
<tr>
<td>Central USA Plains</td>
<td>1226</td>
</tr>
<tr>
<td>Cold Deserts</td>
<td>246</td>
</tr>
<tr>
<td>Everglades</td>
<td>12</td>
</tr>
<tr>
<td>Marine West Coast Forest</td>
<td>226</td>
</tr>
<tr>
<td>Mediterranean California</td>
<td>173</td>
</tr>
<tr>
<td>Mississippi Alluvial and Southeast USA Coastal Plains</td>
<td>844</td>
</tr>
<tr>
<td>Mixed Wood Plains</td>
<td>1717</td>
</tr>
<tr>
<td>Mixed Wood Shield</td>
<td>178</td>
</tr>
<tr>
<td>Ozark/Ouachita-Appalachian Forests</td>
<td>1709</td>
</tr>
<tr>
<td>South Central Semi-Arid Prairies</td>
<td>864</td>
</tr>
<tr>
<td>Southeastern USA Plains</td>
<td>2665</td>
</tr>
<tr>
<td>Tamaulipas-Texas Semi-Arid Plain</td>
<td>28</td>
</tr>
<tr>
<td>Temperate Prairies</td>
<td>1643</td>
</tr>
<tr>
<td>Texas-Louisiana Coastal Plain</td>
<td>392</td>
</tr>
<tr>
<td>Upper Gila Mountains</td>
<td>9</td>
</tr>
<tr>
<td>Warm Deserts</td>
<td>58</td>
</tr>
<tr>
<td>West-Central Semi-Arid Prairies</td>
<td>140</td>
</tr>
<tr>
<td>Western Cordillera</td>
<td>232</td>
</tr>
<tr>
<td>Western Sierra Madre Piedmont</td>
<td>3</td>
</tr>
</tbody>
</table>
Geographic Data Collection and Aggregation

- Data was collected on potentially available land near WWTPs and aggregated at the ecoregion level.

- Definition of potentially available land for algal cultivation
  - Within a 5-km radius from the center of a WWTP
  - Available land cover types:
    - Developed open space
    - Barren land (rock/sand/clay)
    - Shrub/scrub
    - Grassland/herbaceous
    - Pasture/hay
  - Excluding environmentally protected areas
  - Excluding areas with slopes greater than 2%
Determination of LUC Impacts on LC-GHG Emissions of Algal Biofuel

- Direct LUC impacts include the effects of:
  - Changing the albedo on an area
  - Changing the carbon flux on the land
  - Removing original carbon stored on the land

- Assessing direct LUC impacts involves defining the difference between characteristics of an area before and after implementation of algal ponds, then calculating the life cycle climate change impact in units of CO$_2$eq per GJ of fuel associated with this difference.
Microalgae Growth Modeling

- Average monthly data was collected by location using ArcGIS and as inputs to the Python-based algae growth model:
  - N and P concentrations in wastewater effluent
  - Solar radiation
  - 30-year climate normal temperature

- Model allows for algae growth to be modeled according to the limiting factor for growth by ecoregion by month:
  - Allows for flexibility with ranges of data, recycling aqueous product (ACP) from hydrothermal liquefaction, and variable algal nutrient uptake rates
Surface Albedo Change

- A change in albedo induces a radiative forcing by affecting the shortwave radiation budget.
- There is a relationship between CO$_{2}$eq and radiative forcings, and thus albedo change can be translated into a climate change impact in an LCA.
  - Depends on functional unit, the area changed, the difference between initial and final albedo, and the lifetime of the system exerting a change in albedo

http://www.ecocem.ie/environmental/albedo.htm
Surface Albedo Change

- Albedo change effects may increase *or* decrease the effectiveness of a climate change mitigation technology depending on the albedo difference between the original and converted land area.

- For example, the LC-GHG emissions of biofuels produced from salicornia on converted desert land *increased nearly fourfold* when the large decrease in albedo is considered (Caiazzo et al. 2014).

https://www.nc-climate.ncsu.edu/edu/k12/.albedo
Surface Albedo Change Methods

Original conditions:
- Monthly average albedo data from MODIS Albedo product MCD43A3

After algal pond installation:
- Range of algal pond albedo values modeled
- Methods from Bright et al. (2012), Betts (2000), and Caiazzo et al. (2014) used to convert albedo change impacts to CO$_2$eq scaled to the functional unit
Carbon Flux Change Methods

Original conditions:
- MODIS Gross/Net Primary Production product (MOD17) \( \rightarrow \) Existing above-ground carbon fixation rate on available land
- Existing below-ground carbon flux determined from soil organic carbon model

After algal pond installation:
- Carbon fixed per unit area over time in the algal ponds determined using the algal growth model
- Below-ground soil carbon flux deemed negligible.

http://environment.bennington.edu/?p=822
Initial Biomass and Soil Carbon Loss Methods

- Loss of existing carbon in aboveground biomass
  - North American Carbon Program (NACP) Aboveground Biomass and Carbon Baseline Data version 2 for above-ground biomass carbon loss
  - Loss of belowground biomass approximated using published factors

- Loss of existing soil organic carbon (SOC)
  - Fraction of the total SOC from the Rapid Assessment of U.S. Soil Carbon (RaCA) from USDA and NRCS
  - Based on the difference between C in soils beneath urban impervious surfaces and soils in nearby undeveloped areas.
Geographic Analysis by Ecoregion

- Some ecoregions had very little potentially available land within 5km of municipal WWTPs…
Geographic Analysis by Ecoregion

- We will focus on comparing production of algal biofuel in the following ecoregions.
LCA Monte Carlo Results **without LUC**

- **10,000 runs**
- **With conservative technology achievements**
- **CJF = conventional jet fuel**
  - **88.1 kg CO$_{2eq}$/GJ**
Further Results to be Shown at the ABS!
Tradeoffs between land availability and water availability by ecoregion.
Acknowledgments

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Thank you!
Questions?

Selected KU publications related to algae:


Marie-Odile P. Fortier (mfortier@ku.edu)
Additional Slides
Geographic Analyses

- Geographic analyses can help identify land availability and compare potential algal productivities between sites.

- Areas identified as most favorable for algae cultivation by published geographic analyses
  - 14 southern-most states
  - Great Lakes region, southeastern seaboard, Gulf Coast
  - US southwest, California, southern Texas, Florida

- … but how do the environmental impacts differ among algal cultivation regions?

Orfield et al. (2014)
Wigmosta et al. (2011)