DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Pacific Northwest NATIONAL LABORATORY

1.3.5.203 Microalgae Analysis

4th March 2019

Advanced Algal Systems

Principal Investigator

Mark Wigmosta

PNNL

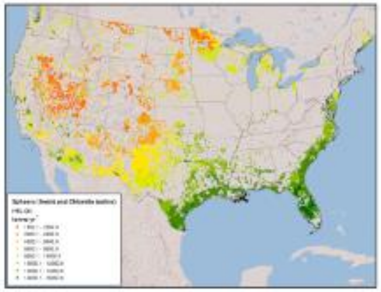
Goal Statement

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 National 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



Quad Chart Overview

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Timeline

- Project start date: October 1, 2016
- Project end date: September 30, 2019
- Percent complete: 75%

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$3,872K	$652K	$527K	$550K
Project Cost Share*				

•Partners: ANL, NREL, ORNL, RAFT, ATP3, BETO HQ, U. Arizona, Arizona State University

Barriers addressed

- Aft-A. Biomass Availability and Cost
- Aft-B. Sustainable Algae Production
- Aft-J. Resource Recapture and Recycle

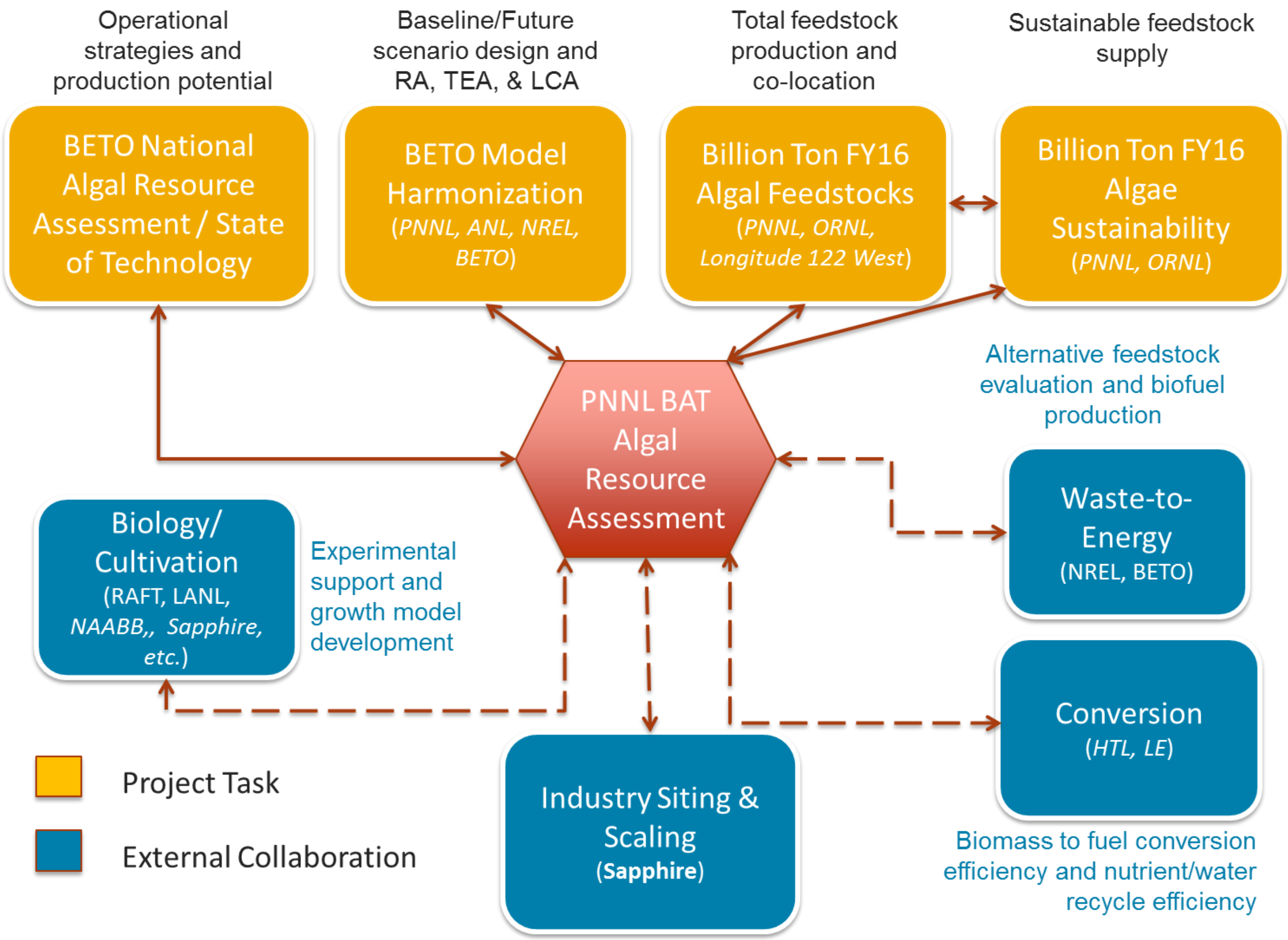
Objective

- Address fundamental questions of where algal production can occur, how much nutrient, land and water resource is required, and how much energy is produced, by evaluating numerous tradeoffs including key techno-economic criteria.
- Evaluate alternative algal feedstock site locations, algal strains, growth media/operations, and process technology to yield the highest sustainable fuel production potential, per unit cost, and resource use efficiency

End of Project Goal

Identify locations and associated pathways that can achieve the MYPP 2022 target of 5,000 gallons/acre/year by employing open ponds, PBRs, saline water, CO2 and waste heat integration, and alternative nutrient sources through ongoing multi-lab/academic/industry coordination, maintenance and enhancement of the PNNL BAT model, and targeted multi-objective analysis.

1 – Overview:
The BAT Provides a Biophysics Based Analysis Framework for Linking Key BETO & Industry Research Activities to Achieve High-Impact Objectives for Multiple Feedstocks



- **19 Peer Reviewed Publications**

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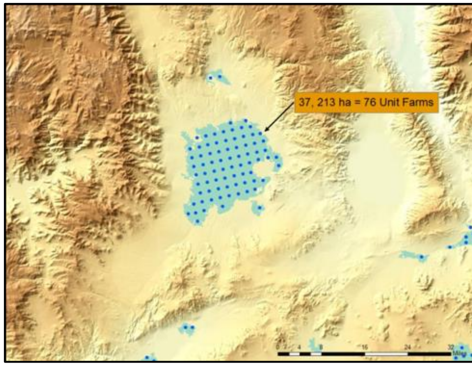
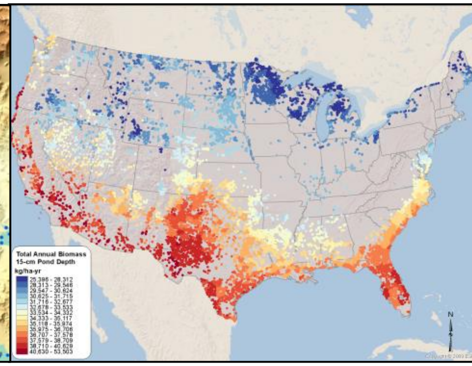
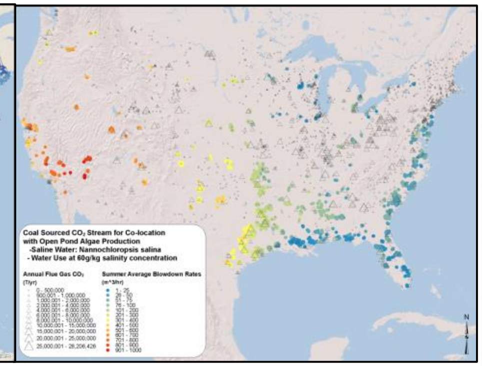
1 - Overview:

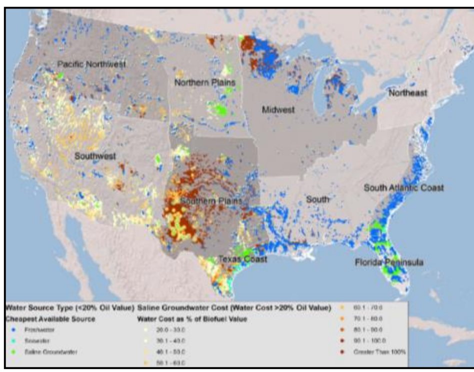
BAT Integrates Detailed Spatiotemporal Data with Biophysical & Geospatial Models for Multi-Scale Analysis



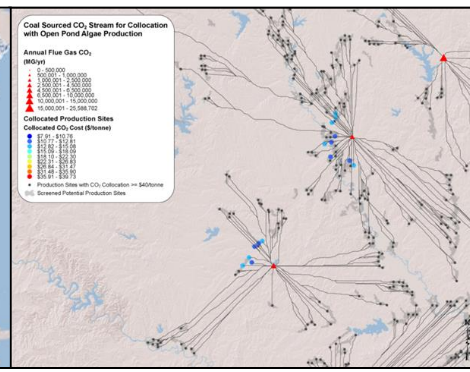
Site Selection

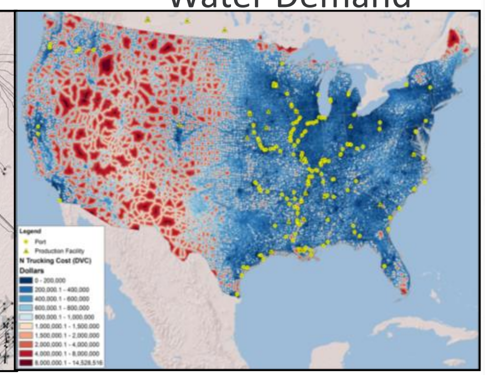

Biomass Growth


Water Demand



Water Supply


CO_2 Co-Location


Transport Costs

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

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

2 – Approach (Management):
Project Coordinator and Microsoft Project to Better Track Tasks and Budget

PI/PM Wigmosta
Project Coordinator: Lilly Burns

Task	Lead
Saline Water	Coleman
PBR's	Sun
Wastewater Co-Location	Seiple
Water Sustainability	Coleman/ Wigmosta
CO2 Co-Location	Coleman
SOT Support	Sun
2020 MYPP Target	Wigmosta

- Following BETO project management protocols
  - Annual Operating Plan (AOP)
  - Quarterly Progress Reports to BETO
- Quarterly Progress Reports to BETO
  - Progress against milestone
  - 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
- Use of Microsoft Project to track tasks, milestones, staffing, and budget
- Potential Challenges
  - Timely access to experimental results and data
  - Communication and feedback from industry

2 – Approach (Technical):

Application of BAT to Evaluate Algal Feedstock Strategies to Improve Production, Cost, and Resource Use Efficiency

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)

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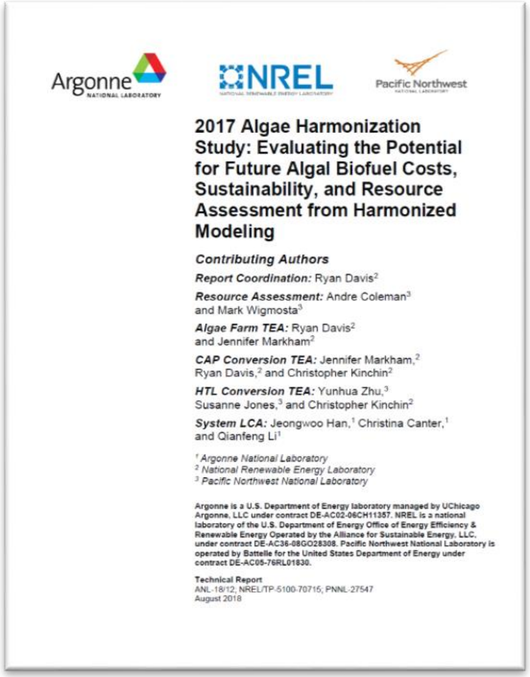
3 – Results:
2017 Algae Harmonization Study to Establish Requirements to Meet Future BETO Goals

Multi-lab (ANL, NREL, PNNL) working group updated and implemented rigorous RA/TEA/LCA data and models with a focus on establishing requirements to meet future goals considering:

- Potential for algal biofuel costs (minimum fuel selling price)
- Environmental sustainability (waste CO_2 utilization, GHGs, and water availability)
- National scale biomass and fuel output with realistic resource constraints

<u>BAT Model Updates</u>

- Land availability refined to 5,000 acre minimum
  - Freshwater: 532 sites at 2.658 million acres
  - Saline: 1,414 sites at 7.071 million acres
- Updated national freshwater & saline water supply and demand balance model
- New Gen-2 CO_2 capture and transport materials, energetics and CapEx/OpEx economics model; Future growth rates
  - Freshwater Avg: 26.37 g/m^2-d w/ $39.69 $/tonne CO_2
  - Saline Avg: 25.66 g/m^2-d w/ $41.20 $/tonne CO_2
- Experimentally-parameterized microalgae growth model (fresh & saline strains)
- Dynamic strain rotation and pond depth with time-varying biomass outputs
- Time-series hourly meteorology (rather than stochastic)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NREL
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2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling

Contributing Authors

Report Coordination: Ryan Davis[2]

Resource Assessment: Andre Coleman[3] and Mark Wigmosta[3]

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HTL Conversion TEA: Yunhua Zhu,[3] Susanne Jones,[3] and Christopher Kinchin[2]

System LCA: Jeongwoo Han,[1] Christina Canter,[1] and Qianfeng Li[1]

[1] *Argonne National Laboratory*
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Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC, under contract DE-AC36-08GO28308. Pacific Northwest National Laboratory is operated by Battelle for the United States Department of Energy under contract DE-AC05-76RL01830.

Technical Report
ANL-18/12; NREL/TP-5100-70715; PNNL-27547
August 2018

3 – Results: Substantial Quantities of Biomass (104–235 MM tons/yr) Projected to be Available at Costs Below $700/ton

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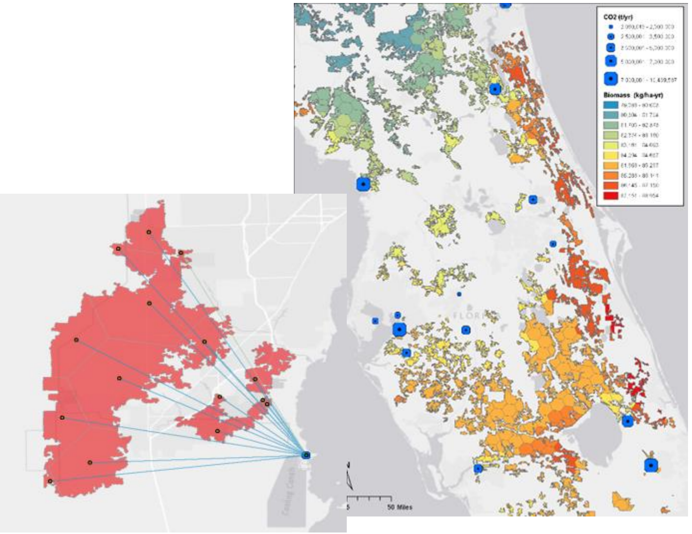


Gen-2 Carbon Capture and Transport Model

- Location-allocation spatial network model developed to optimize pipeline route and associated transport costs
- Costs established for capture (based on source), compression, and pipeline right-of-way, material, diameter, distance, pumps (based on CO2 mass) for each source
- Costs established for pipeline construction, labor, and maintenance (assumed 30-yr life)
- Unique material/cost solution for each source/target

Key Findings:

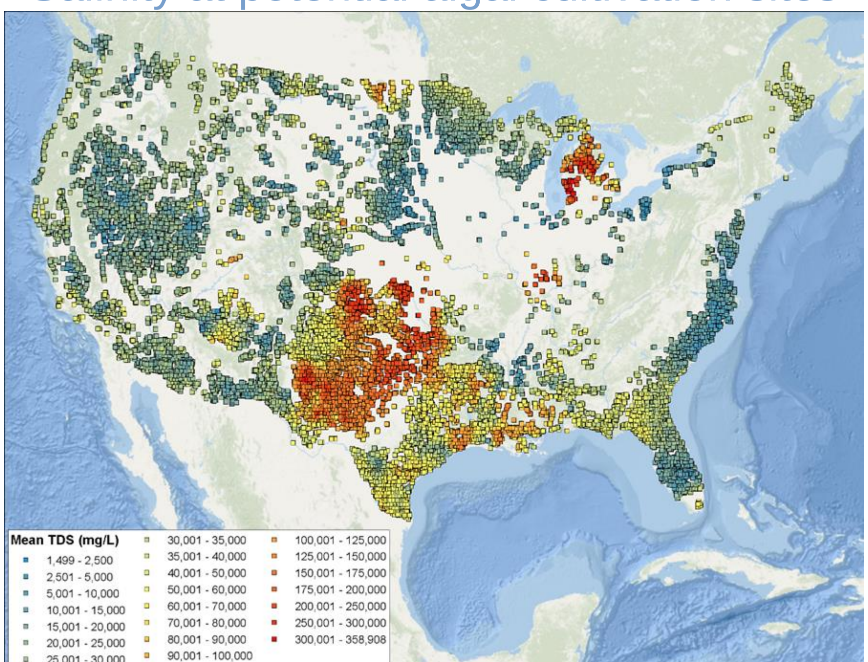
- Gen-2 carbon capture is significantly less costly and logistically challenging for on-site delivery to ponds (8X lower pipeline distribution costs) and extends co-location range yielding 10x more biomass potential over bulk flue gas
- Potential for 104 MM tons/yr (freshwater) and 235 MM tons/yr (saline) algal biomass at a cost of $472/ton (freshwater) and $655/ton (saline)
- CAP Freshwater: 8-11 BGGE/yr biofuels at $1.99-$5.68/GGE
- CAP Saline: 15-28 BGGE/yr biofuels at $2.59-$7.45/GGE
- HTL Freshwater (Algae + Wood): 21 BGGE/yr biofuels at $3.68/GGE
- HTL Saline (Algae + Wood): 56 BGGE/yr biofuels at $4.53/GGE

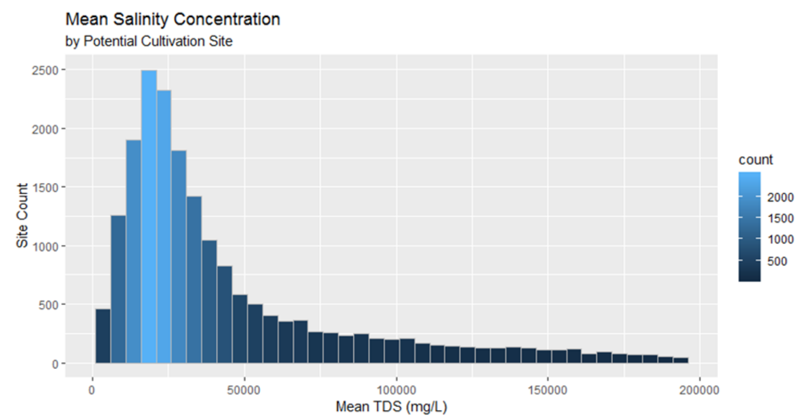
3 – Results:
Assess the Viability of U.S. Saline Groundwater Resources to Support Microalgae Production

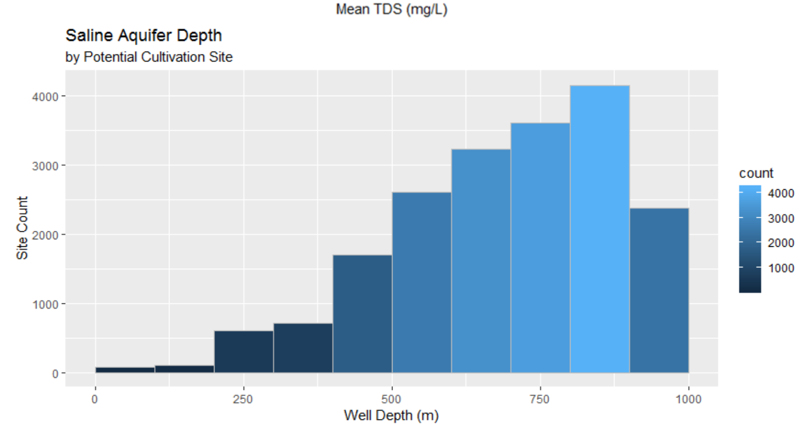
Use of BAT to characterize and assess the viability of U.S. saline groundwater resources to support microalgae production

- Saline Groundwater Characterization
  - Geostatistical analysis of 260,000 well records to establish groundwater salinity and depth to saline groundwater for the conterminous U.S.

Salinity at potential algal cultivation sites







3 – Results:

Current Parameterized Saline Strains for Open Pond Produce ~2,500 gal/ac-yr HTL Renewable Diesel

- Spatial Matching Min/Max and Optimal Salinity Ranges to Algal Strains

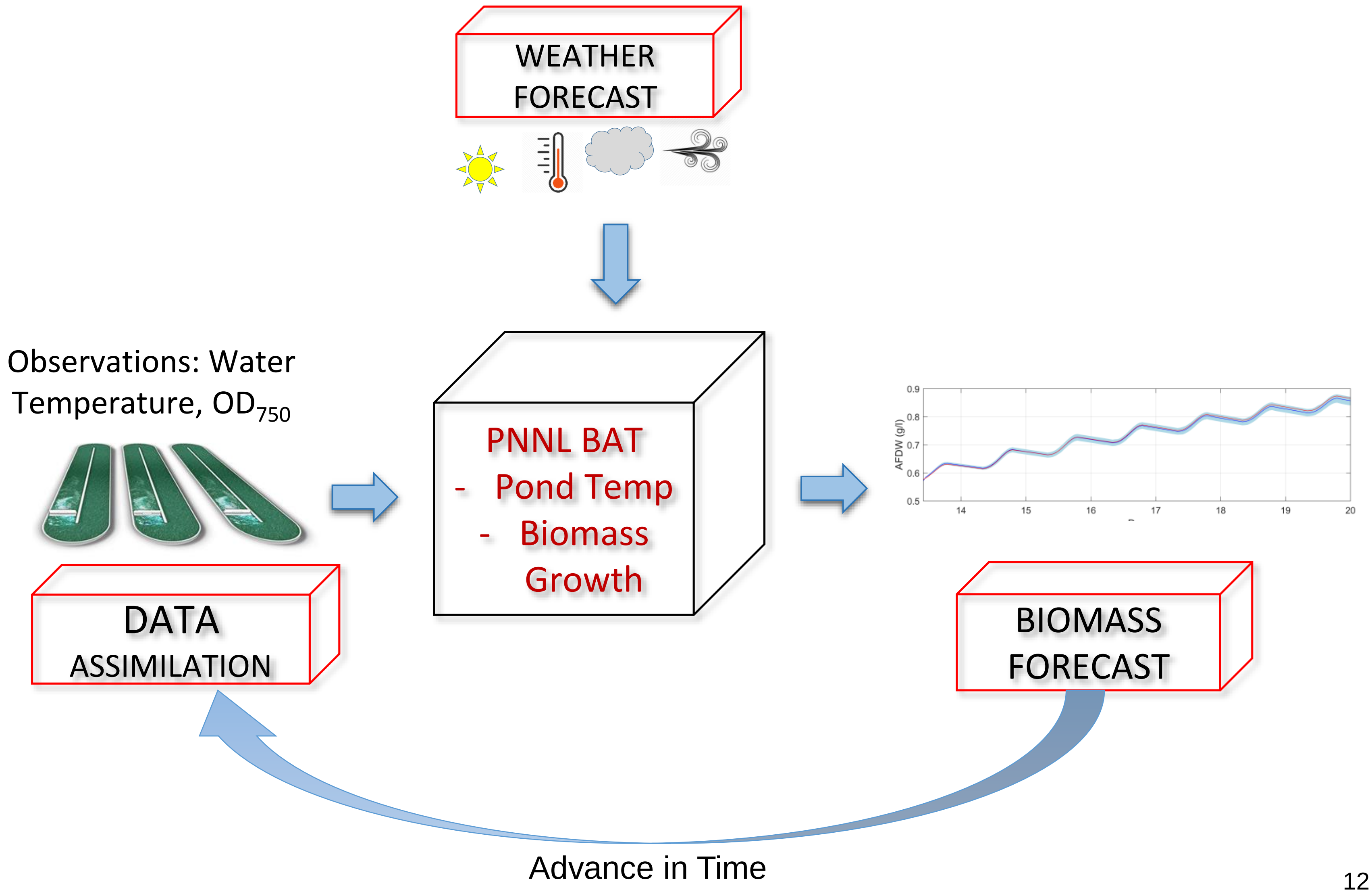
Saline Algal Strain	Min/Max Salinity Range (PSU)	% Sites Min/Max Salinity Range	Optimal Salinity Range (PSU)	% Sites Optimal Salinity
Nannochloropsis salina	6-68	76%	22-35	24%
Picochlorum sp.	1-105	87%	35-70	21%
Nannochloropsis oceanica	5-100	84%	10-50	63%

- Blowdown and Brine Management
  - Economic analysis for conventional (injection, evaporation ponds, crystallizers) and next generation (forward osmosis, membrane distillation, brine disposal techniques, electrodialysis)
  - Blowdown calculations coupled with brine management economics in BAT

Key Findings:

- Conterminous US saline aquifers for TDS are established from well observation data
- The largest number of potential algal cultivation sites fall in the “saline” (10-30 PSU; 42.5% sites) and “brine” (40-300 PSU; 37.3% sites) saline classifications
- On average, current parameterized saline strains for open pond are 9.38 g/m^2-day (2,532 gal/ac-yr HTL renewable diesel)
- Forward osmosis is a viable next-generation scalable brine management option with 65-90% water recovery using 3-8 kW h/m^3 at a cost of $0.10/m^3.

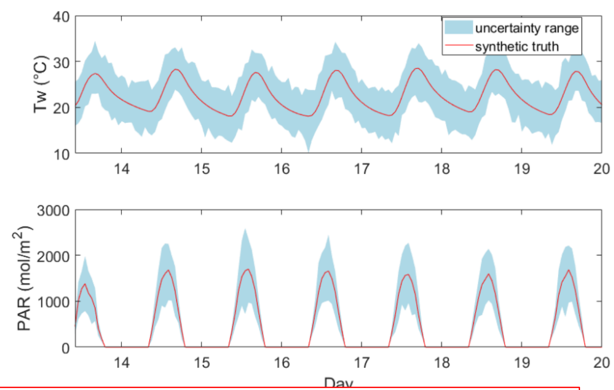
3 – Results:
Framework for Operational Biomass Forecasting to Optimize Pond Operations

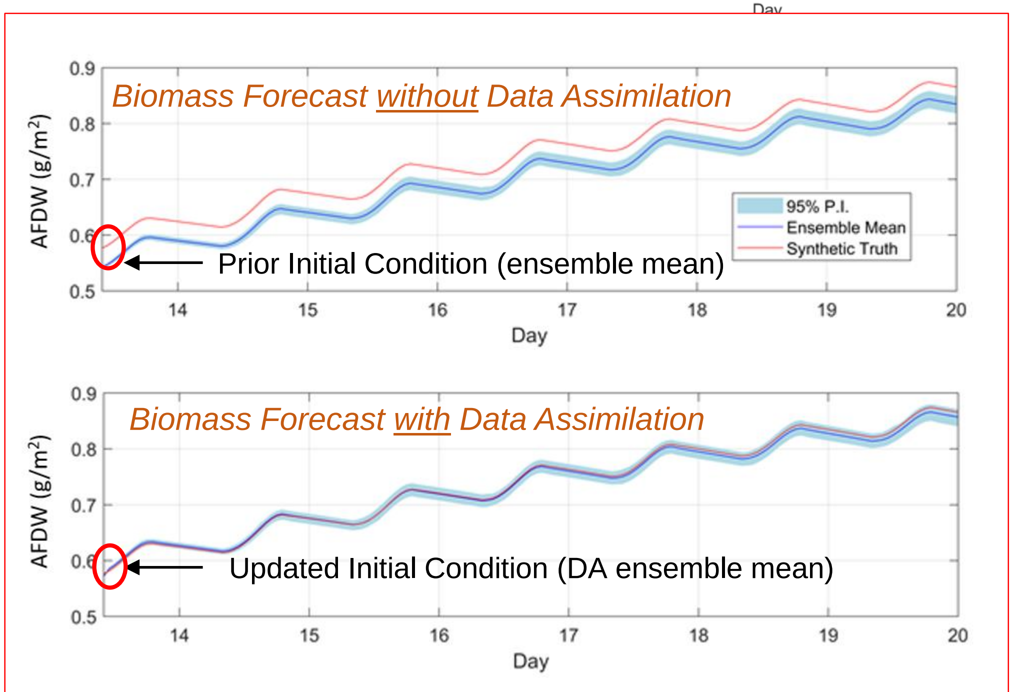


3 – Results:

Use of Data Assimilation Significantly Improves Forecast Accuracy

- 150 ensembles are generated for biomass forecast.





Findings:

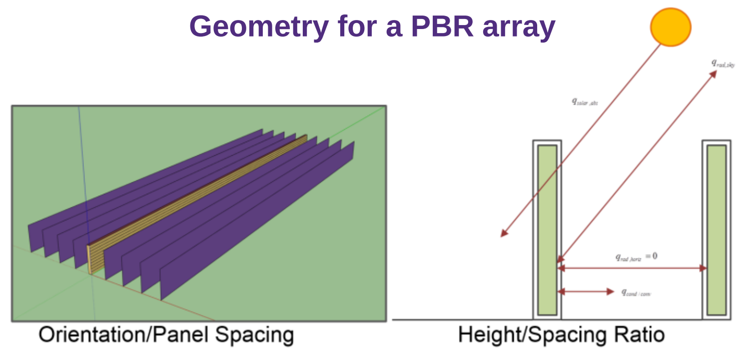
- Errors in initial conditions (water temperature and algal concentration) propagate throughout the biomass forecast.
- With updated initial conditions through data assimilation (DA), the biomass forecast skill can by be improved by 92% in terms of Rank Probability Skill Score (RPSS).
- The longer the lead time, the larger the forecast <u>uncertainty</u>.

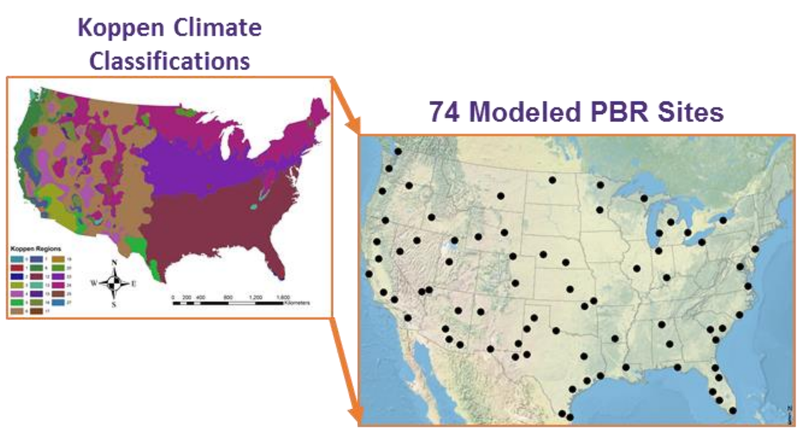
3 – Results:
Evaluating Optimal PBR Configurations and Operations

With a two-way coupling between the PBR and BAT models forced by 10-year gridded NLDAS meteorological data, we determined the maximum potential biomass productivity from a range of PBR configurations and operational strategies at 74 locations representative of climatology in the conterminous United States with access to land, water, waste heat, and CO_2.

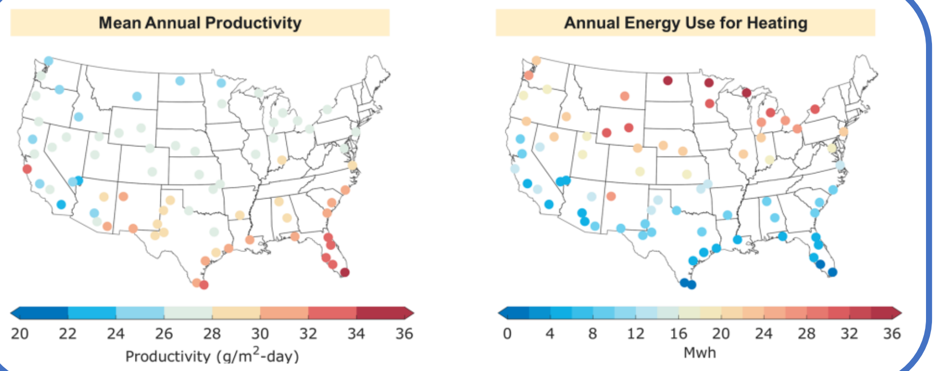
PBR configurations and operational scenarios		Description
Freshwater Strains	1	Chlorella sorokiniana
	2	Scenedesmus
	3	Monoraphidium
Saline Strains	1	Nannochloropsis salina
	2	Picochlorum sp.
	3	Nannochloropsis oceanica
PBR Orientation	1	North-South Orientation (N-S)
	2	East-West (E-W) Orientation
PBR panel height/spacing ratio	1	low (< 1) 30cm spacing, 84cm height
	2	medium (~ 1) 100cm spacing, 84cm height
	3	high (> 1) 100cm spacing, 280cm height
Waste Heating Options	1	With external heating
	2	Without external Heating

Geometry for a PBR array



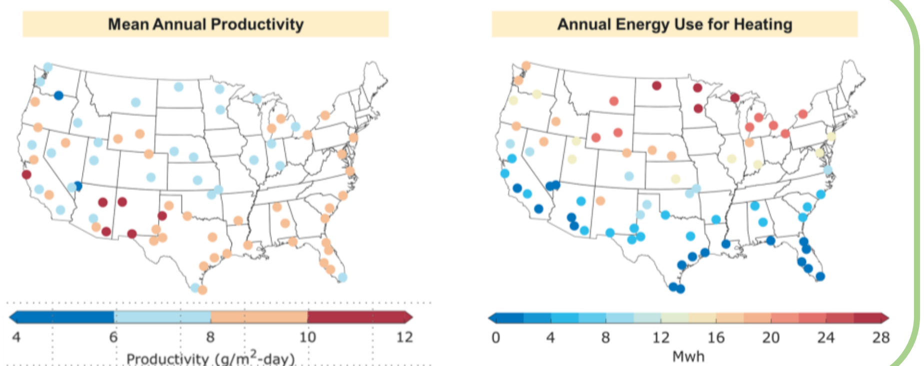


3 – Results:
N-S Orientation with Low Height/Spacing Ratio Generally Yields the Highest Productivity



Freshwater PBRs: Over all locations, the mean annual productivity ranges from 22.3 to 34.7 g/m^2-day, with an average of 28.2 g/m^2-day. More southern locations are most favorable locations, where biomass yield is generally higher with lower annual energy use for heating. At more northern locations, external heating is required most time of the year to achieve maximum productivity.

*Freshwater PBRs with an N-S orientation, **low height/spacing ratio**, and the warm-water strain Chlorella sorokiniana yields the highest productivity at most locations with waste heat provided during cooler months.*

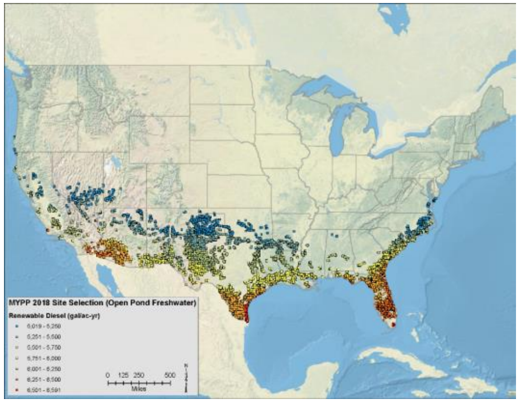
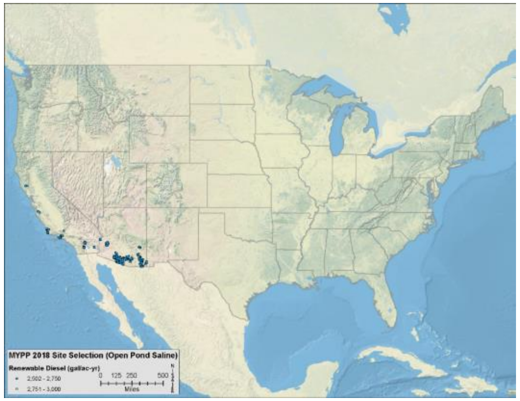
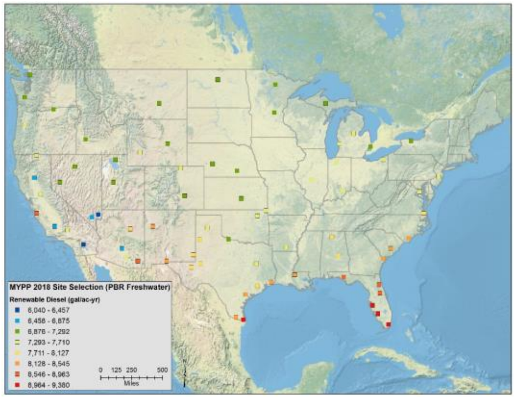
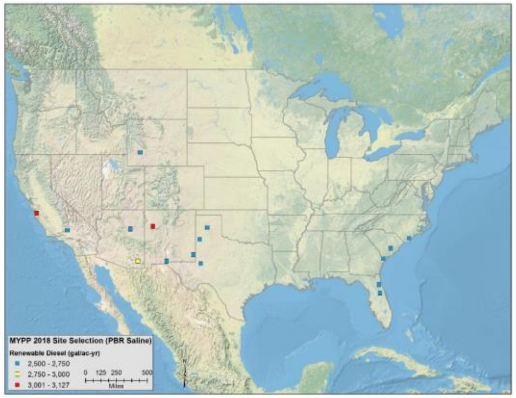


Saline PBRs: The mean annual biomass productivity ranges from 5.7 to 11.6 g/m^2-day across all locations, with an average of 8.3 g/m^2-day. Similar to freshwater PBRs, more southern locations are most favorable locations for saline PBRs, where biomass yield is generally higher and annual energy use for heating is lower.

Saline PBRs with an N-S orientation, low height/spacing ratio, and the warm-water Nannochloropsis oceanica yields the highest productivity at most locations with waste heat provided during cooler months .

3 – Results:

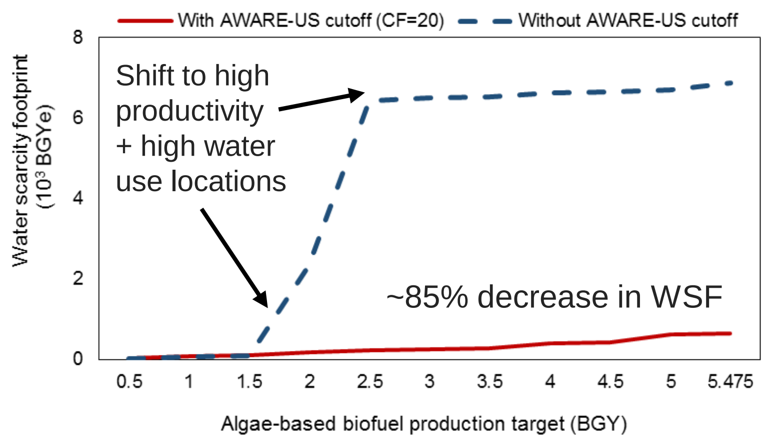
A significant Number of Sites Exceed the BETO MYPP Target of 2,500 Gallons of Biofuel Intermediate Per Acre Per Year

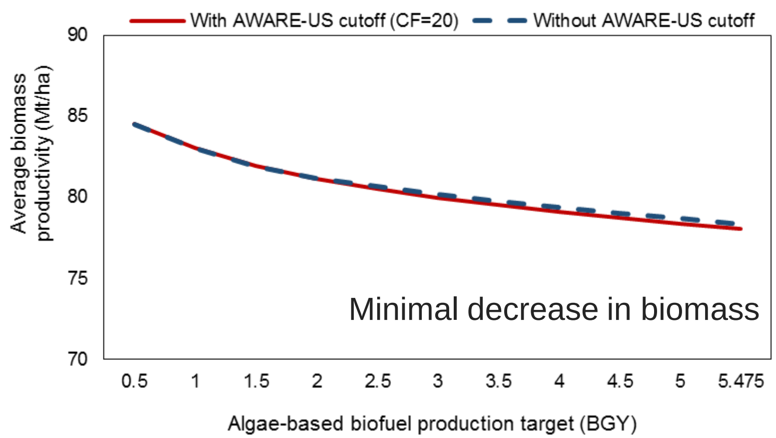
	Freshwater	Saline Water
Open Pond	 10,190 sites with average production of 5,725 gal/ac-yr renewable diesel.	 204 sites with average production of 2,532 gal/ac-yr renewable diesel.
PBR (74 sites)	 74 sites with average production of 7,629 gal/ac-yr renewable diesel.	 16 sites with average production of 2,700 gal/ac-yr renewable diesel.

3 – Results:
Sustainable Freshwater Resources for Large-Scale Algal Production

- Coupled models: PNNL's BAT and ANL's AWARE-US[1]
- Determine site prioritization of large-scale algal production under three strategies:
  - Total annual algal biomass yield
  - Total annual water use efficiency (ratio of biomass production to water used)
  - Combined water stress indicator thresholds and total annual algal biomass yield
- Prioritizations based on two renewable diesel targets and one biomass target:
  - 20 BGY / 5 BGY / 30 MMT AFDW
- Freshwater *Chlorella sorokiniana* DOE-1412 at sites ≥ 20 g/m^2-day mean productivity

30 MMT AFDW



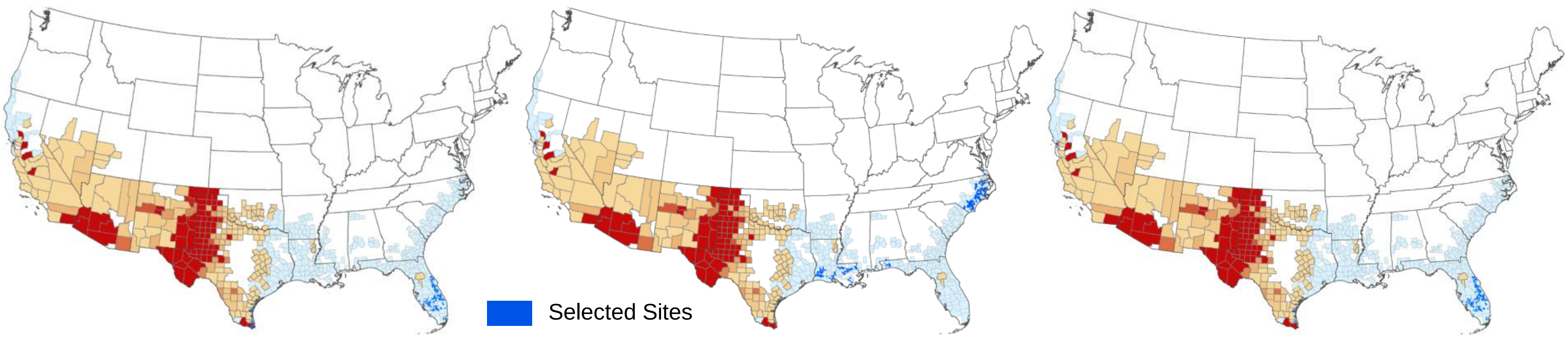


[1] Xu, H, U Lee, AM Coleman, MS Wigmosta, M Wang. 2019. Assessment of algal biofuel resource potential in the United States with consideration of regional water stress, *Algal Research*, 37:30-39, 10.1016/j.algal.2018.11.002.

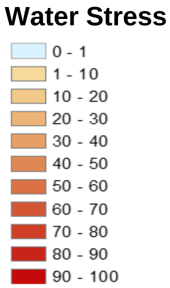
3 – Results:
Significant Reduction in Water Stress with Minimal Loss in Total Biomass Yield

30 MMT AFDW Scenario
Site Prioritization Strategies

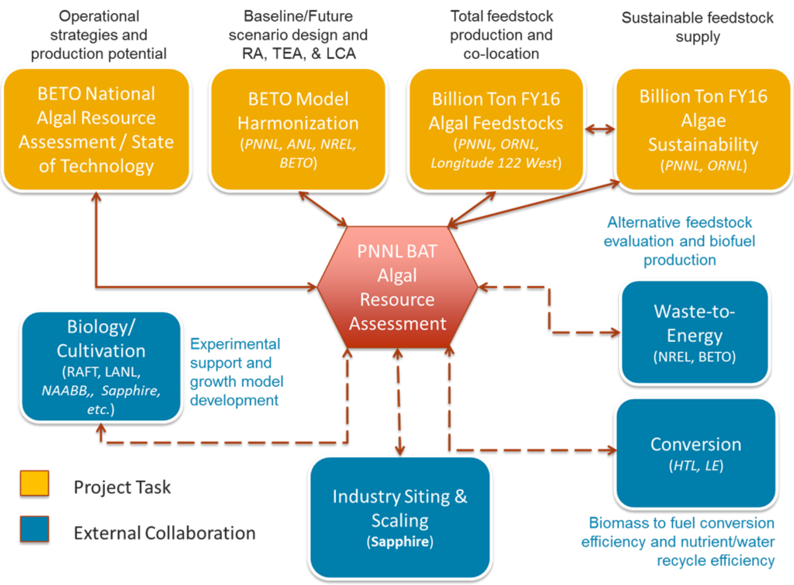
Biomass Productivity | Water Use Efficiency | Water Stress Threshold + Biomass Productivity



- BAT+AWARE-US Modeling approach provides a tradeoff analysis that removes sites in water stressed regions and maintains other high-productivity sites
- Results in ≥55-85% reduction in water stress impacts with ≤4% impact to biomass yield for the evaluated target scenarios



4 – Relevance:
The BAT Provides a Biophysics Based Analysis Framework for Linking Key BETO & Industry Research Activities to Achieve High-Impact Objectives for Multiple Feedstocks



- Outcomes address priority issues for emerging algal biofuels industry
  - Realistic assessments of spatially specific resource constraints noted by NRC (2012)
  - Supports BETO State of Technology Reports
  - Provide basis for DOE's harmonization of RA, LCA and TEA modeling
  - Contributions to Algae Chapter of the 2016 Billion Ton Study (Vol 1 and Vol 2)
  - Support for experimental design and growth model development
  - Assessment of biomass to fuel conversion and associated land, water, and nutrient use for specified production targets
  - Guides industry in siting for feedstock production

4 – Relevance:
The BAT Provides a Biophysics Based Analysis Framework for Linking Key BETO & Industry Research Activities to Achieve High-Impact Objectives for Multiple Feedstocks

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

- Aggressive technology transfer:
  - 19 peer-review publications
  - Numerous workshops and conferences
  - Direct collaboration with industry
  - Technical Assistance Program (TAP)
  - Integration with Bioenergy Knowledge Discovery Framework (KDF)

- Analyses are directly focused on BETO MYPP targets:
  - 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
  - Identify locations and associated pathways that can achieve the MYPP 2022 target of 5,000

5 – Future Work (FY19):

Evaluate MYPP Target and Aggressive Technology Transfer through Six Additional Publications

- Use the BAT to identify locations and associated pathways that can achieve the MYPP 2022 target to "demonstrate at non-integrated process development unit-scale algae yield of 5,000 gallons or equivalent biofuel intermediate per acre per year"
- Manuscripts
  - Saline water 1 describing <u>production potential</u> for algal-based biofuel utilizing saline water sources
  - Saline water 2 describing <u>costs</u> for algal-based biofuel utilizing saline water sources
  - Improved algal production potential through co-location of PBR's with sources of CO_2 and waste heat
  - Total CONUS production potential from co-location with wastewater treatment facilities using available water and nutrients.
  - PNNL/ANL monthly BAT+AWARE Sustainable Freshwater Resources for Large-Scale Algal Production
  - BETO Model Harmonization (Multi-Lab)
- Nine remaining FY19 milestones

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5 – Future Work (FY20): Continued BETO and Industry Support

- Use the BAT to identify locations and associated pathways that can achieve the MYPP 2020 target to "model the sustainable supply of 20 million metric tonnes AFDW cultivated algal biomass".
- Biomass forecasting system
  - Complete development and testing of short/seasonal range biomass forecasting system
  - Develop web-based interface for biomass forecasting system
- More realistic biomass growth modeling
  - Better representation of transition in algal strain rotation
  - Consider pond crashes
  - Ensemble-based approach to represent model and observational uncertainty
- Use of alternative sources of water and nutrients
- Continued BETO State of Technology support

Summary

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
  - Support for State of Technology Reports
  - Support for Waste-to-Energy
  - 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:

- 19 peer reviewed publications (4 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 (2012 President's Energy Policy Speech)

Thank you

Additional Slides

- ❑ Responses to Previous Reviewers' Comments
- ❑ Publications, Patents, Presentations, Awards, and Commercialization

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Responses to Previous Reviewers' Comments

Comment: The overall approach is excellent. Comparisons of the potential of freshwater vs. saline strains will continue to be of high importance given BETO's decision to move toward saline. This should also be harmonized with others' TEA and LCA models to refine cost differences for the two options. Seasonality studies also represent very important work.

Response: The multi-lab (ANL, NREL, PNNL) working group updated and implemented rigorous RA/TEA/LCA data and models considering both fresh and saline water sources. This effort was a focused on establishing requirements to meet future goals considering:

- Potential for algal biofuel costs (minimum fuel selling price)
- Environmental sustainability (waste CO2 utilization, GHGs, and water availability)
- National scale biomass and fuel output with realistic resource constraints

We estimated both production potential and costs for both fresh and saline water sources using CAP and HTL conversion technologies.

Publications, Patents, Presentations, Awards, and Commercialization

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Peer Reviewed Publications

- 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

Peer Reviewed Publications (continued)

- 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
- 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.

Publications, Patents, Presentations, Awards, and Commercialization

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Peer Reviewed Publications (continued)

- Huesemann, M.H., M. Wigmosta, B. Crowe, P. Waller, A. Chavis, S. Hobbs, B. Chubukov, V.J. Tocco, and A. Coleman. 2016. Estimating the maximum achievable productivity in outdoor ponds: Microalgae biomass growth modeling and climate-simulated culturing, In: Micro-Algal Production for Biomass and High-Value Products, Dr. Stephen P. Slocombe and Dr. John R. Benemann (Eds.), CRC Press, Taylor and Francis, LLC, ISBN 9781482219708.
- Huesemann, MH, T. Dale, A. Chavis, B. Crowe, S. Twary, A. Barry, D. Valentine, R. Yoshida, M.Wigmosta, V. Cullinan. 2016. Simulation of outdoor pond cultures using indoor LED-lighted and temperature-controlled raceway ponds and Phenometrics photobioreactors, Algal Research 21:178-190, doi.org/10.1016/j.algal.2016.11.016.
- Huesemann MH, BJ Crowe, P Waller, AR Chavis, SJ Hobbs, SJ Edmundson, and MS Wigmosta. 2016. A Validated Model to Predict Microalgae Growth in Outdoor Pond Cultures Subjected to Fluctuating Light Intensities and Water Temperatures. Algal Research 13:195-206. doi:10.1016/j.algal.2015.11.008.
- Wigmosta MS, A Coleman, E Venteris, and R Skaggs. 2017. "Microalgae Feedstocks for Aviation Fuels." Chapter 11 in Green Aviation: Reduction of Environmental Impact Through Aircraft Technology and Alternative Fuels, ed. ES Nelson and DR Reddy. CRC Press, BOCA RATON, FL.
- Huesemann M H, Dale T ,Chavis A R, Crowe B J, Twary S ,Barry A ,Valentine D C, Yoshida R ,Wigmosta M S, Cullinan V I 2017. "Simulation of outdoor pond cultures using indoor LED-lighted and temperature-controlled raceway ponds and Phenometrics photobioreactors" Algal Research 21():178-190. 10.1016/j.algal.2016.11.016
- Huesemann M H, Chavis A R, Edmundson S J, Rye D K, Hobbs S J, Sun N ,Wigmosta M S. 2018. Climate-Simulated Raceway Pond Culturing: Quantifying the Maximum Achievable Annual Biomass Productivity of Chlorella sorokiniana in the Contiguous USA, Journal of Applied Phycology 30(1):287-298. 10.1007/s10811-017-1256-6
- Hui, X., Lee, U., Coleman, A.M., Wang, M. Wigmosta, M., Wang, M. 2019. Assessment of algal biofuel resource potential in the United States with consideration of regional water stress, Algal Research 37:30-39.