DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

1.3.1.500 Sustainable Development of Algae for Biofuel

March 6, 2017

Advanced Algal Systems Platform

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Oak Ridge National Laboratory

Environmental Sciences Division

U.S. DEPARTMENT OF ENERGY

ORNL is managed by UT-Battelle
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Goal Statement: Putting the "sustainable" in sustainable biomass and biofuel

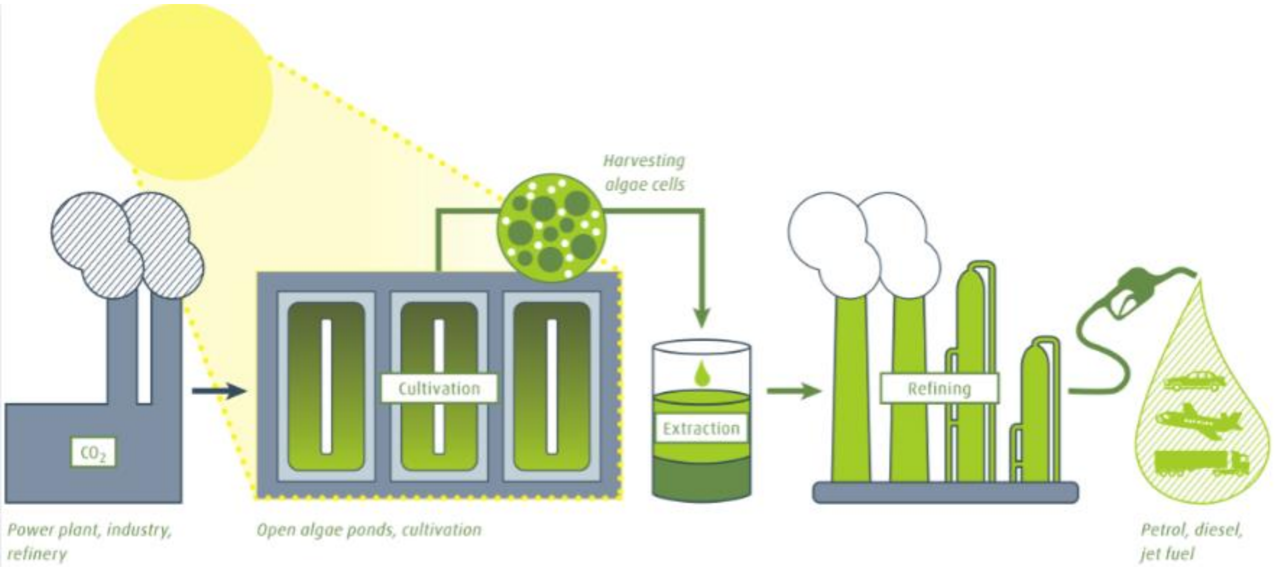
How?

Define indicators of sustainable algal biofuels.

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

Focus on key challenges for algae commercialization.

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



The Linde Group, with permission

Quad Chart Overview

Timeline

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

Barriers

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

Budget

	(K)		
	FY 16	FY 17	FY 18 plan
New BA	265	83	400

Partners

- Contractor: Longitude 122 West, Inc.
- U Tennessee, UC San Diego, U Kansas
- National labs: **(**PNNL, INL, SNL, NREL, ANL)
- Algae Biomass Organization (unfunded)

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How do we measure or model sustainability?

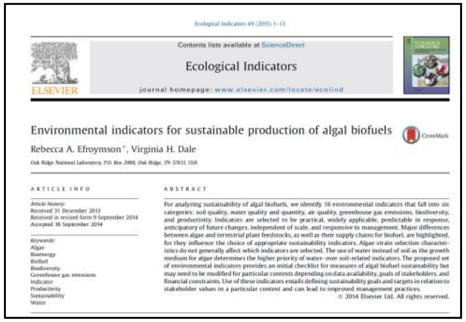
Environmental indicators

Category	Indicator
Soil quality	1. Bulk density
Water quality	2. Nitrate export
	3. Total P export
	4. Salinity
Water quantity	5. Peak storm flow
	6. Minimum base flow
	7. Consumptive water use
Greenhouse gases	8. CO_2 equivalent emissions (CO_2 and N_2O)

Category	Indicator
Biodiversity	9. Presence of taxa of special concern
	10. Habitat area of taxa of special concern
	11. Abundance of released algae
Air quality	12. Tropospheric
	13. Carbon monoxide
	14. Total particulate matter less than 2.5µm diam
	15. Total particulate matter less than 10µm diam
Productivity	16. Primary productivity or yield

Uses of sustainability indicators

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


Ecological Indicators 49 (2015) 1–13

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journal homepage: www.elsevier.com/locate/ecolind

Environmental indicators for sustainable production of algal biofuels

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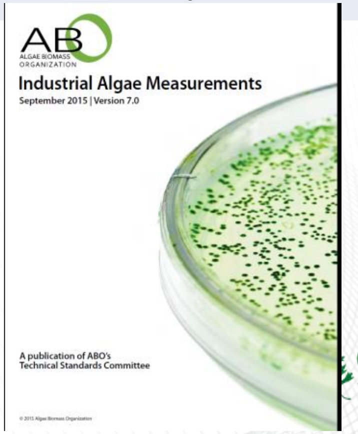
ABSTRACT

For analyzing sustainability of algal biofuels, we identify 16 environmental indicators that fall into six categories: soil quality, water quality and quantity, air quality, greenhouse gas emissions, biodiversity, and productivity. Indicators are selected to be practical, widely applicable, predictable in response, anticipatory of future changes, independent of scale, and responsive to management. Major differences between algae and terrestrial plant feedstocks, as well as their supply chains for biofuel, are highlighted, for they influence the choice of appropriate sustainability indicators. Algae strain selection characteristics do not generally affect which indicators are selected. The use of water instead of soil as the growth medium for algae determines the higher priority of water- over soil-related indicators. The proposed set of environmental indicators provides an initial checklist for measures of algal biofuel sustainability but may need to be modified for particular contexts depending on data availability, goals of stakeholders, and financial constraints. Use of these indicators entails defining sustainability goals and targets in relation to stakeholder values in a particular context and can lead to improved management practices.



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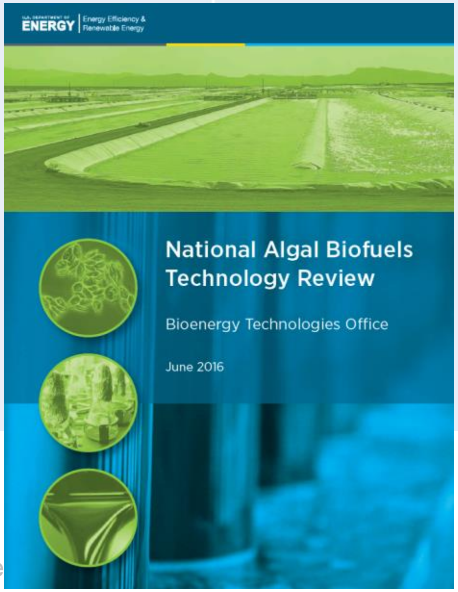
Socioeconomic indicators

General → Site specific

Small scale → Large scale

Uncertain ↓ More certain

	Laboratory or single process	Pilot plant	Commercial plant or collection of plants
Modeling	• Fossil EROI	• ROI • Fossil EROI • *Risk of catastrophe*	• Employment • ROI • NPV • Fossil EROI • *Risk of catastrophe*
Measurement	• Work days lost to injury	• Employment • Worker income • Work days lost to injury • EROI • *Public opinion* • *Effective stakeholder participation* • *Transparency*	• *Food security* • *Employment* • *ROI* • *NPV* • *Energy security premium* • *Fuel price volatility* • *Terms of trade* • *Trade volume* • *Depletion of non-renewable energy resources* • *Fossil EROI* • *Effective stakeholder participation* • *Transparency* • *Public opinion* • *Work days lost to injury* • *Household income*



Italics = expected to be measured or modeled in future

Project Overview and Objectives

Sustainability Indicators

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

Indicators completed FY16
BMPs in FY18

Potential for National Sustainable Biomass Supply

- Estimate potential algae biomass resources at different prices using co-location with CO_2 sources ***(BT16* volume 1)**

Completed FY16

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

Completed FY17

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

Water focus in FY17

Science to Address Sustainability Challenges

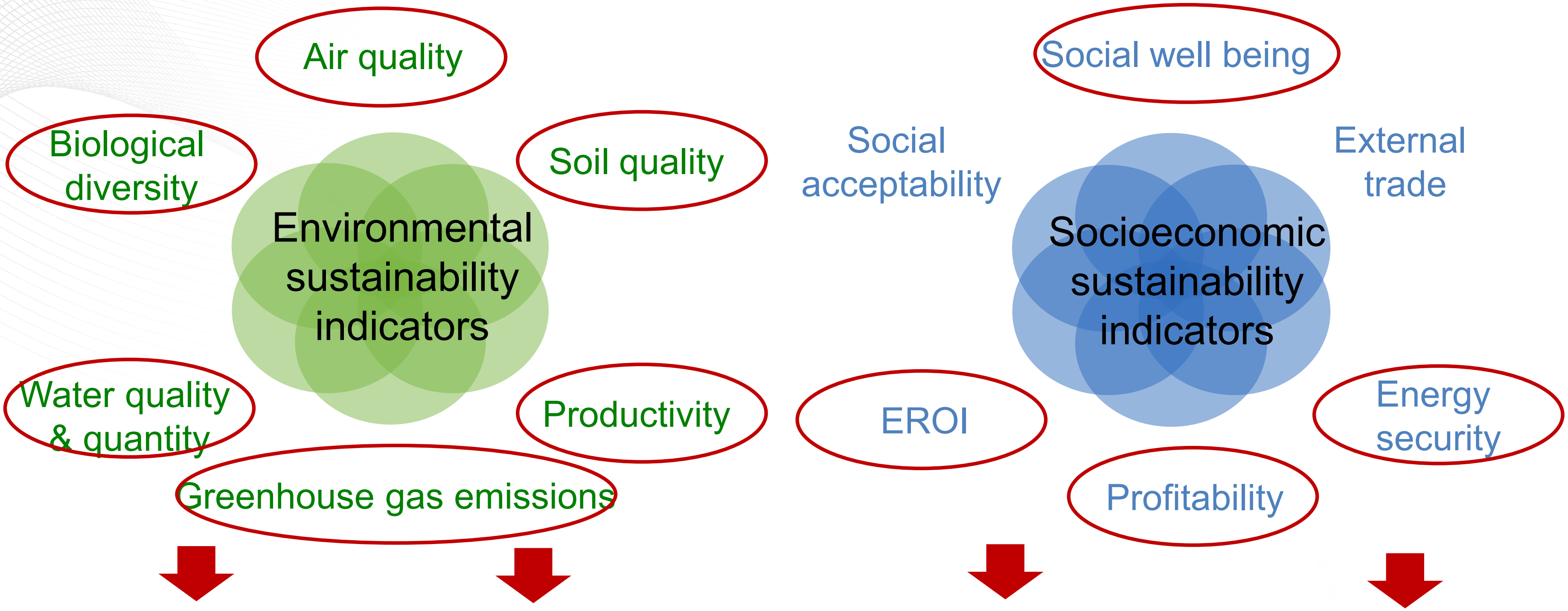
- Develop ecological strategies (polycultures) to scale up production
  - Identify and exploit biological traits in algae that facilitate greater stability and productivity and use nonpotable water

Ends in FY17 Q4

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

Funding ended in FY16
MS thesis extended to FY17 Q3

Project Overview—Pictorial Version



Project addresses

- 10 categories of sustainability
- Intersection between resource analysis and sustainability (modeling)
- Solutions to key productivity and profitability challenges that also have sustainability consequences

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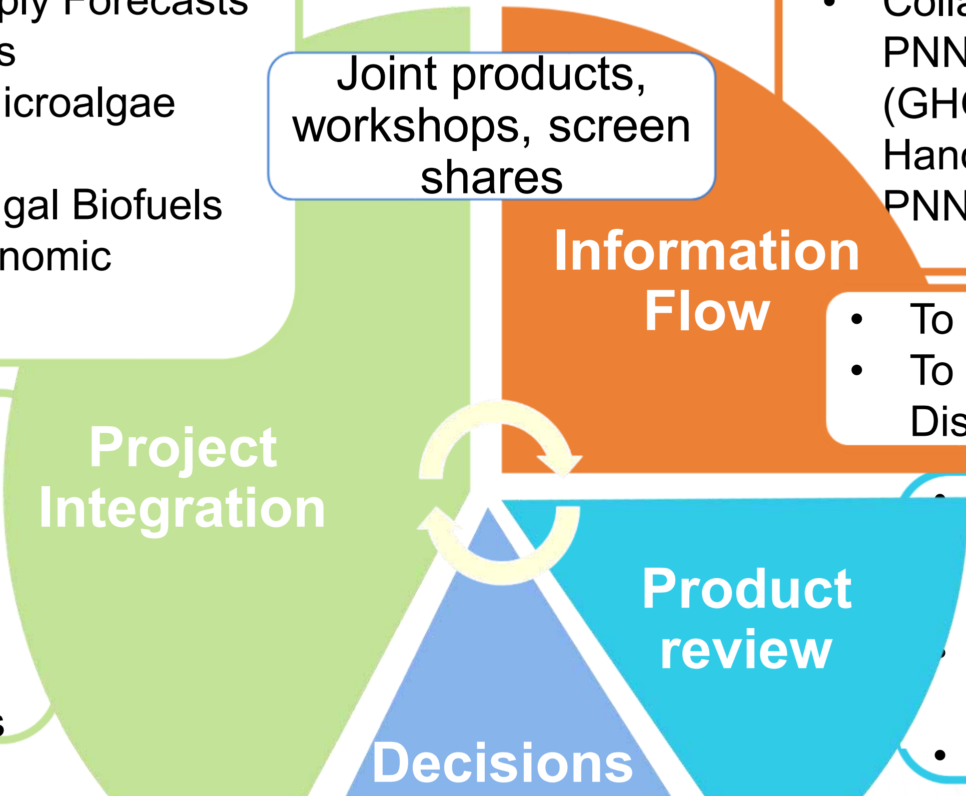
Management Approach

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

- Weekly to monthly calls with PNNL, Longitude 122 West, Inc.
- Collaboration with PNNL (water) and ANL (GHG)
  Handoffs to and from PNNL, NREL

Joint products, workshops, screen shares



- To and from industry
- To DOE and Knowledge Discovery Framework

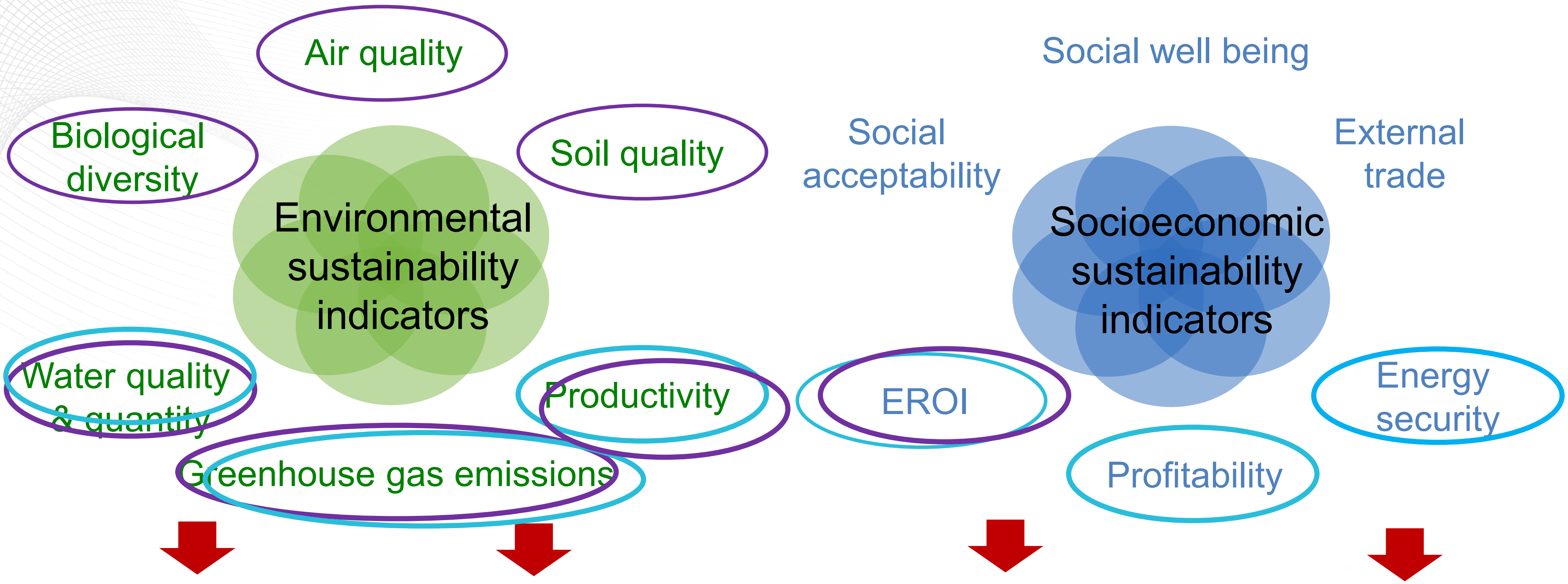
Algae model harmonization
- 4.1.1.10 GREET Development Biofuel Pathway Research and Analysis
- & *BT16* collaborators

- Consultation with Algae Biomass Organization
- *BT16* peer review workshops
- DOE review

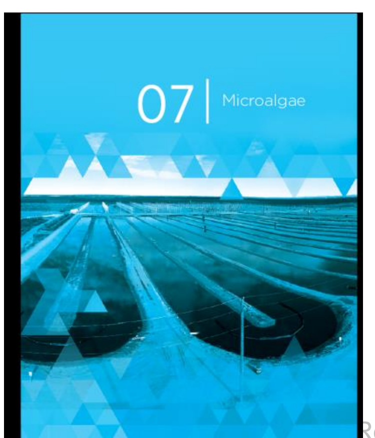
Sustainability Indicators
- 4.2.2.40 Bioenergy Sustainability: How to Define and Measure it

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

Objectives—Billion Ton (*BT16*)

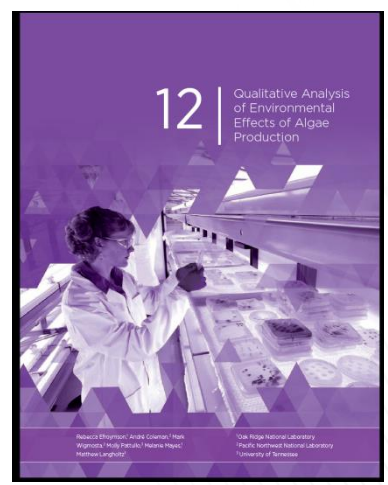


***BT16* volume 1**



- Incorporate algae (for the first time) into a *BT* report
- Quantify potential site-specific to national feedstock production and cost
- Focus on open ponds
- Focus on strategies to reduce production costs
- Use waste CO_2

***BT16* volume 2**



- Describe environmental effects
- Estimate water consumption

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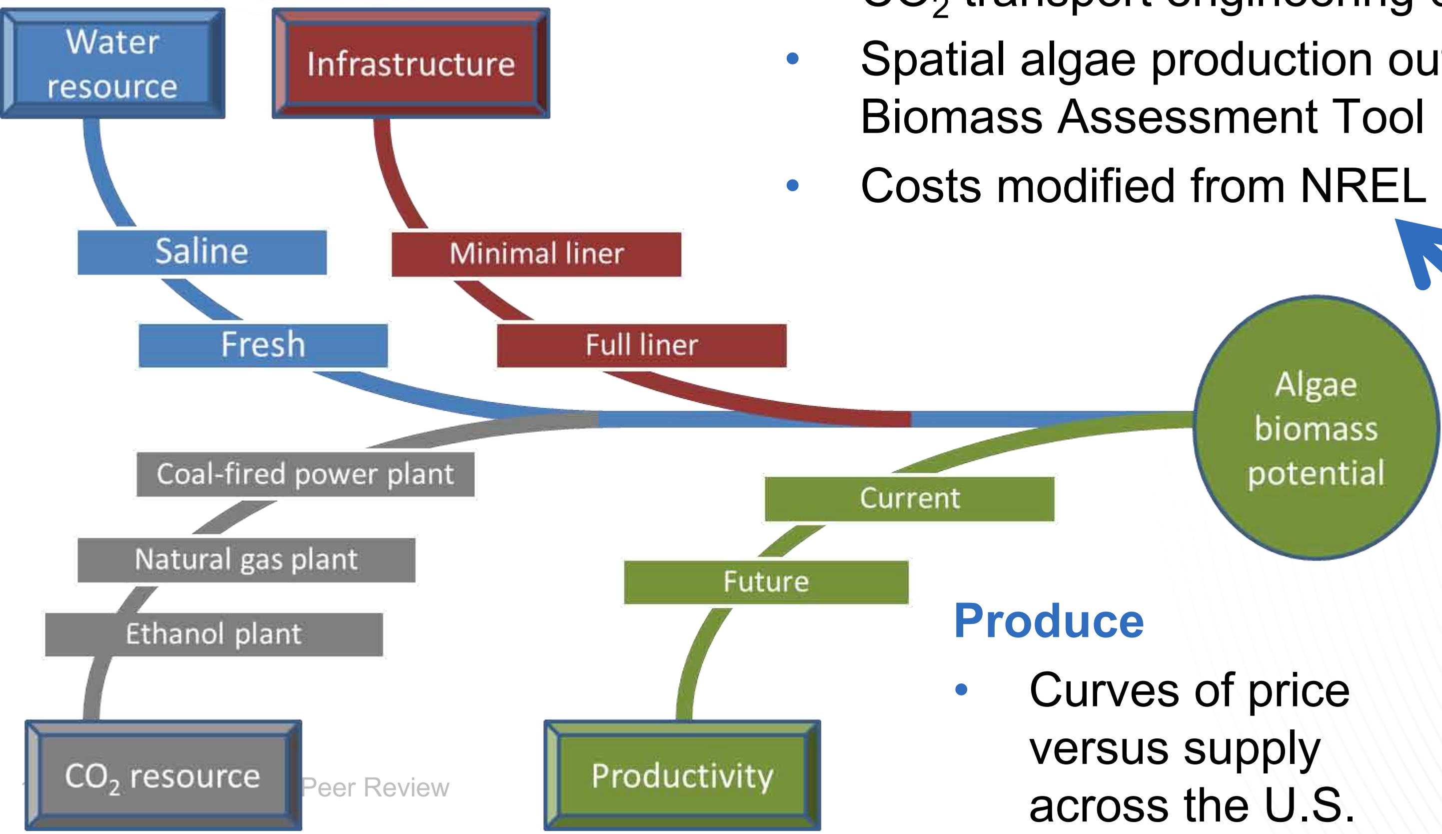
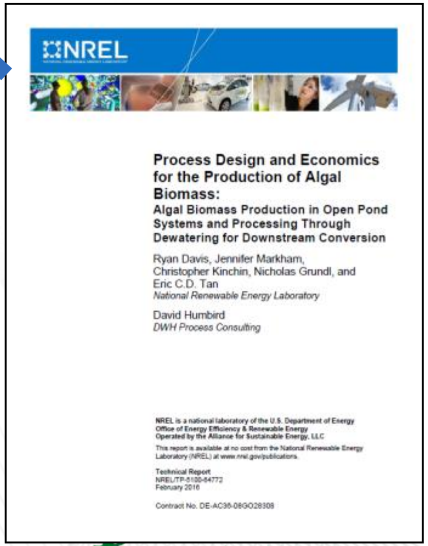
Approach—*BT16* volume 1

- Use CO_2 flue gas instead of purchase
- Assume 100 10-acre ponds
- Strains: *Chlorella sorokiniana, Nannochloropsis salina*
- Productivities: ~13 $g/m^2/d$ or ~25 $g/m^2/d$

Integrate

- CO_2 transport engineering design and costs
- Spatial algae production output from PNNL Biomass Assessment Tool
- Costs modified from NREL design case report




NREL

Process Design and Economics for the Production of Algal Biomass:
Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion

Ryan Davis, Jennifer Markham, Christopher Kinchin, Nicholas Grundl, and Eric C.D. Tan
National Renewable Energy Laboratory

David Humbird
DWH Process Consulting

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

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5100-64772
February 2016

Contract No. DE-AC36-08GO28308

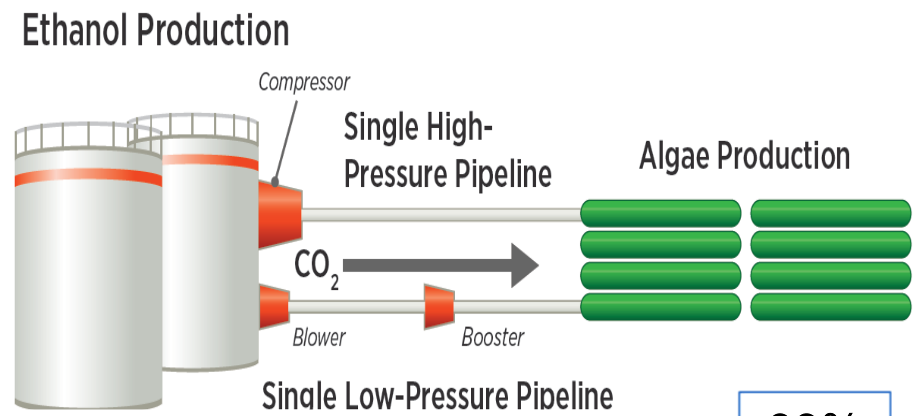
Produce

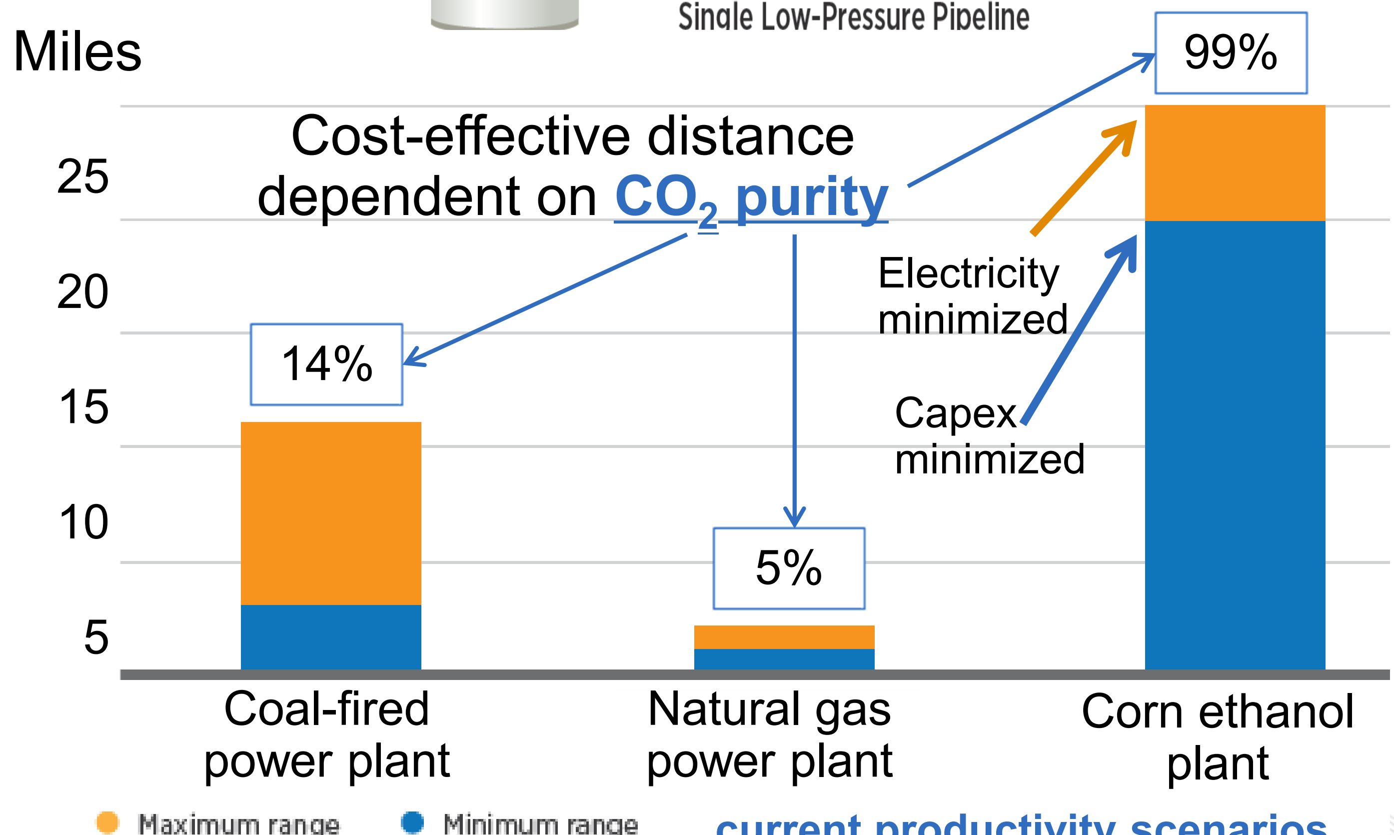
- Curves of price versus supply across the U.S.

Cost-effective distance for CO_2 transport is dependent on CO_2 purity—*BT16* volume 1

GHG Implications
"[some algae] pathways satisfy the RFS2 criteria of advanced biofuels only when the CO_2 is supplied by low-pressure flue gas transported over short distances." 2016 Argonne report

Engineering design based on CO_2 purity



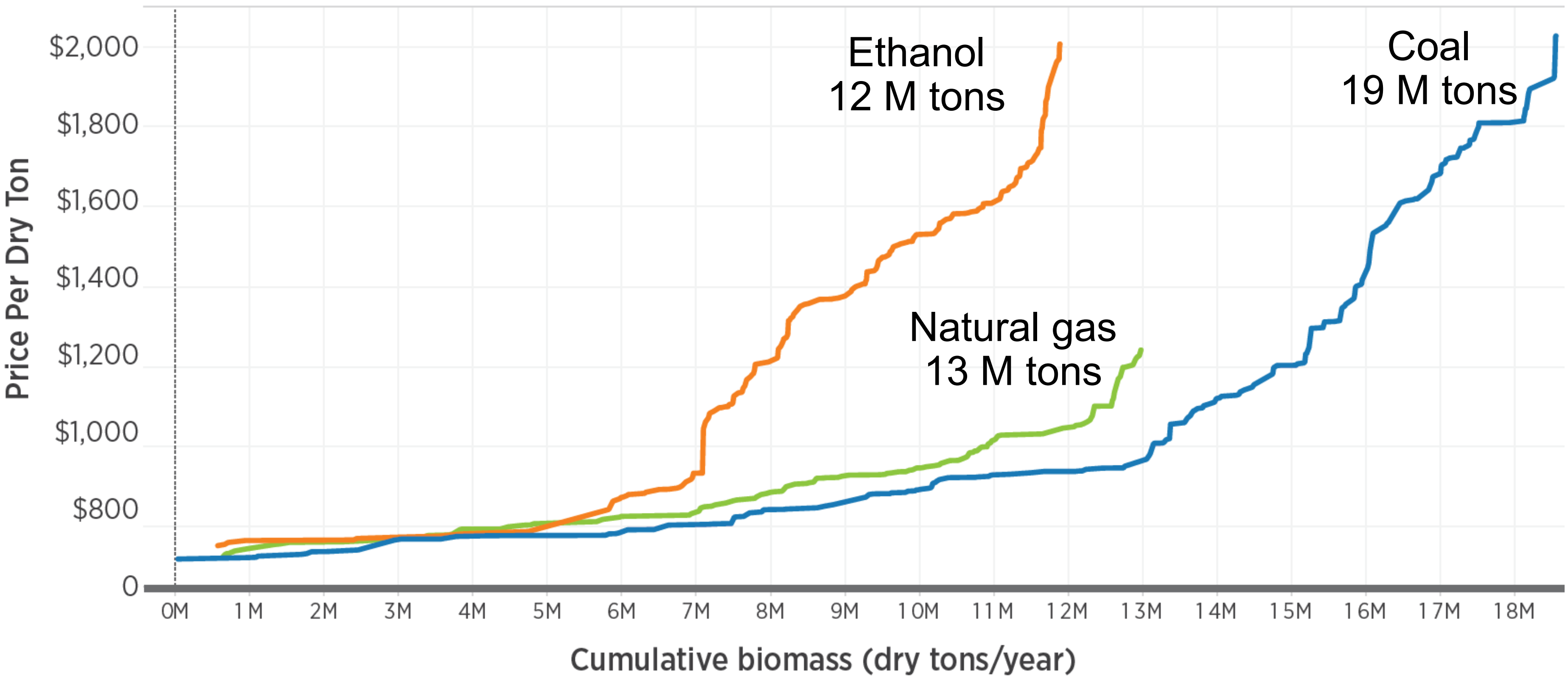


current productivity scenarios

Cost Relevance is on next slide

Biomass supply curves show substantial national biomass potential at high price ranges

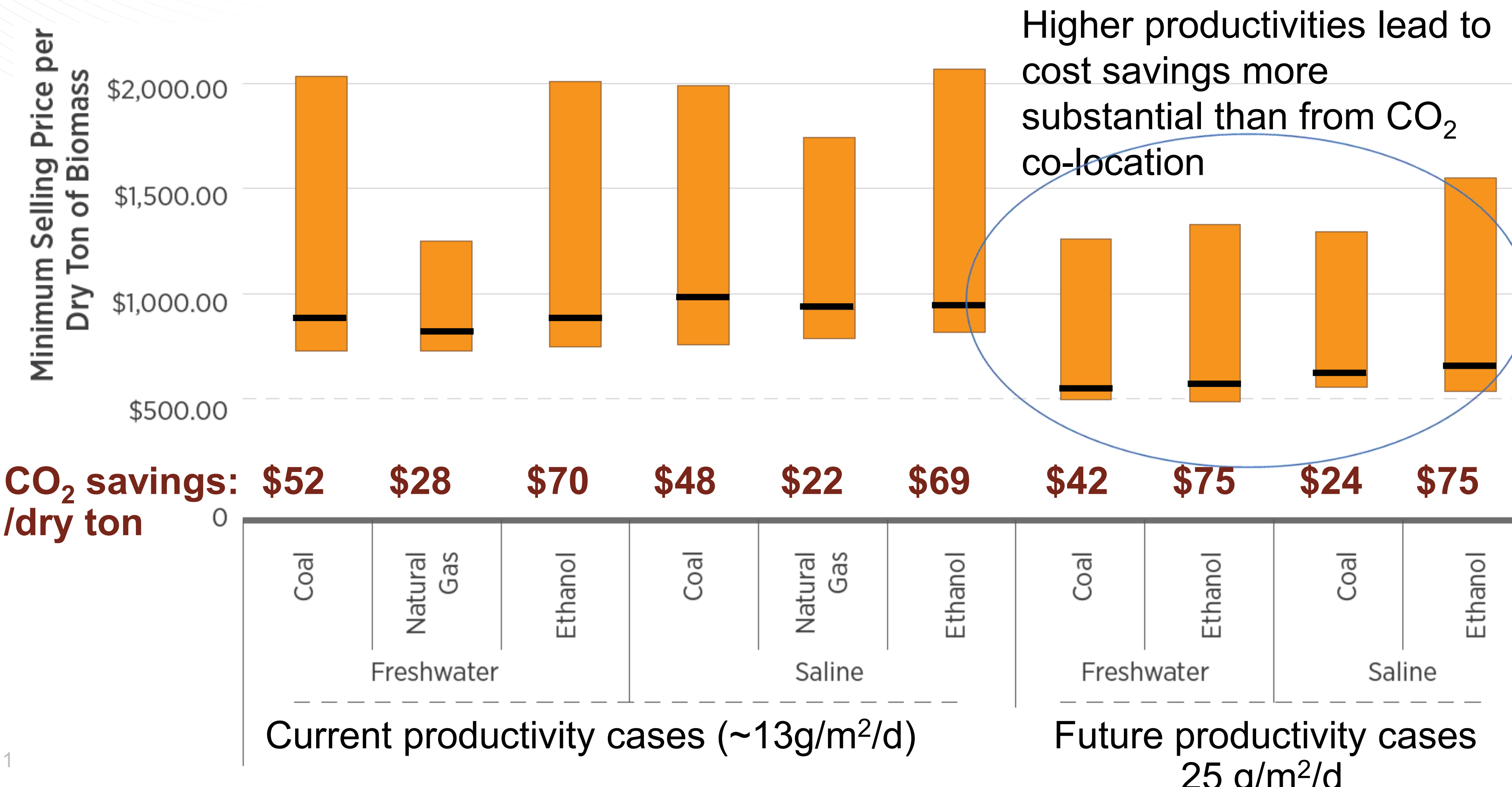
- Biomass supply and price depend on the scenario
- In this freshwater example, more biomass is potentially available at lower prices when coal-fired power plants are the CO_2 source



Present productivities, minimally lined ponds, *C. sorokiniana*

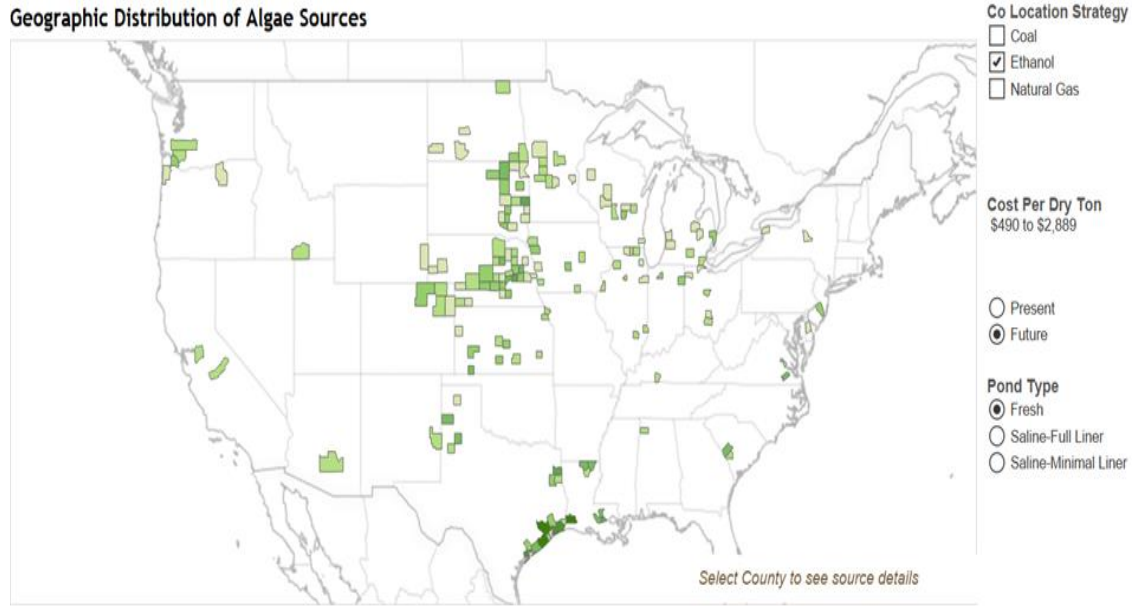
Synthesis of Results for *BT16* volume 1

- Clear but small relative cost savings for CO_2 co-location ($/ton biomass), except for natural gas source under high productivity



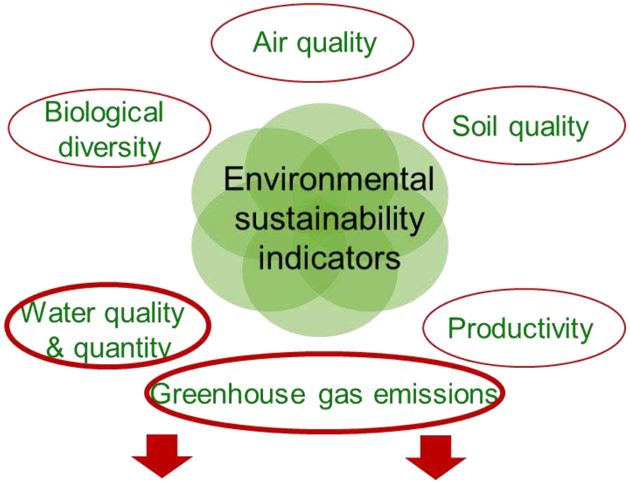
Maps and user interface—*BT16* volume 1

Go to https://bioenergykdf.net/billionton2016/7/1/tableau and change the variables (including price range) to see custom visualizations of maps, supply curves, and bar graphs



From DOE Bioenergy Knowledge Discovery Framework

Tradeoffs and synergies exist between cost and environmental sustainability—*BT16* volume 2

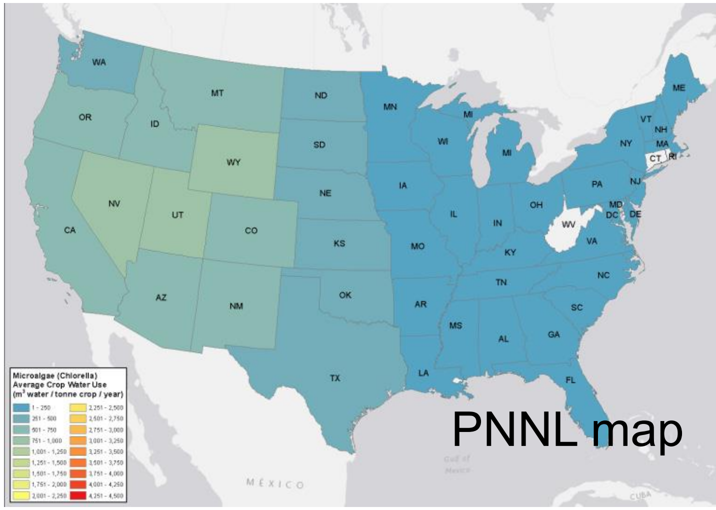


Objectives

- Conduct qualitative environmental analysis of *BT16* scenarios to evaluate
  - CO_2 co-location
  - Saline vs freshwater
  - Fully vs minimally lined ponds
  - High vs current productivities
- Describe water consumption estimated in *BT16* scenarios (PNNL)

Example results

- Some cost-saving measures (co-location with CO_2 and minimally lined ponds) also reduce GHG emissions.
- Biomass is more sustainable if water stress measures and timing of demand are considered, not just mean annual basin flow
- Targets can be identified: e.g., hydraulic conductivity of 1 X 10^{-7} cm/s prevents leaching into subsurface (unlined ponds).



PNNL map

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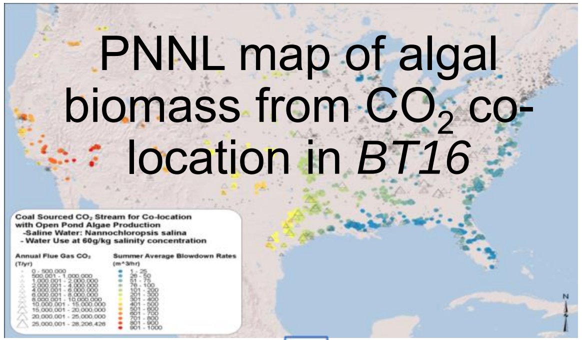
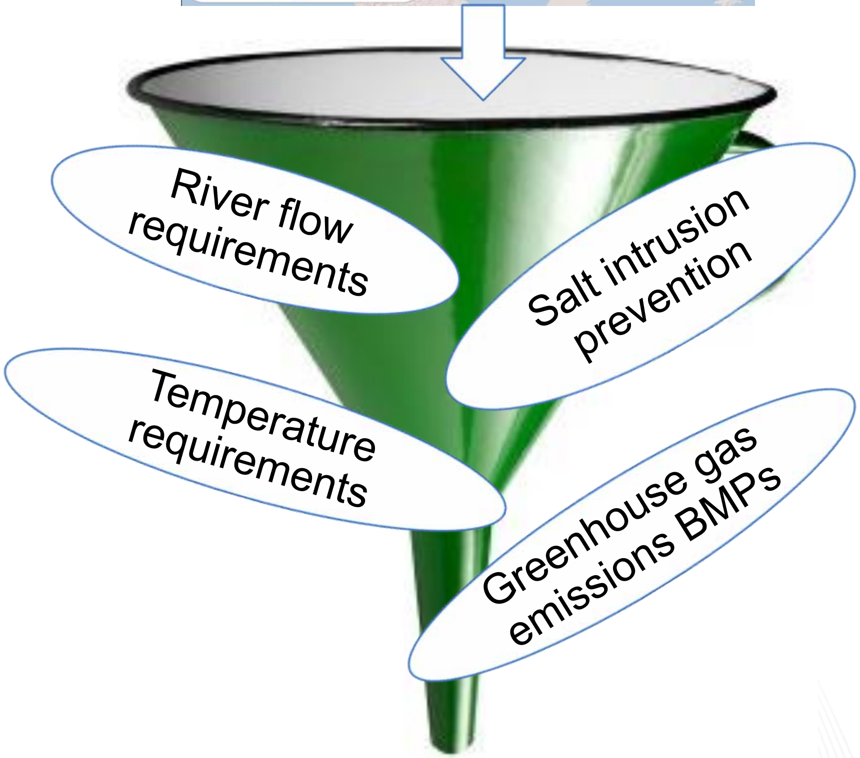
Approach and Results—Meet 2017 Multiyear Program Plan Goal

- Working paper with PNNL in FY16 proposed definition and process to finalize sustainability targets and data needed to support resource modeling.
- Milestone will move toward sustainable biomass production, emphasizing water.
- More sustainability constraints will be incorporated in the future.
- Regions in southeastern Arizona and the Gulf Coast of Texas are being examined, then considering national scale.





1 million metric tonnes of “sustainable” algae biomass

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Can we increase productivity by using polycultures?

Air quality

Biological diversity

Soil quality

Environmental sustainability indicators

Water quality & quantity

Productivity

Greenhouse gas emissions

Social well being

Social acceptability

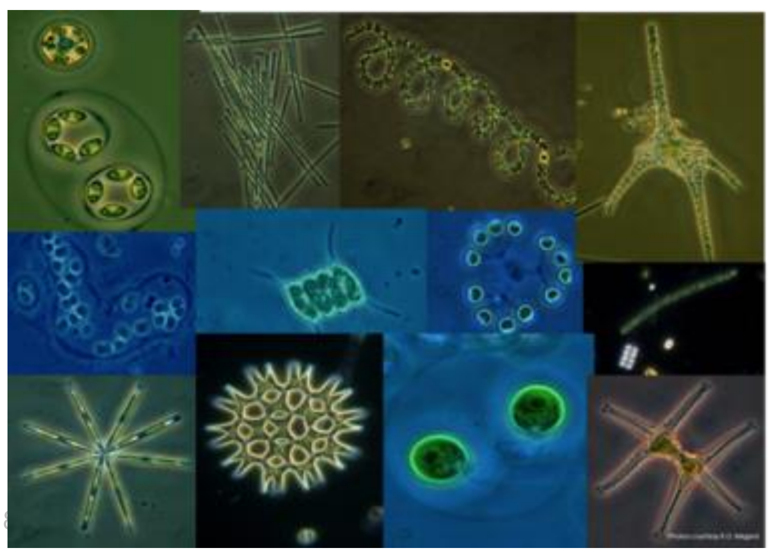
External trade

Socioeconomic sustainability indicators

EROI

Energy security

Profitability



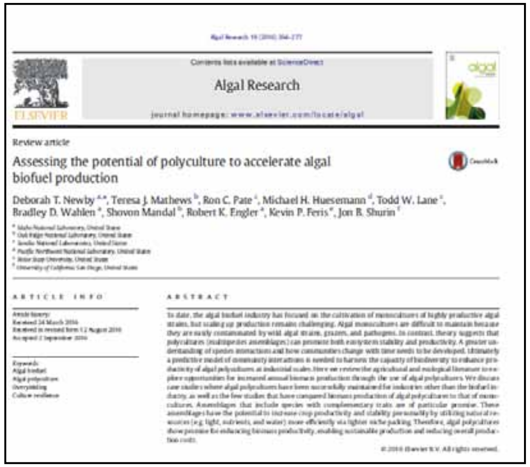
Productivity limits profitability.
How can we increase productivity?

Conclusion: Mixed cultures in wastewater can increase productivity, use N more efficiently, and increase crop reliability

Approach—Ecological strategies for production

Background

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



Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Review article

Assessing the potential of polyculture to accelerate algal biofuel production

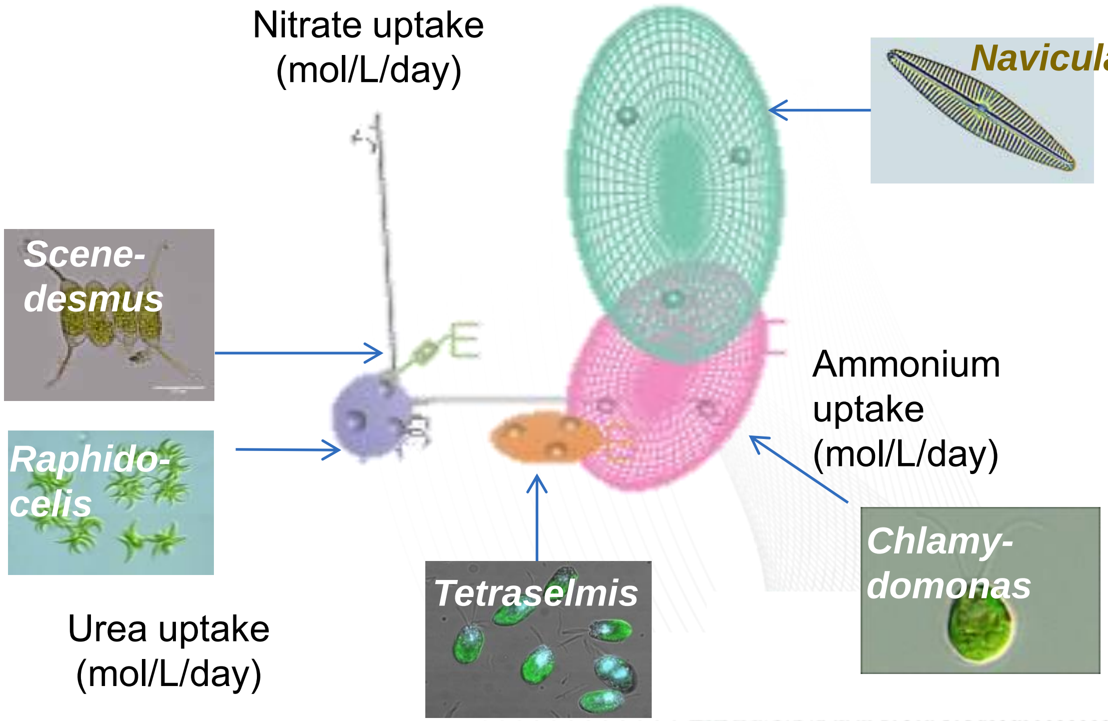
Deborah T. Newby, Teresa J. Mathews, Ron C. Pate, Michael H. Huesemann, Todd W. Lane, Bradley D. Wahlen, Shovon Mandal, Robert K. Engler, Kevin P. Feris, Jon B. Shurin

ARTICLE INFO

ABSTRACT

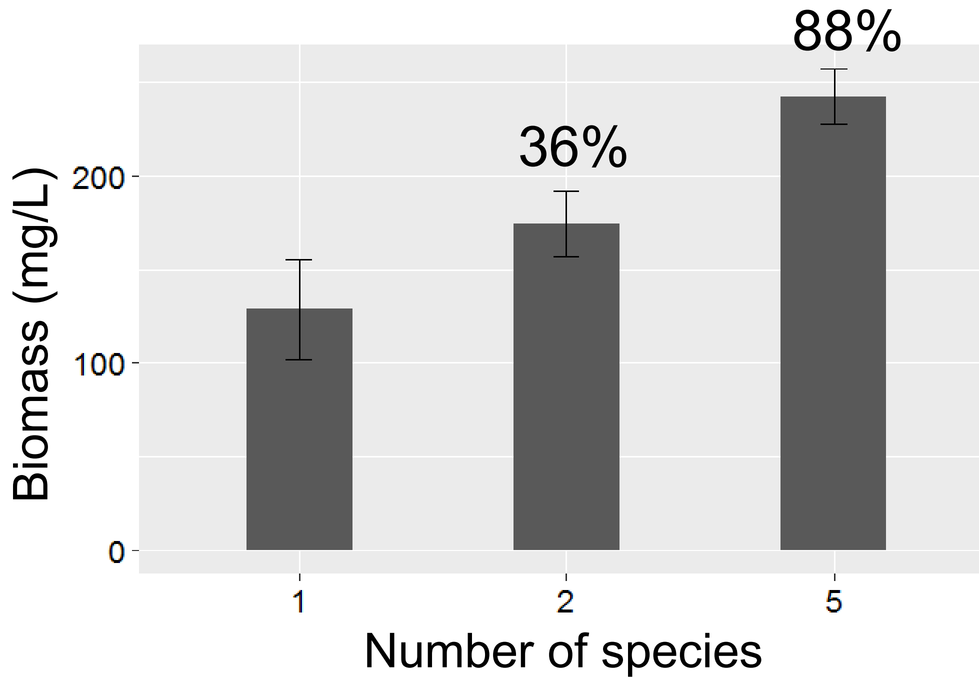
Objectives

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

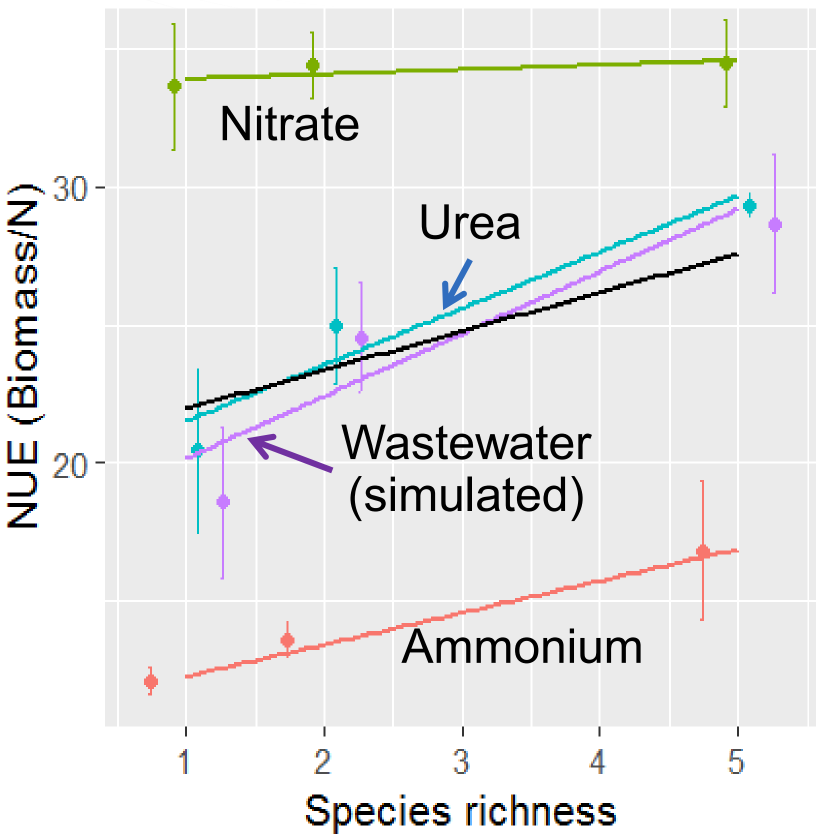


Polycultures increase productivity and nutrient use efficiency

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



Why?

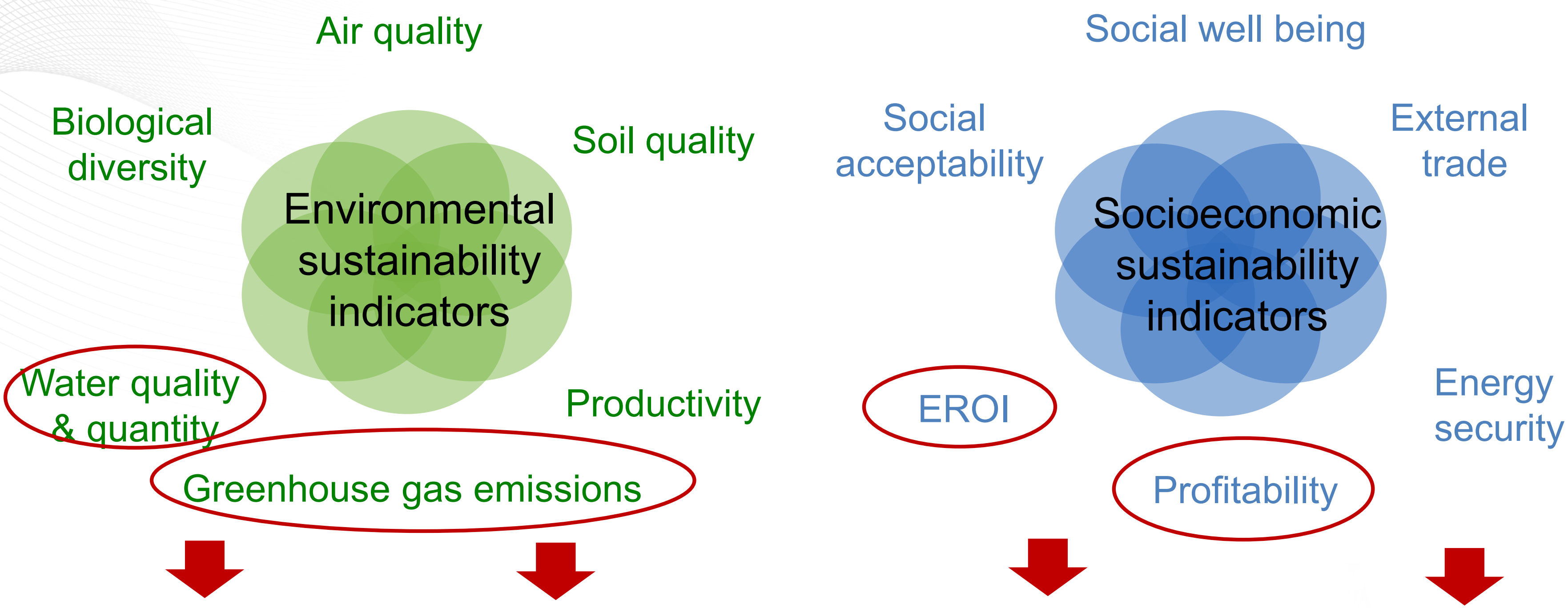


- Nutrient Use Efficiency (NUE)

$$\mathrm{NUE} = \frac{g\ \mathit{Biomass\ produced}}{\mathrm{g\ Nitrogen\ used}}$$

- NUE increases with species richness in wastewater.
- Algae grown in nitrate showed highest NUE and productivity but is most costly.

Can we eliminate the use of pond liners?



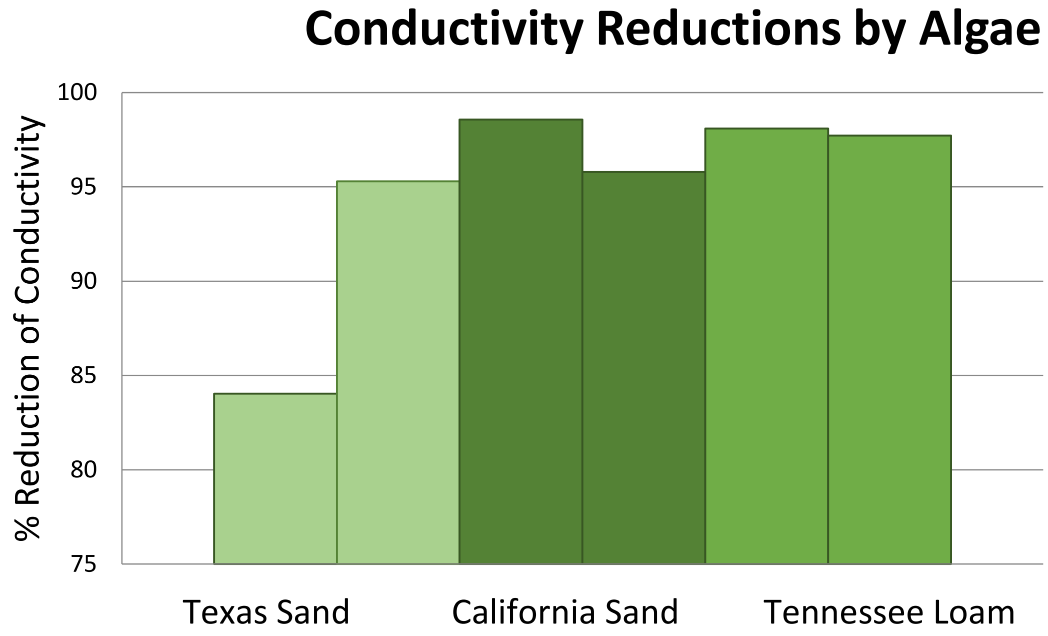
- Plastic pond liners (1/4 of capex) limit profitability and GHG benefits.
- Can we eliminate pond liners in native soils?

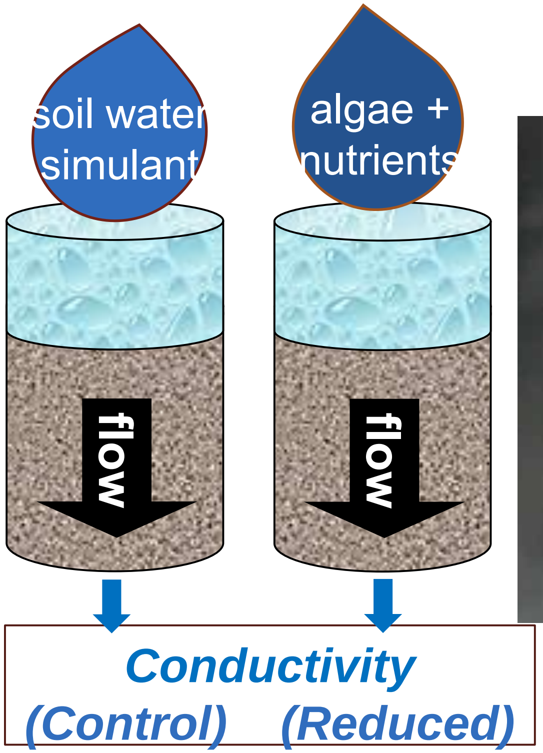
Our proof of concept shows that clogging by algae or bacteria reduces hydraulic conductivity and could protect water quality and quantity.

Proof of Concept for Unlined Ponds

Objective

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



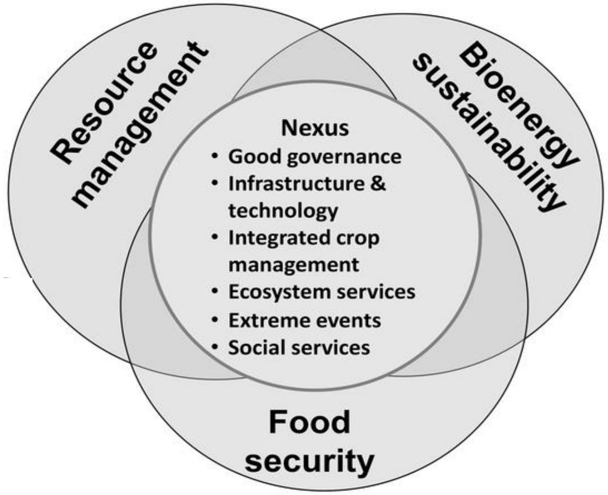


- Soils with swelling clays were nearly impermeable
- Conductivity of coarse soils decreased due to clogging by algae
- Still need to reach **target~10^{-7} cm/s**
- Compacting soils during construction could enable technology

Future work—FY18—Food Security Task

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

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



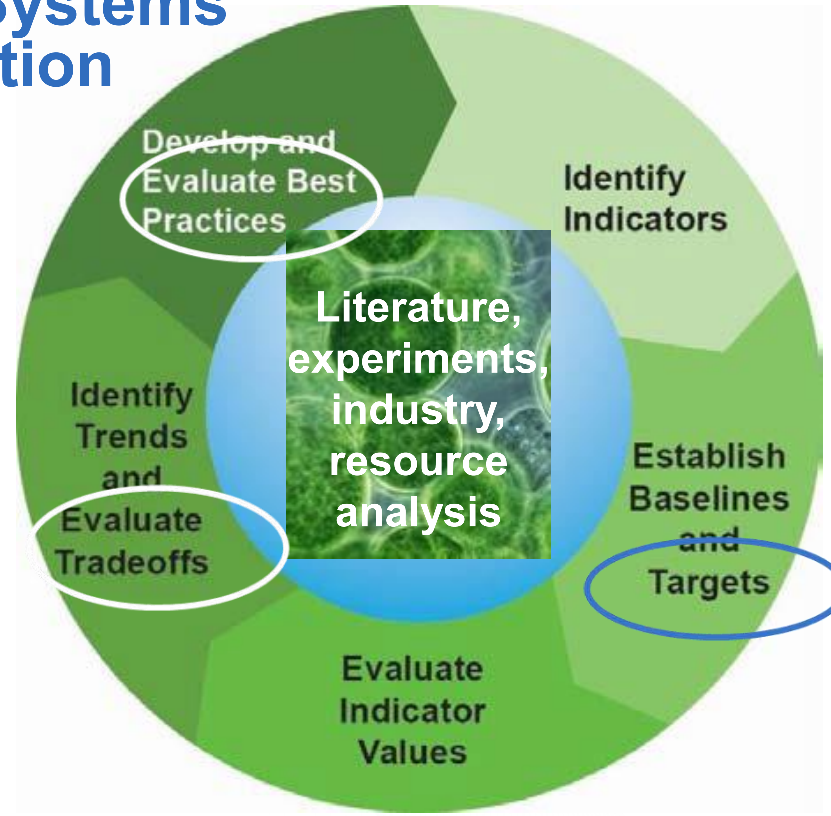
From project 4.2.2.30

Algae provide protein, baking flour, nutritional oils, antioxidants, livestock feed, food colors, biofertilizer.

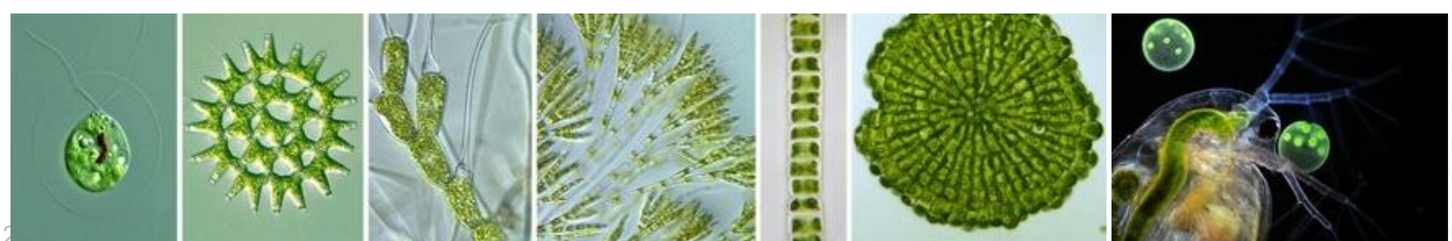
Future work—FY18—Best Management Practices

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

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



From DOE/BETO analysis and sustainability program



Future work—FY18 and beyond—Resource Analysis*

- Consider photobioreactors, including fuel secretion pathways
- Incorporate co-location with wastewater treatment plants
- Incorporate additional co-location with CO_2
- Incorporate co-products
- Understand where unlined ponds maintain water quality and quantity

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

Relevance and Impact

Task	Impact
Sustainability indicators	• Adopted by Algae Biomass Organization (ABO) 2015 *Industrial Algae Measurements Version 7.0*; used by industry
BT16 reports	• 1st US algae resource analysis that includes cost • Potential cost savings from use of waste CO_2 • Importance of productivity and liners in cost • "Landmark publication" for industry (Matt Carr, ABO) • Low pressure CO_2 transport may satisfy RFS2 criteria (ANL)
	Potential impact
Ecological strategies for scaling up production	• Increase in productivity with polyculture • Wastewater use→improvement in water quality and freshwater consumption and reduction in cost • Fewer pond crashes (lit review)
Proof of concept-unlined ponds	• Reduction in hydraulic conductivity, even for sandy soils • Cost savings of $100/ton (current productivities) or $200/ton (future productivities) (*BT16* and NREL) • Reduction in GHG emissions, increase in EROI (ANL, literature)

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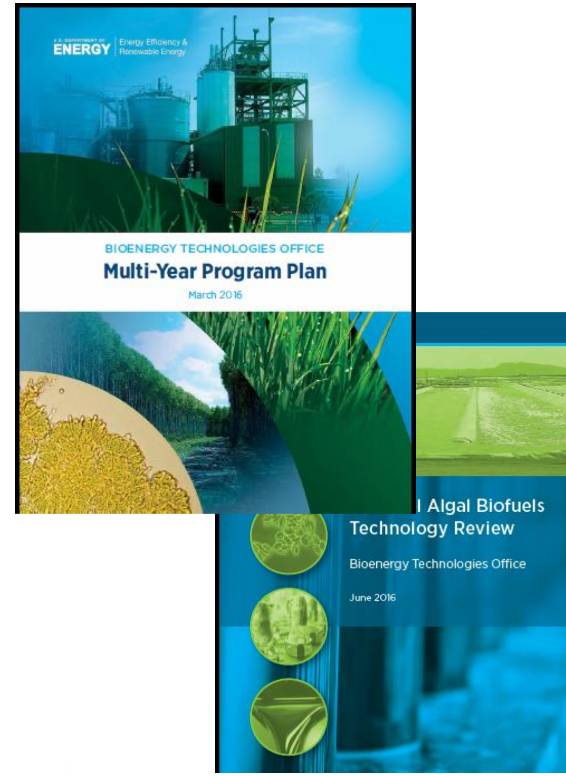
Relevance of Project Goals to BETO Goals

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



Relevant to DOE Advanced Algal Systems goals

. . . 5 billion gallons per year of sustainable, reliable, & affordable algal biofuels by 2030

- By 2017, model sustainable supply of 1 million metric tonnes AFDW cultivated algal biomass
- By 2022, model sustainable supply of 20 million metric tonnes . . .

Relevant to DOE Sustainability Area goals

To understand and promote positive economic, social, and environmental effects and reduce potential negative impacts of bioenergy production

- By 2022, evaluate environmental and socioeconomic indicators across the supply chain for . . . algal bioenergy production systems.

Relevant to DOE Terrestrial Feedstock Supply and Logistics goals

- By 2016, produce . . . assessment of potentially available feedstock supplies . . .

Additional Slides

Acknowledgments

Project team

Oak Ridge National Laboratory
- Virginia Dale
- Henriette Jager
- Matthew Langholtz
- Shovon Mandal
- Teresa Mathews
- Melanie Mayes

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- Molly Pattullo

Longitude 122 West, Inc.
- Susan Schoenung

University of Kansas
- Val Smith

UC San Diego
- Jonathan Shurin

Collaborators

Pacific Northwest National Lab
- André Coleman
- Mark Wigmosta

National Renewable Energy Lab
- Ryan Davis

Reviewers of Billion Ton report algae chapters

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

Additional Advice on Billion Ton report

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

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

DOE Sponsors
Dan Fishman, Devinn Lambert

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Responses to Previous Reviewers' Comments

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

Response: We did not emphasize the inter-laboratory collaborations in our last peer review presentation, though we were collaborating with PNNL at the time. In the past two years, the Billion Ton resource analysis (volume 1) and environmental effects analysis (volume 2) have been done in collaboration with PNNL, and volume 1 in collaboration with NREL. ANL reviewed volume 2, and their research influenced our future CO_2 co-location scenarios. We are engaged with the inter-laboratory model harmonization team, participating in milestones. We are working with PNNL on the 2017 MYPP goal to model 1 million tonnes of sustainable algae biomass and have held discussions with ANL on the topic as well.

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Responses to Previous Reviewers' Comments

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

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

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

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

Responses to Previous Reviewers' Comments

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

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

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

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

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Reviewer Comments on Billion Ton (*BT16*) reports in late 2015

ABO reviewers in special review meeting at Algae Biomass Summit 2015

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

Peer review workshop on *BT16* volume 1

- Include saline scenarios that have minimal or no pond liner in *BT16.*
  - Response: Added
- Include photobioreactors in the next resource analysis as soon as possible.
  - When engineering, cost, and productivity parameters are available, we will include PBRs; but biomass may not be the right endpoint for algae that secrete fuel.
- Priority sustainability indicators for *BT16* volume 2 are water consumption and greenhouse gas emissions
  - These priority indicators were analyzed.

Highlight from Go/No-go Review

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

DOE Response

- Milestone delayed so that ORNL and partners can deliver a detailed research plan and preliminary assessment of available data for modeling 1 million metric tons of sustainable biomass, per definition. [This plan was delivered in FY16 Q4.]
  - Consider feedback from the 2013 Peer Review, contributions to BT16, continued integration of sustainability indicators with analysis projects (RA, TEA, LCA).
- Submit research plan that outlines timeline for defining sustainability, with inclusion of a freshwater and salt water scenario, and collaboration with Harmonization team for defining sustainability and modeling FY17 MYPP goal. [This plan was delivered in FY16 Q4.]
- No further planning requested at this time for the Accidental Release Case Study.

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Acronyms and definitions

Term	Definition
AFDW	Ash-free dry weight
ANL	Argonne National Laboratory
ABO	Algae Biomass Organization
BA	Budget authority
BETO	DOE Bioenergy Technologies Office
BMP	Best management practice
BT16	2016 Billion Ton report
Co-location	Locating an algal biofuel production facility near a source of resources (e.g., CO_2)
EROI	Energy return on investment
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
INL	Idaho National Laboratory
MYPP	Multi-year program plan
NREL	National Renewable Energy Laboratory
NUE	Nutrient use efficiency
PNNL	Pacific Northwest National Laboratory
polyculture	Community with multiple species of algae
resource analysis	Quantification of biomass resources for bioenergy
ROI	Return on Investment
SNL	Sandia National Laboratories
supply curve	Biomass or fuel product versus price

Publications

Efroymson RA, VH Dale. 2015. Environmental indicators for sustainable production of algal biofuels. *Ecological Indicators* 49:1-13

Langholtz M. 2016, Potential land competition between open-pond microalgae production and dedicated feedstock supply systems in the U.S. *Renewable Energy* 93:201-214

*Dale VH, RA Efroymson, KL Kline, MS Davitt. 2015. A framework for selecting indicators of bioenergy sustainability. *Biofuels, Bioproducts and Biorefining* 9:435-446 DOI: 10.1002/bbb.1562

Efroymson RA, VH Dale, MH Langholtz. 2016. Socioeconomic indicators for sustainable design and commercial development of algal biofuel systems. *GCB Bioenergy* doi: 10.1111/gcbb.12359

*Newby D, Mathews T, Pate C, Huesemann MH, Lane TW, Wahlen BD, Mandal S, Engler RK, Feris KP, Shurin JB. 2016. Assessing the potential of polyculture to accelerate algal biofuel production. Algal Research 19:264-277

*Efroymson R, Coleman A, Wigmosta M, Schoenung S, Sokhansanj S, Langholtz M, Davis R. 2016. Microalgae. In. U.S. Department of Energy. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p.

Efroymson R, Coleman A, Wigmosta M, Pattullo M, Mayes M, Langholtz M. Qualitative analysis of environmental effects of algae production. 2017. In U.S. Department of Energy. 2017. 2016 *Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1*. R. A. Efroymson, M. H. Langholtz, K.E. Johnson, and B. J. Stokes (Eds.), ORNL/TM-2016/727. Oak Ridge National Laboratory, Oak Ridge, TN. 642p. doi 10.2172/1338837

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

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

Presentations

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

- Coleman et al. 2016. Opportunities and barriers for waste resource utilization in bioenergy production. International Association for Landscape Ecology, Asheville.
- Coleman et al. 2016. The Billion Ton 2016 Algae Resource Analysis: Waste CO_2 Co-location. Algae Biomass Summit. Phoenix, AZ
- Efroymson, Dale, Langholtz. 2015. Environmental and socioeconomic indicators for sustainable production of algal biofuels. Algae Biomass Summit, Washington, DC
- Efroymson, Langholtz. 2015. The Billion-ton Report and Sustainability Indicators. Algal Harmonization Workshop, Denver.
- Efroymson et al. 2015. The 2016 Billion-Ton Report, volume 1. Review Workshop. Microalgae. (also breakout session)
- Efroymson et al. 2016. Qualitative analysis of environmental sustainability of algae biomass. BT16 volume 2 peer review workshop. Washington, DC
- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. Oak Ridge. December 7, 2016
- Mandal, S., Mathews, T., Shurin, J. Increasing algal productivity using polycultures Poster presentation. SETAC Orlando November 2016
- Mandal, S., Mathews, T., Shurin, J. Increasing algal productivity using polycultures Poster presentation. Algae Biomass Summit, Phoenix AZ Oct 23-23 2016
- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. North Carolina State University August 15, 2016
- Mathews, T. The role of biodiversity in nutrient and contaminant cycling in aquatic ecosystems. Invited talk. ORAU. Oak Ridge. August 16, 2016
- Mandal, S., Shurin, J. B. and Mathews, T. J. Nutrients Heterogeneity Increases Algal Productivity Using polycultures. 4th Annual ORNL Postdoc Research Symposium, ORNL. August 8, 2016.
- Mathews, T., Mandal, S., Shurin, J. The potential of using wastewater for algal biofuel production. (Tennessee American Water Resources Association, Burns, TN) Invited talk, *April 2016*
- Mathews, T., Mandal, S., Shurin, J. Heterogeneous nutrient sources create niche differentiation for algal polycultures (Algal Biomass Summit, Washington, DC) Invited talk, *October 2015*
- Mathews T. How can ecology help engineers solve environmental problems? (Invited talk, Tennessee Tech University, Cookeville, TN) October 20, 2015
- Mandal, S. Abbott, R.,and Shurin, J. B. Trait-based Analysis of Top-down vs. Bottom-up Control Across Algae.*Algae Biomass Summit*, Sept. 29- Oct. 2, 2015.
- Mandal, S., Shurin, J. B. and Mathews, T. J. Does Algal Polyculture enhance Productivity of Biofuel?*3rd AnnualORNL Postdoc Research Symposium*, ORNL. July 30, 2015.
- Schoenung et al. 2016, Algae co-location resources of carbon dioxide and effective transport distances. Poster. Algae Biomass Summit, Phoenix.