2013 DOE Bioenergy Technologies Office (BETO) Project Peer Review

Microalgae Analysis

DATE MAY 22, 2013
TECHNOLOGY AREA REVIEW: ALGAE

PRINCIPAL INVESTIGATOR: MARK WIGMOSTA
PACIFIC NORTHWEST NATIONAL LABORATORY

Goal Statement

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Large-scale, sustainable production of microalgae biomass for biofuels is limited by multiple resources, including climate, water availability, suitable land, CO_2, and nutrient sources.

Goal: This project is providing DOE-BETO with a systematic national assessment to evaluate the US potential for microalgae biofuel production.

Objectives:

- Continued development of an adaptive GIS-based ***Biomass Assessment Tool (BAT)*** for optimal locations, production rates, and resource demands/constraints for microalgae biofuel production
- Develop resource assessment for DOE harmonized 5 billion gallon per year HTL baseline
- Evaluate total algal/terrestrial feedstock potential including land competition
- Continued development of web-based access and direct integration with Bioenergy Knowledge Discovery Framework

Quad Chart Overview

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Timeline

- Project start date: Nov. 2010
- Project end date: Continuing
- Percent complete: 50%

Barriers

- Barriers addressed
  - Ft-A. Feedstock Availability and Cost
  - Ft-B. Sustainable Production
  - Ft-M. Overall Integration and Scale-Up
  - Algal Feedstock Processing

Budget

- Funding for FY10: $53K
- Funding for FY11: $365K
- Funding for FY12: $335K
- Funding for FY13: $540K

Partners

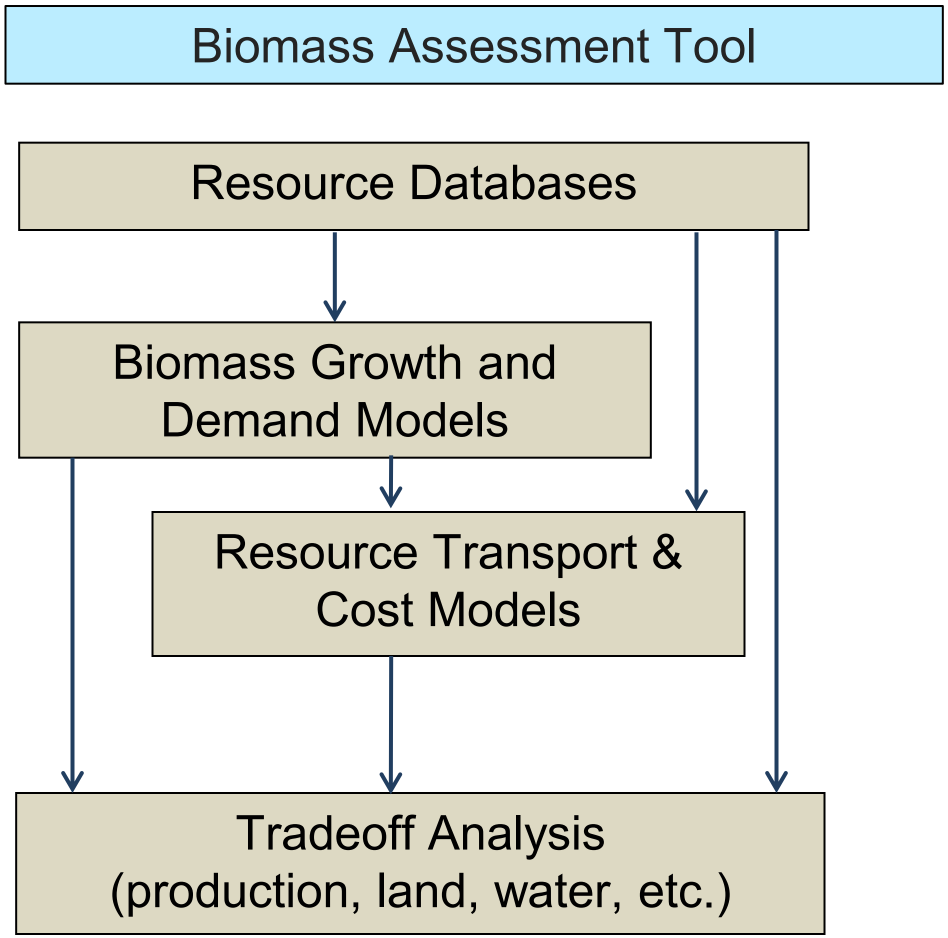
- ANL
- NREL
- ORNL
- NAABB
- BETO HQ

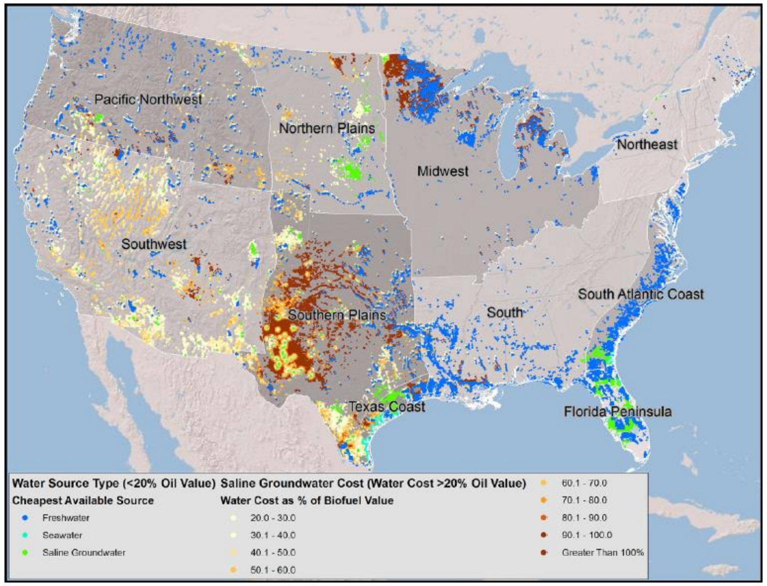
Project Overview

Adding capability and deploying the Biomass Assessment Tool, which provides spatially explicit estimates of open pond microalgae production potential and resource demands/constraints for the coterminous US:

- Maintain and enhance database and analytical elements
  - Upgraded climate data base
  - Enhanced pond temperature model
  - Integrated enhanced strain-specific biomass growth model
  - Increasing operational realism
- Added freshwater supply database
- Added saline groundwater database
  - Salt management
- Exercise the BAT to
  - Evaluate water supply constraints on feedstock siting and production potential
  - Develop resource assessment for DOE harmonized 5 billion gallons (BGY) LE and HTL baselines
- Evaluate total algal/terrestrial feedstock potential including land competition
- Integrate with Bioenergy Knowledge Discovery Framework

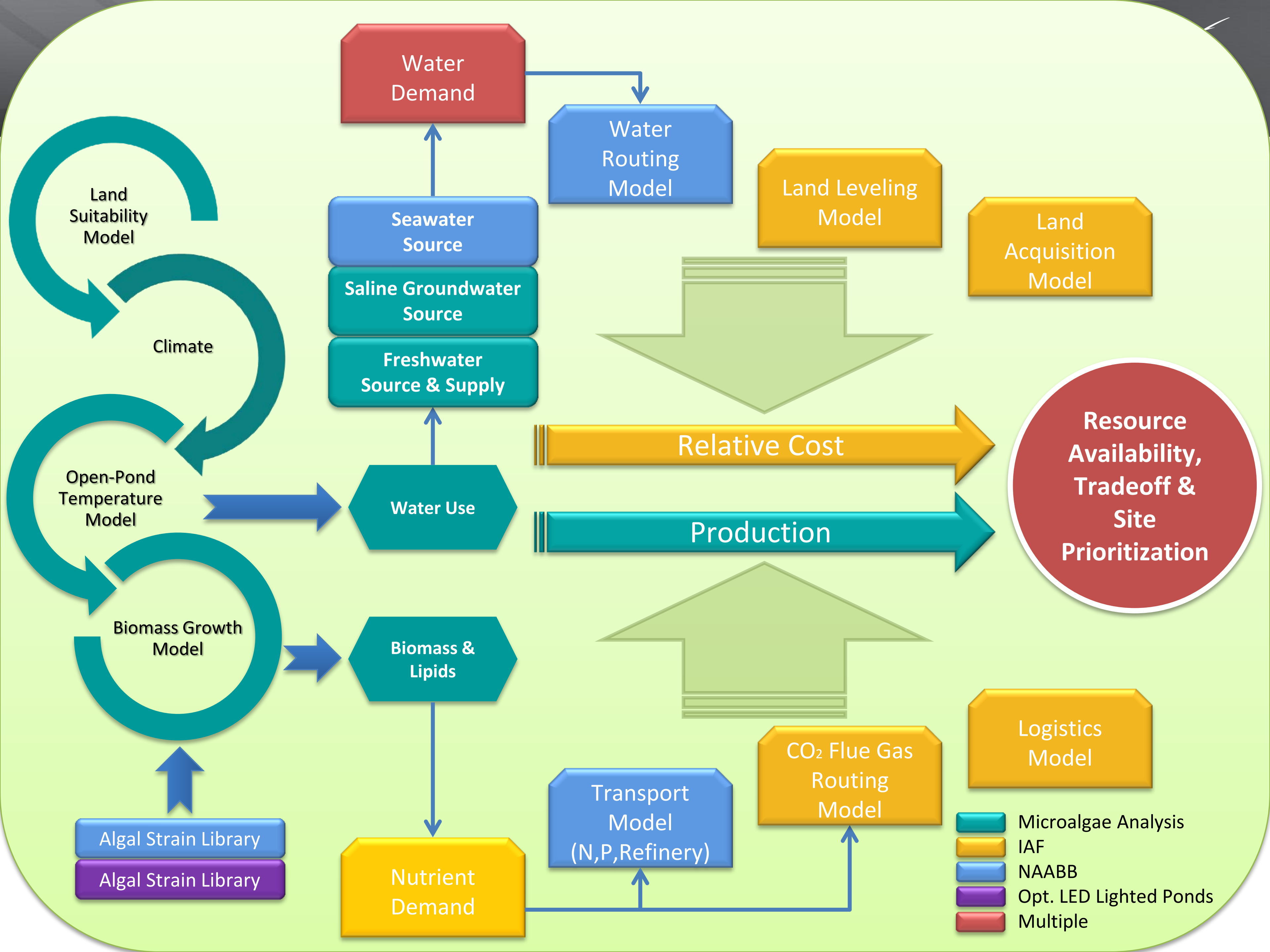
1 - Approach





MANAGEMENT APPROACH

- Project management plans
  - SOW and how it relates to DOE goals
  - Quarterly milestones
- Frequent project communications
  - Bi-weekly conference calls with project team members
  - Quarterly formal reporting to HQ
  - Participate in monthly algae platform conference call reviews



Water Demand
Water Routing Model
Land Leveling Model
Land Acquisition Model
Land Suitability Model
Climate
Open-Pond Temperature Model
Biomass Growth Model
Seawater Source
Saline Groundwater Source
Freshwater Source & Supply
Water Use
Biomass & Lipids
Relative Cost
Production
Resource Availability, Tradeoff & Site Prioritization
Logistics Model
CO_2 Flue Gas Routing Model
Transport Model (N,P,Refinery)
Nutrient Demand
Algal Strain Library
Algal Strain Library
Microalgae Analysis
IAF
NAABB
Opt. LED Lighted Ponds
Multiple

2 - Technical Accomplishments / Production Potential / Water Demand

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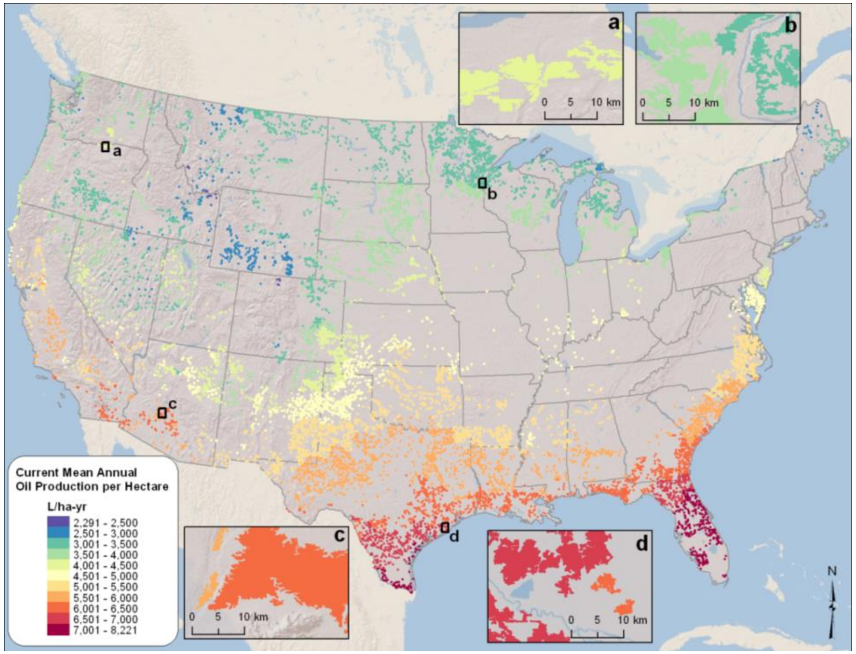

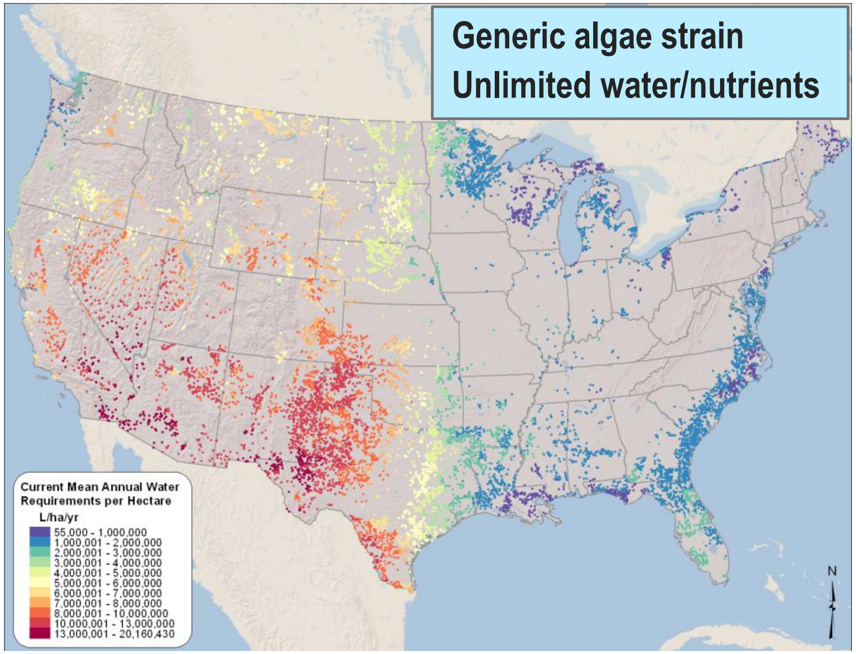

- Potential: 220 billion liters per year of biofuel production
- Freshwater demand for all potentially suitable areas is 300% of current consumptive use for irrigation

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane, 2011, National microalgae biofuel production potential and resource demand, Water Resour. Res., 47, W00H04, doi:10.1029/2010WR009966

2 - Technical Accomplishments

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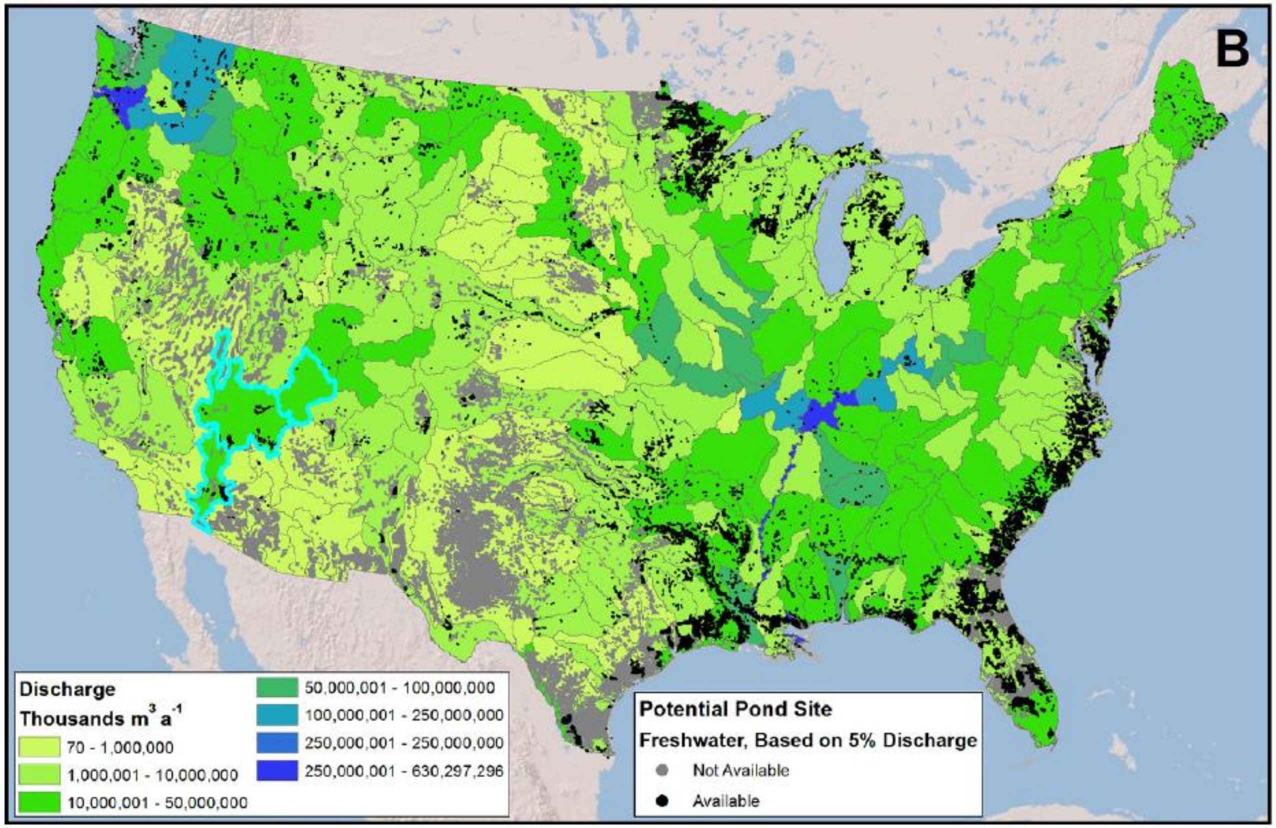
Presentation outline:

- Freshwater resources
- Saline water resources
- Water source tradeoffs and production potential
- Salt management
- Alternative biomass growth model
- DOE model harmonization
- Terrestrial / algal integration

2 - Technical Accomplishments / Freshwater Resources



Venteris, E.R. , R.L. Skaggs, A.M. Coleman, and M.S. Wigmosta, A GIS model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States, Environmental Science & Technology, 2013

- Includes downstream flow accumulation and consumptive use
- 5% withdrawal limit
- Does not consider water rights, compacts, or local regulations
- Freshwater mainly limited by availability

Water supply limits potential for freshwater algal strains in the southwestern U.S.

2 - Technical Accomplishments / Saline Water Resources

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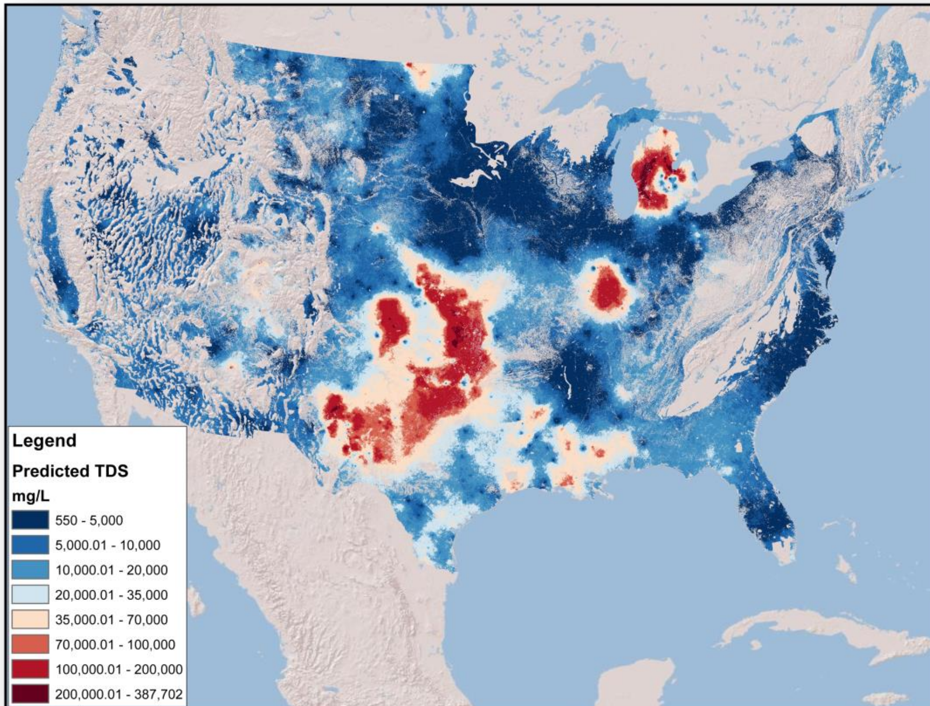
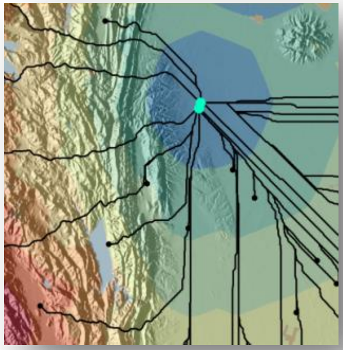
Saline Water Resources



Seawater Routing and Cost Model

Saline Aquifer Routing and Cost Model



- Saline water databases
- Water routing and cost models
  - Capital and operating costs
  - Includes "blowdown" requirements
  - Most cost-efficient pipeline route

2 - Technical Accomplishments / Water Source Tradeoffs

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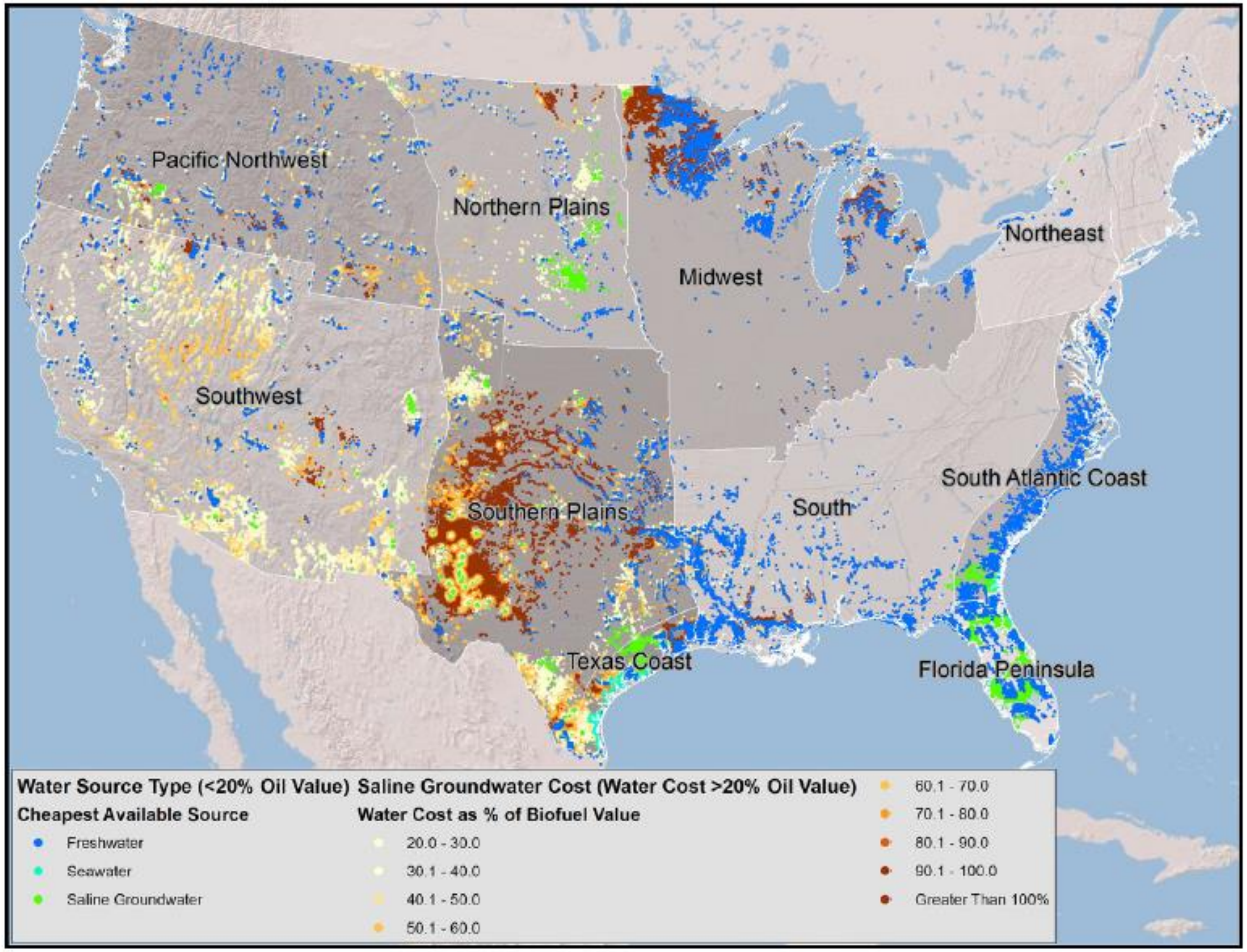
Water Source Tradeoffs



Production with water costs < 10% of biofuel value

- Freshwater: 23.5 BGY
- Saline GW: 12.7 BGY
- Seawater: 2.2 BGY

Production with water costs < 20% biofuel value

- Freshwater: 23.5 BGY
- Saline GW: 19.2 BGY
- Seawater: 3.9 BGY

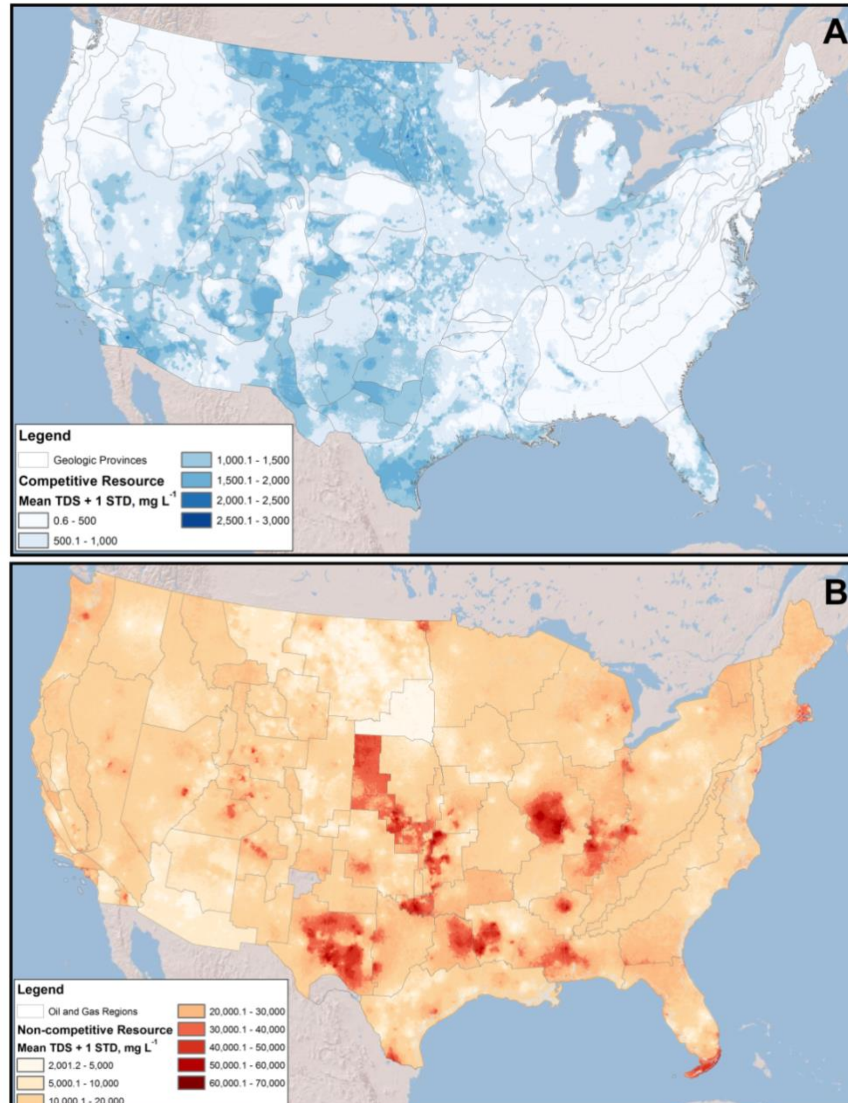
Venteris, E.R. , R.L. Skaggs, A.M. Coleman, and M.S. Wigmosta, A GIS model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States, Environmental Science & Technology, 2013

2 - Technical Accomplishments / Operating Salinity Impacts (cont)

Water Resource Modeling

Model considers two supply categories:

1. **Competitive** resource, supply limited. Salinities ranging from 0-2 g kg^{-1} may have municipal and/ or agricultural use
2. **Non-competitive** resource, supply is specified to be unlimited. Targets salinities ranging from 2 to 60 g kg^{-1}
3. Models of water depth and salinity are based on water well data (USGS-Feth, Produced Water, and NWIS)
   1. Sequential Gaussian simulation of depth and salinity
   2. Well cost model based on estimates of local water demand (blow down + evaporation) and depth of well (construction and operating cost)
   3. Water source assigned using optimal source defined by GIS cost-distance model (EST paper)



2 - Technical Accomplishments / Salt Management

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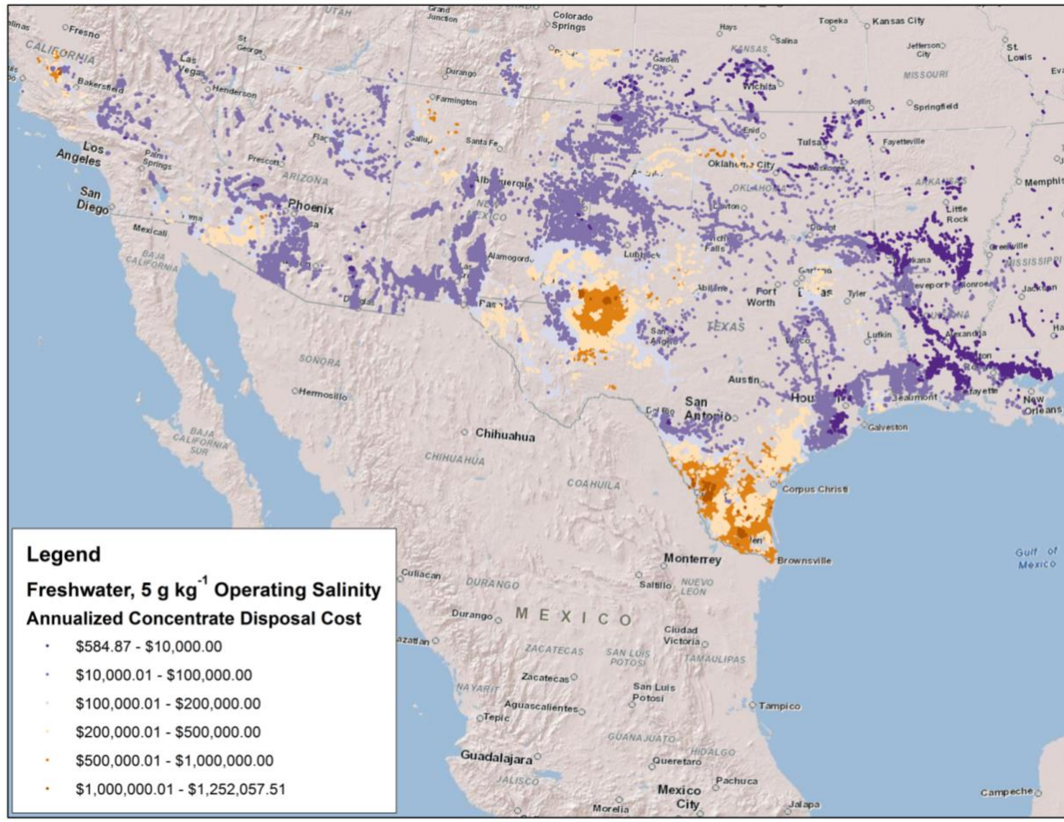
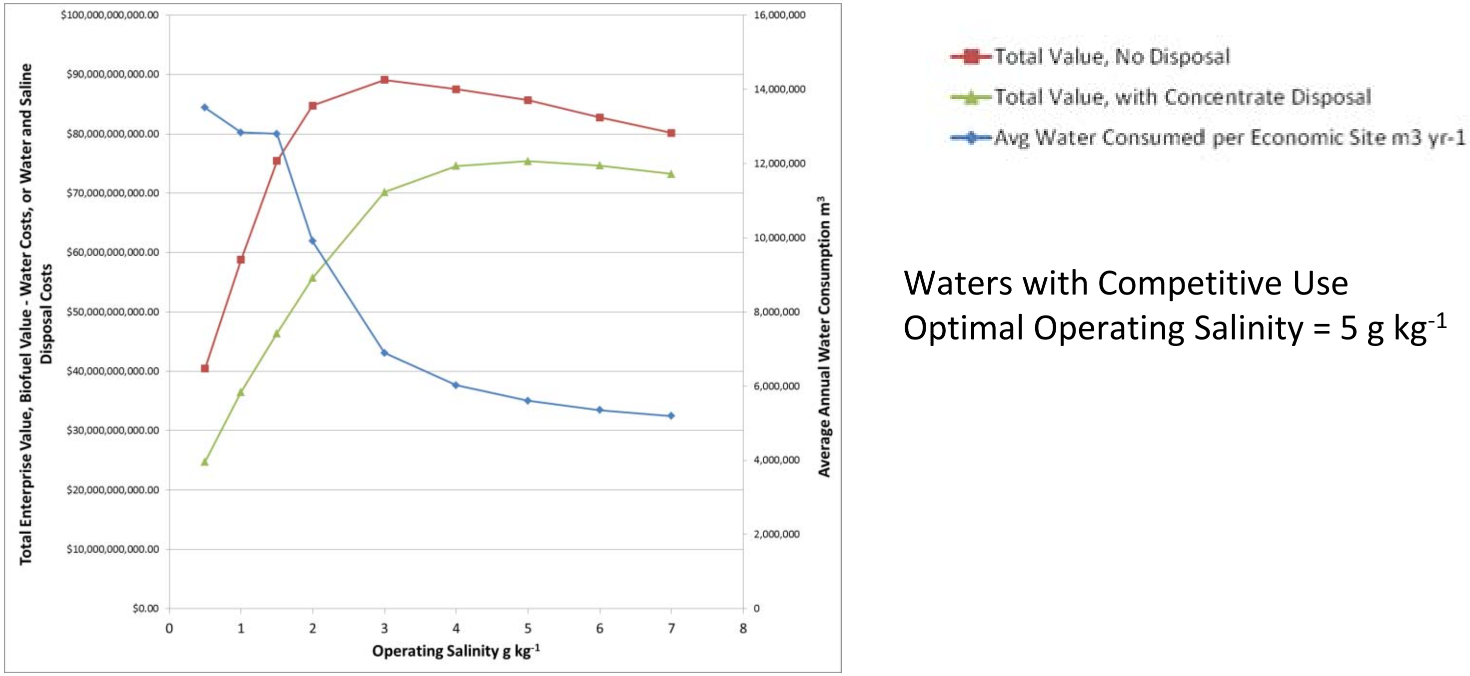
Preliminary Water Concentrate Disposal Costs for Freshwater

- Study area is southwestern US, where production potential is large but water demand issues are critical
- Water costs = annualized well construction and operation
- Added saline concentrate disposal model
  - evaporation pond
  - injection well
- Freshwater supply is not limited for this analysis



Source/operating salinity and climate drive blowdown and concentrate disposal costs

2 - Technical Accomplishments / Operating Salinity Impacts (cont)



Waters with Competitive Use
Optimal Operating Salinity = 5 g kg^{-1}

- Productivity vs. salinity data for *Chlorella* (Huesemann) used to parameterize BAT
- Tradeoff analysis for most cost effective operating salinity
  - Higher operating salinity decreases blowdown and disposal costs, but also decreases productivity for *Chlorella*

2 - Technical Accomplishments / Alternative Biomass Growth Model

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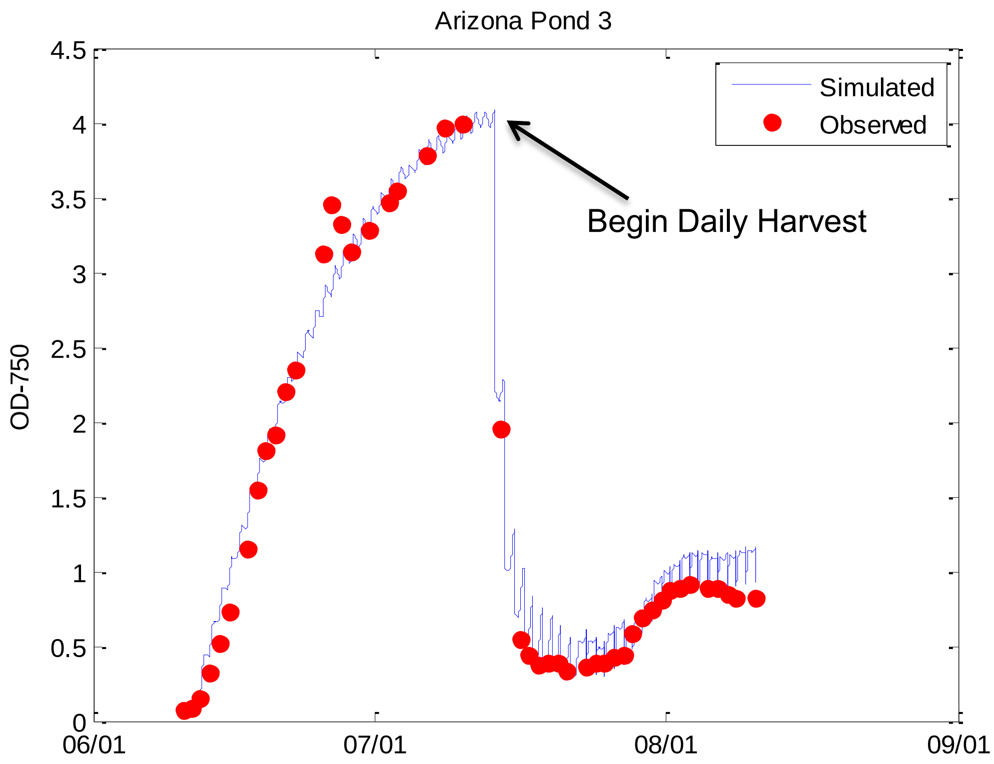
Integration of Alternative Growth Model in BAT

Huesemann, M.H., J. Van Wagenen, T. Miller, A. Chavis, S. Hobbs, and B. Crowe, "A screening model to predict microalgae biomass growth in photobioreactors and raceway ponds", Biotechnology and Bioengineering, Vol. 110 (6), 2013



Excellent agreement between BAT simulated and observed with growth model driven by measured 5-minute PAR and water temperature

2 - Technical Accomplishments / DOE Model Harmonization

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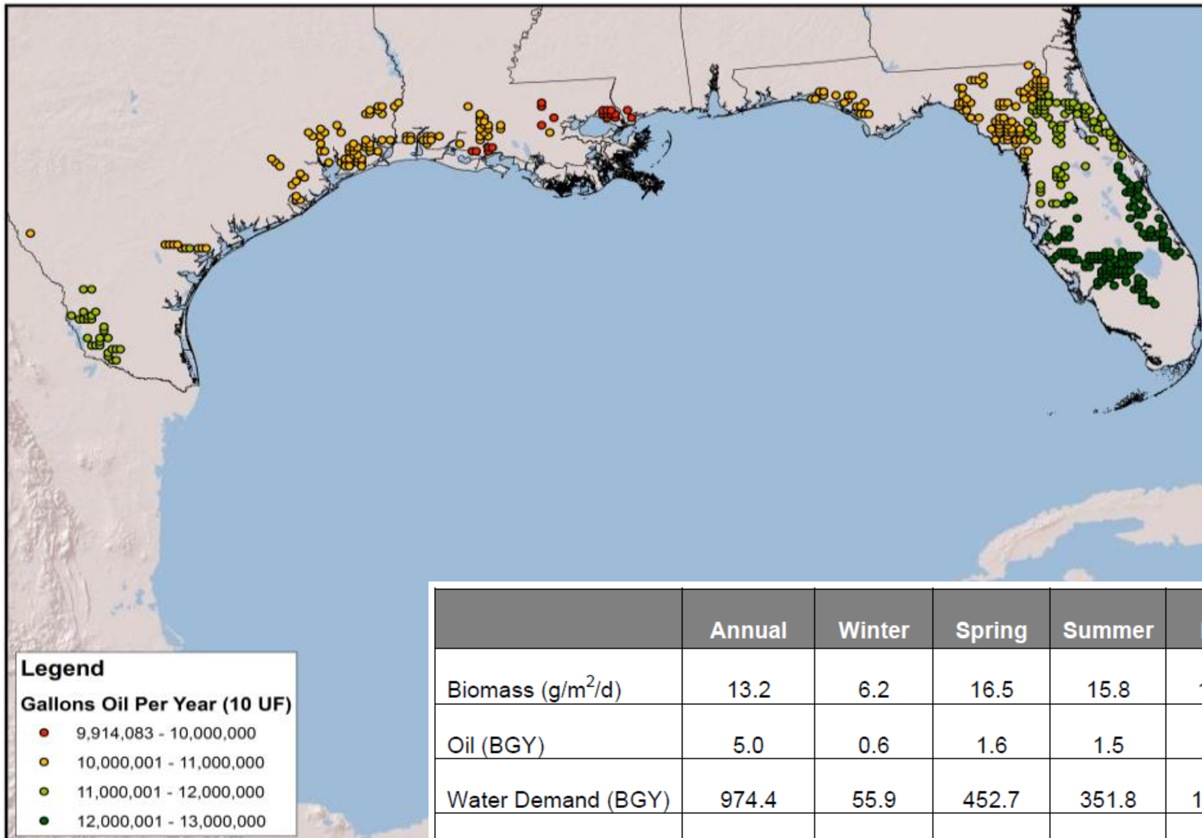
- The DOE Biomass Program launched an initiative to obtain consistent quantitative metrics for algal biofuel production to establish an "integrated baseline" by harmonizing and combining the programs
  - National Resource Assessment (RA) Mark Wigmosta – PNNL
  - Life-Cycle Analysis (LCA) Ed Frank – ANL
  - Techno-Economic Analysis (TEA) Ryan Davis – NREL
- The baseline attempts to represent a plausible near-term production scenario with freshwater microalgae growth, extraction of lipids, and conversion via hydroprocessing to produce a renewable diesel blendstock
- Differences in the prior models were reconciled (harmonized) and the BAT model was used to prioritize and select the most favorable consortium of sites that supports production of 5 BGY of renewable diesel

2 - Technical Accomplishments / DOE Model Harmonization (cont)



	Annual	Winter	Spring	Summer	Fall
Biomass (g/m^2/d)	13.2	6.2	16.5	15.8	14.1
Oil (BGY)	5.0	0.6	1.6	1.5	1.3
Water Demand (BGY)	974.4	55.9	452.7	351.8	113.9
G Water per G Oil	195.0	96.2	286.9	233.0	85.8

Prioritize on:

- Biomass production
- Freshwater availability and pumping costs
- Lipid transport


Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model

Coordinating Authors: Ryan Davis,[3] Daniel Fishman,[2] Edward D. Frank,[1] Mark S. Wigmosta[4]

Contributing Authors: Andy Aden,[3] Andre M. Coleman,[4] Philip T. Pienkos,[3] Richard J. Skaggs,[4] Erik R. Venteris,[4] Michael Q. Wang[1]

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[2] BC3, Incorporated, Laurel, Maryland
[3] National Renewable Energy Laboratory, Golden, Colorado
[4] Pacific Northwest National Laboratory, Richland, Washington

Technical Report
ANL/ESD/12-4
NREL/TP-5100-55431
PNNL-21437
June 2012
Prepared for the U.S. Department of Energy Biomass Program

- Gulf coast identified as most favorable region to meet 5 BGY target
- Freshwater availability was the most important constraint
- Seasonality is potentially key to processing facility scale and operation

2 - Technical Accomplishments / Terrestrial / Algal Integration

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- Recent research (Wigmosta et al., 2011) provides spatially explicit information on potential algal biomass and oil yields, water use, and facility locations
- National biomass feedstock assessments (Perlack et al., 2005; DOE, 2011) have focused on cellulosic biomass resources, and have not included potential algal feedstocks.
- ORNL and PNNL have begun an integrated biomass resource assessment
  - Includes both terrestrial and algal feedstocks
  - Accounts for potential land competition between the two feedstock types
  - Identifies areas where algal and cellulosic feedstocks have opportunities for production with a minimum of competition for available resources

WATER RESOURCES RESEARCH, VOL. 47, W00H04, doi:10.1029/2010WR009966, 2011

National microalgae biofuel production potential and resource demand

Mark S. Wigmosta,[1] André M. Coleman,[1] Richard J. Skaggs,[1] Michael H. Huesemann,[2] and Leonard J. Lane[3]

Received 31 August 2010; revised 20 January 2011; accepted 11 February 2011; published 13 April 2011.

[1] Microalgae are receiving increased global attention as a potential sustainable "energy crop" for biofuel production. An important step to realizing the potential of algae is quantifying the demands commercial-scale algal biofuel production will place on water and land resources. We present a high-resolution spatiotemporal assessment that brings to bear fundamental questions of where production can occur, how many land and water resources are required, and how much energy is produced. Our study suggests that under current technology, microalgae have the potential to generate 220×10^9 L yr^{-1} of oil, equivalent to 48% of current U.S. petroleum imports for transportation. However, this level of production requires 5.5% of the land area in the conterminous United States and nearly three times the water currently used for irrigated agriculture, averaging 1421 L water per liter of oil. Optimizing the locations for microalgae production on the basis of water use efficiency can greatly reduce total water demand. For example, focusing on locations along the Gulf Coast, southeastern seaboard, and Great Lakes shows a 75% reduction in consumptive freshwater use to 350 L per liter of oil produced with a 67% reduction in land use. These optimized locations have the potential to generate an oil volume equivalent to 17% of imports for transportation fuels, equal to the Energy Independence and Security Act year 2022 "advanced biofuels" production target and utilizing some 25% of the current irrigation demand. With proper planning, adequate land and water are available to meet a significant portion of the U.S. renewable fuel goals.

Citation: Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane (2011), National microalgae biofuel production potential and resource demand, *Water Resour. Res.*, 47, W00H04, doi:10.1029/2010WR009966.

1. Introduction

[2] There are a number of factors driving an increase in United States demand for alternative transportation fuels. Currently, the United States consumes approximately 1131×10^9 L (GL) of petroleum per year, of which 57% is imported (Energy Information Administration Independent Statistics and Analysis, Petroleum basic statistics, 2010, Energy Information Agency, U.S. Department of Energy, available at www.eia.gov/basics/quickoil.html). Of the petroleum consumed, 71% is used for transportation fuels. The U.S. Energy Information Administration (EIA) projects that by 2020 U.S. energy consumption will grow by 50% and our reliance on foreign oil production will increase by 30% by 2030 [*Biomass Research and Development Board (BRDB)*, 2008]. There are national energy security concerns as worldwide oil demand outpaces growth in global oil supplies and downstream refining capacity, leading to increased market volatility [*U.S. Energy Information Administration Independent Statistics and Analysis (USEIA)*, 2006]. Furthermore, there are serious concerns about greenhouse gas (GHG) emissions from petroleum-based fuels contributing to climate change and ocean acidification [*Munday et al.*, 2010; *Ormerod et al.*, 2002].

[3] The Energy Independence and Security Act (EISA) was enacted in 2007 to address energy security concerns. EISA established production targets for alternative fuels under the renewable fuels standard (RFS) in recognition that biomass is a domestic source of liquid biofuels that can readily reduce the nation's dependence on imported oil and decrease climate impacts [*U.S. Department of Energy (USDOE)*, 2010]. Under the RFS there is a requirement to produce 136×10^9 L of renewable fuels by 2022. Of this total, at least 79.5×10^9 L must be "advanced biofuels" that are not sourced from corn ethanol, and life cycle GHG emissions must be reduced by at least 50% compared to petroleum-based transportation fuels [*USDOE*, 2010].

[4] There have been a number of studies estimating water requirements for biomass feedstock production [e.g., *Chiu et al.*, 2009; *Gerbens-Leenes et al.*, 2009; *National Research Council*, 2008; *Wu et al.*, 2009a]. For example, *Wu et al.* [2009a] estimates the irrigation water consumed in farming to produce 1 L of ethanol to range from 7 to 321 L, with an additional 3 L of water consumed in the ethanol production process. The U.S. Geological Survey stopped publishing national consumptive water use statistics after 1995, at which

[1] Pacific Northwest National Laboratory, Richland, Washington, USA.
[2] Marine Sciences Laboratory, Pacific Northwest National Laboratory, Sequim, Washington, USA.
[3] L. J. Lane Consulting, Tucson, Arizona, USA.

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0043-1397/11/2010WR009966

W00H04 1 of 13

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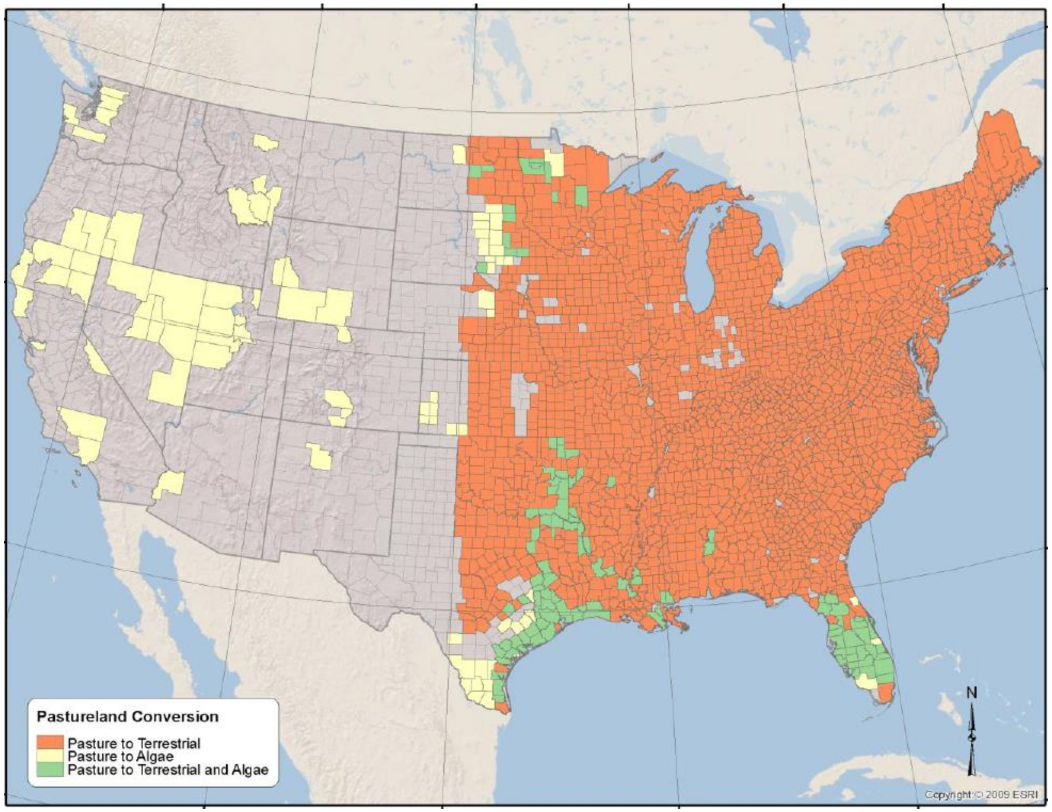
Conversion of private pastureland under high- production scenario of 41.5 billion liters of second-generation biofuels



Non-Compete Terrestrial

- 1,897 US counties
- 12.3 million ha

Non-Compete Algae

- 251 counties
- 0.2 million ha

Compete

- 110 counties
- 1.7 million ha terrestrial
- 1.0 million ha algae
- 38 to 59 counties could experience competition for over 40% of its private pastureland
- The combined 2.7 M ha represents only 2-5% to the total pastureland in the US

Milestones/Metrics and Progress:

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Title/Description	Due Date	Completed
Analyze freshwater supply constraints	**Dec-11**	✓
Saline water supply and transport	**Mar-12**	✓
Salt and water management	**Jun-12**	✓
National assessment of land/water under realistic operating scenarios	**Sep -12**	✓
Harmonization/BT Integration kick-off meetings and revised AOP	**Dec-12**	✓
Validate pond temperature model	**Mar-13**	✓
Validate pond growth model	**Jun-13**	✓
Lipids condition module	**Jun-13**	In progress
National scale tradeoff analysis	**Sep-13**	In progress
Harmonized 5 BGY scenario	**Sep-13**	In progress
Refined national algae/terrestrial biomass potential	**Sep-13**	In progress

3 - Relevance

- Through direct communication with BETO, this project supports the DOE goals and objectives in the Biomass Program Multi-Year Program Plan (updated November 2012) by providing a high-resolution, GIS-based Biomass Assessment Tool to evaluate the US potential for microalgae biofuel production
  - Algae Resource Assessment goal to identify the "geographic location, price, and environmental sustainability of accessing existing and potential future feedstock resource, as well as projecting future supply availability and prices. Algal feedstock resources include sufficient solar isolation, available non-arable land, non-potable water, waste nutrient streams, waste $C0_2$, and supporting transport infrastructure to access downstream conversion processing"
  - "By 2013, establish feedstock resource assessment models with geographic, economic, quality, and environmental criteria under which algal resource supply can be identified to support cultivation of 1 million metric tons ash free dry weight algae biomass by 2017 and 20 million metric tons ash free dry weight (AFDW) by 2022"
  - "By 2022, validate the potential for algae supply and logistics systems to product 5,200 gallons oils (or equivalent biofuel intermediate) per acre of cultivation per year, achieving a modeled nth plant minimum selling price of $3.27/GGE ($2011) of raw biofuel intermediate (corresponding to projected $3.73/GGE ($2011) of renewable diesel minimum fuel selling price)"
- Provides DOE and industry with an understanding of potential microalgae production rates, optimal locations, and resource demands

4 - Critical Success Factors

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- ***Technical Success***: Development of the Biomass Assessment Tool allowing identification of the geographic location, price, and environmental sustainability of accessing existing and potential future feedstock resource, as well as projecting future supply availability and prices
  - On-site resource demands and sustainable supply
  - Resource competition
  - Strain specific production potential
- ***Technical Challenge:*** How to best incorporate scientific data for better model predictions
  - Dynamic nature of the BAT allows rapid assimilation of scientific advances
  - Since last review, we have integrated NAABB derived products, Huesemann growth model, and NWIS water resource database
- ***Technical Challenge:*** Allow integration of research into full TEA and LCA
  - Collaboration with ANL, NREL, and BETO on BETO model harmonization effort
- ***Technical Challenge:*** How to integrate algal and terrestrial feedstock production
  - Collaboration with ORNL on integrated terrestrial and algal biofuel production
- ***Market:***
  - Strategic partnerships with industry – Sapphire
  - Coordination with NAABB
  - Dissemination of study results through peer-reviewed publications, web-based BAT, and integration with Bioenergy Knowledge Discovery Framework
    - AGU WRR Editor's Choice Award (Wigmosta et al., 2011), Venteris et al. 2013

5 - Future Work

ML, DL or Go/No Go	Description	FY13 Q3	FY13 Q4	FY14 Q1	FY14 Q2	FY14 Q3	FY14 Q4
B.3.ML.4	Biomass lipids condition module						
B.3.ML.4	Validate biomass growth model						
B.3.ML.6	National land/water tradeoff analysis						
B.3.ML.7	5 BGY HTL Harmonization						
B.3.ML.8	Refined national algae/terrestrial integration						
B.3.ML.9	Harmonization and algae/terrestrial kickoff meeting and revised AOPs						
B.3.ML.10	Draft manuscript cost /benefit of soil compaction vs. liners for open ponds						
B.3.ML.11	Draft manuscript analyzing comprehensive tradeoffs associated with use of alternative water resources (fresh, saline, marine) and associated operational requirements (strains, residual management, etc.)						
B.3.ML.12	Draft manuscript analyzing potential competition for water and nutrient resources between algae and terrestrial feedstocks						

Summary

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- ***Relevance:*** This study provides DOE and industry with the first spatially explicit estimate of open pond microalgae production potential and resource demands for the coterminous United States. It realistically addresses critical questions of how much energy can be produced, where production can occur, and how much land and water resource will be required
- ***Approach:*** A systematic biophysical evaluation of resource demands and constraints on microalgae biofuel production
- ***Technical accomplishments:*** Development of a GIS-based Biomass Assessment Tool that integrates high-resolution data with biophysical models to provide spatially/temporally explicit estimates of production potential and resource demands and constraints
- ***Success factors and challenges:*** Integration of on-site feedstock production into full lifecycle and TEA analysis
- ***Technology transfer and future work:*** Integration of web-based BAT into Bioenergy Knowledge Discovery Framework, coordination with NAABB, collaboration with ANL, ORNL, NREL, and Sapphire

Additional Slides

Responses to Previous Reviewers' Comments

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- A theme among several reviewers was the need for "operational reality"
  - "A very good start to a very important study. The PI's are encouraged to incorporate the added perspective of the farmer and land developer to the further down select sites that pass the resource nexus criteria. Will become a very important study once this is completed"
  - "This is a good project, but would be even better if potential users were consulted frequently and some sort of "ground-truthing" of results were incorporated"
  - "If the PI's could integrate the view from the ground, i.e., the farmer into their criteria this would become an excellent study"

Responses to Previous Reviewers' Comments

- We are in total agreement with these review comments and a significant effort has been made to ground-truth models and analysis. This has resulted in upgrades to our meteorological database, pond temperature model, development of land cost and land availability data, consideration of alternative water supply, and integration and validation of a new strain-specific growth model. The team has visited Algal feedstock production sites in Arizona, Pecos ,TX, and San Diego, CA to better understand operations and constraints.
- Contract work for Sapphire Energy, Inc. has provided a unique opportunity to better understand the needs of operators and industry. As part of this effort, the analysis approach, databases, and models were independently reviewed and approved by Sapphire for their needs. The multi-scale flexibility of the Biomass Assessment Tool allowed efficient application of additional selection criteria to satisfactorily address specific client needs.

Publications and Presentations

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane, 2011, National microalgae biofuel production potential and resource demand, Water Resour. Res., 47, W00H04, doi:10.1029/2010WR009966

Venteris, E.R. , R.L. Skaggs, A.M. Coleman, and M.S. Wigmosta, A GIS model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States, Environmental Science & Technology, 2013

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Davis, R., D,. Fishman, E.D. Frank, M.S. Wigmosta, A. Aden, A.M. Coleman, P.T. Pienkos, R.L. Skaggs, E.R. Venteris, M.Q. Wang, “Renewable diesel from algal lipids: An integrated baseline for costs, emissions, and resource potential from a harmonized model”, Technical Report ANL/ESD/12-4, NREL/TP-5100-55431, PNNL-21437, June 2012

Langholtz, M.A., A.M. Coleman, L.M. Eaton, M.S. Wigmosta, C.M. Hellwinckel, and C. Brandt, Potential Land Competition Between Open-Pond Microalgae Production and Terrestrial Dedicated Feedstock Supply Systems in the U.S., Biomass and Bioenergy, in review.

Acknowledgements

Project Team

Mark Wigmosta
Andre Coleman
Richard Skaggs
Erik Venteris
Michael Huesemann
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2 - Technical Accomplishments / Terrestrial / Algal Integration (cont)

Pacific Northwest NATIONAL LABORATORY
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High-Production Scenario

- Terrestrial
  - Mean annual production at the county scale
  - NASS county scale land cover
  - POLYSYS simulation assuming framgate price of $66 per dry Mg
  - 29.5 billion liters of biofuel in 2022 from feedstock production on private pastureland east of the 100th meridian
- Algae
  - Hourly production at the “Unit pond farm” scale – 1,200 ac
  - CDL 30-m land cover
  - 12 billion liters of biofuel from feedstock production on private pastureland from Wigmosta et al. (2011)

- Algal results were aggregated to the county scale
- Significant effort to reconcile differences in county level land use data between terrestrial and algae resulting from differences in NAS and CDL scale and land classifications