Pacific Northwest
NATIONAL LABORATORY

Microalgae Analysis (WBS 1.3.5.203)

April 4, 2023

Technology Area Session

Principal Investigators

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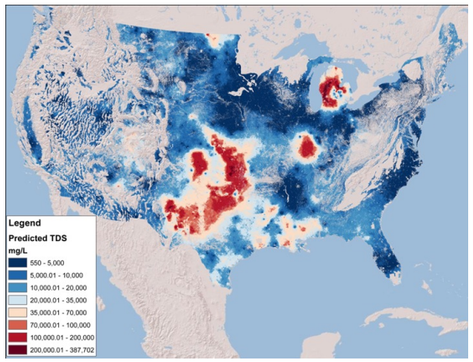
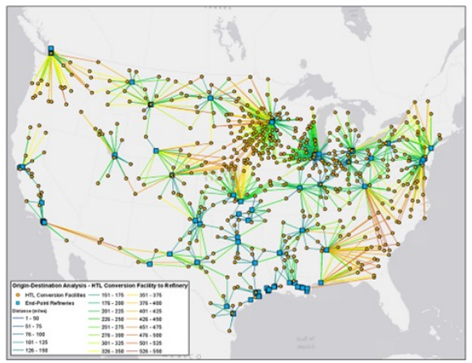
Earth Systems Predictability and Resiliency Group

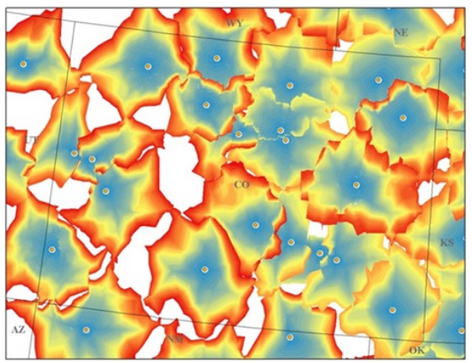
Project Overview

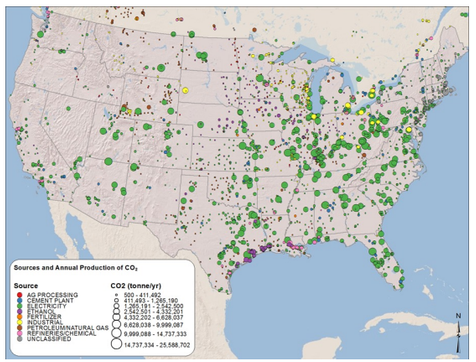
Background: The development, enhancement, and application of the Biomass Assessment Tool (BAT) provides a spatiotemporal, biophysics-based analysis framework for linking key BETO & industry research activities and goals to understand opportunities, trade-offs, and realize pathways for achieving high-impact objectives. The first version of the BAT was developed in 2010 and has continued to evolve based on community needs.

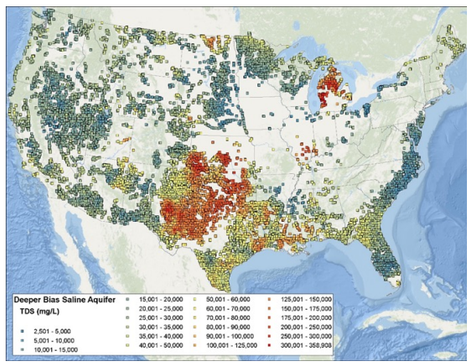
Overall Goal: Provide BETO and industry a national assessment capability focused on fundamental questions of where feedstock production can occur, how much nutrient, land and water resource is required, what co-location opportunities exist, which cultivation strategies and algal strains provide the best productivity, how much biomass & energy is produced, and what interactions/trade-offs exist between technology pathways.











1 – Approach (Overview)

The BAT links the latest research in cultivation and conversion with biophysical process models and multi-scale spatiotemporal analysis to quantify resource requirements, sustainable resource availability, beneficial use of waste resources, biomass production potential, cultivation strategies, energetics and costs, conversion pathways.

Key challenges

- Limited experimental/observational data to support model parameterization and validation
- Linking research and model findings with industry
- Qualitative formulations of economic and environmental sustainability

Technical Success

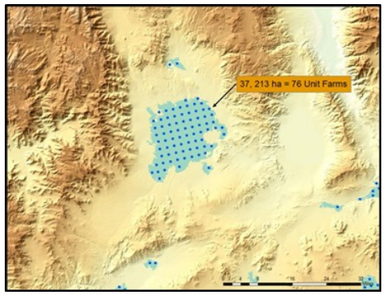
- Continued BAT linkages with other non-PNNL models
- Incorporation of macroalgae site screening, growth productivity, and TEA models
- Coordination with DISCOVR, BETO State of Technology, ORNL BillionTon Next, ANL/NREL/PNNL Multi-Lab Model Harmonization, BETO Waste-to-Energy, ARPA-E MARINER
- Assess impacts of design and operational constraints and risks for algal biofuel feedstock production
- Maturity and demonstrated production improvements of microalgae forecasting system
- Dissemination of study results through peer-reviewed publications, project reports and white papers, conferences/workshops, university and other national lab collaborations
- 31 peer-reviewed publications

1 – Approach

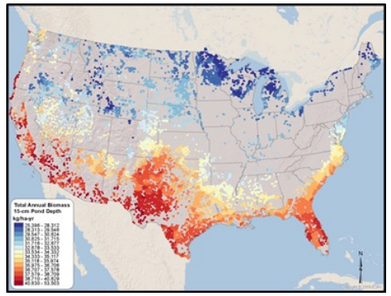
Resource Assessment | Waste-to-Energy Co-Location | Operations and Forecasting | Biology & Cultivation | Conversion | Industry Siting & Scaling

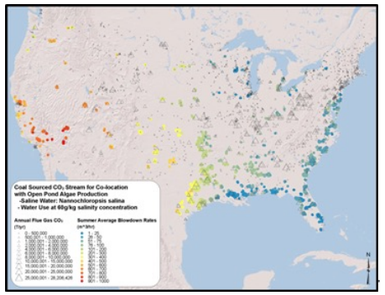
PNNL Biomass Assessment Tool (BAT)

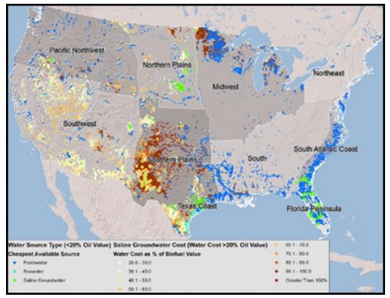
Time-Series Meteorology	Closed Pond Temp. Model	Nutrient Demand	Saline Water Character-ization	CO_2 Co-Location & Transport	Waste Heat Co-Location	HTL Conversion	State-of-Technology Support	Multi-Modal Transport
Site Selection	PBR Model & Site Configuration	Freshwater Supply & Demand	Min. Water Stress Siting	Nutrient Co-Location	Cultivation Strategies	Optimized Feedstock Blending	Tradeoff Modeling	Future Climate
Open Pond Temp. Model	Algae Growth Model	Saline Water Supply & Demand	Brine Treatment & Disposal	Wastewater Co-Location	Biomass Forecasting	Partial TEA	Risk Assessment	Sustainability Framework



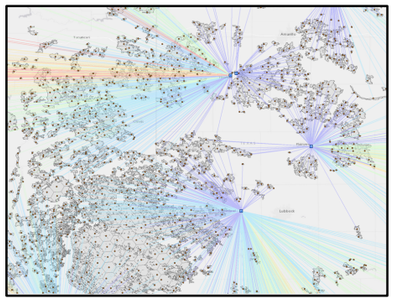
Site Selection

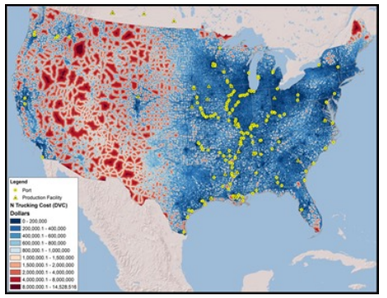

Biomass Growth


Water Demand



Water Supply


Co-Location


Supply Chain

1 – Approach (Management)

PI: Wigmosta
Co-PI/PM: Coleman

- **Period of Performance**: FY20-FY22 (FY23 is carry-over only)
- **History**
  - Original project start in 2011; Current funding under FY20 BETO Lab Call
- **Communications**
  - Regular team and task meetings
  - Bi-monthly discussion with the sponsor
  - Active in publications (31 to date), conferences, and workshops
  - Outreach and collaboration with numerous other projects
- **Project Risks**
  - Modifications to project scope and schedule due to resource constraints and numerous project collaborators [*Active oversight by project coordinator and regular communication w/ BETO sponsor*]
  - Limited and/or timely observation data for model validation [*Regular communication w/ BETO sponsor and link to ongoing field experiment efforts where possible*]

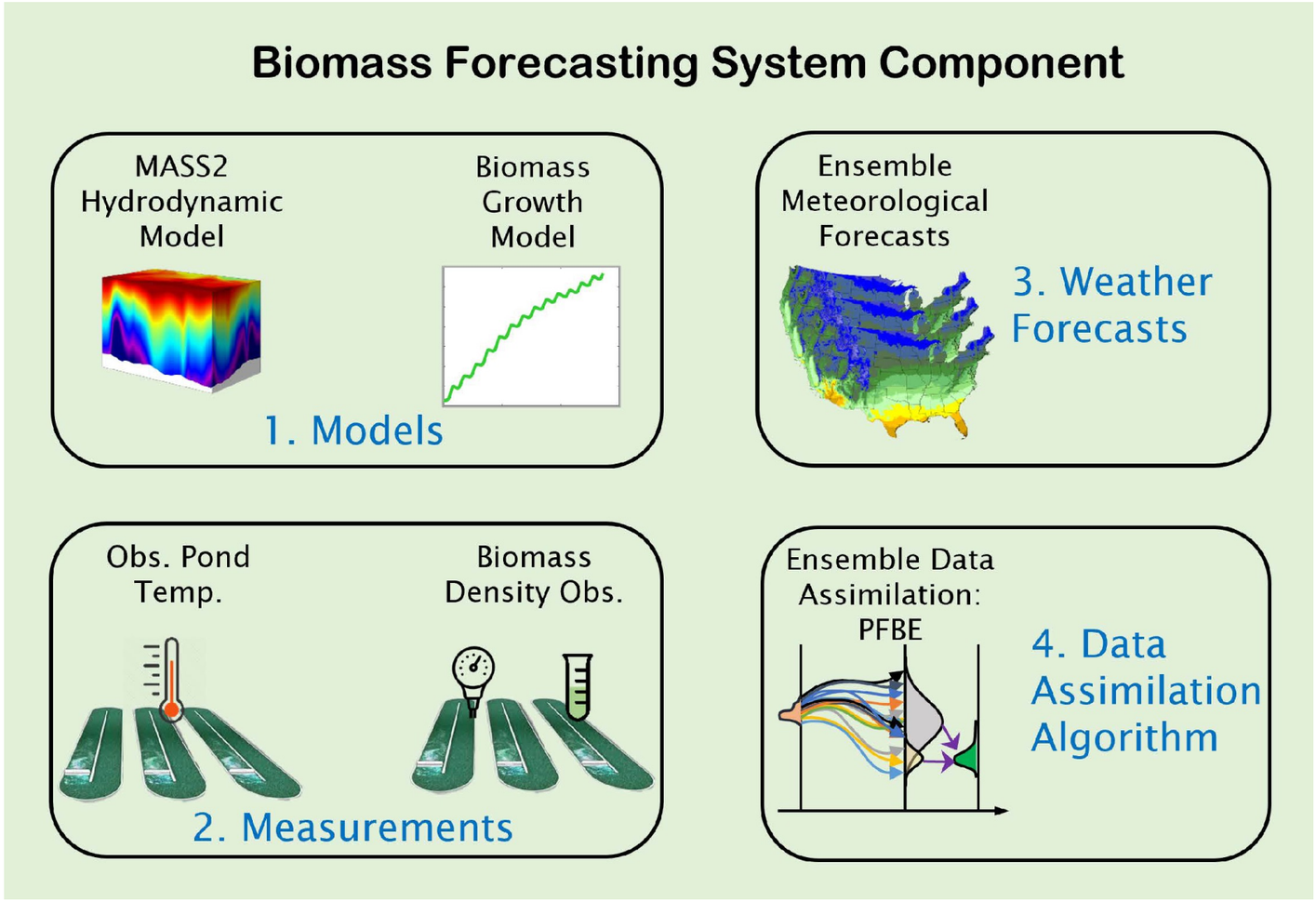
Task	Lead
Task 1: SOT Support	Yan
Task 2: Fresh/Saline Water Sustainability	Coleman
Task 3: CO_2 & Wastewater Co-Location	Coleman
Task 4: Enhanced High-Rate Pond Model	Wigmosta
Task 5: Microalgae Model Harmonization	Coleman
Macroalgae Resource Assessment	
Task 6: Saline strain parameterization	Gao
2023 Peer Review	Coleman

Go/No-Go

- If the total potential from co-location with wastewater facilities exceeds 5% of the BETO MYPP 2030 target of 5 BGY GGE, we will continue to evaluate wastewater co-location with a more refined modeling approach and cost considerations. Milestone met and exceeded (FY21-Q2); manuscript in preparation

2 – Progress and Outcomes

BETO SOT - Microalgae Biomass Forecast System

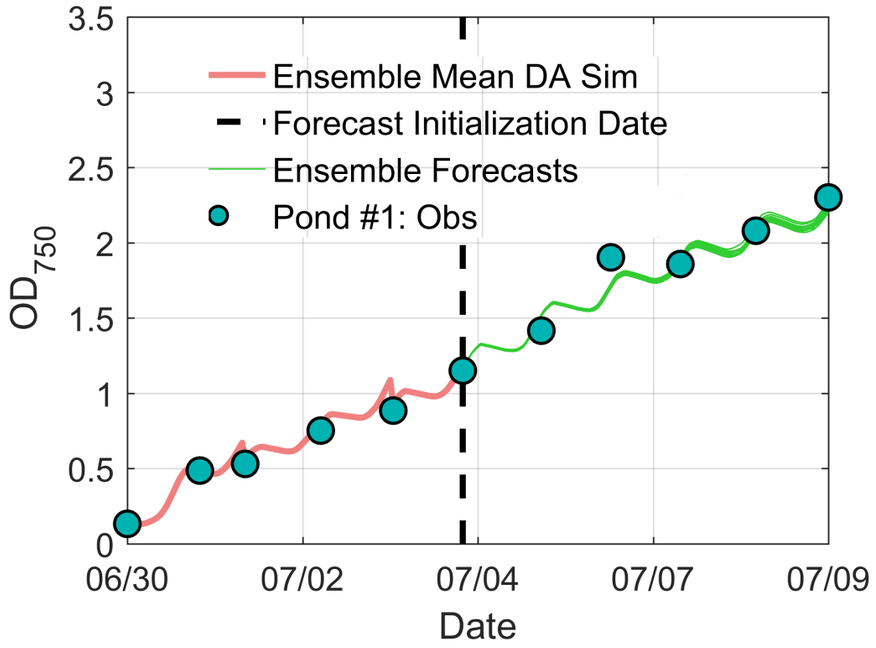


Microalgae Biomass Forecast System enhances biomass production by informing on pond operations and harvesting planning

The accuracy of the Microalgae Biomass Forecast System has been tested in model simulation *and* field experiments, using both warm and cold strains (*Monoraphidium minutum* 26B-AM and *Chlorella sorokiniana*) in different locations (Delhi, CA and Mesa, AZ).

2 – Progress and Outcomes

BETO SOT - Microalgae Biomass Forecast System



Yan et al. (2023). Ensemble biomass forecasts issued on 4th July in Delhi, CA

Run	Mode	Biomass Production (g/m2-day)	Improvement to Control
Run 1	Batch (control)	15.45	
	Batch (control)	14.71	
	Fixed Dilution	19.51	23%
	Fixed Dilution	17.62	
	Forecasting-Informed	21.54	41%
	Forecasting-Informed	20.85	
Run 2	Batch (control)	14.99	
	Batch (control)	13.94	
	Fixed Dilution	18.50	23%
	Fixed Dilution	17.12	
	Forecasting-Informed	22.21	53%
	Forecasting-Informed	22.08	

Gao et al. (2022) evaluated the forecast-informed pond operations against the standard batch or fixed dilution practices (0.6 every 3 days).

In two replicate experiments, the forecast-informed biomass productions were >40% higher than standard batch practices.

1. Yan, H., Wigmosta, M., Huesemann, M., Sun, N., and Gao, S. (2023). “An ensemble data assimilation modeling system for operational outdoor microalgae growth forecasting.” Biotechnology and Bioengineering, 120(2), 426–443. https://doi.org/10.1002/bit.28272
2. Gao, S., Yan, H., Beirne, N., Wigmosta, M., and Huesemann, M. (2022). “Improving microalgal biomass productivity using weather-forecast-informed operations.” Cells, 11(9), 1498. https://doi.org/10.3390/cells11091498
3. Yan, H., Wigmosta, M., Sun, N., Huesemann, M., and Gao, S. (2021). “Real-time ensemble microalgae growth forecasting with data assimilation.” Biotechnology and Bioengineering, 118(3), 1419–1424. https://doi.org/10.1002/bit.27663

2 – Progress and Outcomes

Microalgae Model Harmonization & BillionTon Chapter

Resource Assessment (BAT)

- *Saline Strain Parameterization**
- *Land Screening**
- Saline Groundwater Sourcing
- *Saline Pond Operations**
- *Brine Disposal**
- CO_2 Co-location
- Biomass Growth

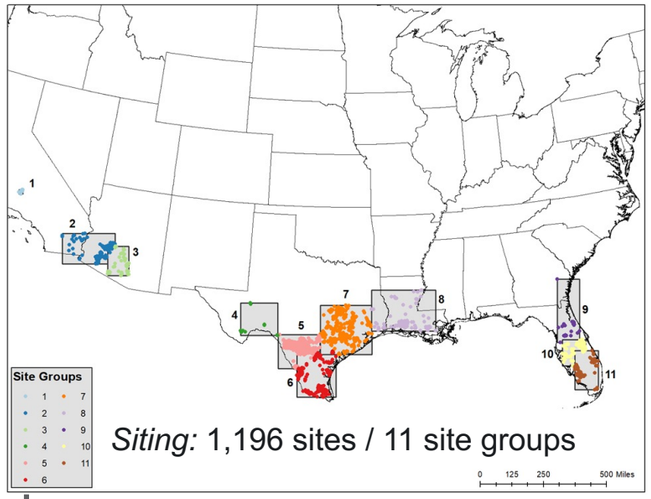
* New BAT modules under current AOP

Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae

2022 Algae Harmonization Update

Argonne National Laboratory
National Renewable Energy Laboratory
Pacific Northwest National Laboratory

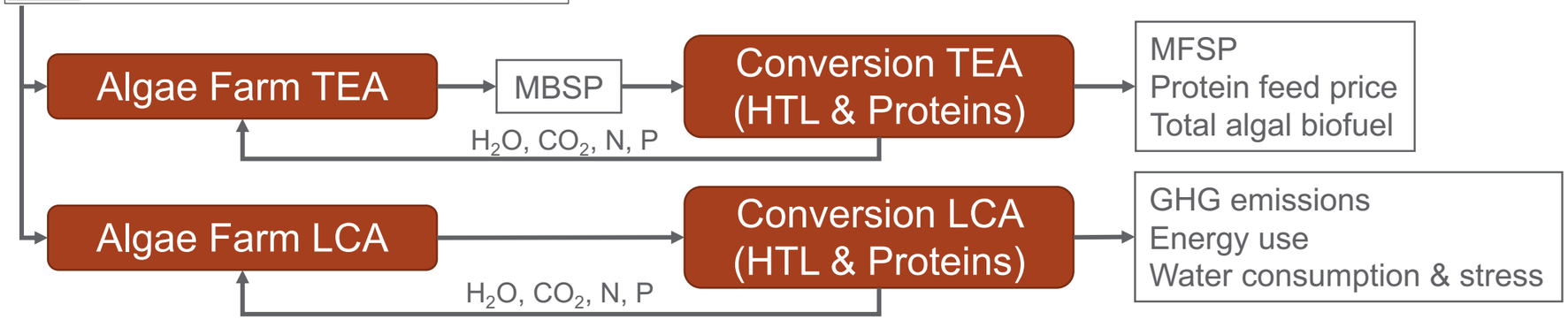
In Review



Siting: 1,196 sites / 11 site groups

- Microalgae production for SAF & proteins
- Land screening at 1,000 acre minimum
- Saline strains w/ groundwater source & brine mgt.
- Waste CO^2 co-location via CCU / pipeline transport

- *Total Biomass:* 178 Tg/yr / Avg: 26.4 g/m^2-day
- HTL algae w/ protein extraction pre-treatment:
  - *Total Fuel*: 9.3 billion GGE/yr
  - *SAF from Total Fuel*: 5.6 billion GGE/yr
  - *MFSP*: $2.10 - 4.54/GGE
  - *Total Protein*: 63 Tg/yr (whey concentrate)
  - *GHG Emissions*: 34% reduction when compared to petroleum fuel benchmark

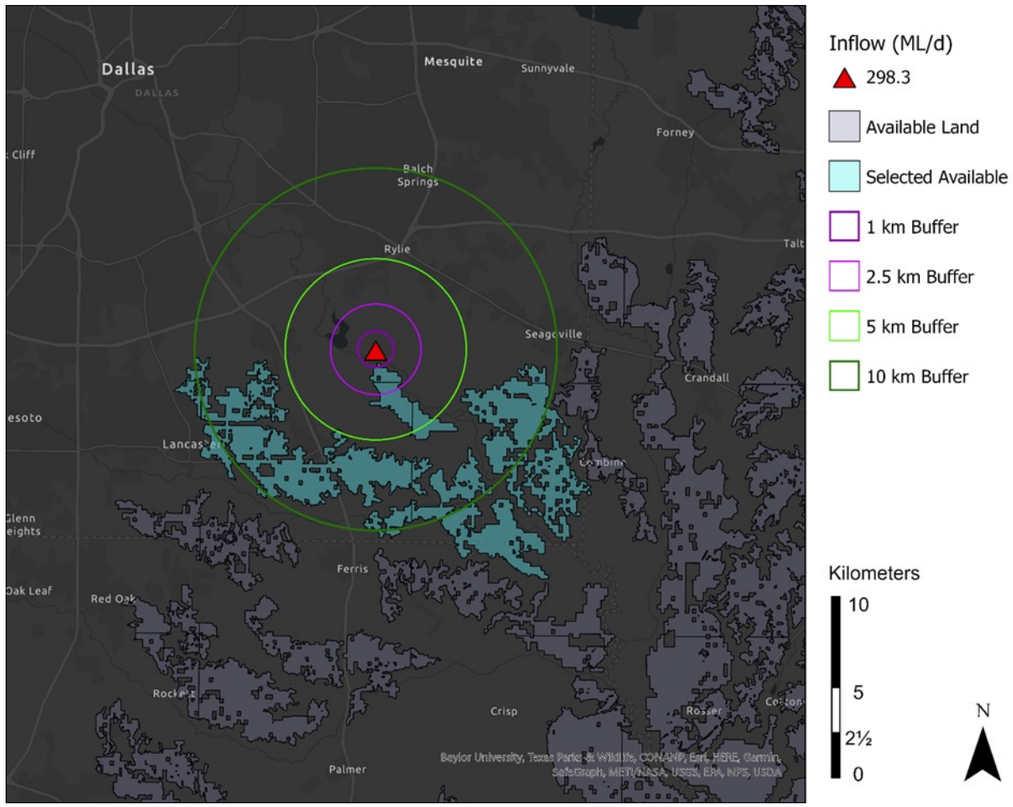


2 – Progress and Outcomes

Co-Location Opportunities: Municipal Wastewater Co-Location

- CONUS assessment of 14,920 municipal wastewater treatment plants for their potential to support algae biomass production in high-rate algae ponds
- Strain rotation biomass growth model (*Chlorella sorokiniana* DOE-1412 (warm season), *Kirchneriella cornuta* (cold season), and *Scenedemus obliquus* (all-season)
- Total N, P, and water supply modeled at various wastewater treatment phases influent, primary clarifier sludge, secondary clarifier sludge, treated biosolids, and facility effluent
- Supply/demand accounting model factors input nutrient loss due to oxidation, volatilization, and algae utilization efficiencies

- 17.1 million ha land available within 10-km
- 6.56 Tg/yr of biomass per year on 120k hectares
- 17.2 GL/yr (4.53 Bgal/yr) renewable diesel potential
- Exceeded Go/No-Go target of 250 Mgal/yr GGE



Coleman, AM, T. Saltiel, T. Seiple, M. Wigmosta. Potential of High-Rate Algae Ponds Co-Located with U.S. Municipal Wastewater Treatment Plants, *in preparation*

2 – Progress and Outcomes

Enhanced High-Rate In-Ground Open Pond Model

- Energy-balance formulation for water temperature and two-way linkage with PNNL Biomass Growth Model
- Utilization of co-located waste heat to better maintain pond water temperature
- Salt balance with blowdown at pond operation salinity thresholds
- Full tracking of N, P, and pH during pond operations
- Significant advancement over current BAT pond and temperature model

- Validating simulated pond water temperature against observations
- Linking the energy-balance pond model with the PNNL Biomass Growth Model
- Model documentation and validation (FY23)

2 – Progress and Outcomes

Offshore Macroalgae Biomass Potential and TEA

- First time macroalgae included as part of the Billion Ton Report feedstocks
- Full US Exclusive Economic Zone (EEZ) assessment, including territories
- ARPA-E MARINER program coordination model parameterization / validation
- UC-Irvine MACMODS model for biomass potential and “farm-gate” (dock) TEA
  - Tropical reds, tropical browns, temperate reds, and temperate browns
- Newly developed high-resolution marine area screening model
- Results compiled into current draft chapter of the Billion Ton Next report

Siting & TEA: ≤$2k/t DW @ 20% area (Preliminary)

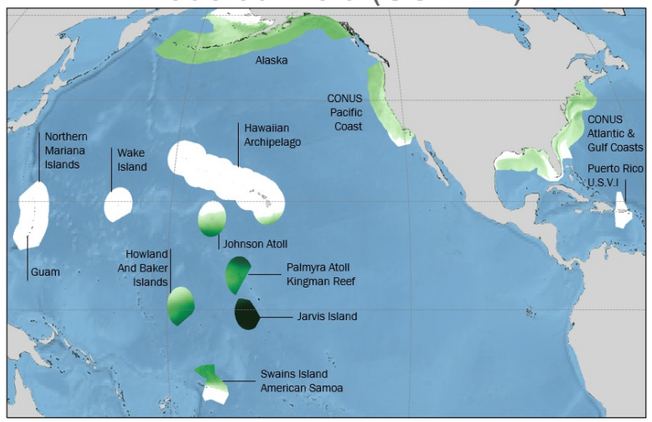
Alaska
1.6M km² / 415M t/DW

Pac. Coast
353k km² / 41M t/DW

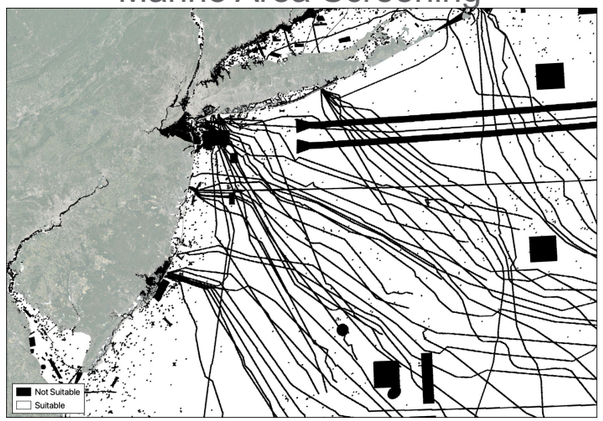
Atl. Coast
233k km² / 69 M t/DW

Total
2.2M km² / 525M t/DW

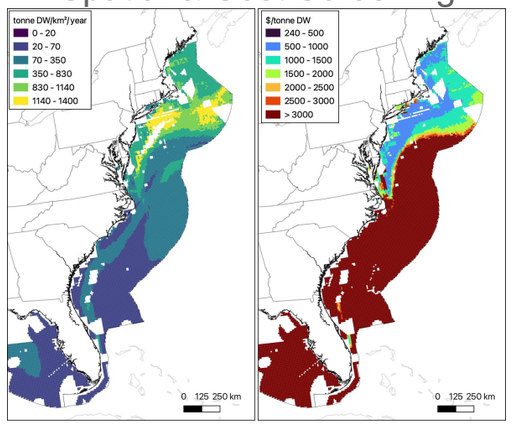
Modeled Yield (US EEZ)



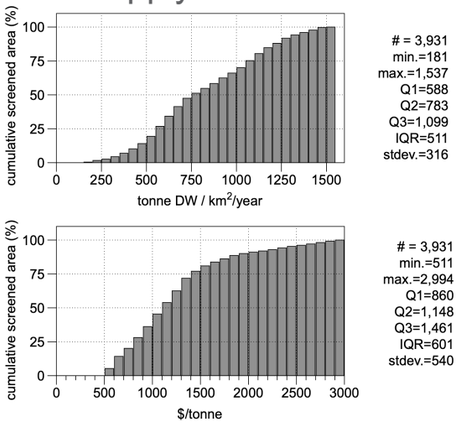
Marine Area Screening



Spatial & Cost Screening



Supply Curves



3 – Impact

Advancing the state of technology through national extent site-scale evaluation of potential microalgae and macroalgae feedstock site locations, productivity potential, site-scale freshwater and saline algal strains performance, alternative water and nutrient sources, operational efficiency, and conversion technologies to yield the highest sustainable fuel and co-product production potential per unit cost and resource use efficiency

- **Communications and Collaborations**
  - Numerous workshops and conferences
  - Experimental Support (BETO State of Technology, DISCOVR)
  - BETO Multi-Lab Algae Model Harmonization, Billion Ton Study, Waste-to-Energy, Forest Restoration, ARPA-E (Macroalgae)
- **Supporting BETO Objectives**
  - Supports BETO goal of 3 Bgal/yr of multi-modal transportation biofuels at $2.50/GGE & 50% GHG reduction by 2030
  - Supports commercialization of Sustainable Aviation Fuel (SAF) goals
  - Supports the BETO Algae State of Technology 2030 seasonal and annual areal productivity goals
- **Peer Reviewed Publications**
  - 31 total since 2011 (**1 > 300 citations, 3 > 170 citations; 7 > 60 citations**; 11 > 27 citations; 16 > 12 citations)
  - 4 published since last review, 2 additional in preparation for 2022 submission

Summary

- **Overview:** This project provides BETO and industry a national assessment site-scale capability focused on fundamental questions of where production can occur, how much nutrient, land and water resource is required, how much biomass/energy is produced, and what interactions/trade-offs exist between technologies
- **Management:** Task-driven approach following BETO management protocols
- **Approach:** Continued enhancement and application of the PNNL Biomass Assessment Tool (BAT) to evaluate alternative algal feedstock production strategies that will yield the highest sustainable fuel and co-product production potential as a function of unit cost and resource / waste resource use efficiency
- **Impact:** The BAT provides a biophysics-based analysis framework for linking key BETO & industry research activities to achieve high-impact objectives for multiple feedstocks
  - BETO MYPP, updated multi-lab model harmonization focused on use of newly parameterized saline water strains, Billion Ton Next study ongoing and including microalgae and for the first time, macroalgae, State of Technology, DISCOVR
  - 31 peer reviewed publications with 4 since the last review, and 2 additional in preparation
- **Progress & Outcomes:** Further maturity of the biomass forecasting system, multi-lab model harmonization evaluation of spatiotemporal water scarcity with freshwater and freshwater + saline mixes, evaluated brine management options, and estimated biomass potential through co-location with CO_2 and wastewater treatment facilities

Quad Chart Overview

Timeline

- Project start date: 10/01/2020
- Project end date: 09/30/2023 (FY23 Carryover Only)

$0 to PNNL $120k subcontract to UC-Irvine	$1,725,120
$0	$0 (FY 20-23)

TRL at Project Start: 5
TRL at Project End: 7

Project Goal

Model the sustainable supply of cultivated algal biomass to achieve 5 billion GGE per year by employing open ponds, PBRs, saline water, CO2 co-location, and alternative nutrient sources by September 2022

End of Project Milestone

Through collaboration with the DISCOVR project, make enhancements to the BAT and growth model parameterization library to include additional fresh and saline, cold- and heat-tolerant algal strains, model maximized production operations, and evaluate tradeoffs in alternative technology pathways to achieve the MYPP 2030 target to model the sustainable supply of cultivated algal biomass to achieve 5 billion GGE per year.

Funding Mechanism

BETO Lab Call for FY20

Project Partners

- *National Lab: ANL, NREL, ORNL*
- *University: ASU, UC-Irvine*
- *Programs: ARPA-E MARINER, BETO DISCOVR, SOT, Waste-to-Energy*

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Additional Slides

Responses to Previous Reviewers' Comments

- "In considering brine management options, the team may find value and efficiencies in connecting with the relatively recently formed National Alliance for Water Innovation if they are not already working together; brine management is a key focus area for them."
  - This was an excellent suggestion, as the team found great value in tapping the resources from the National Alliance for Water Innovation through its numerous publications and our interviews/surveys from NAWI industry partners. As the research evolves under NAWI, the microalgae industry will benefit by the integration of new technologies and updated techno-economics that can be incorporated into the BAT.

- "…the greatest risk for most of the broad modeling efforts still seems to be a lack of industry adoption and input, as the user base for the BAT model may not be growing."
  - Our team has continued to publish and present its research in public forums, work closely with the BETO State of Technology efforts, DISCOVR's industry advisory board, and industry partners via the ARPA-E MARINER program. While our team has not had a formal industry partner during this AOP, it is challenging to quantify the impact the BAT program has had on industry. Numerous requests for model datasets have been fulfilled over the years from various entities ranging from academia, industry, government orgs, and lab partners. With the recent publications of the microalgae forecast system, we feel this may be of interest and will publicize the capability and target communications to industry.

Publications and Presentations

- Yan, H., Wigmosta, M., Huesemann, M., Sun, N., and Gao, S. (2023). “An ensemble data assimilation modeling system for operational outdoor microalgae growth forecasting.” Biotechnology and Bioengineering, 120(2), 426–443. https://doi.org/10.1002/bit.28272
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- Milbrandt, A, T Seiple, D Heimiller, R Skaggs, A Coleman. 2018. Wet waste-to-energy resources in the United States, Resources, Conservation and Recycling, 137(2018):32-47, 10.1016/j.resconrec.2018.05.023
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