DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

1.3.1.500 Sustainable Development of Algae for Biofuel

March 6, 2017
Advanced Algal Systems Platform

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Oak Ridge National Laboratory
Environmental Sciences Division
Goal Statement: Putting the “sustainable” in sustainable biomass and biofuel

How?

Define indicators of sustainable algal biofuels.

Determine best practices for sustainably meeting productivity and profitability targets through national resource analysis and experimentation.

Focus on key challenges for algae commercialization.

Guide BETO and Advanced Algal Systems Program on a path toward environmentally and socioeconomically viable technologies.

The Linde Group, with permission
# Quad Chart Overview

## Timeline

- **Project start date:** FY16
- **Project end date:** FY18
- **Percent complete:** 50% (as of end Feb 2017)

## Barriers

- **Aft-A. Biomass Availability and Cost** ([need] data on potential price, location, environmental sustainability & quantity of algal biomass . . .)
- **Aft-B. Sustainable Algae Production** ([need] data on environmental effects to support LCA; need to address a number of sustainability issues—water and fertilizer inputs, land conversion, and liner use; cost and productivity . . .)
- **St-D. Implementing Indicators and methodology for evaluating and improving sustainability**
- **St-E. Best Practices and Systems for sustainable bioenergy production**

## Budget

<table>
<thead>
<tr>
<th>(K)</th>
<th>FY 16</th>
<th>FY 17</th>
<th>FY 18 plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>New BA</td>
<td>265</td>
<td>83</td>
<td>400</td>
</tr>
</tbody>
</table>

## Partners

- **Contractor:** Longitude 122 West, Inc.
- **U Tennessee, UC San Diego, U Kansas**
- **National labs:** (PNNL, INL, SNL, NREL, ANL)
- **Algae Biomass Organization (unfunded)**
How do we measure or model sustainability?
## Environmental indicators

<table>
<thead>
<tr>
<th>Category</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil quality</td>
<td>1. Bulk density</td>
</tr>
<tr>
<td></td>
<td>2. Nitrate export</td>
</tr>
<tr>
<td></td>
<td>3. Total P export</td>
</tr>
<tr>
<td></td>
<td>4. Salinity</td>
</tr>
<tr>
<td>Water quality</td>
<td>5. Peak storm flow</td>
</tr>
<tr>
<td></td>
<td>6. Minimum base flow</td>
</tr>
<tr>
<td></td>
<td>7. Consumptive water use</td>
</tr>
<tr>
<td>Water quantity</td>
<td>8. CO₂ equivalent emissions (CO₂ and N₂O)</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td>9. Presence of taxa of special concern</td>
</tr>
<tr>
<td></td>
<td>10. Habitat area of taxa of special concern</td>
</tr>
<tr>
<td></td>
<td>11. Abundance of released algae</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>12. Tropospheric</td>
</tr>
<tr>
<td></td>
<td>13. Carbon monoxide</td>
</tr>
<tr>
<td></td>
<td>14. Total particulate matter less than 2.5μm diam</td>
</tr>
<tr>
<td>Air quality</td>
<td>15. Total particulate matter less than 10μm diam</td>
</tr>
<tr>
<td>Productivity</td>
<td>16. Primary productivity or yield</td>
</tr>
</tbody>
</table>

### Uses of sustainability indicators

- Modeling future effects
- Energy comparisons
- Units for life-cycle analysis
- Setting sustainability targets
# Socioeconomic indicators

## General

<table>
<thead>
<tr>
<th>Uncertain</th>
<th>Small scale</th>
<th>Site specific</th>
<th>Large scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling</td>
<td>Lab. or single process</td>
<td><strong>Pilot plant</strong></td>
<td><strong>Commercial plant or collection of plants</strong></td>
</tr>
</tbody>
</table>
| Modeling  | • Fossil EROI | • ROI  
• Fossil EROI  
• Risk of catastrophe | • Employment  
• ROI  
• NPV  
• Fossil EROI  
• Risk of catastrophe |
| Measurement | • Work days lost to injury | • Employment 
• Worker income  
• Work days lost to injury 
• EROI  
• Public opinion  
• Effective stakeholder participation  
• Transparency | • Food security  
• Employment  
• ROI  
• NPV  
• Energy security premium  
• Fuel price volatility  
• Terms of trade  
• Trade volume  
• Depletion of non-renewable energy resources  
• Fossil EROI  
• Effective stakeholder participation  
• Transparency  
• Public opinion  
• Work days lost to injury  
• Household income  

*Italic* = expected to be measured or modeled in future

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Image: "National Algal Biofuels Technology Review" by Oak Ridge National Laboratory
Project Overview and Objectives

Sustainability Indicators

• Identify indicators to move toward targets and best management practices.

Potential for National Sustainable Biomass Supply

• Estimate potential algae biomass resources at different prices using co-location with CO₂ sources (*BT16* volume 1)

• Estimate environmental effects of potential algae biomass, with an emphasis on GHG emissions and water consumption (*BT16* volume 2)

• Define *sustainable biomass* for algae and provide spatial data to PNNL to model 1 million tons of sustainable biomass in 2017

Science to Address Sustainability Challenges

• Develop ecological strategies (polycultures) to scale up production
  • Identify and exploit biological traits in algae that facilitate greater stability and productivity and use nonpotable water

• Conduct proof of concept for minimally lined ponds
  • Investigate saturated hydraulic conductivity

Indicators completed FY16
BMPs in FY18

Completed FY16

Completed FY17

Water focus in FY17

Ends in FY17 Q4

Funding ended in FY16
MS thesis extended to FY17 Q3
Project Overview—Pictorial Version

Project addresses
• 10 categories of sustainability
• Intersection between resource analysis and sustainability (modeling)
• Solutions to key productivity and profitability challenges that also have sustainability consequences
Management Approach

**BT16 volume 1 and 2**
- 1.1.1.1 Supply Forecasts and Analysis
- 1.3.1.102 Microalgae Analysis
- 1.3.1.200 Algal Biofuels Techno-economic Analysis

**Algae model harmonization**
- 4.1.1.10 GREET Development Biofuel Pathway Research and Analysis
- & BT16 collaborators

**Sustainability Indicators**
- 4.2.2.40 Bioenergy Sustainability: How to Define and Measure it

**Information Flow**
- Weekly to monthly calls with PNNL, Longitude 122 West, Inc.
- Collaboration with PNNL (water) and ANL (GHG) Handoffs to and from PNNL, NREL
- Consultation with Algae Biomass Organization
- BT16 peer review workshops
- DOE review

**Joint products, workshops, screen shares**
- To and from industry
- To DOE and Knowledge Discovery Framework

**Project Integration**
- Move BT16 resource analysis work to 1.1.1.1 (FY16)
- Join ecological strategies task with project (FY15, end in FY17)
- Embark on proof-of-principle for reducing soil conductivity for unlined ponds (start FY15, end in FY16)
- Compare saline vs fresh water sustainability (FY16 go/no-go)
- Do not investigate accident scenario at this time (FY16 go/no-go)
- Plan future work
Objectives—Billion Ton (BT16)

- Incorporate algae (for the first time) into a BT report
- Quantify potential site-specific to national feedstock production and cost
- Focus on open ponds
- Focus on strategies to reduce production costs
- Use waste CO₂

BT16 volume 1

- Biological diversity
- Air quality
- Soil quality
- Social acceptability
- External trade

Environmental sustainability indicators

- Water quality & quantity
- Productivity
- EROI
- Profitability
- Energy security

Socioeconomic sustainability indicators

BT16 volume 2

- Describe environmental effects
- Estimate water consumption

Social well being

- Greenhouse gas emissions
- Social acceptability
- Socioeconomic sustainability indicators

BT16 volume 2

- Water quality & quantity
- Productivity
- EROI
- Profitability
- Energy security

Social well being

- Greenhouse gas emissions
- Social acceptability
- Socioeconomic sustainability indicators
Approach—*BT16 volume 1*

- Use CO$_2$ flue gas instead of purchase
- Assume 100 10-acre ponds
- Strains: *Chlorella sorokiniana, Nannochloropsis salina*
- Productivities: ~13 g/m$^2$/d or ~25 g/m$^2$/d

**Integrate**

- CO$_2$ transport engineering design and costs
- Spatial algae production output from PNNL Biomass Assessment Tool
- Costs modified from NREL design case report

**Produce**

- Curves of price versus supply across the U.S.
Cost-effective distance for CO$_2$ transport is dependent on CO$_2$ purity—*BT16* volume 1

**GHG Implications**

“[some algae] pathways satisfy the RFS2 criteria of advanced biofuels only when the CO$_2$ is supplied by low-pressure flue gas transported over short distances.” 2016 Argonne report

**Cost Relevance**

Cost Relevance is on next slide

12 BETO 2017 Project Peer Review
Biomass supply curves show substantial national biomass potential at high price ranges

- Biomass supply and price depend on the scenario.
- In this freshwater example, more biomass is potentially available at lower prices when coal-fired power plants are the CO$_2$ source.

Present productivities, minimally lined ponds, *C. sorokiniana*
Clear but small relative cost savings for CO$_2$ co-location ($/ton biomass), except for natural gas source under high productivity.

Higher productivities lead to cost savings more substantial than from CO$_2$ co-location.
Maps and user interface—*BT16 volume 1*

Go to [https://bioenergykdf.net/billion ton2016/7/1/tableau](https://bioenergykdf.net/billion ton2016/7/1/tableau) and change the variables (including price range) to see custom visualizations of maps, supply curves, and bar graphs.

From DOE Bioenergy Knowledge Discovery Framework

Marginal minimum selling price vs supply

$500/ton max price → 2.7 million tons
Tradeoffs and synergies exist between cost and environmental sustainability—*BT16 volume 2*

**Objectives**
- Conduct qualitative environmental analysis of *BT16* scenarios to evaluate
  - CO₂ co-location
  - Saline vs freshwater
  - Fully vs minimally lined ponds
  - High vs current productivities
- Describe water consumption estimated in *BT16* scenarios (PNNL)

**Example results**
- Some cost-saving measures (co-location with CO₂ and minimally lined ponds) also reduce GHG emissions.
- Biomass is more sustainable if water stress measures and timing of demand are considered, not just mean annual basin flow.
- Targets can be identified: e.g., hydraulic conductivity of $1 \times 10^{-7}$ cm/s prevents leaching into subsurface (unlined ponds).
Approach and Results—Meet 2017 Multiyear Program Plan Goal

- Working paper with PNNL in FY16 proposed definition and process to finalize sustainability targets and data needed to support resource modeling.

- Milestone will move toward sustainable biomass production, emphasizing water.

- More sustainability constraints will be incorporated in the future.

- Regions in southeastern Arizona and the Gulf Coast of Texas are being examined, then considering national scale.

1 million metric tonnes of "sustainable" algal biomass
Can we increase productivity by using polycultures?

Productivity limits profitability. How can we increase productivity?

Conclusion: Mixed cultures in wastewater can increase productivity, use N more efficiently, and increase crop reliability.
Approach—Ecological strategies for production

Background
- Mixed cultures (polycultures) can
  - utilize resources more efficiently
  - increase productivity
  - have a longer growing season
  - provide crop protection (increasing stability)

Objectives
- Increase annual biomass production from current 13 g m$^{-2}$ d$^{-1}$ to target of 25 g m$^{-2}$ d$^{-1}$ while decreasing freshwater consumption
- Identify high production strains that have complementary traits (affinity for nutrients) and culture together in wastewater (mixed nutrients)
Polycultures increase productivity and nutrient use efficiency

- Biomass production increased with species richness in wastewater.
- The effect of species richness on biomass productivity was greatest when grown in wastewater.

**Why?**

<table>
<thead>
<tr>
<th>Number of species</th>
<th>Nitrate</th>
<th>Ammonium</th>
<th>Urea</th>
<th>Wastewater (simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36%</td>
<td></td>
<td></td>
<td>88%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Nutrient Use Efficiency (NUE)
  \[ \text{NUE} = \frac{g \text{ Biomass produced}}{g \text{ Nitrogen used}} \]
- NUE increases with species richness in wastewater.
- Algae grown in nitrate showed highest NUE and productivity but is most costly.
Can we eliminate the use of pond liners?

- Plastic pond liners (1/4 of capex) limit profitability and GHG benefits.
- Can we eliminate pond liners in native soils?

Our proof of concept shows that clogging by algae or bacteria reduces hydraulic conductivity and could protect water quality and quantity.
Proof of Concept for Unlined Ponds

Objective

- Unlined ponds work for animal waste holding facilities.
- Microbial growth clogs the soils and inhibits leaching.
- Will unlined ponds work for algae?

Conductivity Reductions by Algae

- Soils with swelling clays were nearly impermeable
- Conductivity of coarse soils decreased due to clogging by algae
- Still need to reach target $10^{-7}$ cm/s
- Compacting soils during construction could enable technology

Conductivity (Control) (Reduced)

Algal mats at soil/solution surface

Texas Sand California Sand Tennessee Loam
Future work—FY18—Food Security Task

Develop plan for maintaining or increasing food security for algae produced for food/feed and fuel together.

- Review food versus fuel debate.
  - Can findings and strategies for terrestrial crops inform strategies for algae?
- Evaluate sustainability synergies.
  - Does producing food with fuel improve water consumption and GHG emissions?
  - How does producing food with fuel improve profitability and employment?
- Reassess suitable lands.
  - Can we produce algae on agricultural land without putting food security at risk?

Algae provide protein, baking flour, nutritional oils, antioxidants, livestock feed, food colors, biofertilizer.
Future work—FY18—Best Management Practices

Barrier St-E. Best Practices and Systems for sustainable bioenergy production

- Final FY18 deliverable is summary of sustainability targets and best management practices (BMPs) with consideration of tradeoffs.
- BMPs from this research, other national labs, industry, and academic publications will be included.
- All environmental indicators and some socioeconomic sustainability indicators will be included.

From DOE/BETO analysis and sustainability program
Future work—FY18 and beyond—Resource Analysis*

- Consider photobioreactors, including fuel secretion pathways
- Incorporate co-location with wastewater treatment plants
- Incorporate additional co-location with CO₂
- Incorporate co-products
- Understand where unlined ponds maintain water quality and quantity

*Task has been moved to Project 1.1.1.1 with the rest of the Billion Ton work, but we would still like comments from algae reviewers
## Relevance and Impact

<table>
<thead>
<tr>
<th>Task</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sustainability indicators</strong></td>
<td>• Adopted by Algae Biomass Organization (ABO) 2015 <em>Industrial Algae Measurements Version 7.0</em>; used by industry</td>
</tr>
</tbody>
</table>
| **BT16 reports**                    | • 1st US algae resource analysis that includes cost  
• Potential cost savings from use of waste CO$_2$  
• Importance of productivity and liners in cost  
• “Landmark publication” for industry (Matt Carr, ABO)  
• Low pressure CO$_2$ transport may satisfy RFS2 criteria (ANL) |
| **Potential impact**                |                                                                                                                                                      |
| **Ecological strategies for scaling up production** | • Increase in productivity with polyculture  
• Wastewater use→improvement in water quality and freshwater consumption and reduction in cost  
• Fewer pond crashes (lit review) |
| **Proof of concept-unlined ponds**  | • Reduction in hydraulic conductivity, even for sandy soils  
• Cost savings of $100/ton (current productivities) or $200/ton (future productivities) (*BT16* and NREL)  
• Reduction in GHG emissions, increase in EROI (ANL, literature) |
Relevance of Project Goals to BETO Goals

Project guides strategic plans of BETO and Advanced Algal Systems to pursue environmentally, economically, and socially viable technologies.

Relevant to DOE Advanced Algal Systems goals
. . . 5 billion gallons per year of sustainable, reliable, & affordable algal biofuels by 2030
• By 2017, model sustainable supply of 1 million metric tonnes AFDW cultivated algal biomass
• By 2022, model sustainable supply of 20 million metric tonnes . . .

Relevant to DOE Sustainability Area goals
To understand and promote positive economic, social, and environmental effects and reduce potential negative impacts of bioenergy production
• By 2022, evaluate environmental and socioeconomic indicators across the supply chain for . . . algal bioenergy production systems.

Relevant to DOE Terrestrial Feedstock Supply and Logistics goals
• By 2016, produce . . . assessment of potentially available feedstock supplies . . .
Additional Slides
Acknowledgments

Project team
Oak Ridge National Laboratory
- Virginia Dale
- Henriette Jager
- Matthew Langholtz
- Shovon Mandal
- Teresa Mathews
- Melanie Mayes
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- Molly Pattullo
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- Susan Schoenung
University of Kansas
- Val Smith
UC San Diego
- Jonathan Shurin

Collaborators
Pacific Northwest National Lab
- André Coleman
- Mark Wigmosta
National Renewable Energy Lab
- Ryan Davis

Reviewers of Billion Ton report algae chapters
- David Babson, Amanda Barry, Jacques Beaudry-Losique, John Benemann, Matt Carr, Ed Frank, David Hazlebeck, Jeff Li, Raffi Mardirosian, Becky Ryan, Stephanie Shaw, Eric Tan, Colleen Tomaino, Rebecca White

Additional Advice on Billion Ton report
- Toby Ahrens, Yan Poon, Timothy Zenk, Martin Sabarsky, Mark Allen, David St. Angelo, Sissi Liu, Al Darzins, Greg Mitchell, Laurie Purpuro, Colin Beal, Michael Huesemann, Richard Skaggs, Ron Kent, Alexis Wolfe, Hans Kistenmacher

Providers of Soils
- University of Tennessee
- California soil from Delhi County Wastewater Treatment Plant, Tryg Lundquist
- Texas A&M AgriLife test bed, Corpus Christi, Anthony Siccardi
- Texas A&M Agrilife BioEnergy Program in Pecos, TX
- Arizona Center for Algae Technology, Mesa, AZ, Thomas Dempster

DOE Sponsors
- Dan Fishman, Devinn Lambert
**Comment:** The methods developed by ORNL for sustainability assessment, while always evolving, seemed sound and robust. I have scored this project lower because I am concerned that it is operating in a silo relative to DOE's other modelling projects. Assumptions used in existing LCA and TEA models, developed by other national labs (NREL, PNNL), and commonly referred to by laboratory projects in this Peer Review, have either not been shared with ORNL or not utilized by ORNL.

**Response:** We did not emphasize the inter-laboratory collaborations in our last peer review presentation, though we were collaborating with PNNL at the time. In the past two years, the Billion Ton resource analysis (volume 1) and environmental effects analysis (volume 2) have been done in collaboration with PNNL, and volume 1 in collaboration with NREL. ANL reviewed volume 2, and their research influenced our future CO$_2$ co-location scenarios. We are engaged with the inter-laboratory model harmonization team, participating in milestones. We are working with PNNL on the 2017 MYPP goal to model 1 million tonnes of sustainable algae biomass and have held discussions with ANL on the topic as well.
Responses to Previous Reviewers’ Comments

Comment: This group seems poised to best contribute in terms of the salinity debate -- what is the cost of using freshwater vs. nonpotable water to grow algae at the 1000 acre scale?

Response: We included saline scenarios in the Billion Ton reports, along with comparative costs and comparative environmental effects of freshwater and saline water. We are also investigating polycultures in a model wastewater system and beginning to design systems for co-location of algae with wastewater in a separate feedstock project whose task originated with this project.

Comment: The presentation and mixture of objectives appears disjointed, and the projects do not complement one another well or benefit from being joined as a broader project.

Response: The resource analysis task (Task 2. Billion Ton work) was moved to a feedstock supply project after the 2015 peer review, but that occurred in the new FY2016 (7 months after the 2015 peer review and 10 months after the carryover funds ran out), so more than half of the Billion Ton volume 1 algae research was done under 1.3.1.500, which is why the results are presented here. A decision was made to close out the hydraulic conductivity proof-of-concept research related to minimally lined ponds, as well as the ecological strategies (polyculture) tasks, but it did not make sense to move those tasks out of this project prior to closing them out. We hope we have presented the linkages between tasks better this year.
**Responses to Previous Reviewers’ Comments**

**Comment:** The polyculture work was insufficiently explained and connected to the rest of the project.

**Response:** The polyculture task (now renamed “Ecological strategies for sustainably scaling up production) relates to productivity, energy security (maintaining reliable supply with fewer crashes), and water quantity and quality (using nonpotable water). Therefore, the task is related to three of the sustainability indicators, as well as to profitability, indirectly. The Billion Ton research has shown the need for increasing productivity to reduce costs, and the polyculture task is important for understanding productivities and nitrogen utilization in resource analysis scenarios that use nonpotable water.

**Comment:** The [unlined pond research] is all aimed at downward infiltration without any consideration of lateral erosion caused by constant water movement in ponds.

**Response:** The initial proof-of-concept experiments had so many variables that initial studies needed to be conducted in small-diameter soil columns. We recognize that liners would be needed at lateral erosion points for many ponds, which is why we have included “minimal liners” rather than entirely unlined ponds as options in the Billion Ton reports, as in the 2016 NREL design report.
Reviewer Comments on Billion Ton (*BT16*) reports in late 2015

ABO reviewers in special review meeting at Algae Biomass Summit 2015

- Include saline scenarios in *BT16*.
  - Response: Added

Peer review workshop on *BT16* volume 1

- Include saline scenarios that have minimal or no pond liner in *BT16*.
  - Response: Added

- Include photobioreactors in the next resource analysis as soon as possible.
  - When engineering, cost, and productivity parameters are available, we will include PBRs; but biomass may not be the right endpoint for algae that secrete fuel.

- Priority sustainability indicators for *BT16* volume 2 are water consumption and greenhouse gas emissions
  - These priority indicators were analyzed.
Highlight from Go/No-go Review

• June 2016. Complete two research plans for sustainability case studies, to be provided to DOE, along with preliminary assessment of available data.
  1) modeling an accident scenario (breach of pond or PBR with nutrients and algae)
  2) comparing sustainability of freshwater and nonpotable water.

DOE Response

• Milestone delayed so that ORNL and partners can deliver a detailed research plan and preliminary assessment of available data for modeling 1 million metric tons of sustainable biomass, per definition. [This plan was delivered in FY16 Q4.]
  – Consider feedback from the 2013 Peer Review, contributions to BT16, continued integration of sustainability indicators with analysis projects (RA, TEA, LCA).

• Submit research plan that outlines timeline for defining sustainability, with inclusion of a freshwater and salt water scenario, and collaboration with Harmonization team for defining sustainability and modeling FY17 MYPP goal. [This plan was delivered in FY16 Q4.]

• No further planning requested at this time for the Accidental Release Case Study.
# Acronyms and definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFDW</td>
<td>Ash-free dry weight</td>
</tr>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory</td>
</tr>
<tr>
<td>ABO</td>
<td>Algae Biomass Organization</td>
</tr>
<tr>
<td>BA</td>
<td>Budget authority</td>
</tr>
<tr>
<td>BETO</td>
<td>DOE Bioenergy Technologies Office</td>
</tr>
<tr>
<td>BMP</td>
<td>Best management practice</td>
</tr>
<tr>
<td>BT16</td>
<td>2016 Billion Ton report</td>
</tr>
<tr>
<td>Co-location</td>
<td>Locating an algal biofuel production facility near a source of resources (e.g., CO&lt;sub&gt;2&lt;/sub&gt;)</td>
</tr>
<tr>
<td>EROI</td>
<td>Energy return on investment</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model</td>
</tr>
<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
</tr>
<tr>
<td>MYPP</td>
<td>Multi-year program plan</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>NUE</td>
<td>Nutrient use efficiency</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>polyculture</td>
<td>Community with multiple species of algae</td>
</tr>
<tr>
<td>resource analysis</td>
<td>Quantification of biomass resources for bioenergy</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on Investment</td>
</tr>
<tr>
<td>SNL</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td>supply curve</td>
<td>Biomass or fuel product versus price</td>
</tr>
</tbody>
</table>
Publications


*Jager H, Efroymson R. in review. Biomass for energy mediates the flow of ecosystem goods and services. Biomass and Bioenergy

* funded 50% or more by another DOE/BETO project
Presentations

- Numerous presentations of Billion Ton report that (included algae) to DOE, including Secretary Moniz, as well as White House Office of Management and Budget and Council on Environmental Quality

- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. Oak Ridge. December 7, 2016
- Mandal, S., Mathews, T., Shurin, J. Increasing algal productivity using polycultures Poster presentation. SETAC Orlando November 2016
- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. North Carolina State University August 15, 2016
- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. Oak Ridge. August 16, 2016
- Mathews, T., Mandal, S., Shurin, J. Heterogeneous nutrient sources create niche differentiation for algal polycultures (Algal Biomass Summit, Washington, DC) Invited talk, October 2015
- Mathews T. How can ecology help engineers solve environmental problems? (Invited talk, Tennessee Tech University, Cookeville, TN) October 20, 2015