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DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Microalgae Analysis

March 6, 2017
Algal Feedstocks Review

Mark Wigmosta
Pacific Northwest National Laboratory

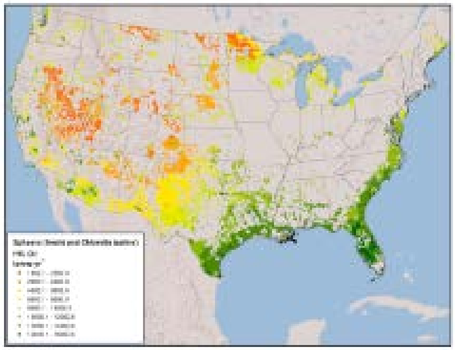
Microalgae Resource Assessment Goal

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 2012

Goal: Provide BETO and Industry a **Resource Assessment** capability focused on fundamental questions of where production can occur, how much nutrient, land and water resource is required, how much energy is produced

Technical Objectives: Enhancement and application of the PNNL Biomass Assessment Tool (BAT) to evaluate alternative algal feedstock production strategies that will yield the highest sustainable fuel production potential as a function of unit cost and resource use efficiency.

- Multi-scale: site → national
- Site specific climate, resource supply/demand
- Appropriate algal strains
- Best growth media/operations
- Conversion technology and up & downstream logistics



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

Quad Chart Overview

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Timeline

- Project start date: Oct 2016
- Project end date: Sep 2019
- Percent complete: 10%

Budget

	Total Costs FY 12 – FY 14	FY 14 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date
DOE Funded				$1,800K
Project Cost Share (Comp.)*				

*If there are multiple cost-share partners, separate rows should be used.

Barriers

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

To address these barriers this project will evaluate alternative algal feedstock production strategies to yield the highest sustainable fuel production as a function of unit cost and resource use efficiency

Partners

- ANL, NREL, ORNL
- RAFT, ATP3
- BETO HQ
- U. Arizona, Arizona State University
- Longitude 122 West

1 - Project Overview: Role of PNNL Resource Assessment to Define Sustainable Algal Feedstock Production

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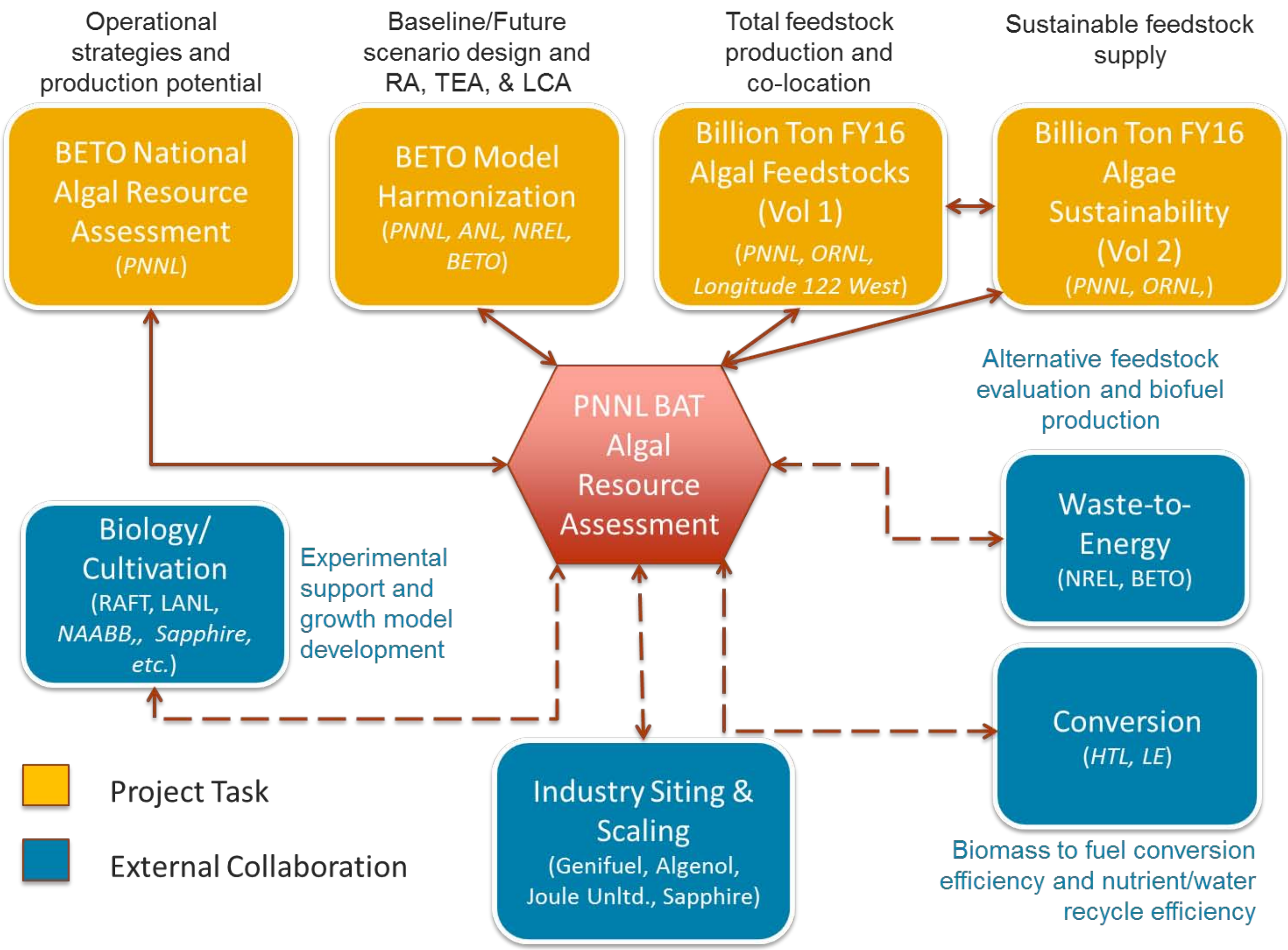

The BAT provides a biophysics based analysis framework and tool set for linking key BETO & Industry research activities to achieve high-impact objectives for multiple feedstocks

Technical Approach: BAT Integrates Detailed Spatiotemporal Data with Biophysical & Geospatial Models for Multi-Scale Analysis

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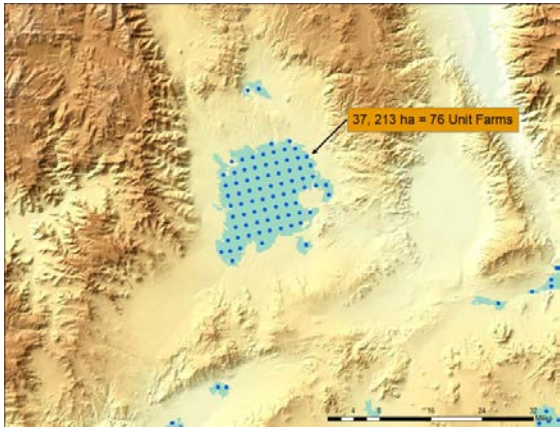
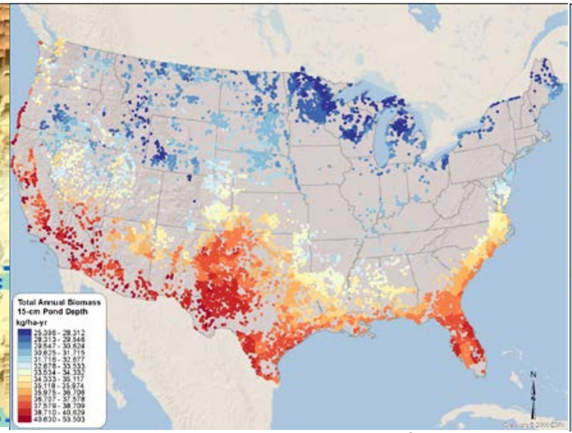
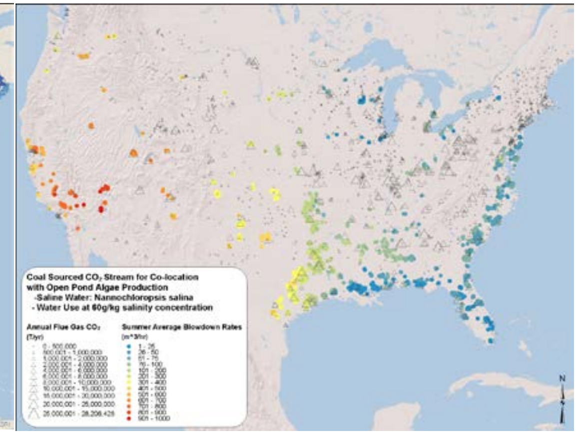


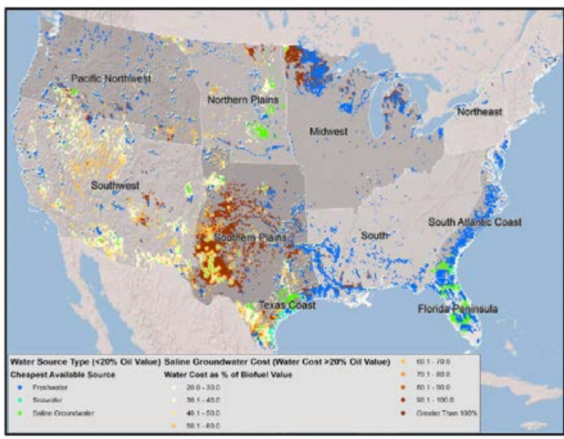
Site Selection



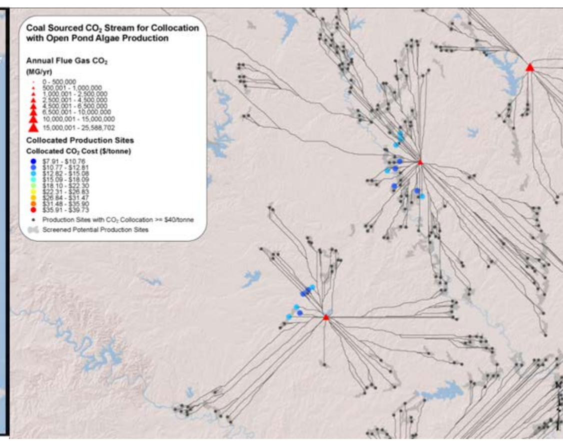
Biomass Growth



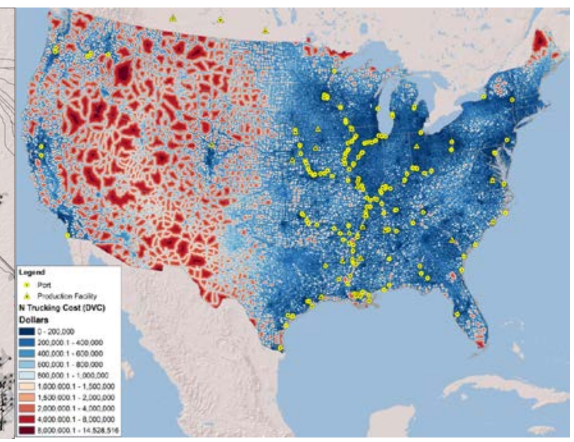
Water Demand



Water Supply



CO_2 Co-Location



Transport Costs

Multiple criteria must be considered and the highest biomass production site might not be the "best" site due to infrastructure or resource constraints

BAT

- Meteorology
- Site Selection
- Open Pond Temp. Model
- Closed Pond Model
- PBR Model
- Growth Model
- Nutrient Demands
- Water Supply/Use
- Least-Cost Route Models
- Co-Location Model
- Alt. Nutrient Resources
- Risk Assessment
- Land Value
- Tradeoff Models
- Conversion Pathways
- Infiltration Model
- Land Leveling Model

BAT's Dynamic National Resource Database Allows Multi-Objective Tradeoff Analysis

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For Each Screened & Geo-Referenced Algal Biofuel Site (89,756 total)

- **Land Characteristics (30 m resolution)**
  - Minimum Area
  - Topography
  - Land and Site leveling
  - Land Use/Land Cover
  - Soils
  - Land Price
- **Climate/Growth Conditions**
  - Strain parameterization
  - Temperature, solar, humidity, precipitation
  - 30-yrs hourly simulations
    - Biomass/biofuel 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
- **National resource availability and supply cost**
  - Freshwater
  - Saline groundwater
  - Seawater
  - Waste CO_2
  - Resource transport distance/energy/cost
  - N and P fertilizers & alternative nutrients
  - Alternative feedstock materials
    - Municipal solid waste (MSW)
    - Wastewater sludge
    - Manure
- **National Infrastructure**
  - Electrical transmission lines
  - Gas pipelines / terminals
  - Roads
  - Rail & Barge
  - Rail & Shipping Ports
  - Refineries

2 – Approach (Management)

- Annual Operating Plan (AOP)
  - Detailed Statement of Work
  - Quarterly milestones
  - Planned spend rate
  - Updated annually
- Quarterly Progress Reports to BETO
  - Progress against milestone PMP milestones
  - Actual costs against PMP planned spend rate
  - Discussion on any variances and plans for next quarter
- Project Communications
  - Weekly planning with PNNL staff
  - Regular conference calls with external partners
  - Outreach: publications, press releases, and other related projects
- Potential Challenges
  - Timely access to experimental results and data
  - Communication and feedback from industry

PI/PM Wigmosta

Task	Lead
BAT Enhancement	Wigmosta
Sustainability Metrics	Coleman
Model Harmonization	Wigmosta
Tradeoff analysis among alternative pathways to meet the 2017 MYPP Target	Coleman

2 – Approach (Technical)

BAT links the latest research in cultivation and conversion with biophysical process models and spatiotemporal information to quantify interactions between resource availability and costs, biomass production, and biomass to biofuel conversion technology across a range of scales.

- **Technical Success**: 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, ATP3) into the BAT
- **Market Success**:
  - Coordination with RAFT and ATP3
  - Dissemination of study results through peer-reviewed publications, conferences and workshops, and integration with Bioenergy KDF
  - Strategic partnerships with industry including the Technical Assistance Program
- **Key challenges**:
  - Limited, but increasing, observational data to support model parameterization and validation
  - Seasonality in biomass production
  - Sustainability: economic and resource
  - Integration in bioenergy feedstock mix (e.g., Billion Ton)

Key Results from 15 Journal Publications

- Abundant low slope, low to non productive land
  - 90,000 (1,200 acre) unit farm locations potentially suitable for open pond algal feedstock production
  - ~Inexpensive, unproductive land often lacks water and infrastructure
    - Potential competition for forest and pasture land
    - Climate in SE appears to support higher annual growth rates than SW
- Sustainable water resources are a key constraint
  - 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; further research needed on salt disposal/management.
  - Freshwater most cost effective and can support large quantities of biofuel (> 20 BGY), although risks associated with drought and regulatory constraints require further investigation.
- Nutrient resources must consider recycle and infrastructure costs
  - CO_2 co-location
  - Full N, P consumption (co-products, sequestration) problematic
  - Recycling of nutrients in byproducts is essential
  - With recycling, significant production potential from municipal sewage and animal manure

Key Results from 15 Journal Publications

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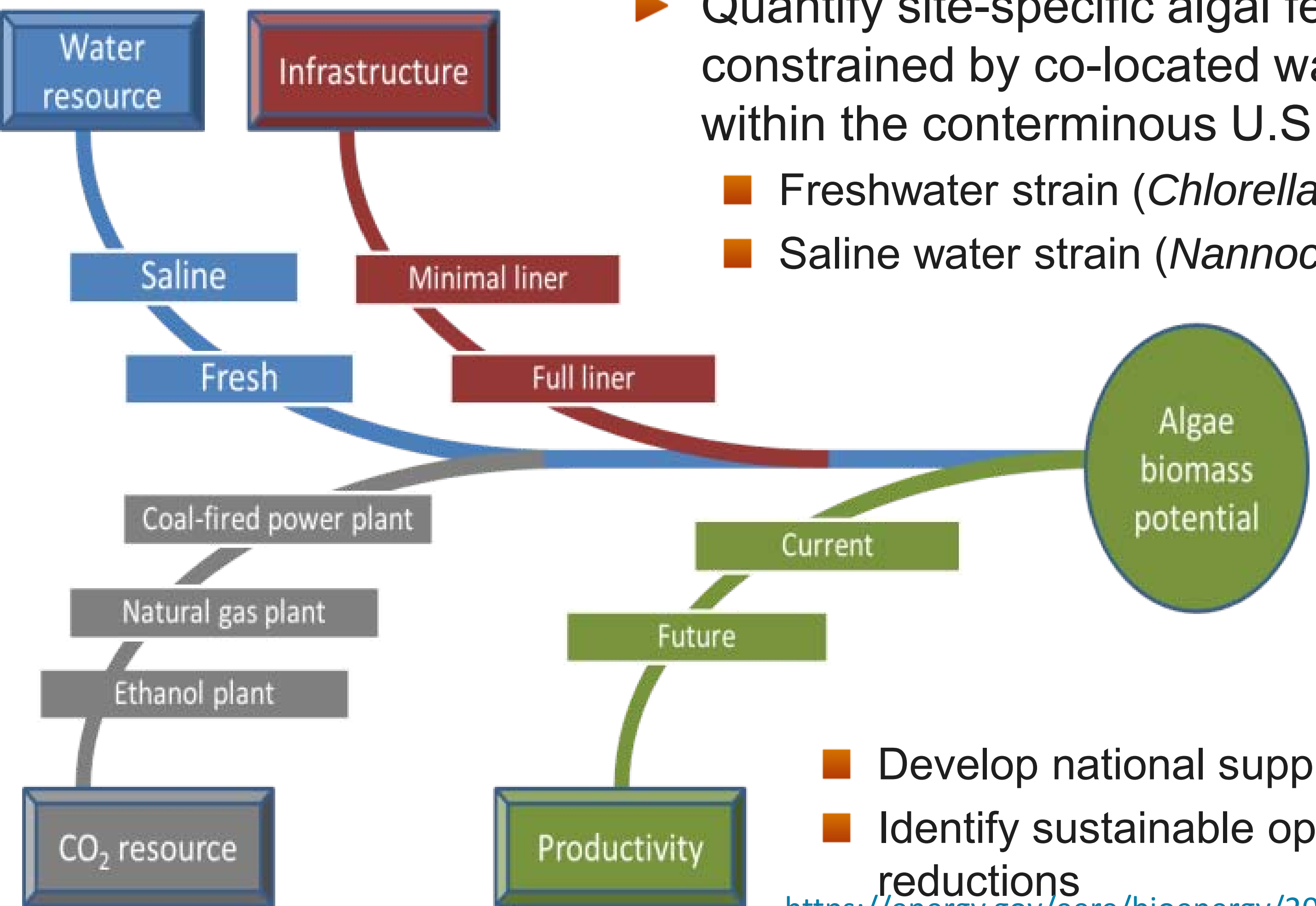
- Integrated approach to predict real-world performance of algal strains
  - Climate simulation pond culturing system to mimic growth in outdoor ponds subjected to diurnal fluctuations in sunlight and water temperature
  - Biomass growth modeling and productivity mapping via BAT
- Seasonal & Annual Variability Drive Siting and Design Capacity
  - Assessment of production, resources, logistics, energetics, cost, and design trade-offs are site-specific
  - Seasonal and annual variations in production present significant challenges for TEA and LCA
    - Over- vs. under-sizing downstream processing equipment
    - Improved pond operations (i.e., strain rotation) can be used to dampen seasonal variability and increases annual biomass production
- Downstream processing technologies directly impact resource demand
  - HTL improves resource use efficiency compared to LE by reducing
    - 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.

Key Results: Billion Ton 2016 Vol. 1 Contribution of Algae to the Nation's Bioenergy Supply

In collaboration with ORNL and Longitude 122 West

- Quantify site-specific algal feedstock production constrained by co-located waste CO_2 resources within the conterminous U.S.
  - Freshwater strain (*Chlorella sorokiniana*)
  - Saline water strain (*Nannochloropsis salina*)



- Current & future productivities
- Dominant <u>waste</u> CO_2 sources
- Fresh and saline water source and resource availability

- Develop national supply curves
- Identify sustainable opportunities for cost-reductions

https://energy.gov/eere/bioenergy/2016-billion-ton-report

Key Results: Billion Ton 2016 Vol. 1 Waste CO_2 Supply and Transport

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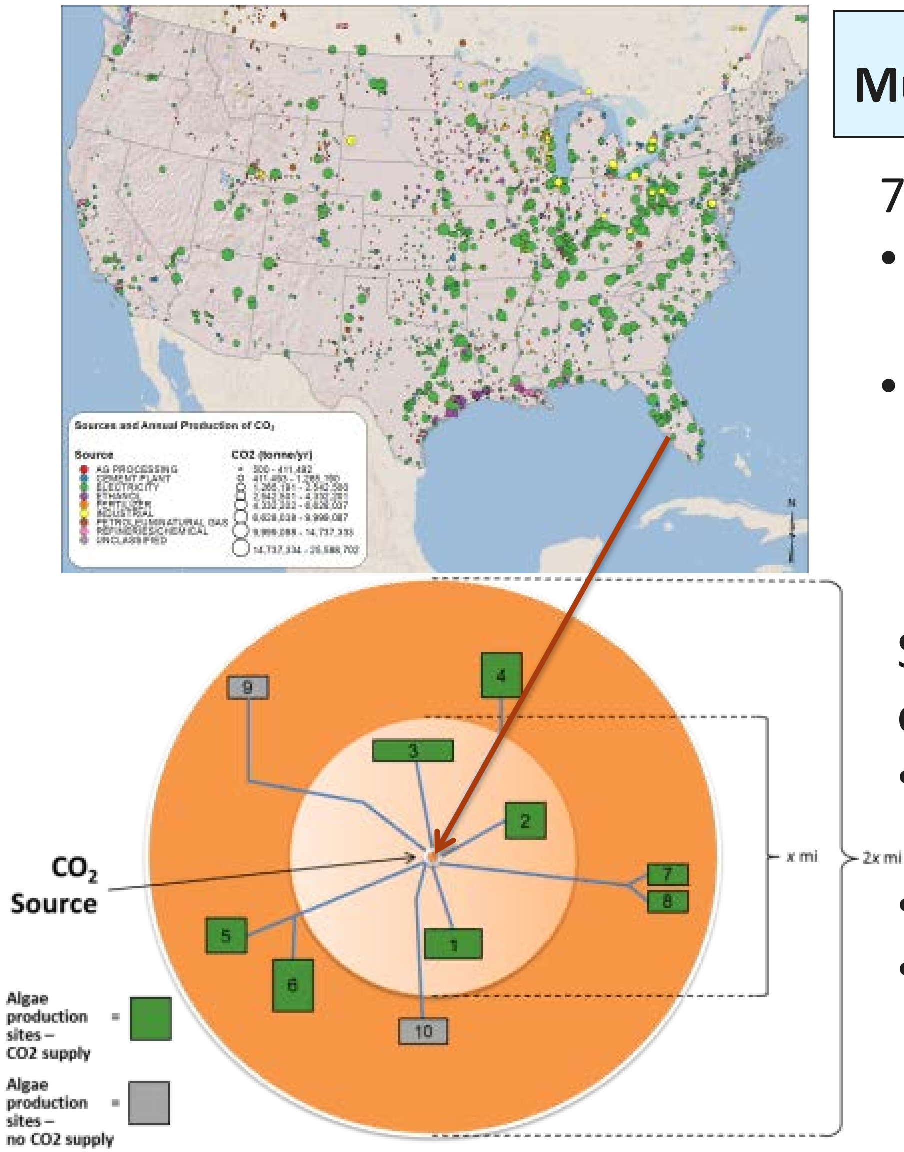

Multi-Scale Analysis: Site to National (CONUS)

7,096 CO_2 point sources reported in the U.S.

- Total potential to produce 720 million tons algae biomass; <u>unconstrained</u>
- Coal Thermal Electric, natural gas Thermal Electric, and ethanol production represent 86.6% of point-source CO2 emissions

Site prioritization based on multiple criteria contributing to least cost:

- Annualized CapEx (i.e., pipe length, material, sizing, compressor, blowers)
- Annual OpEx (i.e., transport energy costs)
- Restrict to sites where CO_2 transport costs < $40/t

Key Results: Billion Ton 2016 Vol. 1 Significant Biomass Potential through CO_2 Co-Location

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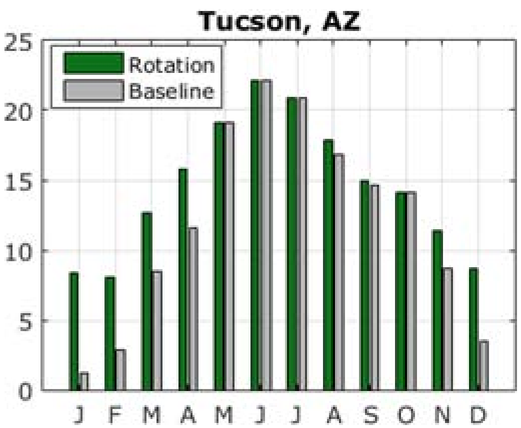
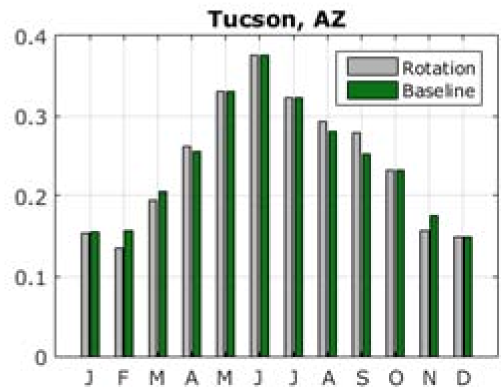
- The lowest-cost biomass potential is from Thermal Electric co-location scenarios rather than the ethanol plant scenarios, despite the higher costs of moving low-purity CO_2.
  - The gains in productivity for warmer locations outweigh the CO_2 cost savings differential from higher-purity CO_2 ethanol plants
- Combined fresh and saline water [constrained]
  - 45 - 85 million tons of AFDW biomass
  - 1.7 – 19.3 % of total CONUS CO_2
  - \$10.67 – \$34.43 per ton CO_2
- Identifying strategies to achieve of DOE targets of sustainable supply
  - 1 million metric tonnes (1.1 million tons) of AFDW algal biomass by 2017
  - 20 million metric tonnes (22 million tons) of AFDW algal biomass by 2022

Key Results: Site operations to increase biomass production, reduce seasonality, and increase resource use efficiency

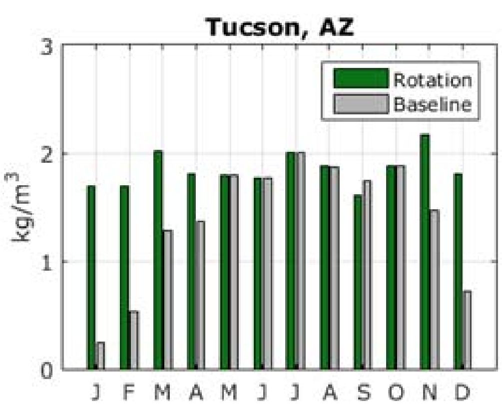
- Baseline: single strain, pond depth, and harvest volume to produce best results
- Rotation: alternating algae strain (warm/cool), variable pond depth, and harvest volume (with 85% water recycle)



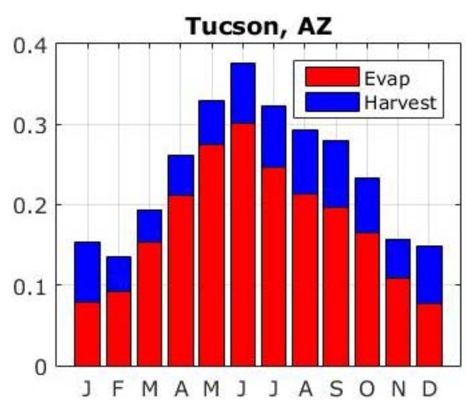
Biomass (g/m^2/day)



Water Use (m^3/m^3)



Biomass per Unit Water

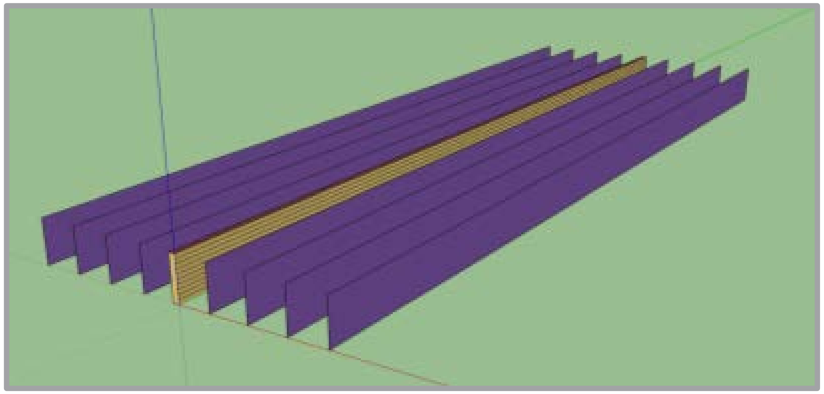


Water Use (m^3/m^3)

- Improved Operations
  - Increase biomass yield (21%)
  - Similar total water use to baseline
  - Increase biomass per unit water used (32%)
- Open pond evaporation dominates consumptive water use

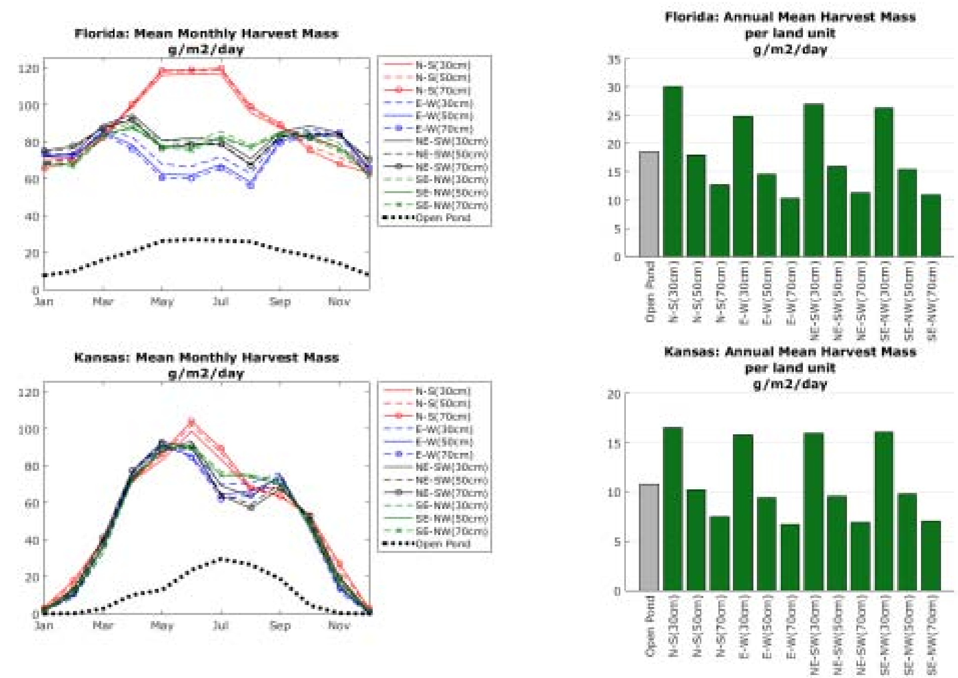
Builds from Venteris ER, MS Wigmosta, AM Coleman, and R Skaggs. 2014. Strain selection, biomass to biofuel conversion, and resource colocation have strong impacts on the economic performance of algae cultivation sites. Frontiers in Energy Research, August 2014, doi: 10.3389/fenrg.2014.00037

Key Results: Use of PBRs to Promote Growth in Northern Latitudes and Increase Production at all Sites



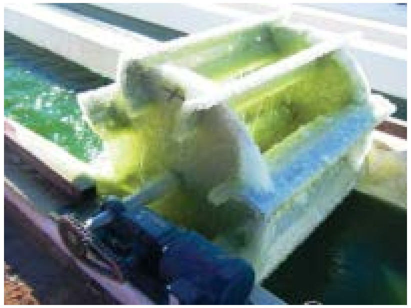
- Preliminary results show significant improvement over open pond in g/m^2 per top surface area
- Panel spacing and orientation can be very important
- Production per land surface area is highly depended on panel spacing

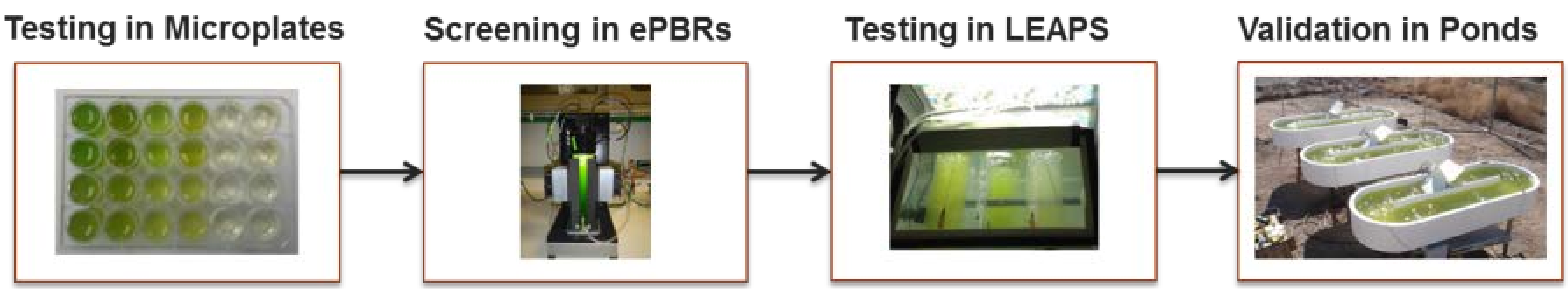
- Flat Panel
  - User defined panel dimensions, spacing, and orientation
  - Full energy-balance accounting for interaction with adjacent panels
  - Complete two-way coupling with Huesemann growth model
  - Allows use of waste heat via co-location or cooling



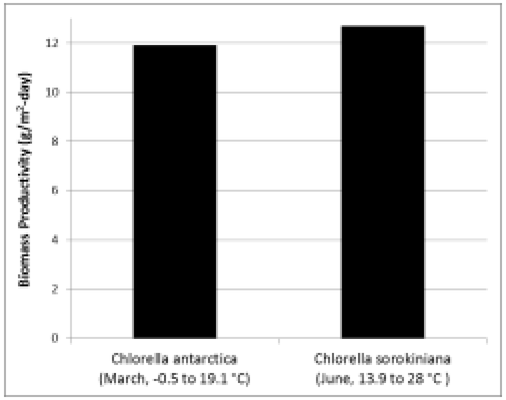
Key Results: Improved Cold Season Productivities to Reduce Seasonality and

- Cold weather can reduce productivity in outdoor algae cultures by over 80% (Sheehan *et al.* 1998)
  - Not just northern locations, even Earthrise (in southern California) has to shutdown facilities in winter due to poor winter growth





- Using a tiered screening approach, *Chlorella antarctica* was identified and validated as a high productivity cold season strain for outdoor cultivation.
- The cold-season outdoor pond biomass productivity of *Chlorella antarctica* was almost 12 g/m^2-day, very similar to the summer season productivity of *Chlorella sorokiniana* at the same Arizona location.



Sheehan, J., Dunahay, T., Benemann, J. & Roessler, P. *A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae*. (1998)

4 – Relevance

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Use the BAT to evaluate alternative algal feedstock site locations, algal strains, growth media, operations, and process technology that will yield the highest sustainable fuel production potential per unit cost and resource use efficiency

- Outcomes address priority issues for emerging algal biofuels industry
  - Realistic assessments of spatially specific resource constraints noted by NRC (2012)
  - Provide basis for DOE's harmonization of RA, LCA and TEA modeling
  - Framework for evaluating impacts of technology advances (e.g., new strains, HTL)
  - Operational strategies (e.g., PBRs, strain rotation, water/thermal management, etc.)
  - Importance of infrastructure access to siting (e.g., roads, rail, electrical grid)
- Contributions to Algae Chapter of the 2016 Billion Ton Study (Vol 1 and Vol 2)
- Technology transfer through 15 peer-review publications, numerous workshops and conferences, expansion into emerging BETO RA activities, direct collaboration with industry, Technical Assistance Program (TAP), 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 tonne 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

5 – Future Work

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- Provide an improved estimate of sustainable algal biomass productivity for **harmonized integrated assessment** (w/ ANL, NREL, ORNL)
  - Key focus to evaluate future potential for algal biofuels on a national scale, given constraints imposed by TEA, LCA, resource availability
  - Consider CO_2 sourcing, saline vs fresh water, requirement for liners, max farm size
- Complete improved metrics for sustainable algal feedstock production to reduce impact to water and land resources (w/ ORNL)
- Achieve an improved understanding of tradeoffs associated with alternative pathways (including PBRs) to achieve
  - MYPP 2017 target to “model the sustainable supply of 1 million metric tonnes (AFDW) cultivated algal biomass”
  - MYPP 2018 target to “demonstrate at non-integrated process development unit-scale algae yield of 2,500 gallons or equivalent of biofuel intermediate per acre per year”
- Quantify feedstock production potential associated with alternative sources of nutrients
  - Geo-locate wastewater treatment facilities and other alternative nutrient sources (e.g., CAFOs)
  - Complete an alternative nutrient source and demand model for target processing technologies accounting for technology pathway-specific recycle potential
  - CONUS-wide tradeoff analysis

Summary

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Through development and application of the BAT, this project

- Addresses critical questions identified by the National Academy of Sciences 2012 report on sustainable algal biofuels production
- Contributing to multiple BETO goals including
  - RA, TEA, & LCA Model Harmonization
  - Algae Chapters of the 2016 Billion Ton Study Volumes 1 and 2
- Direct benefit to industry as evidenced by the Sapphire Domestic Siting Analysis
- Through a high degree of collaboration, we successfully utilize the most current BETO and Industry research on biomass cultivation and conversion technology to help address near-tem MYPP algal biofuel production targets

Through aggressive technology transfer, this project achieved:

- 15 peer reviewed publications (5 since the last Peer Review)
- An American Geophysical Union Editors Choice Award
- Technology transfer through the Technical Assistance Program (TAP)
- Impact at the highest levels of government (President's Energy Policy Speech)

Additional Slides

Responses to Previous Reviewers' Comments

- We agree with the reviewer comment recommending the use of data generated by other BETO projects, particularly those being used as benchmarks across BETO's portfolio. We have made a concerted effort to utilize the latest algal strain growth parameters, nutrient demand/recycle data, physical pond data/observations, and biophysical process representation from individual projects (e.g., LANL, UA, ASU), BETO initiatives (e.g., RAFT, NAABB, APT3, REAP, ABY), and industry (Sapphire).
- As noted in the reviewer comments, the BAT provides a method to "truth-test the biologists' best case scenarios." We have also integrated representation of the latest conversion technologies, including ALU (NREL) and HTL (PNNL). Participation in the DOE Harmonization effort has provided significant benefit to this project and BETO. We feel that this effort must be continued in the future.
- We agree with reviewer comments that co-location with brackish aquifers appears viable and that continued assessments of extreme weather impacts on potential site location as well as a comparison of sites co-located with emissions sources versus the base case will be very informative. The use of saline water and CO_2 co-location was described in this presentation as part of our contribution to Chapter 7 of the 2016 Billion Ton Report. We are also currently using spatially detailed, hourly meteorological data from the North American Land Data Assimilation System (NLDAS-2). This spatially-correlated data is allowing us to identify risks and mitigation strategies in response climate variability and extreme weather events such as hurricanes and drought.

Publications, Patents, Presentations, Awards, and Commercialization

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- **Moore, BC, AM Coleman, MS Wigmosta, RL Skaggs, and ER Venteris**, 2015, A High Spatiotemporal Assessment of Consumptive Water Use and Water Scarcity in the Conterminous United States. Water Resource Management. DOI 10.1007/s11269-015-1112
- Langholtz M, **AM Coleman**, LM Eaton, **MS Wigmosta**, CM Hellwinckel, and CC Brandt. 2016. Potential Land Competition Between Open-Pond Microalgae Production and Terrestrial Dedicated Feedstock Supply Systems in the U.S. Renewable Energy, 93:201-214. doi:10.1016/j.renene.2016.02.052.

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