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DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Microalgae Analysis

March 24, 2015
Algal Feedstocks Review

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Goal: Enable Economically Feasible and Sustainable Algal Biofuels to Achieve Advanced Biofuel Targets

- **Key challenge:** "A national assessment of land requirements for algae cultivation that takes into account climatic conditions; fresh water, inland and coastal saline water, and wastewater resources; sources of CO2; and land prices is needed to inform the potential amount of algal biofuels that could be produced economically in the United States." – **National Research Council 2013.**
- This project is developing and applying DOE's high-resolution spatio-temporal resource assessment modeling capability (Biomass Assessment Tool) to quantify commercial scale algal biofuel production potential and associated demands for water-land-nutrient resources and upstream/downstream infrastructure.
- Project designed and executed to enable BETO MYPP targets:
  - By 2017, model the sustainable supply of 1 million metric ton ash free dry weight (AFDW) cultivated algal biomass.
  - By 2018, demonstrate at non-integrated process development unit-scale algae yield of 2,500 gallons or equivalent of biofuel intermediate per acre per year.
  - By 2022, model the sustainable supply of 20 million metric ton AFDW cultivated algal biomass.

Quad Chart Overview

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Timeline

- Project start date: Nov 2010
- Project end date: Sep 2017
- Percent complete: 65%

Barriers

- AFt-A: Biomass Availability and Cost
- AFt-B: Sustainable Algae Production
- AFt-H: Overall Integration and Scale-up

Budget

	Total Costs FY 10 – FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$609,547	$566,810	$707,392	$1,584,622
Project Cost Share (Comp.)*				

Partners

- ANL, INL, LANL, NREL, ORNL
- RAFT, NAABB, APT3, REAP ABY
- BETO HQ
- University of Arizona, Arizona State University
- Longitude 122 West
- Sapphire Energy, Inc.

1 - Project Overview

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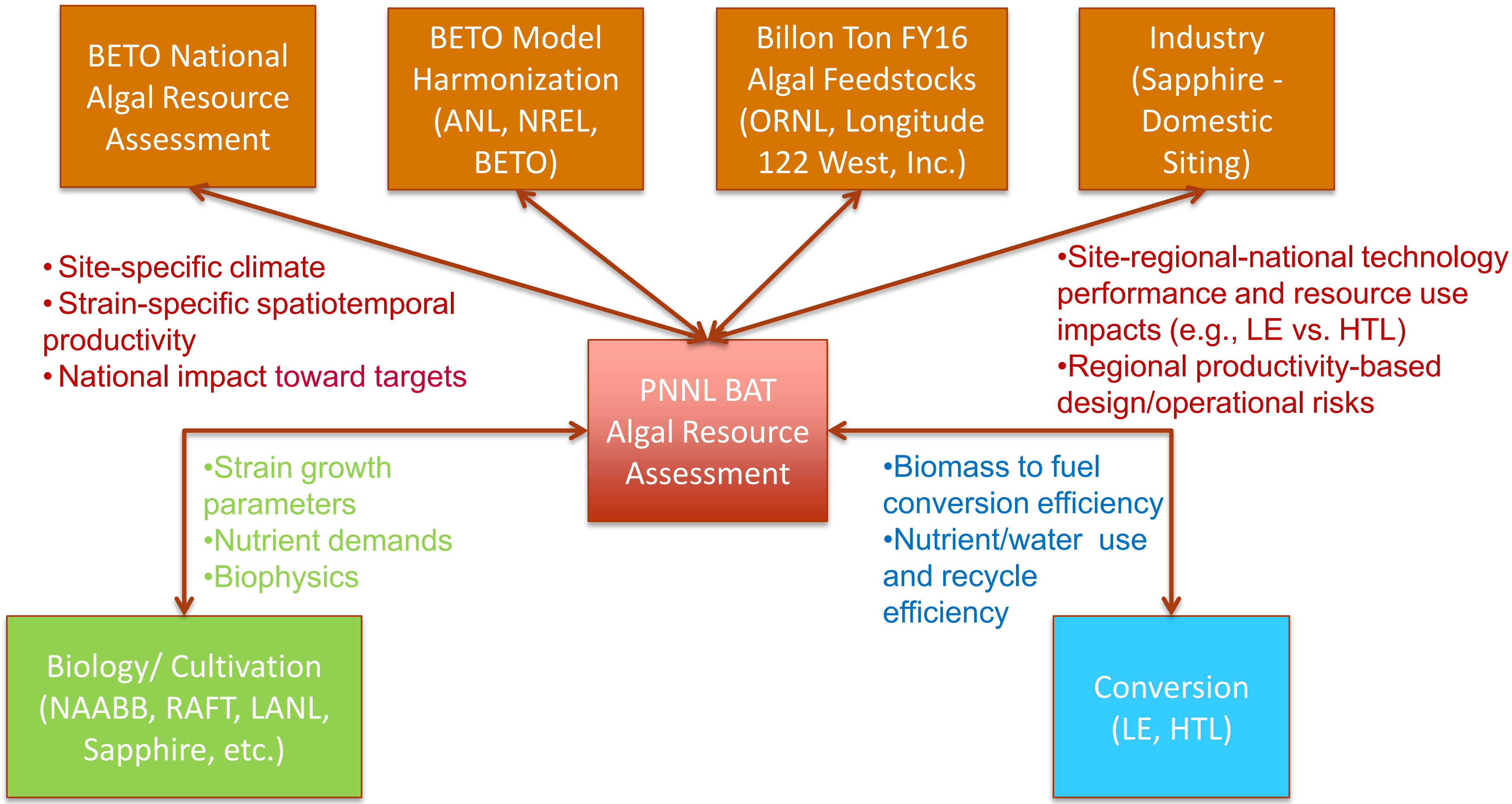
Development and application of the (Biomass Assessment Tool) to quantify commercial scale algal biofuel production potential and associated demands for water-land-nutrient resources and downstream infrastructure has occurred in 3 phases:

- **Phase 1 (FY11-12) :** Core development of the Biomass Assessment Tool (BAT) for high resolution spatiotemporal assessments of algal biofuel production potential; deep dive on "optimum" climate; resource availability and constraints including land availability, alternative water resources, nutrients; and algal strain performance.

- **Phase 2 (FY13-14) :** Evaluate advanced operation strategies to increase overall feedstock production efficiency (strain selection and seasonal rotation, operating depth, alternative fresh and impaired water sources, liner alternatives, nutrient sources, proximity to infrastructure).

- **Phase 3 (FY15-17) : I**dentify feedstock production risks and mitigation strategies to meet BETO targets integrating improved strain rotations, improved water and thermal management, the use of PBR's, and co-location with alternative nutrient resources.

1 – Technical Approach
Biomass Assessment Tool (BAT)



The BAT provides a biophysics based analysis tool for linking key BETO & Industry research activities to achieve high-impact objectives.

BAT Integrates Detailed Spatiotemporal Data with Biophysical and Geospatial Models

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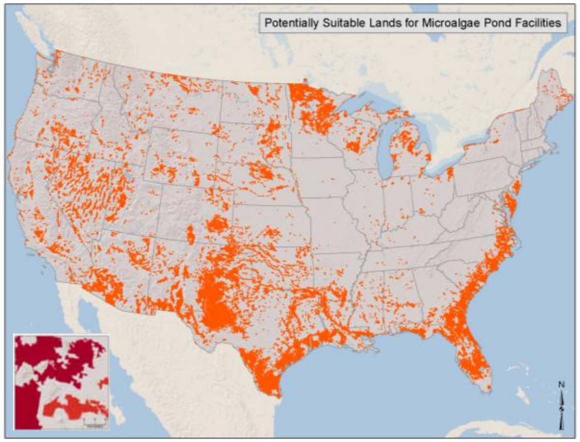
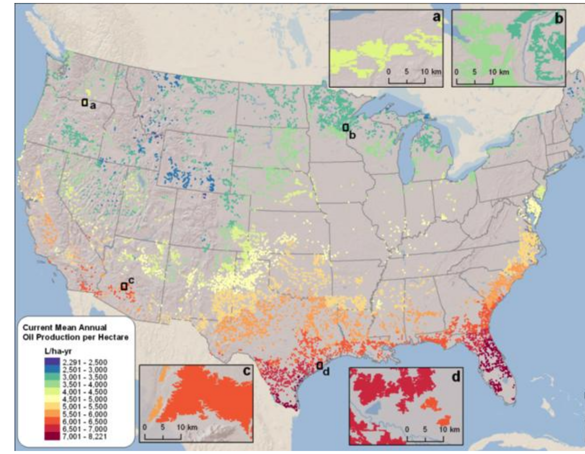
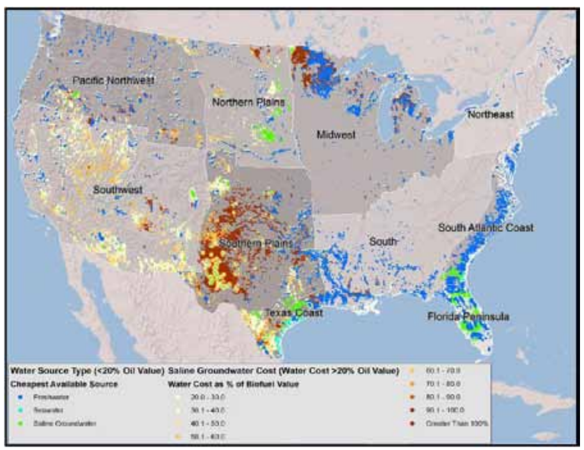


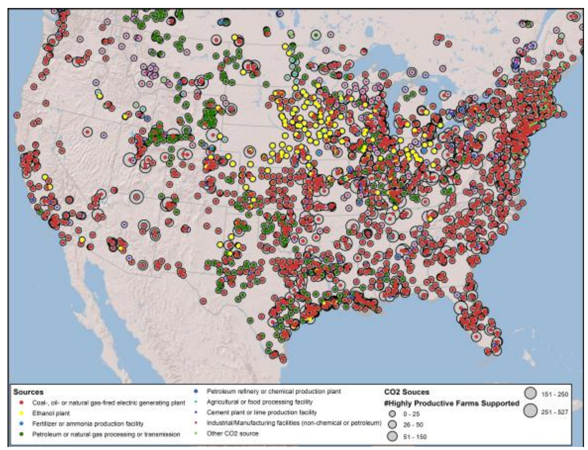
30 Years of Local Hourly Meteorology

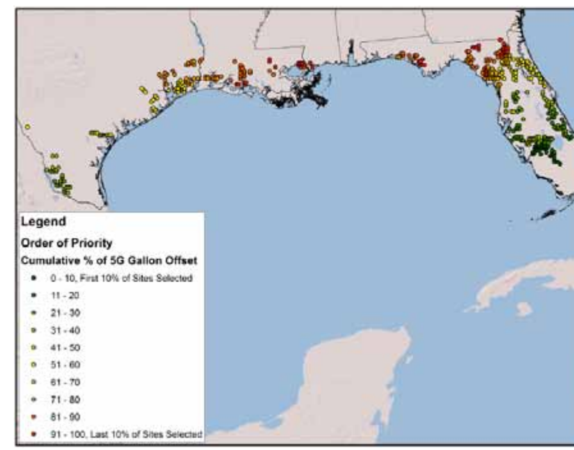
2D Hydrodynamic Model

Biophysical Pond Growth Model









The BAT provides a linked suite of spatiotemporal databases and models that we have used to systematically address key resource sustainability issues identified by the NRC. These results provide the framework to identity opportunities in the algal biofuels supply chain to increase efficiency and sustainability.

BAT's Extensive National Resource Database Enables Multi-Objective Tradeoff Analysis

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e.g., For Each Geo-Referenced Algal Biofuel Site (89,756 total)

- **Land Characteristic (30 m resolution)**
  - Area
  - Topography
  - Land and Site leveling
  - Land Use/Land Cover
- **Climate/Growth Conditions**
  - 30-yrs hourly simulations
  - Biomass/biofuel/energy production
  - 30-yrs of hourly simulated H_2O demand
    - Evaporation
    - Loss through seepage/percolation
    - Makeup to meet salinity target
- **Nutrient Demand**
  - Nitrogen
  - Phosphorus
  - CO_2

Multiple criteria must be considered in site selection

- **National resource availability and supply cost**
  - Freshwater
  - Saline groundwater
  - Seawater
  - Carbon Dioxide
  - Transport of fuel precursors to refinery
  - N and P, fertilizers, alternatives
  - Alternative feedstock materials
    - Municipal solid waste (MSW)
    - Wastewater and derived biosolids
    - CAFO wastes
- **National Infrastructure**
  - Electrical transmission lines
  - Gas pipelines
  - Roads
  - Rail
  - Ports
  - Refineries

2 – Approach (Technical)

- **Technical Approach:** Development and deployment of the BAT to link current research in cultivation and conversion with biophysical process models and spatiotemporal information to quantify the complex interactions between resource availability and costs, biomass production, and biomass to biofuel conversion technology across a range of scales.
- **Technical Success:** The use of BAT results by DOE, the research community, and industry to identify and assess impacts of design and operational constraints and risks for algal biofuel feedstock production
  - Ongoing process incorporating best available process modules (Huesemann Growth model, HTL conversion) and databases (NAABB, RAFT, NLDAS2) into the BAT.
- **Market Success:**
  - Strategic partnerships with industry – Sapphire Energy, Inc.
  - Coordination with NAABB & RAFT
  - Dissemination of study results through peer-reviewed publications, conferences and workshops, and integration with Bioenergy Knowledge Discovery Framework
- **Key challenges:**
  - Limited observational data to support model parameterization and validation
  - Enable integration of research into full TEA and LCA
  - How to integrate algal and terrestrial feedstock production

2 – Approach (Management)

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- Project Management Plans
  - SOW and impact on achieving DOE goals
  - Quarterly milestones
  - Planned spend rate
- Quarterly Progress Reports to BETO
  - Progress against PMP milestones and review of relevance to MYPP goals
  - Actual costs against PMP planned spend rate
  - Impact assessment and mitigation approach for any variances
  - Plans for next quarter
- Project Communications
  - Weekly status and technical discussion with PNNL staff
  - Regular conference calls with non-PNNL partners
  - Quarterly formal reporting to BETO
- Potential Challenges
  - Timely access to experimental results and data
  - Communication and feedback from industry

Key Results from Peer-Reviewed Publications

- Aggressive Technology Transfer
  - 8 peer-reviewed publications since last review
  - American Geophysical Union Editors Choice Award
  - Project results quoted by President in major energy policy speech
- Land Resources
  - Ample suitable land in priority locations
  - Co-location issues
    - Inexpensive, unproductive land often lacks water and infrastructure
    - Climate in SE appears to support higher annual growth rates than SW
      - Potential competition for forest and pasture land
- Water Resources
  - Seawater is attractive from a sustainability standpoint, but production potential is modest (~4 BGY) due to pipeline construction costs.
  - Saline groundwater can support significant production (> 15 BGY), but with increased cost relative to freshwater.
  - Freshwater most cost effective and can support large quantities of biofuel (> 20 BGY), although risks associated with drought and regulatory constraints require further investigation.

Key Results from Peer-Reviewed Publications

- Nutrient Resources
  - CO_2 mainly an infrastructure cost issue
  - Full N, P consumption problematic
  - Recycling of nutrients in residuals is essential
  - With recycling, significant production potential from municipal sewage and animal manure
- Conversion Technology
  - Compared to LE, HTL reduces
    - Land requirements at least 50%, freshwater consumption at least 33%, and saline groundwater by 85%.
    - Without recycling, nitrogen (N) and phosphorous (P) demand is reduced 44%, but remains significant relative to current U.S. agricultural consumption.
  - The most nutrient-efficient pathways compared to LE with full consumption are LE + CHG for N (by 94 %) and HTL + CHG for P (by 81%).

Resource use efficiency is directly linked to conversion technology.

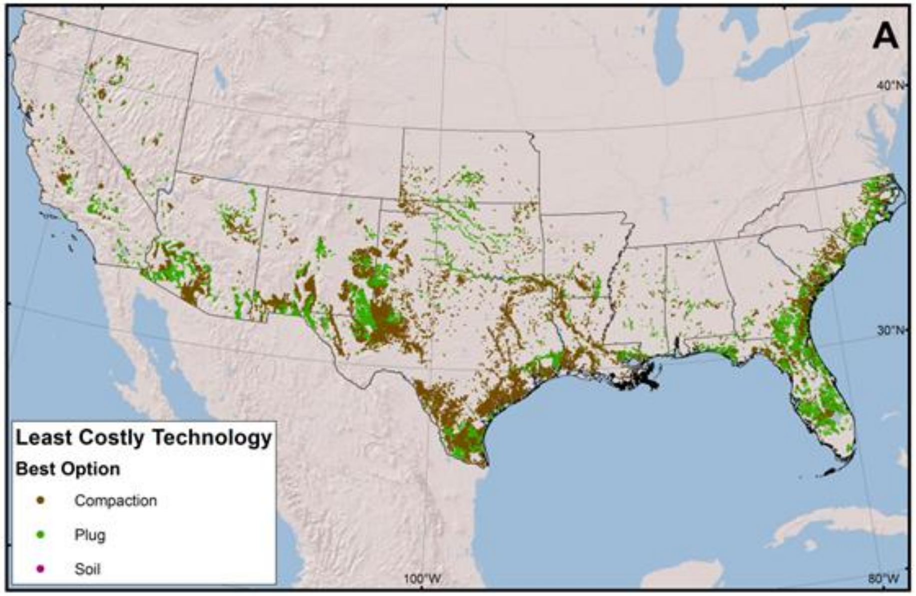
Key Results from Peer-Reviewed Publications

- Siting and Design Capacity to Address Seasonal & Annual Variability
  - Assessment of production, resources, logistics, energetics, cost, and design trade-offs are necessarily site-specific.
  - Seasonal and annual variations in production present significant challenges for TEA and LCA
    - Over- vs. under-sizing downstream processing equipment
  - Using harmonized 5-BGY sites in the southeastern U.S.
    - The ideal design capacity is site specific.
    - High capital costs for lined pond construction drive the need for significant efficiency improvement in each step of the algal biofuel supply chain. The financial risk of overdesigning downstream processing equipment is less than that of putting ponds in standby while waiting for production capacity to become available.

Due to resource and infrastructure constraints, the highest yield sites are not always the best sites for industrial-scale algal feedstock production.

Ongoing: Cost Tradeoffs Between Pond Liners and Non-Liner Alternatives

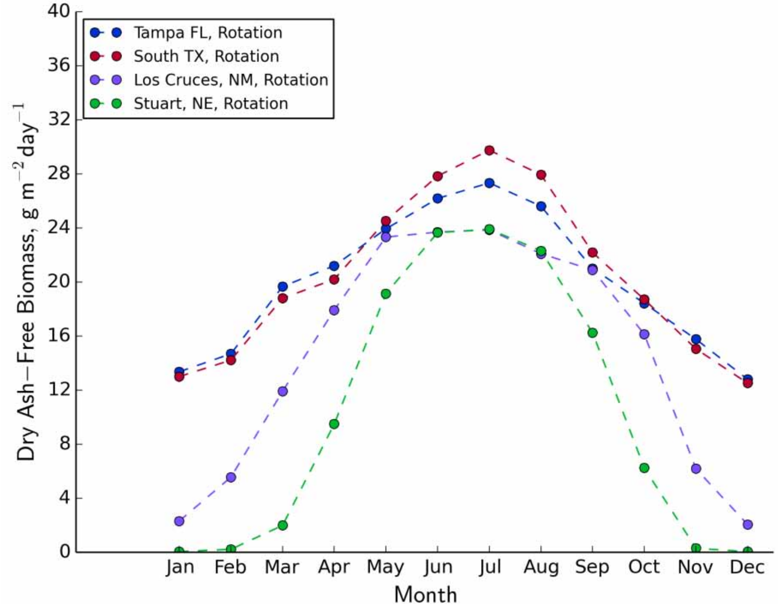
- Pond liners add $0.70 - $1.40 per gallon renewable diesel (annualized cost).
- We evaluated spatially dependent water demand and associated costs for plastic (HDPE) lined ponds, along with three alternatives:
  - unaltered (natural) soil
  - compacted soil
  - soil plugged by natural settling of dead algae
- Water loss through evaporation, leakage through the pond bottom, and blowdown to maintain salinity requirements
- Annualized costs include:
  - construction of necessary wells and pipelines
  - electricity demand to pump makeup water

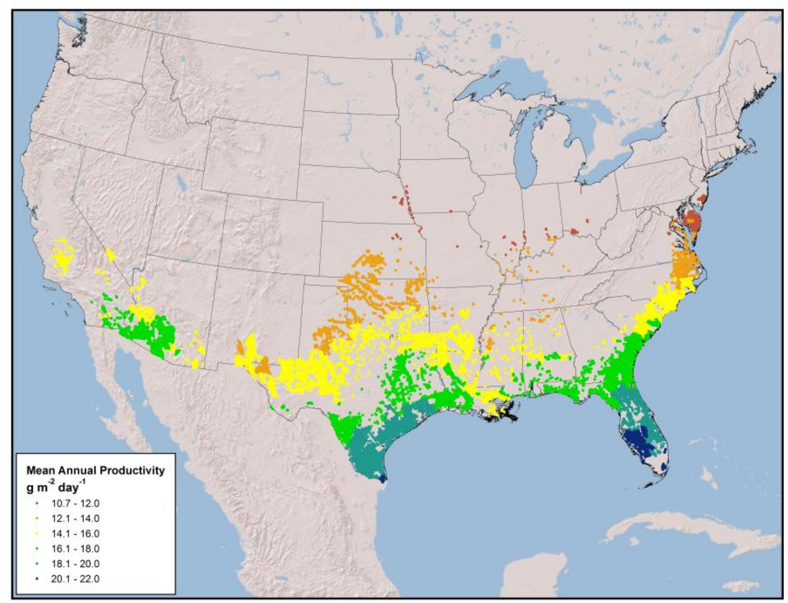


Liner alternatives resulted in an average cost reduction of $0.94 per gallon compared to plastic liners.

Ongoing: Improving Biomass Yield and Reducing Seasonal Variability with Strain Rotation

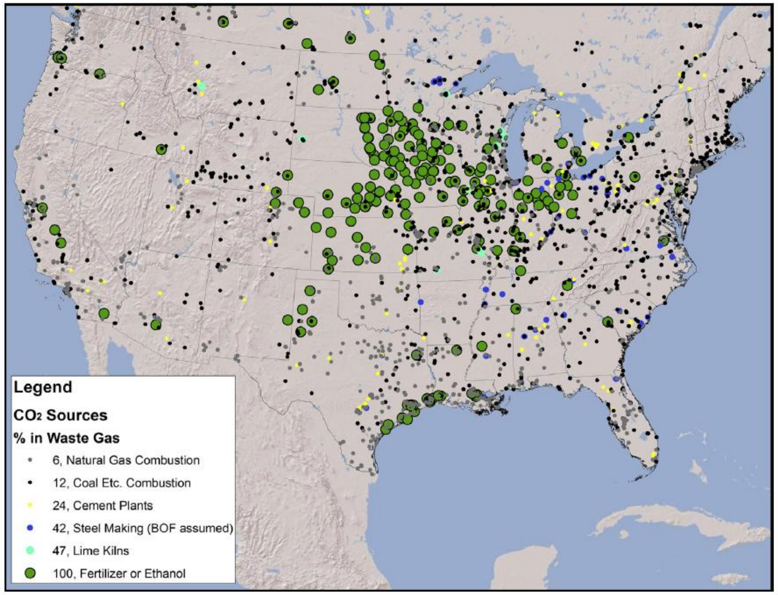
- Challenge: Seasonal variation in biomass productivity present significant challenges to TEA and LCA.
- Solution: Strain rotation
  - *Chlorella sp.* (unimodal with summer peak)
  - *Sphaeropleales* (unimodal in cooler climates; bimodal in warmer climates with peaks in the spring and fall and relatively high winter production)

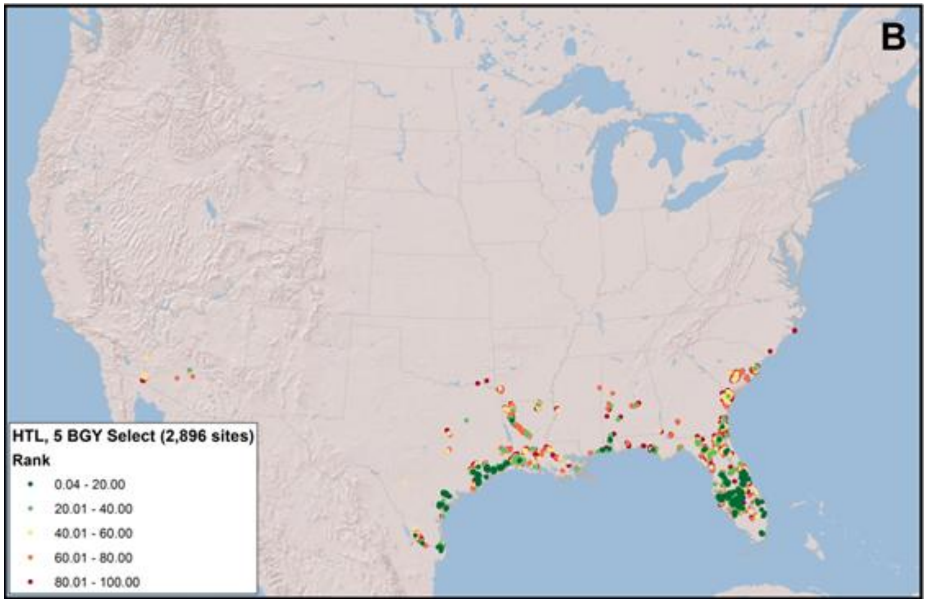


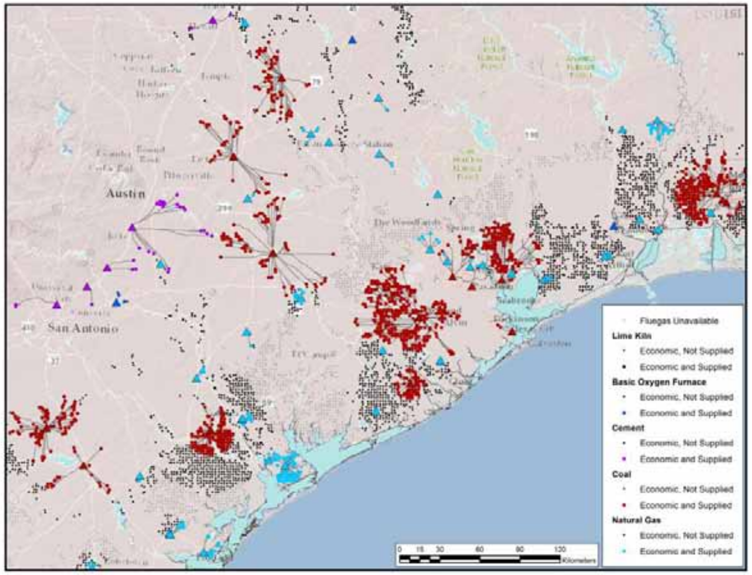


- At least a nominal benefit at ~ 50% of the CONUS sites
- Greatest benefit – Florida Peninsula and Gulf Coast of Texas

Leverage BAT to Examine Nutrient Co-Location Strategies for the Billion Ton 2016 Algae Chapter







Building from Venteris et al. (2014):

- Update CO_2 and nutrient database
- Update engineering cost estimates
- Integrate PBR
- Integrate waste heat
- Generate biophysically-based production estimates and select priority land areas for resource co-location

to ORNL

Ongoing: Climate Simulation Pond Culturing

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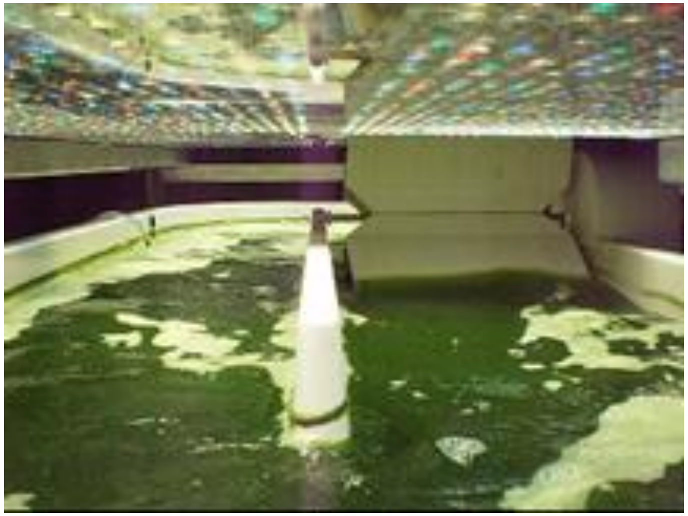
Climate simulation pond culturing system to mimic growth in outdoor ponds subjected to diurnal fluctuations in sunlight and water temperature



- 800 L culture volume (25 cm depth)
- 4500 LEDs simulate sunlight spectrum
- Temperature control (heating/cooling)
- pH control (CO_2)
- Validated to simulate outdoor pond cultures subjected to diurnal sunlight and water temperature fluctuations.

Climate-simulation pond culture studies have been/will be carried out in support of other BETO funded projects:

- Quantified seasonal biomass productivities of *Chlorella* DOE 1412 at optimal Southern Florida location (REAP ABY Project, Pete Lammers, PI)
- Quantified biomass productivity of *Chlorella* UTEX 1228 wild type and LANL's cell-sorted isolate (LANL AOP, Taraka Dale, PI)
- Plan to compare biomass productivities of designer poly-cultures and contributing mono-cultures (INL polyculture hub AOP, Deborah Newby, PI)

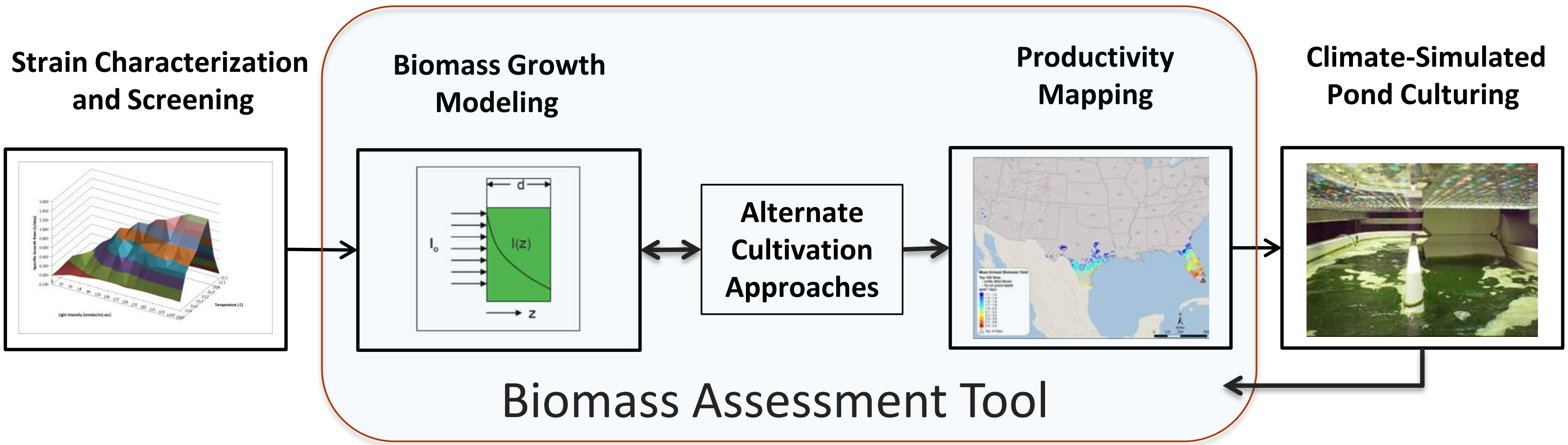
Ongoing: Climate Simulation Pond Culturing

The Challenge

Effective and practical strain screening protocol to down select laboratory strains for outdoor pond cultivation, i.e., exhibit high biomass productivity

The Solution

Integrated approach to predict real-world performance of novel strains



4 – Relevance

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- BAT provides direct benefit to industry (e.g., Sapphire domestic siting analysis)
- Outcomes address priority issues for emerging algal biofuels industry
  - Realistic assessments of spatially specific resource constraints noted by NRC (2013)
  - Key element for DOE's harmonization of RA, LCA and TEA modeling
  - Framework to evaluate impacts of technology advances (e.g., new strains, HTL)
  - Alt. operational strategies (e.g., strain rotation, water / thermal management, etc.)
  - Importance of infrastructure access to enterprise siting
- Contributions to the Algae Chapter of the 2016 Billion Ton Study
- Technology transfer through 10 peer-review publications, workshops and conferences, direct collaboration with industry, and integration with Bioenergy Knowledge Discovery Framework (KDF)
- Analyses are directly focused on BETO MYPP targets:
  - By 2017, model the sustainable supply of 1 million metric ton ash free dry weight (AFDW) cultivated algal biomass
  - By 2018, demonstrate at non-integrated process development unit-scale algae yield of 2,500 gallons or equivalent of biofuel intermediate per acre per year
  - By 2022, model the sustainable supply of 20 million metric ton AFDW cultivated algal biomass

5 – Future Work

- Risk Identification and Mitigation Strategies for Sustainable Feedstock Production
  - Strain rotation and thermal management in open pond and PBR's to reduce seasonal/annual variability and improve yield
  - Conduct quantitative risk assessment of extreme weather impacts on likelihood of achieving MYPP 2017 resource assessment goals
  - Submit publication on benefits of optimal pond selection (e.g., open/PBR) and strain rotation on production potential and resource sustainability
- Billion Ton 2016 - Algae Chapter
  - Spatially explicit, national biomass production estimates for co-location with ethanol and coal-fired power plants along with non-co-located base case
  - Draft of BT16 to BETO, including algae chapter and summary text that integrates algae supply curves with terrestrial supply curves
  - Generate algal supply curves illustrating economic availability of algal feedstocks under nutrient co-location scenarios, including wastewater
- Climate Simulation Pond Culturing
  - Demonstrate increased pond culture lipid productivity of cell-sorted subpopulations relative to *Chlorella sorokiniana* 1230 wild type.
  - Determine growth performance and stability of INL-ORNL designer polyculture.
  - Climate-simulated culturing of ATP3 testbeds

5 – Future Work

- Go/No-Go Decision
  - If the use of strain rotation reduces the risk of missing the MYPP 2017 production target by 20% we will continue to evaluate the viability of this mitigation strategy.
  - Risk will be defined as the probability of missing the 2017 production target in a given year. The risk analysis will be based on 30 year continuous simulations of algal biomass productivity in the Gulf Region. The baseline scenario will be calculated as algal productivity from the most productive single algal species. Risk reduction will be calculated as the increased probability of achieving the target in a given year using strain rotation.

Summary

Through development and application of the BAT, this project

- Addressing many critical questions identified by the National Academy of Sciences 2013 report on sustainable algal biofuels production.
- Contributing to multiple BETO goals including
  - RA, TEA, & LCA Model Harmonization
  - Algae Chapter of the 2016 Billion Ton Study
- Direct benefit to industry as evidenced by the Sapphire Domestic Siting Analysis
- Successful in utilizing the most current BETO and Industry research on biomass cultivation and conversion technology to help address near-term MYPP algal biofuel production targets

Through aggressive technology transfer, this project achieved:

- 10 peer reviewed publications (8 since the last Peer Review)
- An AGU Editors Choice Award
- Impact at the highest levels of government (President's Energy Policy Speech)

Additional Slides

Responses to Previous Reviewers' Comments

- **It is not clear whether availability and distribution of CO2 sources and meteorological data on increasingly frequent extreme weather events (e.g., hurricanes, drought) have been accounted for, and plans to address these potential shortcomings should be considered.**
  - The BAT now includes the latest CO2 databases with source locations by type, percent purity, and volume. We are currently using spatially detailed, hourly meteorological data from the North American Land Data Assimilation System (NLDAS-2). This spatially-correlated data is allowing use to identify risks and mitigation strategies in response climate variability and extreme weather events such as hurricanes and drought.
- **It is not clear from what was presented to what extent the geographic predictions of water resources, land mass, etc., have been verified with actual conditions in any given region, and a series of random checks using obtained data from actual counties should be made to increase confidence in predictions.**
  - To the extent possible, BAT is being validated against observations. Results for NAABB and the current RAFT project are of particular valuable. For example, the pond hydrodynamic and growth model results have been compared to observations, a subset of lands identified as potential locations have been compared against current land use identified from Google Earth and the water-cost models were evaluated against similar construction projects.

Publications, Patents, Presentations, Awards, and Commercialization

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- **Wigmosta MS, AM Coleman, RL Skaggs, MH Huesemann**, and LJ Lane, 2011, National microalgae biofuel production potential and resource demand, *Water Resour. Res.*, 47, W00H04, doi:10.1029/2010WR009966
- **Venteris ER, R Skaggs, AM Coleman, and MS Wigmosta**, 2012, An Assessment of Land Availability and Price in the Coterminous United States for Conversion to Algal Biofuel Production. *Biomass & Bioenergy*, 47:483-497. doi:10.1016/j.biombioe.2012.09.060
- **Venteris ER , RL Skaggs, AM Coleman, and MS Wigmosta**, 2013, A GIS model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States, *Environmental Science & Technology*, 47(9):4840 4849. doi:10.1021/es304135b
- **Venteris ER, R Skaggs, MS Wigmosta, and AM Coleman**, 2014, A National-Scale Comparison of Resource and Nutrient Demands for Algae-Based Biofuel Production by Lipid Extraction and Hydrothermal Liquefaction, *Biomass & Bioenergy* 64:276-290. doi:http://dx.doi.org/10.1016/j.biombioe.2014.02.001
- **Venteris ER, R McBride, AM Coleman, R Skaggs, and MS Wigmosta**, 2014, Siting algae cultivation facilities for biofuel production in the United States: trade-offs between growth rate, site constructability, water availability, and infrastructure, *Environmental Science & Technology,* 48(6):3559-3566. doi:10.1021/es4045488
- **Venteris ER, RL Skaggs, MS Wigmosta, AM Coleman**, 2014, Regional algal biofuel production potential in the coterminous United States as affected by resource availability trade-offs, *Algal Research*, 5:215-225. doi: 10.1016/j.algal.2014.02.002

Publications, Patents, Presentations, Awards, and Commercialization

- Davis RE, DB Fishman, ED Frank, MC Johnson, **SB Jones**, CM Kinchin, **RL Skaggs, ER Venteris, and MS Wigmosta**, 2014, Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale, *Environmental Science & Technology*, available online, http://pubs.acs.org/doi/abs/10.1021/es4055719.
- Abodeely J, **AM Coleman**, DM Stevens, AE Ray, and DT Newby. 2014. Assessment of Algal Farm Designs using a Dynamic Modular Approach. *Algal Research*, 5:264-273 doi: 10.1016/j.algal.2014.03.004
- **Coleman AM**, JM Abodeely, **RL Skaggs**, WA Moeglein, DT Newby, **ER Venteris, MS Wigmosta**, 2014, An integrated assessment of location-dependent scaling for microalgae biofuel production facilities, *Algal Research* 5:79-94. doi: 10.1016/j.algal.2014.05.008
- **Venteris ER, MS Wigmosta, AM Coleman, and R Skaggs**. 2014. Strain selection, biomass to biofuel conversion, and resource colocation have strong impacts on the economic performance of algae cultivation sites. *Frontiers in Energy Research*, August 2014, doi: 10.3389/fenrg.2014.00037

5 – Future Work

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- FY 15 Q3
  - Conduct quantitative risk assessment of extreme weather impacts on likelihood of achieving MYPP 2017 resource assessment goals
  - BT16: Spatially explicit, national biomass production estimates and cost estimates for co-located and base case (non-co-located) cases (open pond and PBR)

- FY15 Q4
  - Submit draft publication on benefits of optimal pond selection (e.g., open/PBR) and strain rotation on production potential and resource sustainability
  - Draft of BT2016 Algal Chapter to BETO, including algae chapter and summary text that integrates algae supply curves with terrestrial supply curves
  - Quantify the biomass productivity of LANL's *Chlorella sorokiniana* 1230 parent and up to two cell-sorted subpopulation strains in PNNL's climate-simulation raceways.
  - Measure the biomass productivity of *Chlorella sorokiniana* DOE 1412 exposed to different short-term light-dark cycles and incorporate the resulting biomass loss rates into the biomass growth model and the BAT
  - LANL-PNNL Milestone: Demonstrate increased pond culture lipid productivity of cell-sorted subpopulations relative to *Chlorella sorokiniana* 1230 wild type.
  - INL-ORNL-PNNL Milestone: Determine growth performance and stability of INL-ORNL designer polyculture.

5 – Future Work

- FY 16 Q1
  - Submit draft publication on benefits of water and thermal management on biomass yield
  - Climate-simulated culturing of strains from LANL pipeline
- FY16 Q2
  - Climate-simulated culturing of polycultures
- FY16 Q3
  - BT16: Generate algal supply curves illustrating economic availability of algal feedstocks under nutrient co-location scenarios, including wastewater
  - Climate-simulated culturing of ATP3 testbeds FY16 Q4
- FY16 Q4
  - BT2016 Algal Chapter to BETO, including algal supply curves illustrating economic availability of algal feedstocks under nutrient co-location scenarios, including wastewater
  - Model validation for additional strains and culturing conditions

Ongoing: Nutrient Co-Location Strategies for the Billion Ton 2016: Algae Chapter

- Site prioritization based on multiple criteria contributing to least cost:
  - Capital costs (i.e., pipe length/size; trenching/veg clearing; capture & transport)
  - Operating costs (i.e., transport energy costs)
  - Facility size; biomass production / CO_2 demand