The Promise and Challenges of Algae Biofuels

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Techno-economics, Resource Demands, & Sustainability

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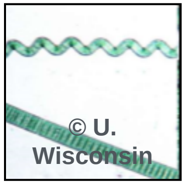
Algal Biofuels … *Benefits & Challenges*

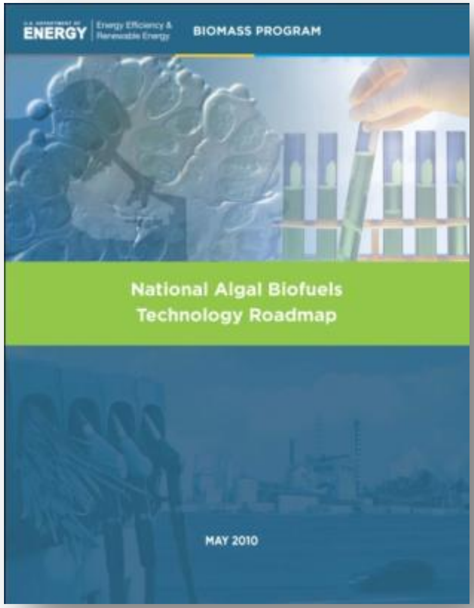


Benefits of Algal Biofuels

- High productivity potential
- Can minimize competition with agriculture
- Can use non-fresh wastewater and saline water
- Can recycle carbon dioxide and other nutrients (N, P, etc.)
- Feedstock for integrated production of fuels and co-products
- Algae oils provide high quality feedstock for advanced biofuels

Challenges to commercializing Algal Biofuels

- Affordable, scalable, and reliable algal biomass production
  - Reliable feedstock production & crop protection at scale
  - Energy efficient harvesting and dewatering
  - Extraction, conversion, and product purification
  - Siting and sustainable utilization of resources
- Algae Biofuels Technology Roadmap, released June 2010, helps guide RD&D http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf



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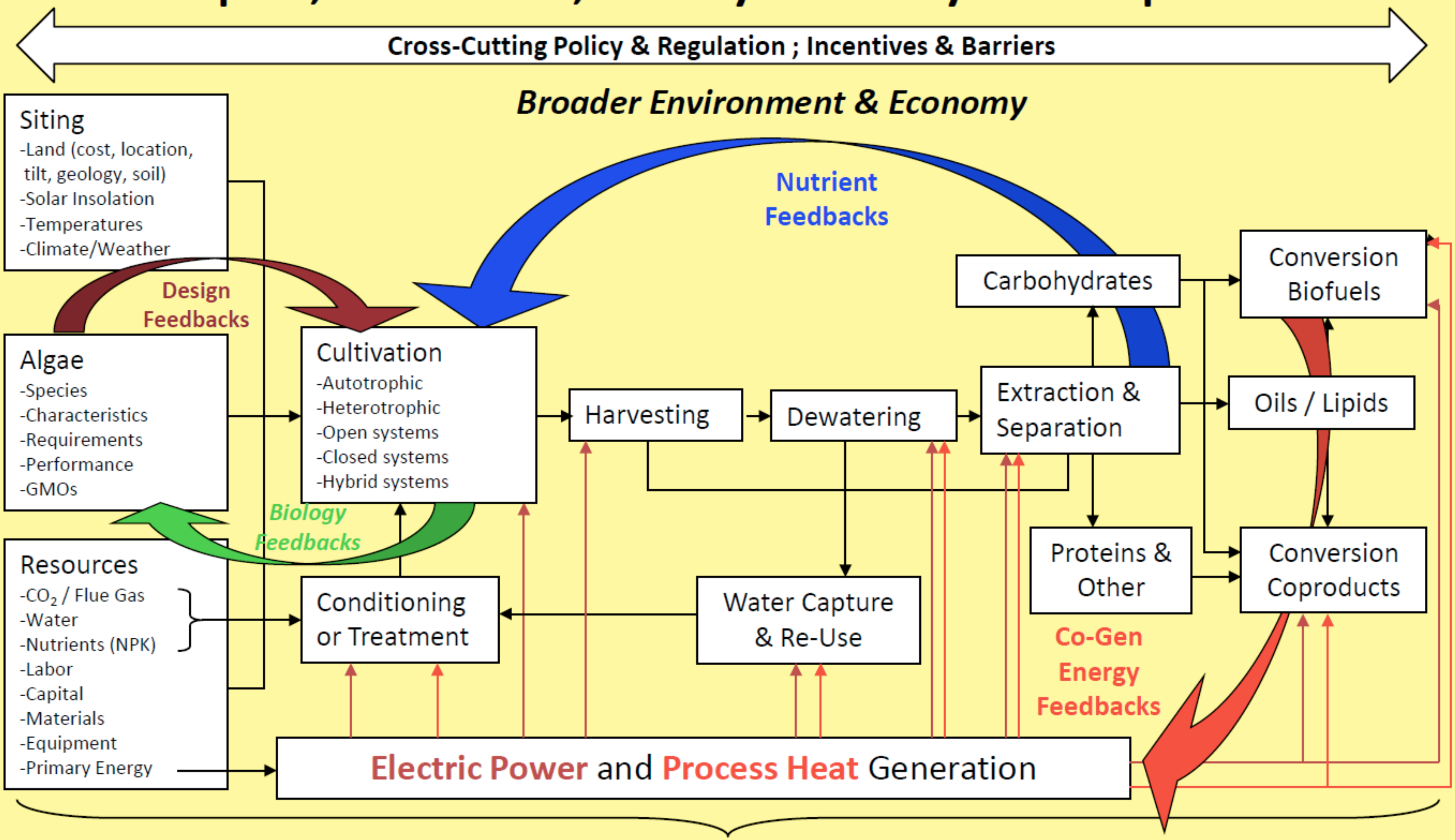
Algal Biofuel Value Chain

Complex, Multi-Path, and Dynamically Interdependent



Systems & Operations: Capital Construction, Operations, Monitoring, Maintenance, Replacement

Market Externalities: Cost of Energy, Cost of Petroleum & Conventional Fuels, Demand & Price for Co-Products vs. Their Alternatives, etc.

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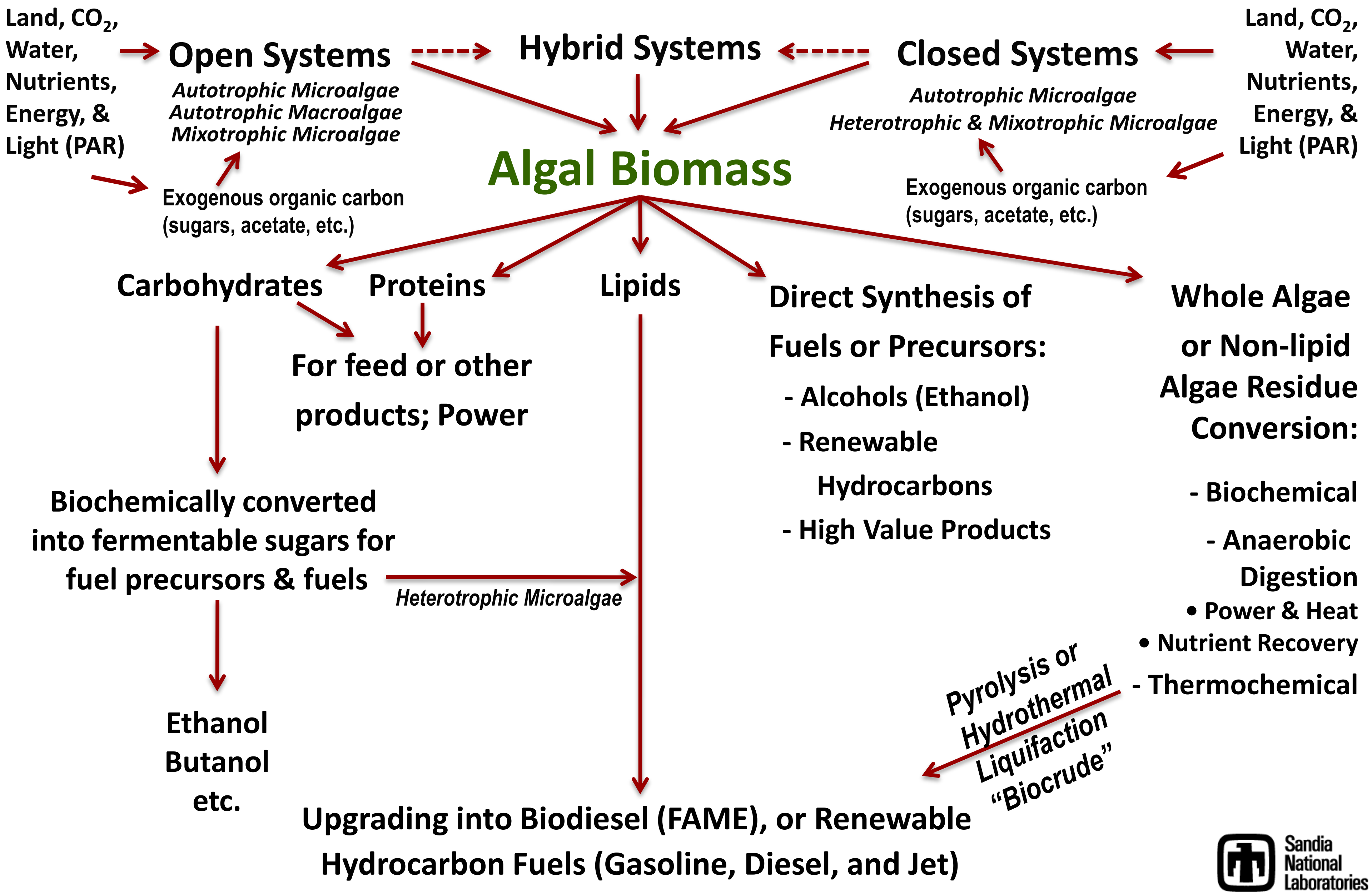
Algae Biofuels Pathways Overview

Production & Conversion to Fuels/Products



Heterotrophic Algae Approach

Considered a conversion process by DOE … not a primary feedstock

- Heterotrophic algae oil production is a ***biochemical conversion process***

  … Not a stand-alone feedstock derived directly from photosynthesis

- Relies on an upstream source of organic carbon feedstock (e.g. sugars)
- Uses mature bioreactor (fermentation) technology capable of scale-up
- Controlled process enabling dense algae culture with high oil content

  … Culture densities of 50 to ≥ 150 grams/liter (dry weight)

  … Oil content of 50% to ≥ 75% (dry weight basis)

- Cost of production highly dependent on cost of sugar feedstock
- Has the same "sustainable feedstock" issues as today's ethanol biofuel

  … Food & Feed vs. Fuel issues can arise if commodity sugar or starch crops are used

  … Will be most sustainable at large scale using C5 and C6 sugars from cellulosic biomass

- Capable of biofuel feedstock oil scale-up in same manner as ethanol production, to extent that affordable feedstock sugars can be made available
- Life cycle assessment (LCA) and resource use impacts *(e.g., land, water, nutrients, energy, GHG)* must include the upstream sugar feedstock production
- Combination of heterotrophic with autotrophic (mixotrophic approach) can boost microalgae oil production using a dual metabolic path process

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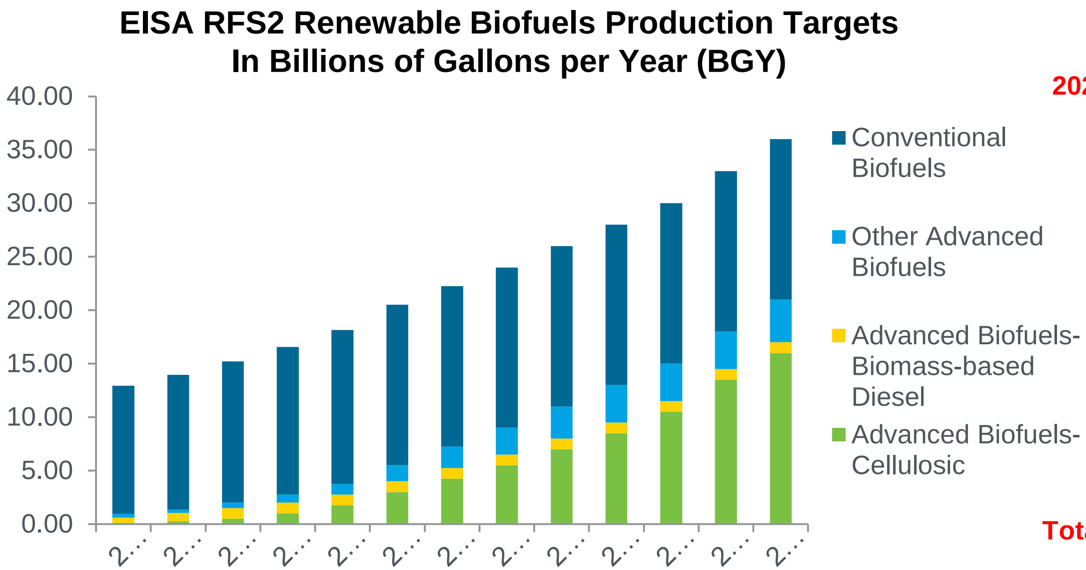
Policy Driver for Biofuels in the U.S.

Renewable Fuels Standard (RFS2)



Biofuels Policy Mandate*

2022 Targets

15 BGY

4 BGY

1 BGY

16 BGY

Total: 36 BGY by 2022

Categories for Algae Contribution

*** EISA (2007): "Energy Independence and Security Act of 2007", H.R.6, 110th Congress, Public Law No: 110-140 December 19, 2007.**

Putting into Context

Fuel Type	2008 Demand**	2020 Projection**	2035 Projection**
Gasoline blend (including E85)	8.99 MBD (137.8 BGY) 17.2 Quads	9.42 MBD (144.4 BGY) 18.1 Quads	10.26 MBD (157.3 BGY) 19.7 Quads
Diesel Fuel	3.94 MBD (60.4 BGY) 8.38 Quads	4.24 MBD (65.0 BGY) 9.02 Quads	4.91 MBD (75.3 BGY) 10.4 Quads
Jet Fuel	1.54 MBD (23.6 BGY) 3.19 Quads	1.68 MBD (25.8 BGY) 3.48 Quads	1.84 MBD (28.2 BGY) 3.81 Quads

U.S. Fuel Demand**

**** "Annual Energy Outlook 2010: with projections to 2035" U.S. Energy Information Administration Department of Energy DOE/EIA-0383 (2010).**

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The Algal Biofuels Sustainability Challenge

Establishing Sustainable Practices & Meeting Requirements

- Life cycle and techno-economic analyses, site selection, resource use management
- Improved energy balance, reduced costs (CAPEX & OPEX) and lower GHG footprint
- Land, water, and energy resources demand and utilization
- Demand and sourcing of nutrients (N, P, etc.) and carbon:
  - Inorganic carbon (e.g., CO_2) for autotrophic (photosynthetic) growth
  - Organic carbon (e.g., sugars) for heterotrophic and mixotrophic growth
  - N, P, and other micronutrients needed for algae health & growth
- Social, economic, environmental risks and impacts
- Policy and regulations
- Public acceptance and support
- Human and technical capacity building
  - Education, Training, Analysis Tools, Equipment, Manufacturing & Processing, etc.)

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Recent Baseline Techno-Economic, Life Cycle, and Resource Assessments for Algae Biofuels

Argonne NATIONAL LABORATORY · NREL NATIONAL RENEWABLE ENERGY LABORATORY · Pacific Northwest NATIONAL LABORATORY *Proudly Operated by* **Battelle** *Since 1965*

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

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Resource demand implications for US algae biofuels production scale-up

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ABSTRACT

Photosynthetic microalgae with the potential for high biomass and oil productivities have long been viewed as a promising class of feedstock for biofuels to displace petroleum-based transportation fuels. Algae offer the additional benefits of potentially being produced without using high-value arable land and fresh water, thereby reducing the competition for those resources between expanding biofuels production and conventional agriculture. Algae growth can also be enhanced by the use of supplemental CO_2 that could be supplied by redirecting concentrated CO_2 emissions from stationary industrial sources such as fossil-fired power plants, cement plants, fermentation industries, and others. In this way, algae may offer an effective means to capture carbon emissions for reuse in renewable fuels and co-products, while at the same time displacing fossil carbon fuels to help bring about a net reduction in overall carbon emissions. Significant displacement of petroleum fuels will require that algae feedstock production reach large volumes that will put demands on key resources. This scenario-based analysis provides a high-level assessment of land, water, CO_2 and nutrient (nitrogen, phosphorus) demands resulting from algae biofuel feedstock production reaching target levels of 10 billion gallons per year (BGY), 20 BGY, 50 BGY, and 100 BGY for four different geographical regions of the United States. Different algae productivities are assumed for each scenario region, where relative productivities are nominally based on annual average solar insolation. The projected resource demands are compared with data that provide an indication of the resource level potentially available in each of the scenario regions. The results suggest that significant resource supply challenges can be expected to emerge as regional algae biofuel production capacity approaches levels of about 10 BGY. The details depend on the geographic region, the target feedstock production volume, and the level of algae productivity that can be achieved. The implications are that the supply of CO_2, nutrients, and water, in particular, can be expected to severely limit the extent to which US production of algae biofuel can be sustainably expanded unless approaches are developed to mitigate these resource constraints in parallel to emergence of a viable algae technology. Land requirements appear to be the least restrictive, particularly in the Western half of the country where larger quantities of potentially suitable classes of land exist. Within the limited scope and assumptions of this analysis, sustainable photosynthetic microalgae biofuel feedstock production in the US in excess of about 10 BGY will likely be a challenge due to other water, CO_2 and nutrient resource limitations. Developing algae production approaches that can effectively use non-fresh water resources and minimize both water and nutrient requirements will help reduce resource constraints. Providing adequate CO_2 resources for enhanced algae production appears the biggest challenge, and could emerge as a constraint at oil production levels below 10 BGY.

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ANL/ESD/11-5

Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model

Energy

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]

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[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.

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Techno-economic analysis of autotrophic microalgae for fuel production

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ABSTRACT

It is well-established that microalgal-derived biofuels have the potential to make a significant contribution to the US fuel market, due to several unique characteristics inherent to algae. Namely, autotrophic microalgae are capable of achieving very high efficiencies in converting solar energy into biomass and oil relative to terrestrial oilseed crops, while at the same time exhibiting great flexibility in the quality of land and water required for algal cultivation. These characteristics allow for the possibility to produce appreciable amounts of algal biofuels relative to today's petroleum fuel market, while greatly mitigating "food-versus-fuel" concerns. However, there is a wide lack of public agreement on the near-term economic viability of algal biofuels, due to uncertainties and speculation on process scale-up associated with the nascent stage of the algal biofuel industry.

The present study aims to establish baseline economics for two microalgae pathways, by performing a comprehensive analysis using a set of assumptions for what can plausibly be achieved within a five-year timeframe. Specific pathways include autotrophic production via both open pond and closed tubular photobioreactor (PBR) systems. The production scales were set at 10 million gallons per year of raw algal oil, subsequently upgraded to a "green diesel" blend stock via hydrotreating. Rigorous mass balances were performed using Aspen Plus simulation software, and associated costs were evaluated on a unit-level basis. Upon completing the base case scenarios, the cost of lipid production to achieve a 10% return was determined to be $8.52/gal for open ponds and $18.10/gal for PBRs. Hydrotreating to produce a diesel blend stock added onto this marginally, bringing the totals to $9.84/gal and $20.53/gal of diesel, for the respective cases. These costs have potential for significant improvement in the future if better microalgal strains can be identified that would be capable of sustaining high growth rates at high lipid content. Given that it is difficult to maximize both of these parameters simultaneously, it was determined that the near-term research should focus on maximizing lipid content as it offers more substantial cost reduction potential relative to an improved algae growth rate. Additional economic sensitivity studies were established to identify other important cost drivers, and a resource assessment comparison was made to evaluate parameters such as water and CO_2 requirements.

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SNL's Algae Biofuels Resource Assessment

for U.S. *Autotrophic Microalgae Oil Feedstock Scale-Up*

Purpose: To address the following high-level questions …

- *How far can U.S. algae biofuels be sustainably scaled up?*
  - *To be relevant, fuel volumes must be significant in context of current & future U.S. demand for transportation fuels, and policy mandates for biofuels*
  - ***Must think in terms of many Billions of Gallons per Year (BGY)***
- *What are most likely resource constraints? … at what level?*
  - *Focus on land, water, CO_2, and nutrients (N, P)*
- *Can limitations be extended or overcome? … How?*

Goals:

1) To provide greater awareness and insight to technology developers and policy makers regarding the need to pursue promising algae biofuels approaches capable of sustainable build-up to significant fuel production levels on a national scale;

2) To manage expectations for algae biofuels that factors in resource requirements and constraints.

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High-Level Algae Biofuels Scale-up Assessment
Using *Scenario-based Approach*[1]

- Consider hypothetical algae production scale-up scenarios & locations in US
  - *Target algal oil production levels of 10, 20, 50, & 100 BGY*
  - *Ignore all systems and processes details … **assume it exists & works !***

- Assume range algae productivities … Moderate to Very Optimistic
  - *Land requirements based on cultivation area needed for assumed productivity*

- Assume open system cultivation (subject to evaporative water loss)
  - *Limit water demand estimate to evaporative loss only (ignore all other)*
  - *Based on fresh water pan evaporation data … **likely to be worst case***

- Assume CO_2 and nutrient (N, P) demand based on simple mass balance with an assumed algae C:N:P composition ratio and 100% utilization efficiency

- Compare projected land, water, CO_2 and nutrient (N, P) demand with estimates for resources available and/or similarly used

- Draw ***preliminary conclusions*** within limited scenario scope & assumption

[1] Pate, R.C., G. Klise, and B. Wu, "Resource Demand Implications for U.S. Algae Biofuels Production Scale-up", *Applied Energy - Special issue of Energy from Algae: Current Status and Future Trends, 88 (10), October 2011.*

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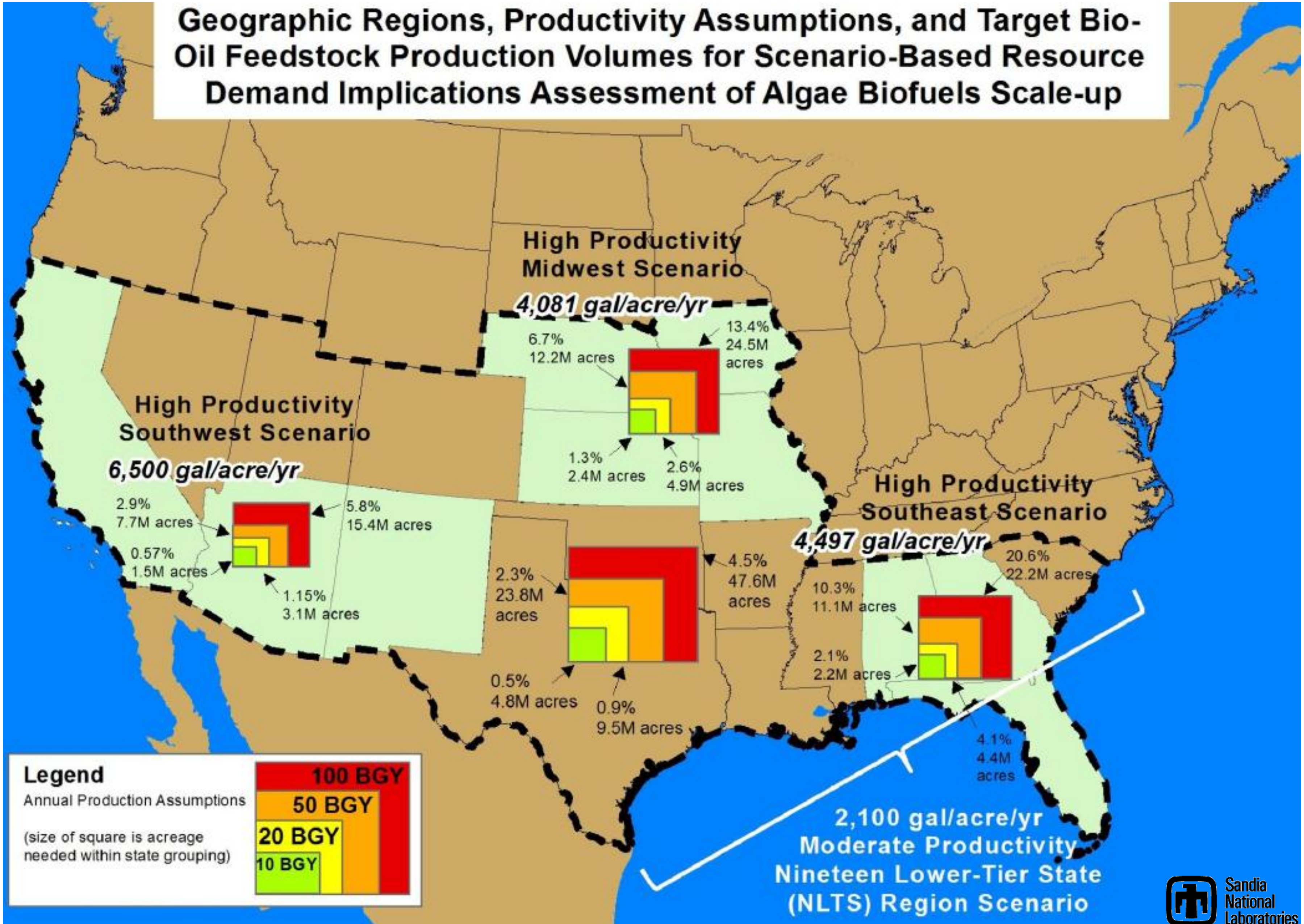
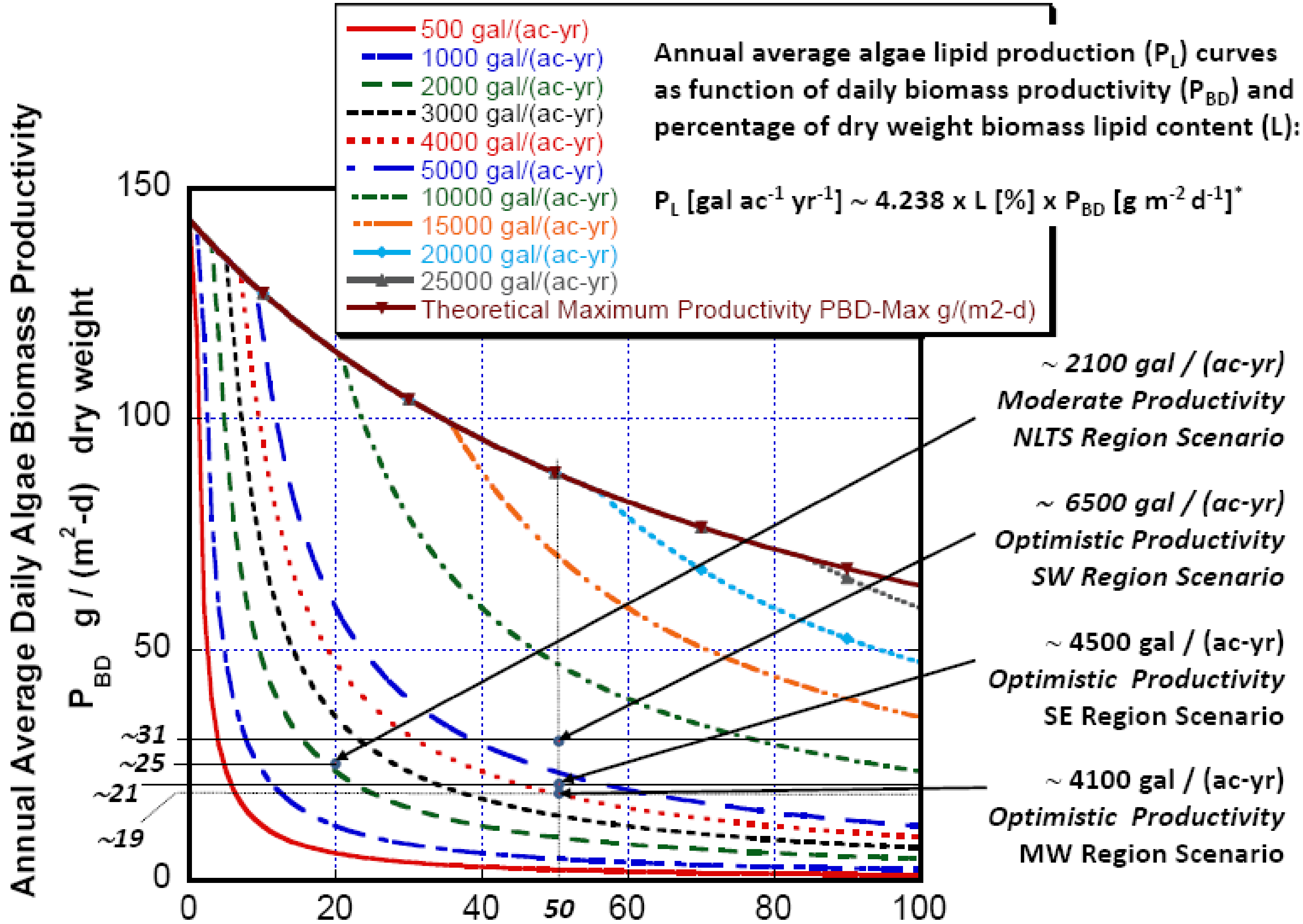
Algae Biofuels Scale-Up Scenarios



Algae Oil Productivity Curves & Scenario Points
as Function of Daily Biomass Productivity and Oil Content



* Cooney, Michael, Greg Young, and Ronald Pate (2010). "Bio-oil from photosynthetic microalgae: Case study", Bioresource Technology, 9 July.

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Key Factors for Scenarios

Basis for geographic region focus and resource demand

- Solar resource availability – drives productivity
- Temperature regime – moderates productivity
- Land availability – appropriate category of use
  - Suitable for algae cultivation with minimum competing uses
- Evaporative water loss - Issue for open systems
  - Evaporative loss is the assumed basis for water demand
  - Loss estimates based on fresh water pan evaporation data
  - Assumed use of open systems subject to evaporative loss
- Basis of scaling assumptions for CO_2 demand
- Basis of scaling assumptions for N & P demand

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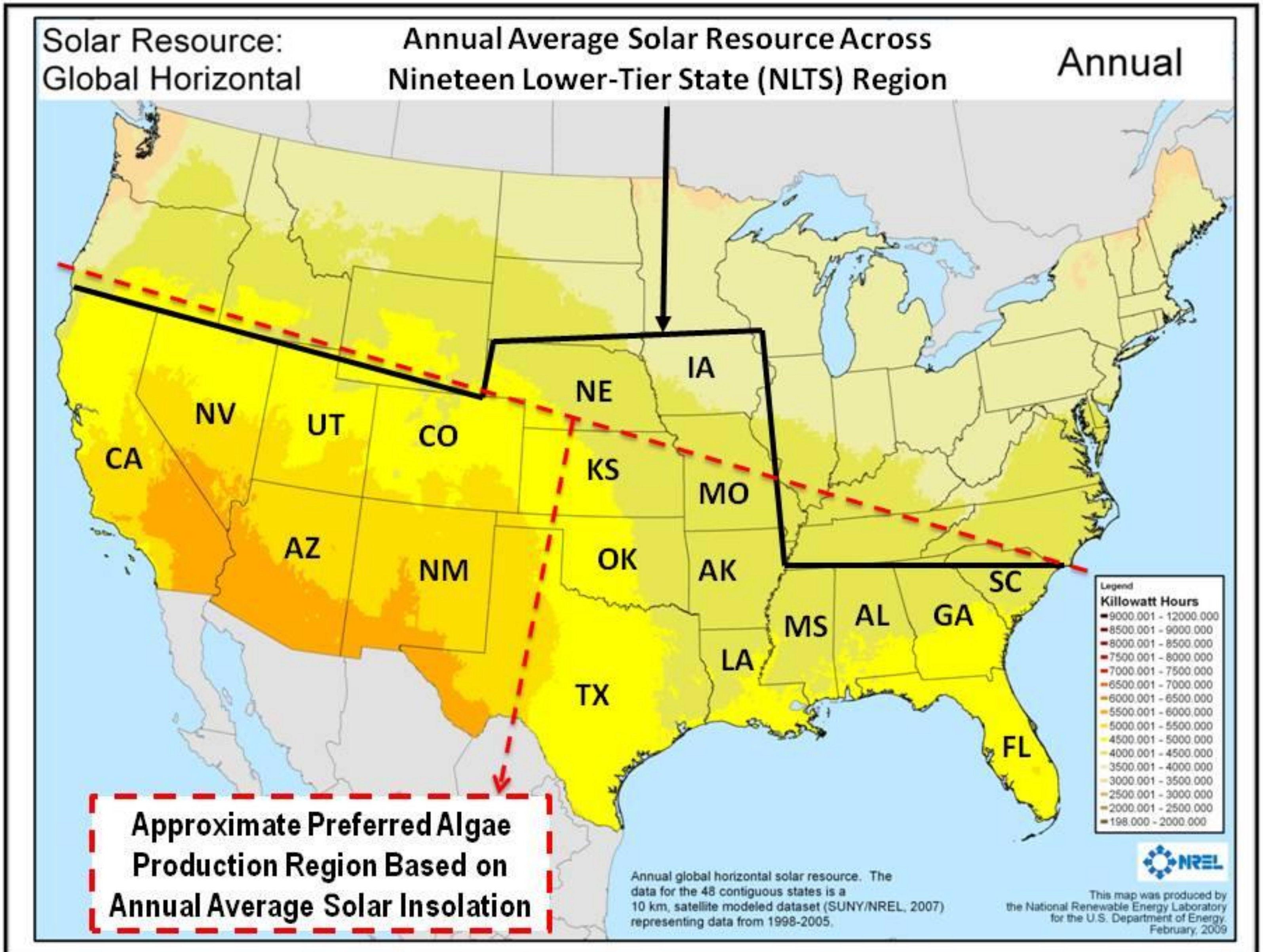
Key Factor for Algae Cultivation - Sunlight

Drives Focus on Lower Latitude Scenario Regions



Solar resource map courtesy of NREL

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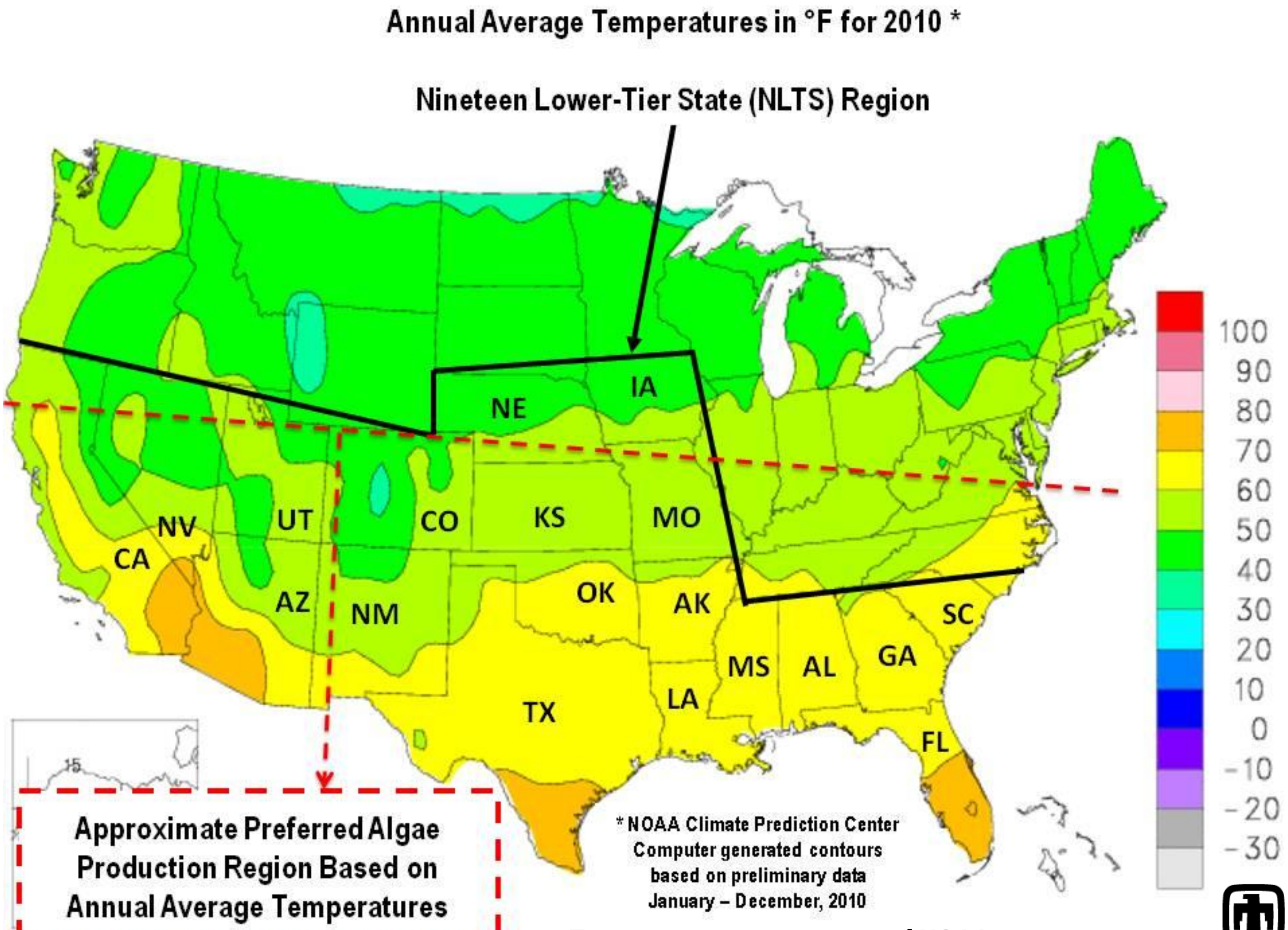
Key Factor for Algae Cultivation - Temperature

Drives Focus on Lower Latitude Scenario Regions



Temperature map courtesy of NOAA

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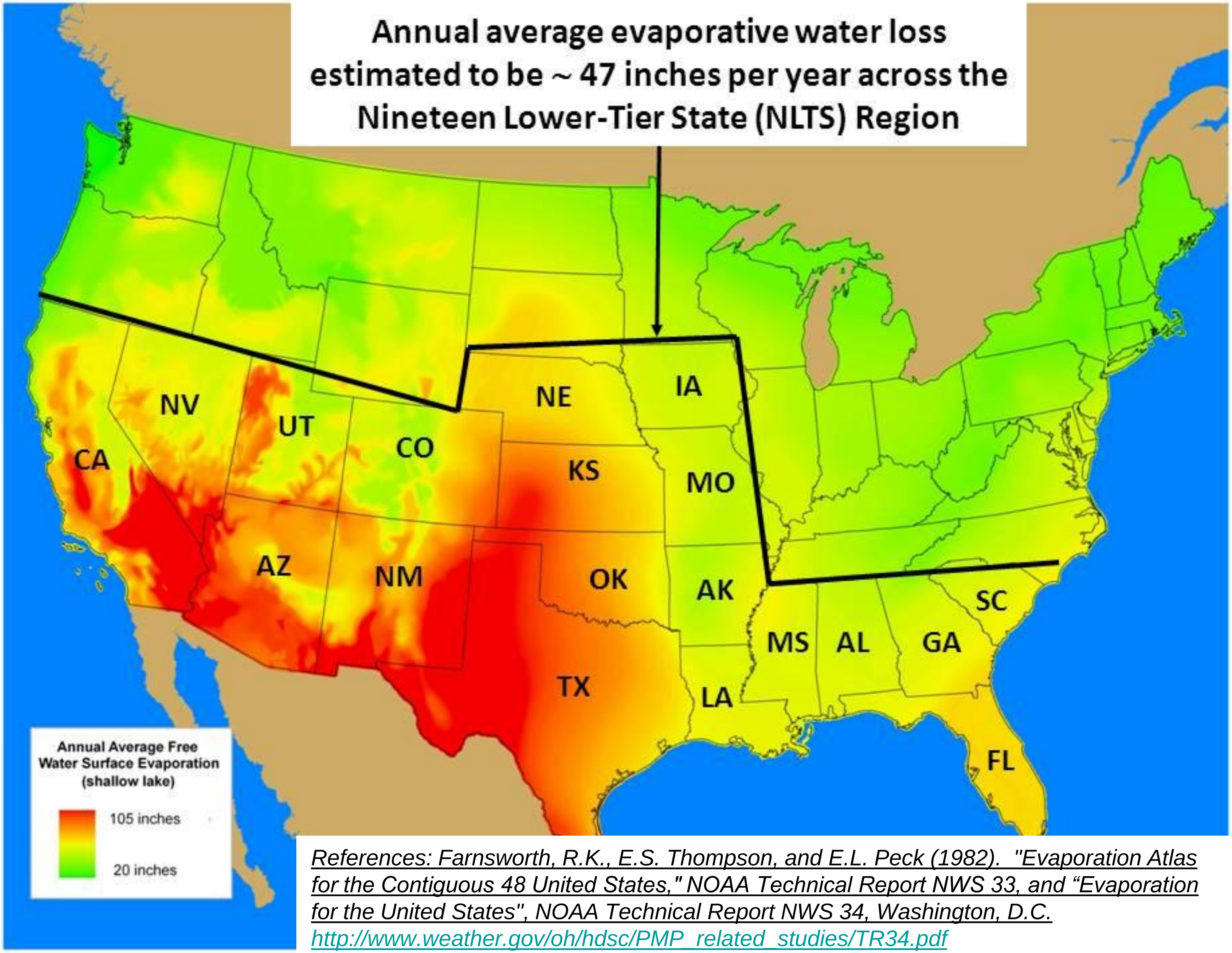
Key Factor for Algae Cultivation - *Evaporation*

Assuming Open Systems (fresh water pan evaporation data)



References: Farnsworth, R.K., E.S. Thompson, and E.L. Peck (1982). "Evaporation Atlas for the Contiguous 48 United States," NOAA Technical Report NWS 33, and "Evaporation for the United States", NOAA Technical Report NWS 34, Washington, D.C. http://www.weather.gov/oh/hdsc/PMP_related_studies/TR34.pdf

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Basis of scaling assumptions for CO_2 demand

CO_2

Stationary CO_2 Sources
Fossil Fuel Fired Power Plants,
Ethanol Plants, Cement Plants, etc.

1) Mass fraction of Carbon in CO_2
$= 12 / [12 + (2 \times 16)] = 12 / 44 = 27.3\%$

2) Assume ~ 50% Carbon content in dry algae biomass

3) Assume all carbon in algae biomass comes from input CO_2 with 100% transfer and uptake efficiency (ignore atmospheric diffusion)

4) Mass of input CO_2 / Mass of dry algae output ~ 50 / 27.3 ~ 1.83

Therefore, approximately two (2) mass units of CO_2 are required for each mass unit dry algae produced

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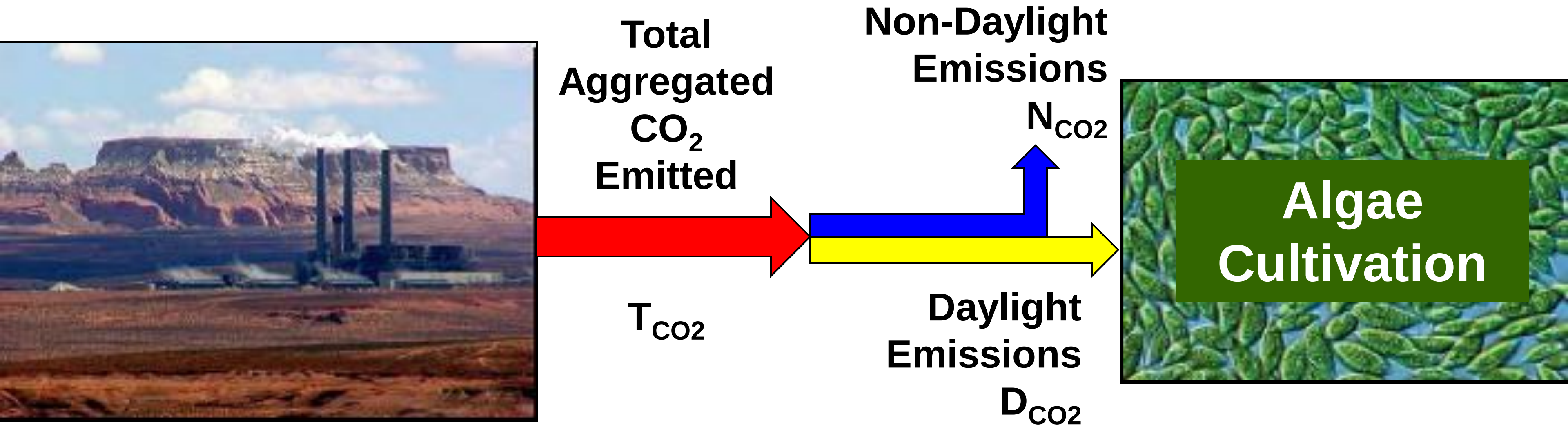
Estimating CO_2 emissions during daylight hours*

Availability *for use in photosynthetic algae production*



Aggregated Emissions from All Stationary CO_2 Sources in Scenario Region

1) Total CO_2 Emissions $T_{CO2} = D_{CO2} + N_{CO2}$

2) Nominal Daylight Hours = 12 hours per 24 hour day

3) Some CO_2 produced by stationary industrial sources will be emitted 24 hours per day, but we assume over half will be emitted during daylight hours; So,

$$0 \leq N_{CO2} \leq T_{CO2} / 2$$

4) It then follows that $0 \leq T_{CO2} - D_{CO2} \leq T_{CO2} / 2$ and $D_{CO2} \leq T_{CO2} \leq D_{CO2} + T_{CO2} / 2$, resulting in: $T_{CO2} / 2 \leq D_{CO2} \leq T_{CO2}$

Thus, we estimate that D_{CO2} falls somewhere between 50% to 100% of T_{CO2} *

* CO_2 emissions data is not broken down by hours of the day, or daylight vs. non-daylight

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Basis of scaling assumptions for N & P demand

Elemental Nitrogen (N)
(N atomic weigh = 14)

Elemental Phosphorus (P)
(P atomic weigh = 31)

Elemental Carbon (C)
(C atomic weigh = 12)

1) Assume inputs of elemental N, P, and C are transferred to and taken up by algae biomass with no losses and 100% efficiency

2) Assume C:N:P atomic ratio = 106:16:1 (Redfield Ratio) in dry algae biomass with ~ 50% C content (by weight)

3) C:N:P mass ratio in dry algae becomes = (106x12):(16x14):(1x31) = 1272:224:31

4) With 50% C content by weight, the C:N:P mass ratio of 1272:224:31 converts to a mass percentage ratio of 50:(224x50/1272):(31x50/1272) = 50% C: 8.8% N: 1.22% P

Therefore, we assume that ~ 88 kg N and ~ 12 kg P are required for each metric ton (1000 kg) of dry algae biomass produced

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Projected Algae Cultivation Area Demand
vs. Land Use Profile in Scenario Regions

Shaded cells show Pasture as category assumed most suitable to avoid land use conflicts

LAND USE	10 BGY	20 BGY	50 BGY	100 BGY	Profile of Land Resources in Scenario Region by Land Category[1] (1000s of acres)				
Scenario Region	Land Required[2] (1000s of acres)				Pasture[3]	Cropland	Forest[4]	Other[5]	Total
Southwest (SW)	1,540	3,080	7,700	15,400	113,938	14,561	66,366	55,343	250,208
Midwest (MW)	2,440	4,880	12,200	24,400	45,573	99,866	17,695	18,269	181,403
Southeast (SE)	2,220	4,440	11,100	22,200	7,833	12,498	61,360	22,358	104,049
NLTS[6]	4,760	9,520	23,800	47,600	388,734	220,939	268,863	168,356	1,046,892

[1] USDA (2006): Major Uses of Land in the United States, 2002, USDA/ERS, Economic Information Bulletine 14;
[2] SW, MW, and SE scenarios assume annual average algae lipid productivities of ~6500, ~4100, and ~4500 gal ac^{-1} yr^{-1};
[3] Combination of grassland and other non-forested pasture, range, and open grazing land, excluding cropland pasture;
[4] Combination of grazed and non-grazed forest, excluding 98-million forest acres in parks and other special use lands;
[5] Combination of urban, defense and industrial, parks, rural transport, misc farm, and other land uses;
[6] Nineteen lower-tier state (NLTS) scenario assumes annual average lipid productivity of ~2,100 gal ac^{-1} yr^{-1} across the states of AZ, AK, AL, CA, CO, FL, GA, IA, KS, LA, MO, MS, NE, NM, NV, OK, SC, TX, & UT.

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Open Algae System Evaporative Water Loss

vs. Fresh Water Use Profile in Scenario Regions

Shaded cells show irrigation as water use category most likely to provide allocation of freshwater resources for algae

WATER USE	10 BGY	20 BGY	50 BGY	100 BGY	Profile of Fresh Water Withdrawals & Use in Scenario Region by End-Use Category[10] (BGY)				
Scenario Region	Annual Average Evaporative Water Loss[11] (BGY) [inches/year][12]				Electric Power Gen Cooling[13]	Irrigation	Domestic/ Public[14]	Other[15]	Total
Southwest	2,800 [69]	5,400 [66]	12,100 [58]	22,300 [53]	71	11,682	3,282	456	15,491
Midwest	3,300 [49]	6,500 [49]	15,100 [46]	28,300 [43]	4,648	4,603	775	391	10,417
Southeast	2,500 [42]	5,000 [42]	12,600 [42]	25,200 [42]	4,209	1,455	1,779	664	8,107
NLTS[16]	6,070 [47]	12,140 [47]	30,350 [47]	60,700 [47]	18,162	31,356	9,424	4,133	63,075

[10] Water use data for the U.S. in 2005, from USGS: Kenny, et al. (2009); Irrigation is considered the key comparative use in each region

[11] Evaporative loss estimates based on annual average freshwater pan evaporation (likely to be worst-case) from estimated land footprint area required for algae cultivation in scenario regions, assuming open cultivation systems

[12] Evaporative loss rate decreases with increasing cultivation area due to averaging of rates over larger regional area

[13] Combination of fresh surface and groundwater withdrawals (excluding saline water withdrawals) for thermoelectric power plant cooling

[14] Combination of domestic and public fresh water supply use categories, as defined by Kenny, et al. (2009)

[15] Combination of livestock, aquaculture, mining, and industrial use categories (excluding saline water withdrawals)

[16] Annual evaporation rate averaged over nineteen lower-tier state region assumed to be ~47 inches per year

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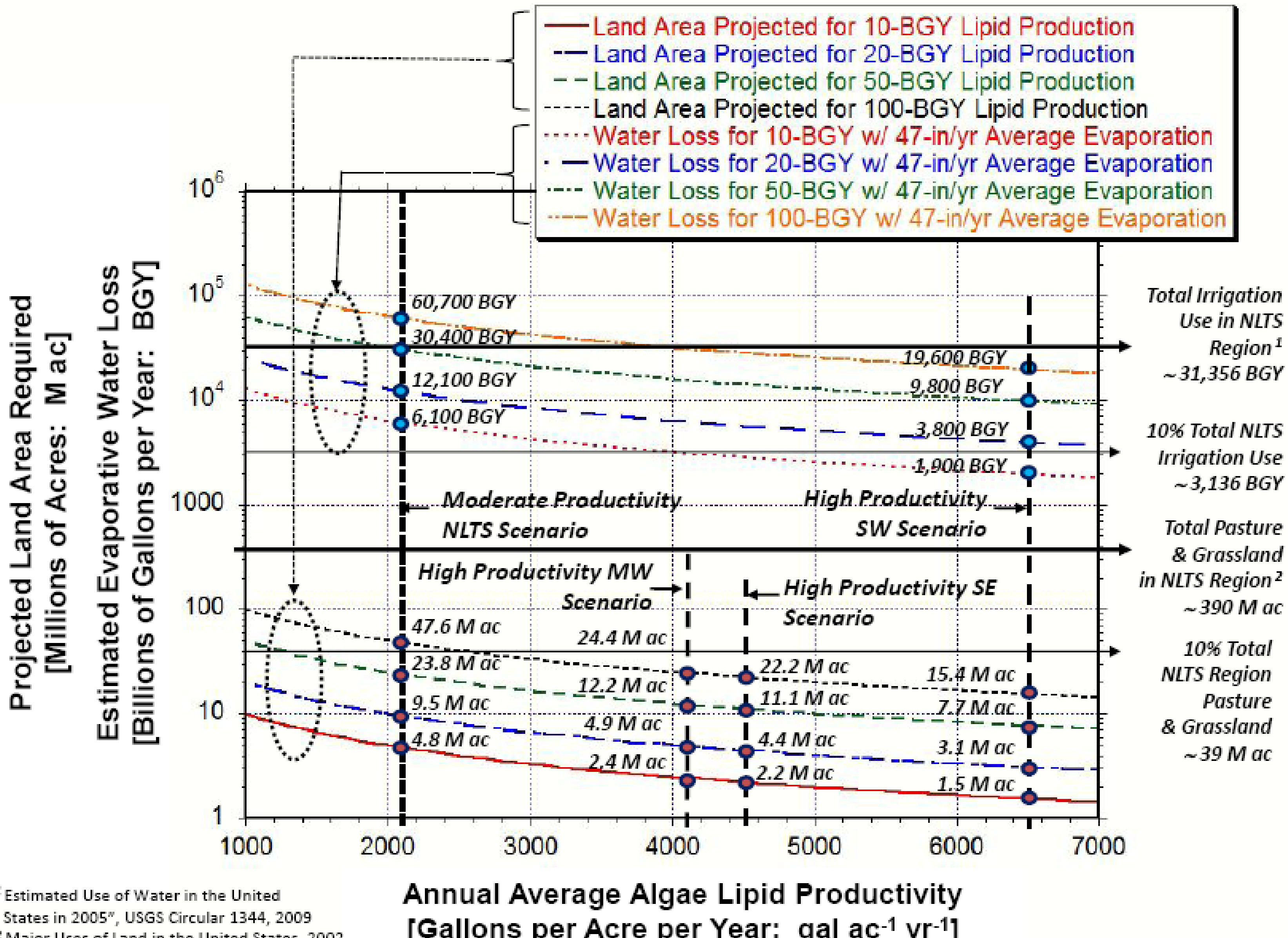
Summary of Land Area & Evaporative Water Loss

As Function of Oil Productivity Levels Assuming Open Systems



[1] Estimated Use of Water in the United States in 2005", USGS Circular 1344, 2009

[2] Major Uses of Land in the United States, 2002, USDA/ERS Bulletin 14, 2006.

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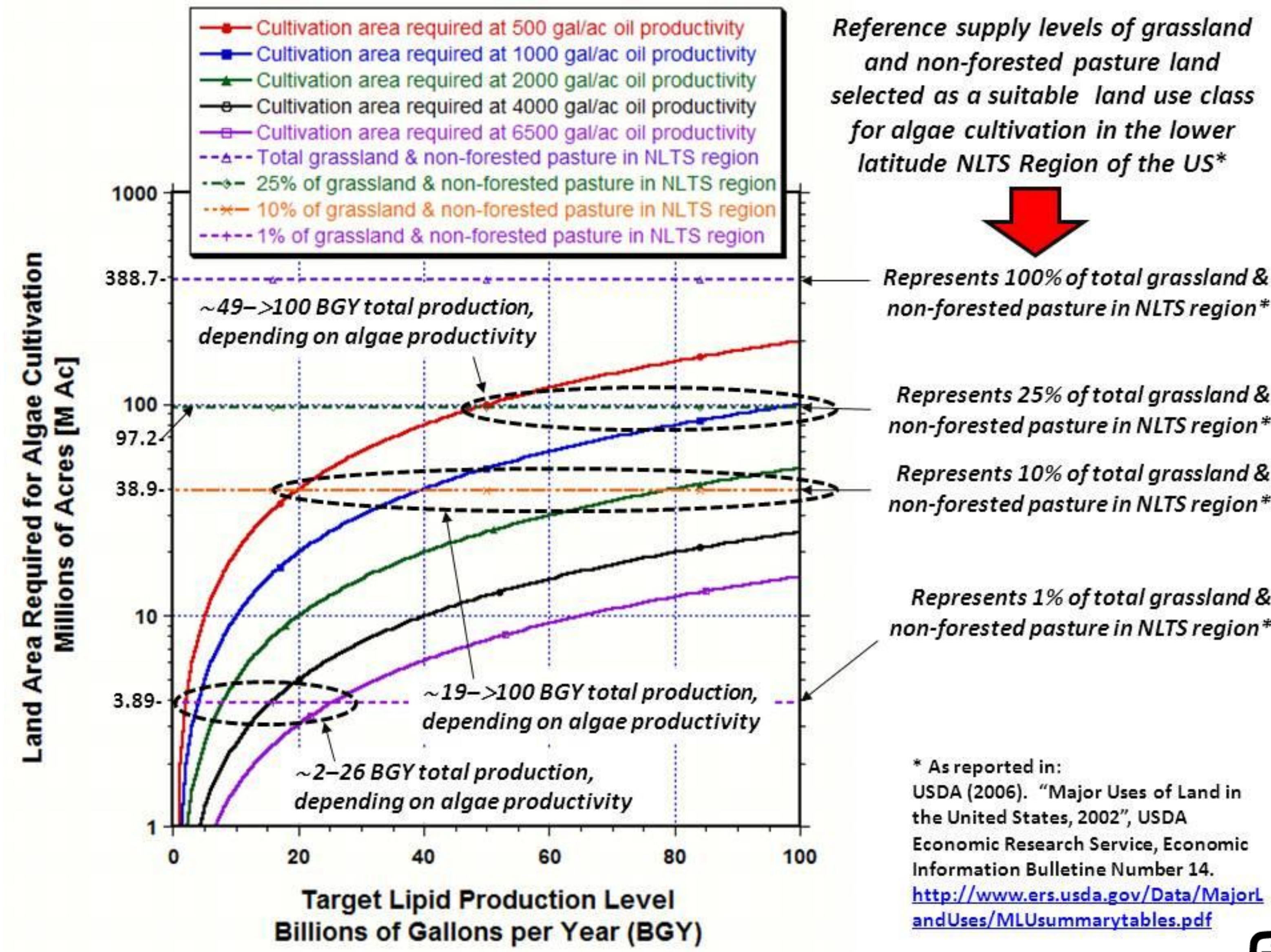
Closer Look at Algae Cultivation Land Area Demand

As function of lipid productivity and target production level



* As reported in:
USDA (2006). "Major Uses of Land in the United States, 2002", USDA Economic Research Service, Economic Information Bulletine Number 14. http://www.ers.usda.gov/Data/MajorLandUses/MLUsummarytables.pdf

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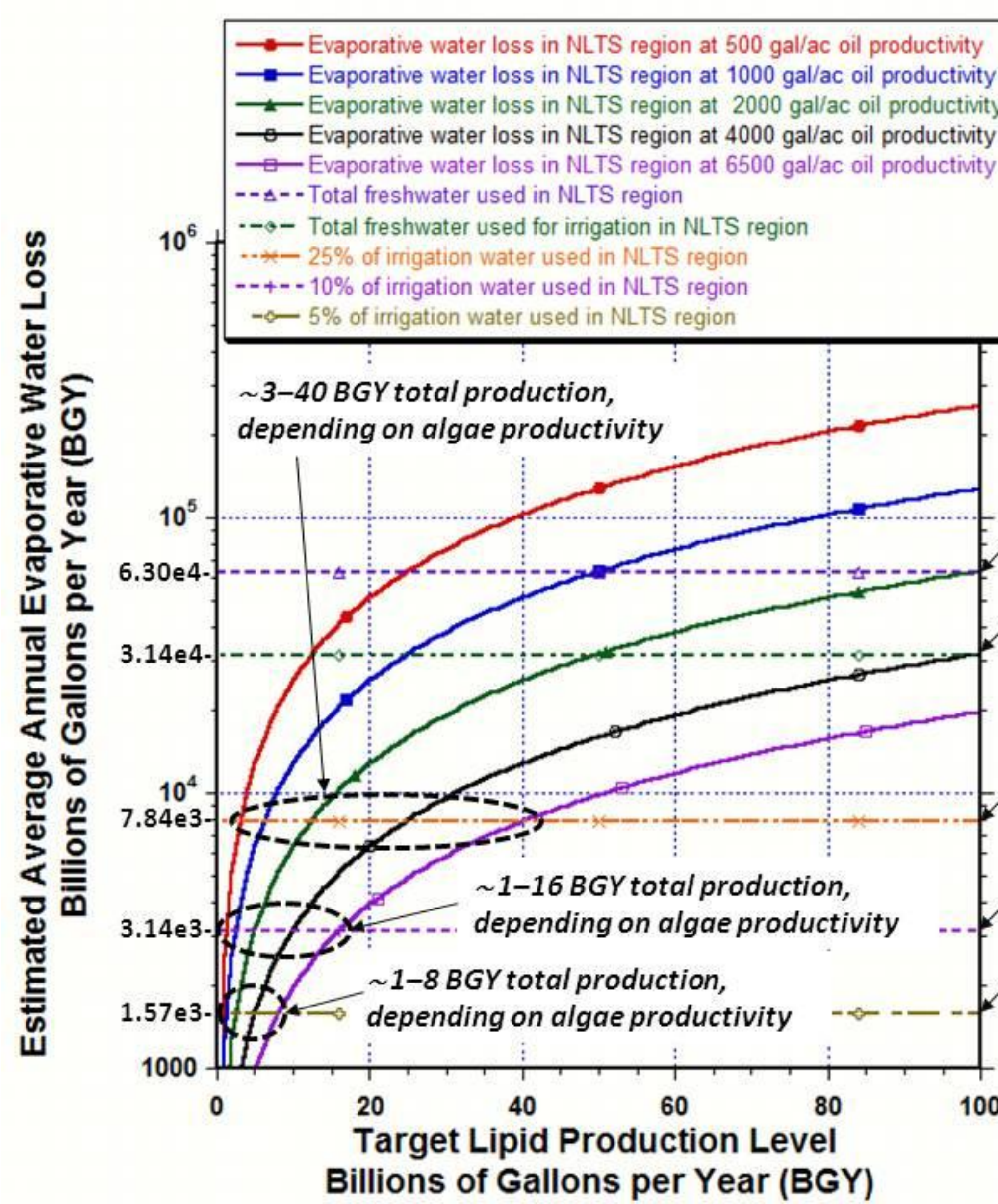
Closer Look at Projected Evaporative Water Loss

As function of lipid productivity and target production level



*Reference supply levels of freshwater resources used in 2005 in the lower latitude NLTS Region of the US**. Irrigation is the most likely category of freshwater use that can be appropriated in sufficient volumes for growing algae**

*Represents total freshwater used for all purposes in the NLTS region**

*Represents 100% of total freshwater used for irrigation in the NLTS region**

*Represents 25% of total freshwater used for irrigation in the NLTS region**

*Represents 10% of total freshwater used for irrigation in the NLTS region**

*Represents 5% of total freshwater used for irrigation in the NLTS region**

* Annual average evaporation rate for NLTS region estimated to be 47 inches per year, based on freshwater pan evaporation data: Farnsworth, R.K., E.S. Thompson, and E.L. Peck (1982). "Evaporation Atlas for the Contiguous 48 United States," NOAA Technical Report NWS 33, and "Evaporation for the United States", NOAA Technical Report NWS 34, Washington, D.C. http://www.weather.gov/oh/hdsc/PMP_related_studies/TR34.pdf

** Water use estimates for the US taken from: Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin (2009). "Estimated Use of Water in the United States in 2005", USGS Circular 1344. http://pubs.usgs.gov/circ/1344/.

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Algae CO_2 Demand vs. CO_2 Emissions Profile

for Scenario Regions & Target Production Levels

CO_2 USE	10 BGY	20 BGY	50 BGY	100 BGY	Profile of CO_2 Emissions from Stationary Sources in Scenario Region[7a] (millions of metric tons)				
Scenario Region	Required[8] CO_2 (millions of metric tons)				Electricity Generation[9]	Ethanol Plants	Cement Plants	Other	Total[7b]
Southwest	140	280	700	1,400	158	1	8	26	193 [174]
Midwest	140	280	700	1,400	173	23	12	10	218 [232]
Southeast	140	280	700	1,400	296	2	13	1	312 [313]
NLTS	350	700	1740	3490	-	-	-	-	[1,482]

[7a] Profiles for stationary CO_2 sources from NATCARB (2008b); [7b] Total CO_2 emissions in [•] from NATCARB (2010)

[8] Assuming two tons of CO_2 required to produce each dry ton of algal biomass with 100% utilization efficiency

[9] Fossil fuel fired electrical power generation plants

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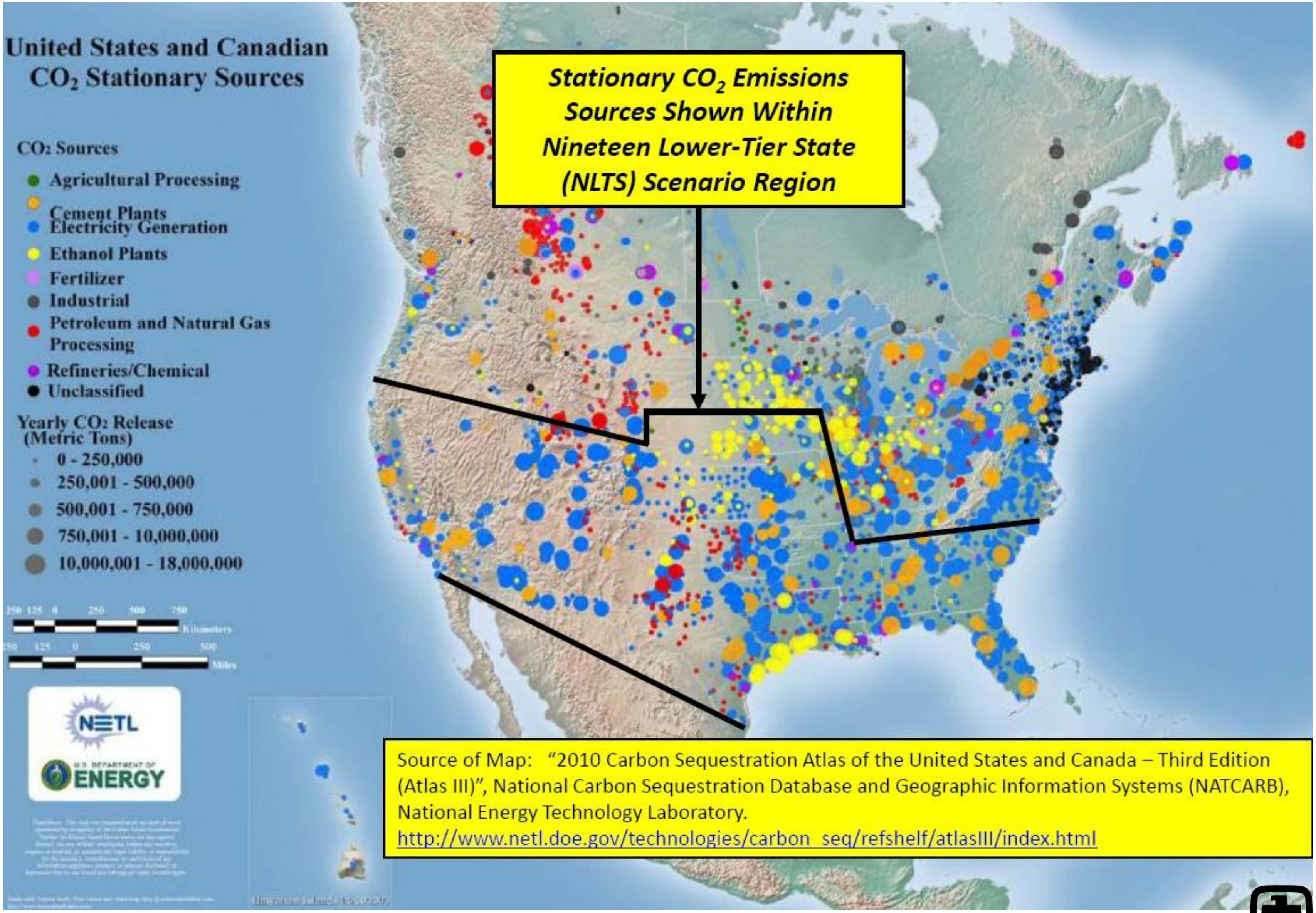
Stationary CO_2 Emission Sources
in Lower-Tier State (NLTS) Scenario Region



Stationary CO_2 sources map courtesy of NETL

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Algae Nutrient (N, P) Demand

for Scenario Target Production Levels and Lipid Content

Shaded Cells signify potential problem levels for resource availability & sustainable use

NUTRIENT USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	Total Biomass (BM) Produced and Projected Nitrogen (N) & Phosphorus (P) Needed[8] in millions of metric tons per year				Elemental Nitrogen (N) and Elemental Phosphorus (P) needed for algae biomass production scale-up as % of total U.S. use in 2006[9]			
SW, MW, & SE w/ 50% Lipid	BM: 70 N: 6.1 P: 0.8	BM: 140 N: 12.3 P: 1.7	BM: 350 N: 31 P: 4.2	BM: 700 N: 61 P: 8.3	N: 44 P: 20	N: 88 P: 41	N: 221 P: 102	N: 436 P: 202
NLTS Region w/ 20% Lipid	BM: 170 N: 15 P: 2.1	BM: 350 N: 31 P: 4.2	BM: 870 N: 77 P: 10	BM: 1740 N: 153 P: 21	N: 107 P: 51	N: 221 P: 102	N: 550 P: 244	N: 1093 P: 512

[8] Assuming elemental algae biomass composition C:N:P ratio of 106:16:1 [Redfield 1934] and 100% nutrient uptake efficiency independent of algae productivity and cultivation system area at 50% dry weight biomass lipid content for SW, MW, and SE scenarios, and 20% lipid content for NLTS scenario region.

[9] Total U.S. consumption in 2006 estimated as 14.0 M mt elemental N consumed as ammonia and 4.1 M mt elemental P consumed as phosphate rock: Data taken from 2010 Mineral Commodity Summaries and 2010 Minerals Yearbook (USGS 2010).

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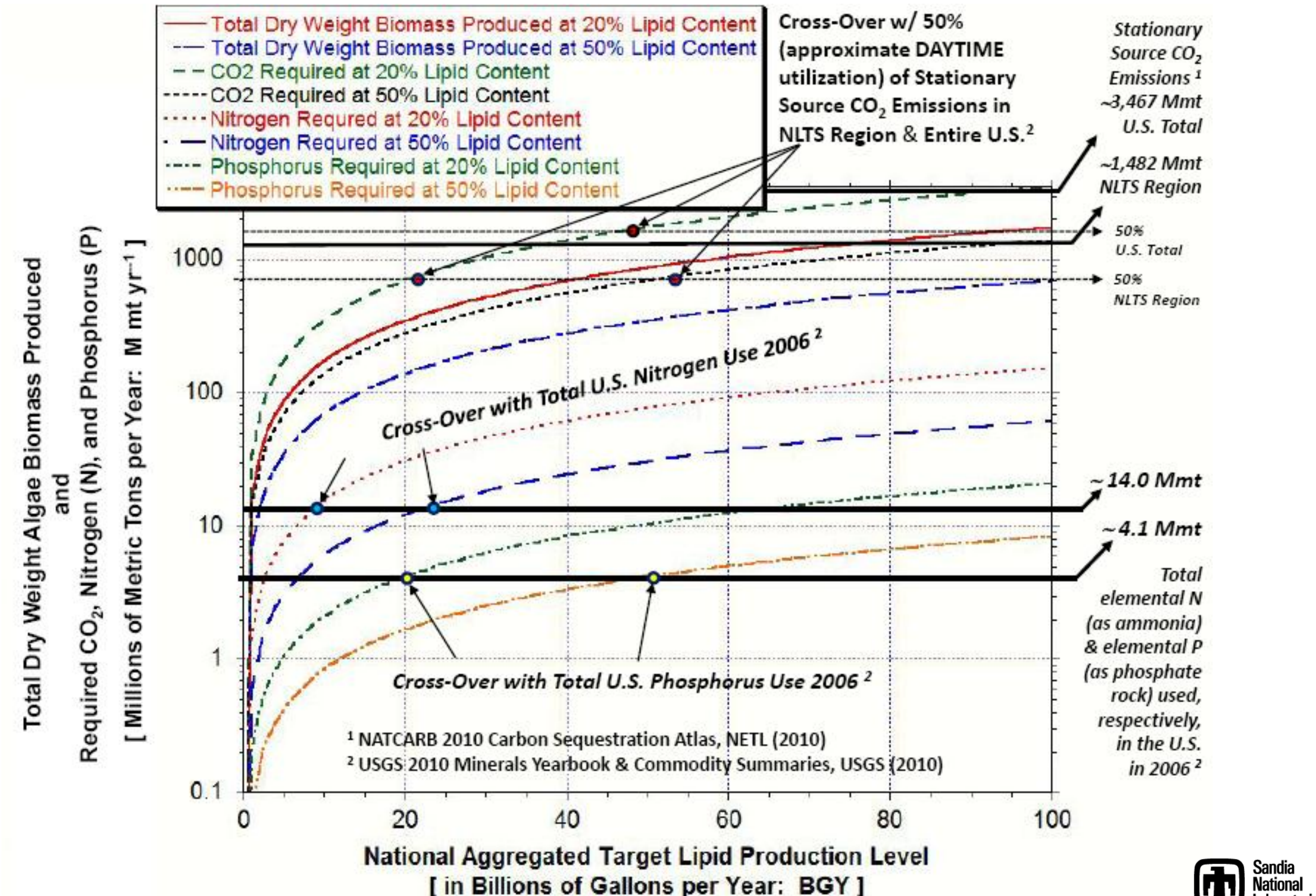
Summary of Biomass Production and Demand for CO_2, N, & P

As a Function of Algae Oil Production Levels & Lipid Content



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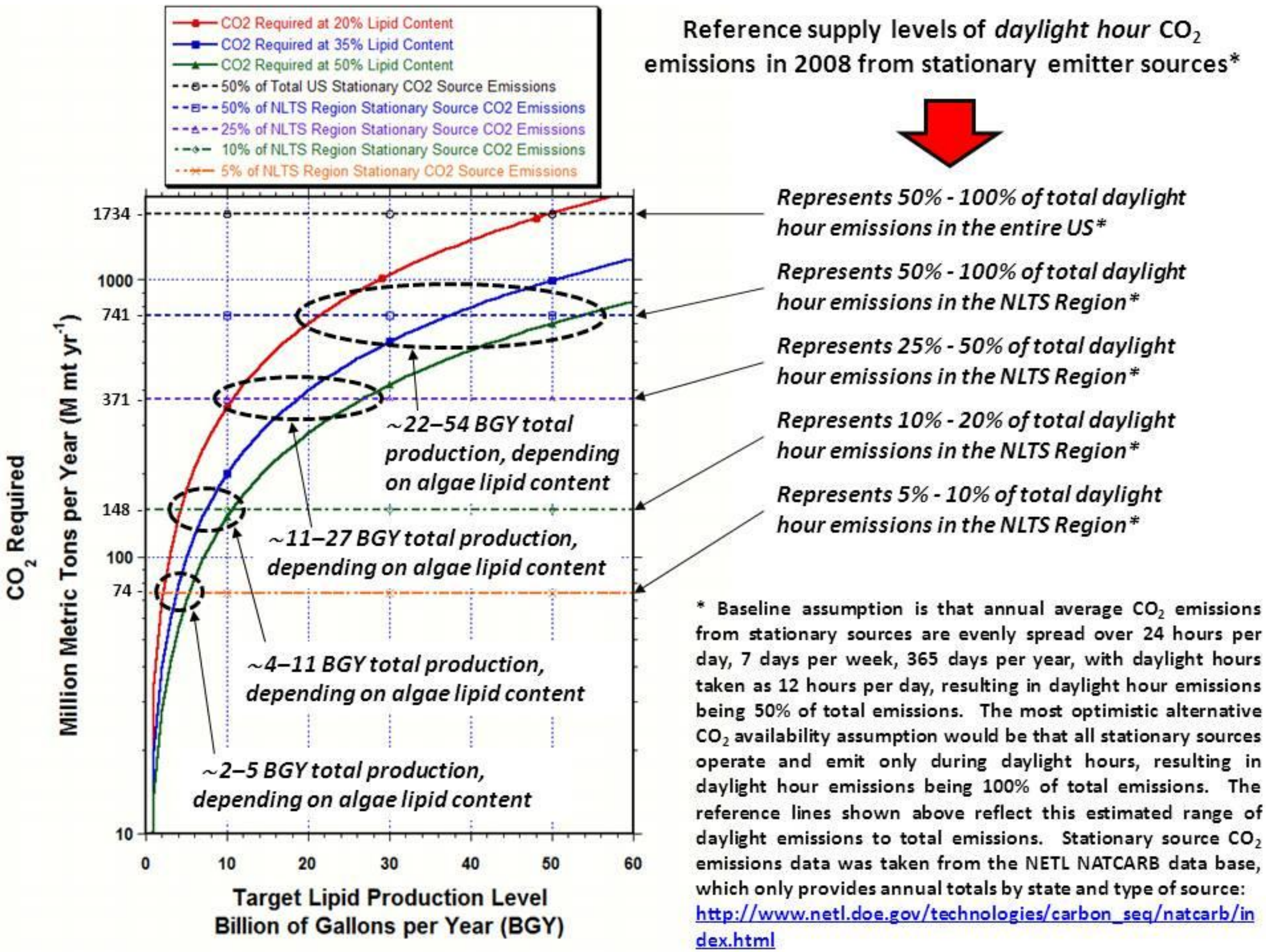
Closer Look at Algae Cultivation CO_2 Demand

as function of algae lipid content and target production level



* Baseline assumption is that annual average CO_2 emissions from stationary sources are evenly spread over 24 hours per day, 7 days per week, 365 days per year, with daylight hours taken as 12 hours per day, resulting in daylight hour emissions being 50% of total emissions. The most optimistic alternative CO_2 availability assumption would be that all stationary sources operate and emit only during daylight hours, resulting in daylight hour emissions being 100% of total emissions. The reference lines shown above reflect this estimated range of daylight emissions to total emissions. Stationary source CO_2 emissions data was taken from the NETL NATCARB data base, which only provides annual totals by state and type of source: http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html

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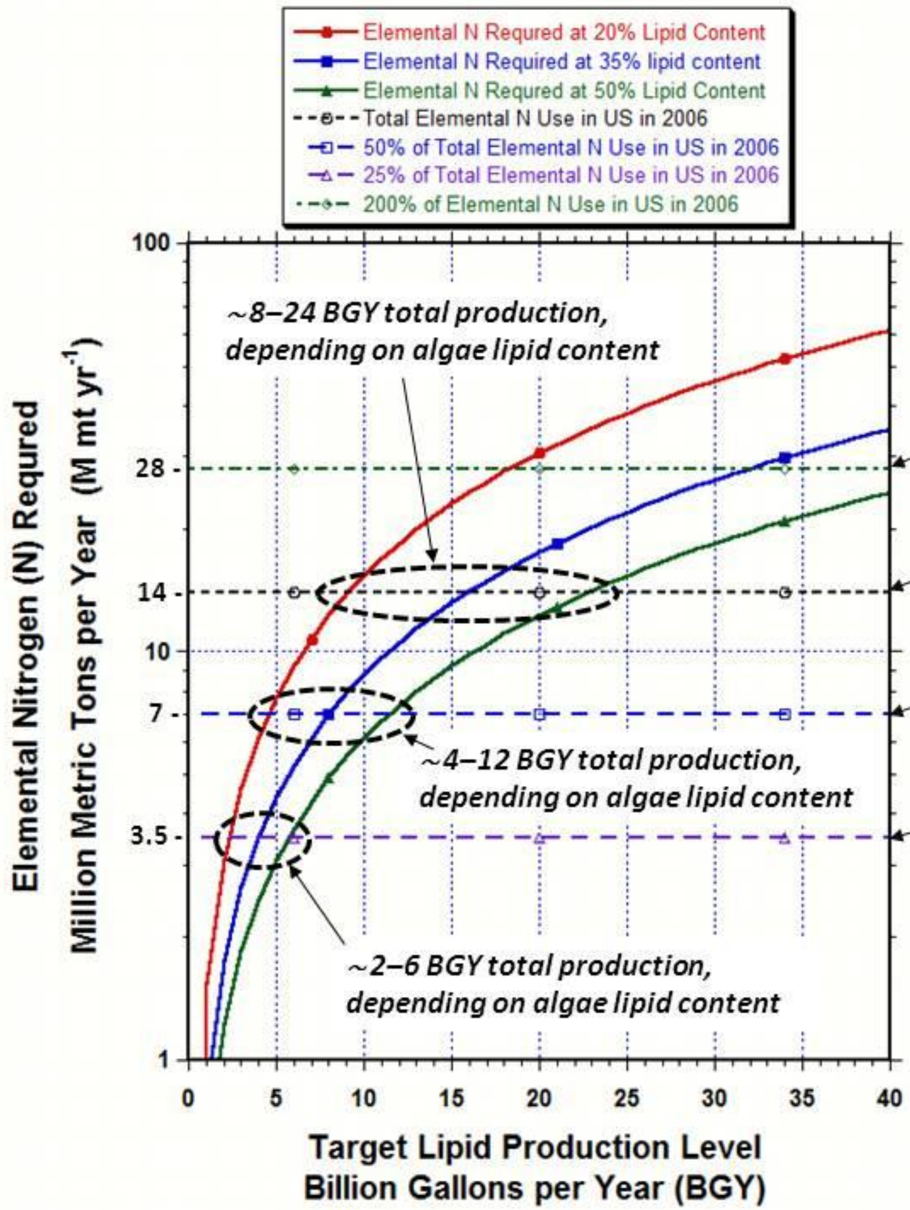
Closer Look at Algae Cultivation N Demand
as function of algae lipid content and target production level



*Reference supply levels of elemental Nitrogen (N) based on U.S. use as ammonia in 2006**

*Represents 200% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

*Represents 100% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

*Represents 50% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

*Represents 25% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

* As reported in:
- USGS, "Mineral Commodity Summaries 2010", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/myb.htm
- USGS, "Minerals Yearbook", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf

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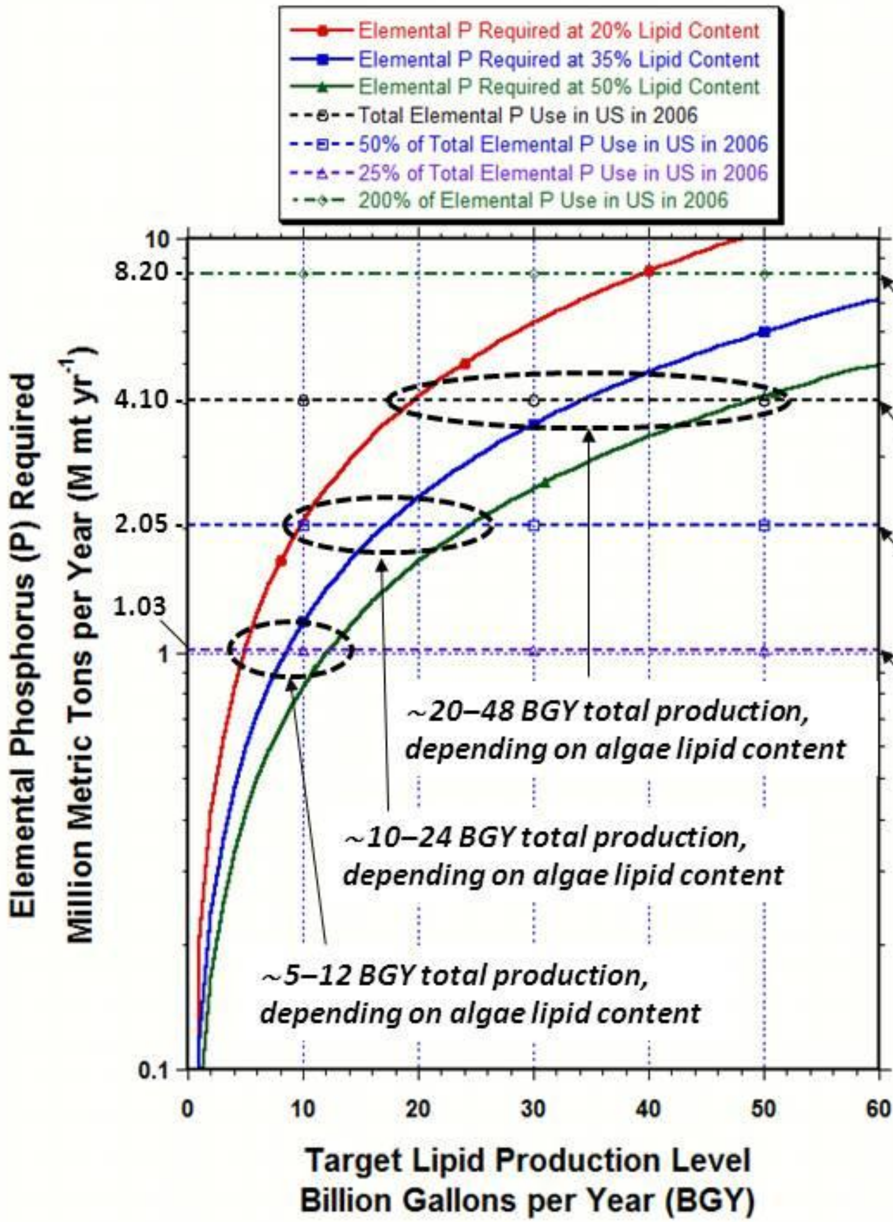
Closer Look at Algae Cultivation P Demand
as function of algae lipid content and target production level



*Reference supply levels of elemental Phosphorus (P) based on U.S. use as phosphate rock in 2006**

*Represents 200% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 100% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 50% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 25% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

* As reported in:

- USGS, "Mineral Commodity Summaries 2010", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/myb.htm
- USGS, "Minerals Yearbook", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf

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Resource Demand Implications from SNL Study

- Resource constraints likely to emerge at the 5-15 BGY oil production range
  - *Based on assessment scenario assumptions and resource demand trends with scale-up*
  - *Fuel production volumes would still be a significant contribution to U.S. fuel supplies*
  - *5-15 BGY oil represents ~8-24% transport diesel or ~16-48% of aviation fuel used in the U.S.*
- CO_2 Sourcing … significant challenge
  - *How much from stationary emitters can be affordably tapped and utilized?*
  - *Co-location opportunities vs. affordable range for transporting concentrated CO_2?*
  - *Can other sources and/or forms of inorganic carbon be affordably used?*
- Nutrients (N & P) … significant challenge
  - *Could seriously compete with agriculture and other commercial fertilizer uses*
  - *Cost and sustainability issues likely to arise with commercial fertilizer use at large algae scale-up*
  - *Need approaches enabling cost-effective nutrient capture and recycling*
- Water … significant challenge with limited freshwater resources
  - *Can't plan on big national scale-up using freshwater with evaporative loss*
  - *Need approaches that use marine and other non-fresh waters*
  - *Need Inland approaches that can reduce or better manage evaporative loss (closed systems?)*
  - *Open system salinity build-up with non-fresh waters will be issue for inland sites*
- Land … requirements likely manageable even for very large scale-up
- *Constraint reduction/relaxation possible with innovation*
  - *Resource use intensity improves with increased algae productivity & oil content*
  - *Resource use intensity improves with capture and recycling of water and nutrients*
  - *How much can this be improved for reliable large scale operations? … TBD !*

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Harmonized Algae Biofuel Modeling Results*

*ANL; NREL; PNNL. (June 2012). *Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model*. ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory.

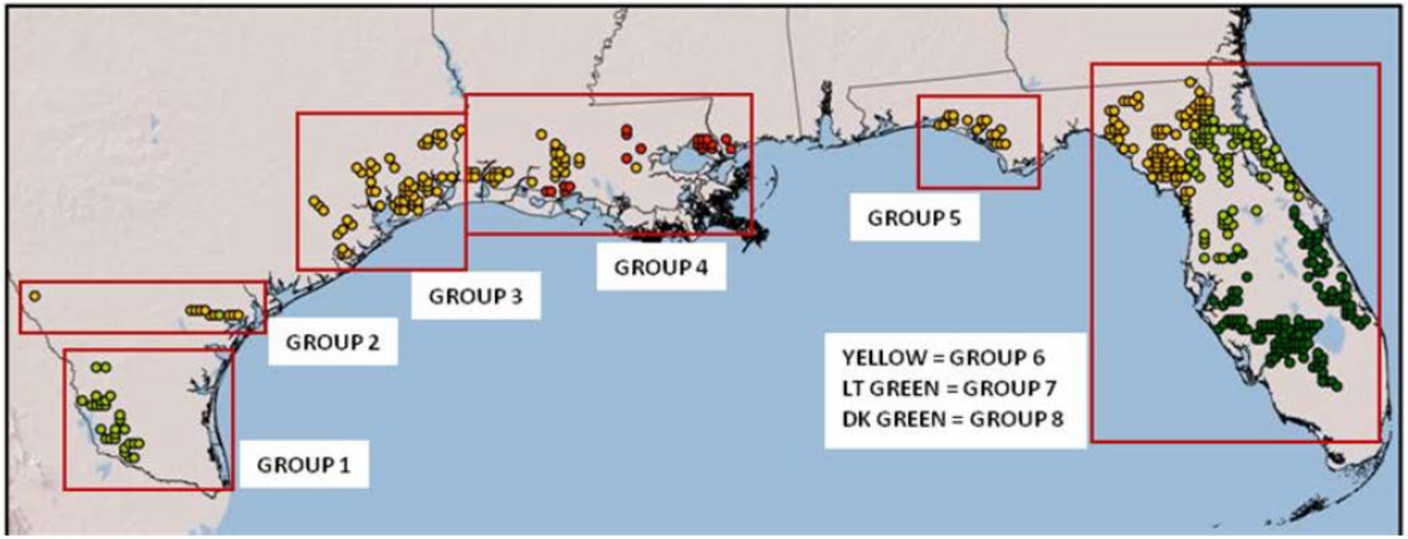


Figure 3.3.3a: Grouping of RA 5 BGY unit farms into representative sites for TEA modeling.

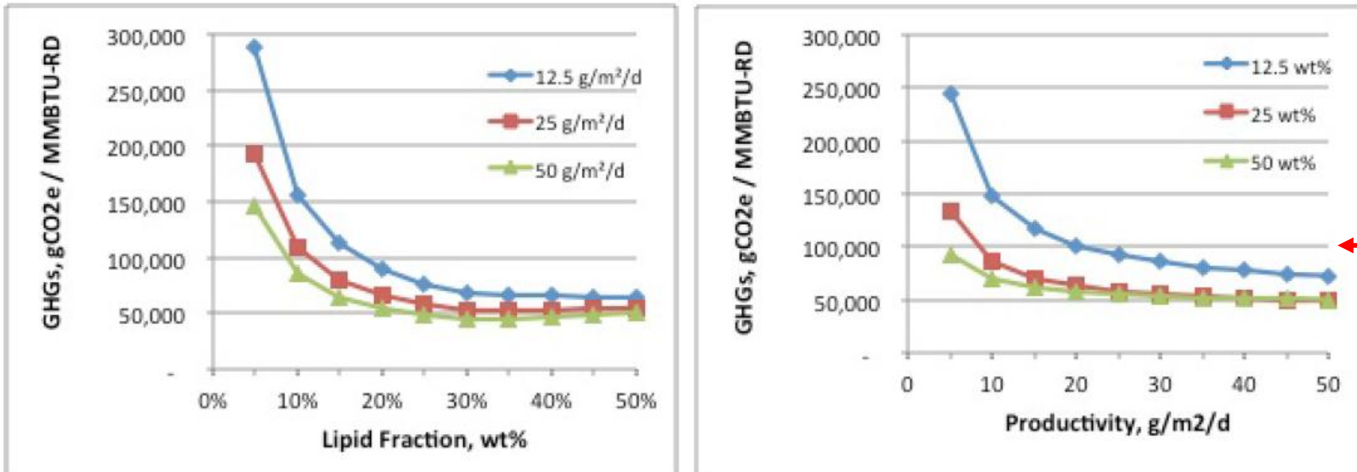
Table 3.3.3a: Average Productivity and Water Consumption Per Season for Each Site Group
Maximum productivity (design case) for each site emphasized in **bold.**

Site Group	# of Sites in Group	Productivity, $g/m^2/day$				Net Water Loss (Evaporation-Precipitation), cm/day			
		Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
1	27	**16.6**	14.0	5.5	16.5	0.5	0.16	0.09	0.37
2	11	15.8	13.6	5.1	**16.2**	0.36	0.12	0.03	0.21
3	60	14.8	13.2	4.3	**15.8**	0.17	0.05	0.002	0.06
4	49	**16.5**	12.6	2.8	15.0	0.04	0.01	0.001	0.02
5	16	**16.0**	12.9	3.4	15.9	0.03	0.004	0.001	0.04
6	77	**16.3**	13.5	4.5	16.2	0.04	0.01	0.003	0.08
7	82	16.1	14.4	6.5	**16.9**	0.05	0.01	0.01	0.11
8	124	15.4	15.4	10.0	**17.6**	0.03	0.01	0.02	0.15
Average[1]		13.2				0.06			

[1] Overall year-average of all unit farms in 5 BGY screening

Harmonized Study TEA & LCA Results*

*ANL; NREL; PNNL. (June 2012). *Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model*. ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory.



Relative Emissions Level for Low-Sulfur Petroleum Based Diesel Fuel: 101,000 gCO_2e/MMBTU

Figure 3.1c: Effect of lipid fraction and productivity on GHG emissions. Although lipid fraction and productivity are not independent variables, the plots display the system sensitivity to both parameters.

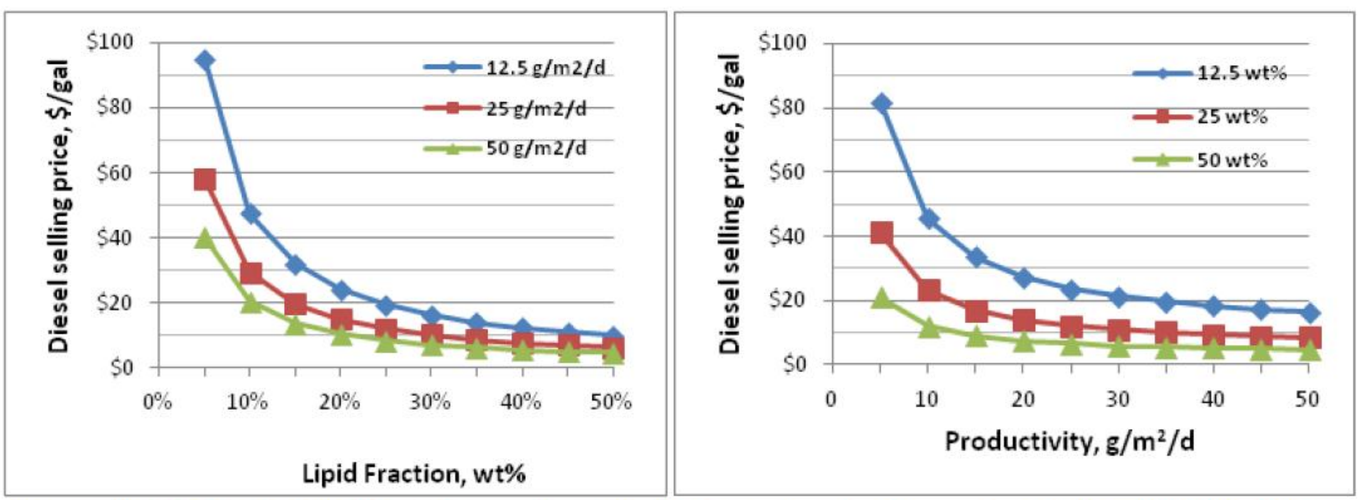


Figure 3.1d: Effect of lipid fraction and productivity on diesel selling price. Although lipid fraction and productivity are not independent variables, the plots display the system sensitivity to both parameters.

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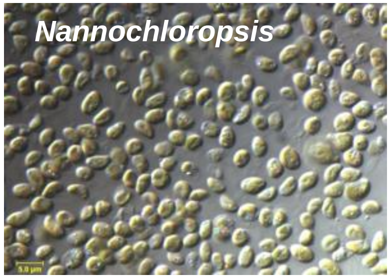
Other Sandia Capabilities and Recent Project Activities Related to Algae Biofuels

- ***Metagenomics*** for rapid identification of contamination agents leading to pond crashes
- ***Computational modeling*** of algae growth kinetics for production optimization and oil yield projections
- ***Hyperspectral Imaging and Spectroscopy*** for real-time monitoring of algae growth, oil production, and early crash indicators
- ***Metabolic & Genetic Engineering*** for enhanced biofuel production
- ***Harvesting, De-watering, Extraction, and Separation*** technologies and processes with reduced energy use

Challenges at the Bottom of the Food Chain
for Robust and Reliable Large-scale Cultivation

Algae

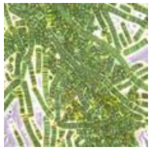


+

Etiological Agents

Virus

Bacteria

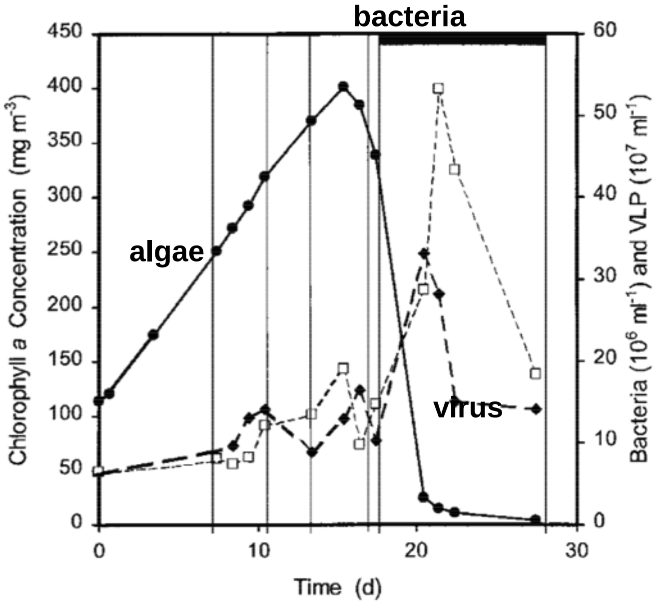


Zoo-plankton

Environment (Temp, salinity, pH, CO2, nutrients)

=

Collapse



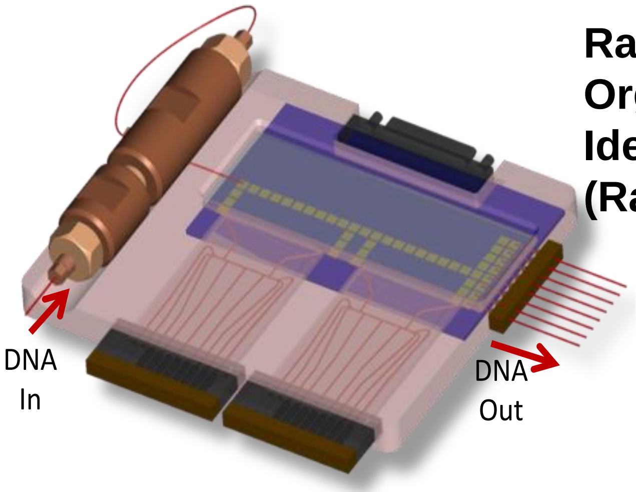
Herman Gons et al., Antonie van Leeuwenhoek, 81: 319-326, 2002.

"Perhaps the most worrisome component of the large-scale algal cultivation enterprise is the fact that algal predators and pathogens are both pervasive and little understood."

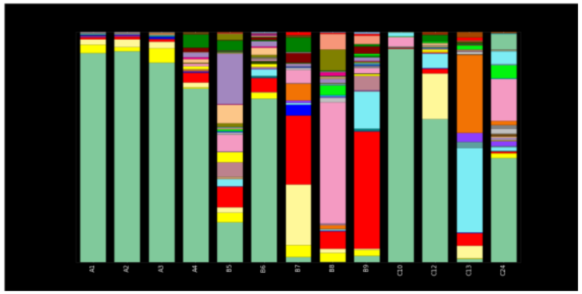
- DOE Draft Algal Biofuels Technology Roadmap (2009)

Use of Metagenomics for Rapid Identification of Biological Agents Causing Algae Cultivation System Crashes

- ***Identification < 24 hrs***
  - *Next generation DNA sequencing*
  - *Compare healthy to crashed samples*
  - *Remove non-informative nucleic acids*
  - *Multiplex samples*
  - *Create molecular assays*



Rapid Threat Organism Identification (RapTOR)



PI: Todd Lane

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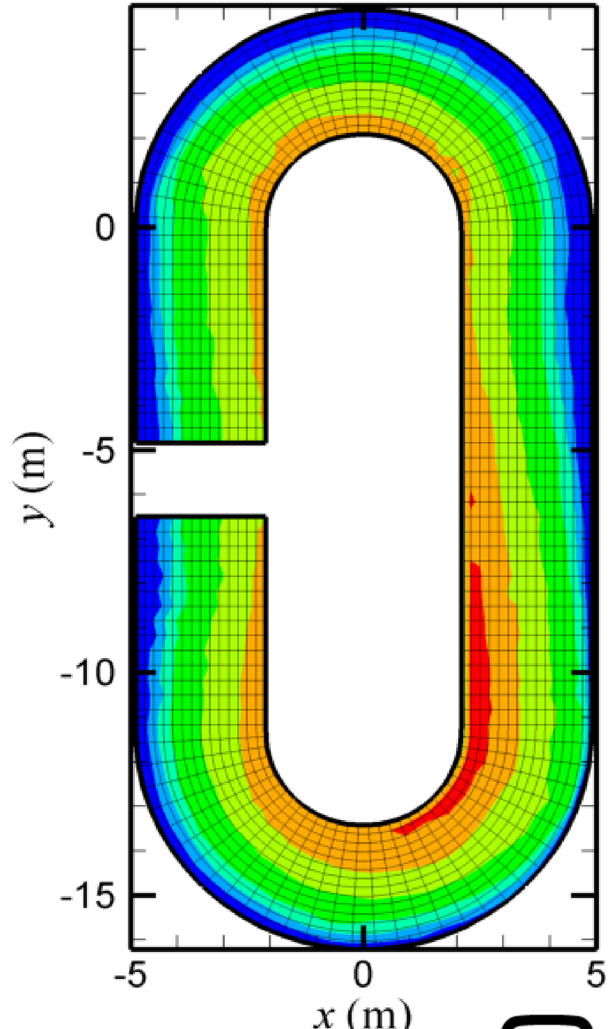
Computational Fluid Dynamic Modeling for Algae Production Insight and Optimization

- ***Environmental Fluid Dynamics Code (EFDC)***
- ***CE-QUAL couples kinetics with 22 variables***

$$\frac{\partial}{\partial t} B(\mathbf{x},t) = \left(P - B_M - P_R - W_S \frac{\partial}{\partial z} \right) B(\mathbf{x},t)$$

- ***Inform engineering design, farm operations, and strain selection to maximize productivity at each site***



PI: Tricia Gharagozloo and Scott James

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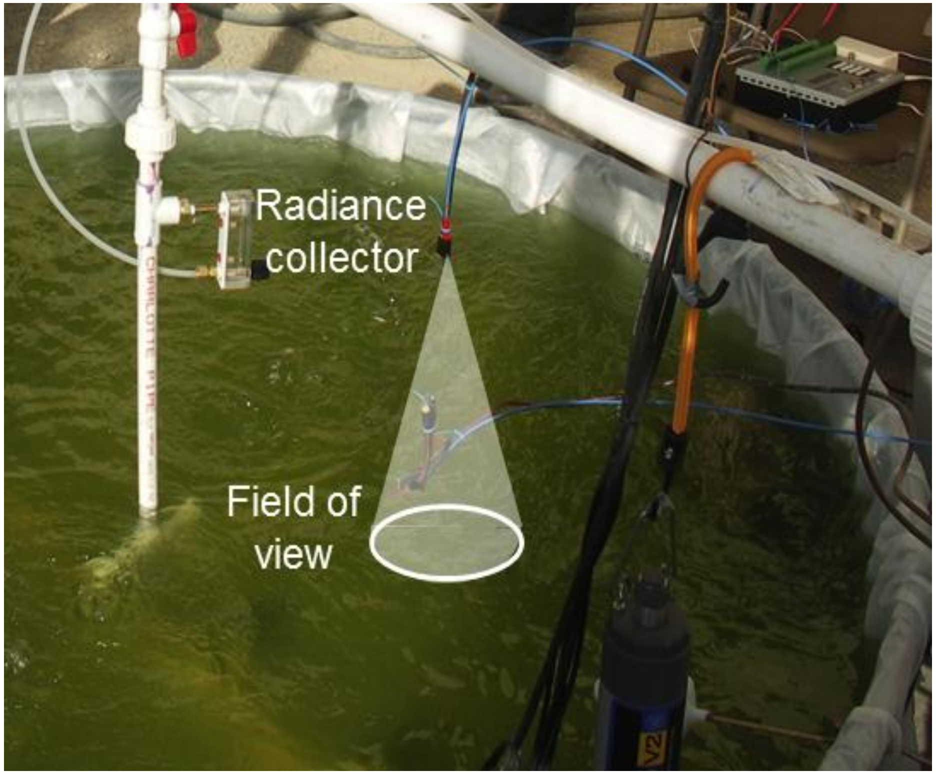
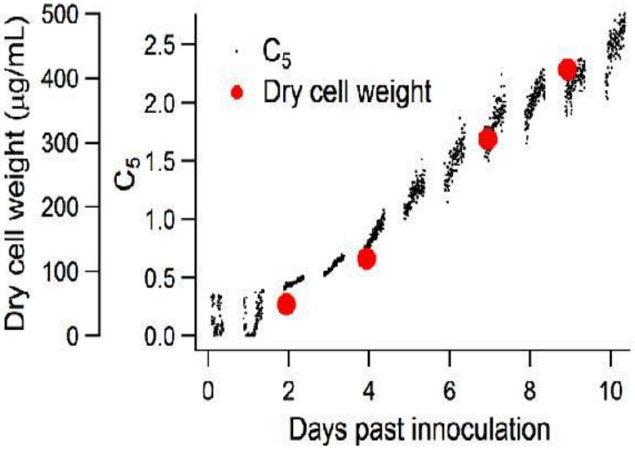
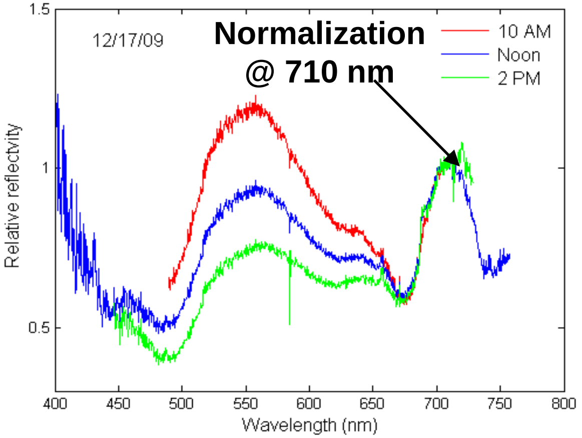
Algal Production and Culture Health Monitoring using Remote Hyperspectral Spectroradiometry

Fiber-coupled spectroradiometric monitoring of a fluidically mixed greenhouse pond







PI: Tom Reichardt

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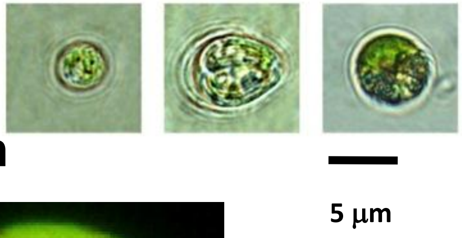
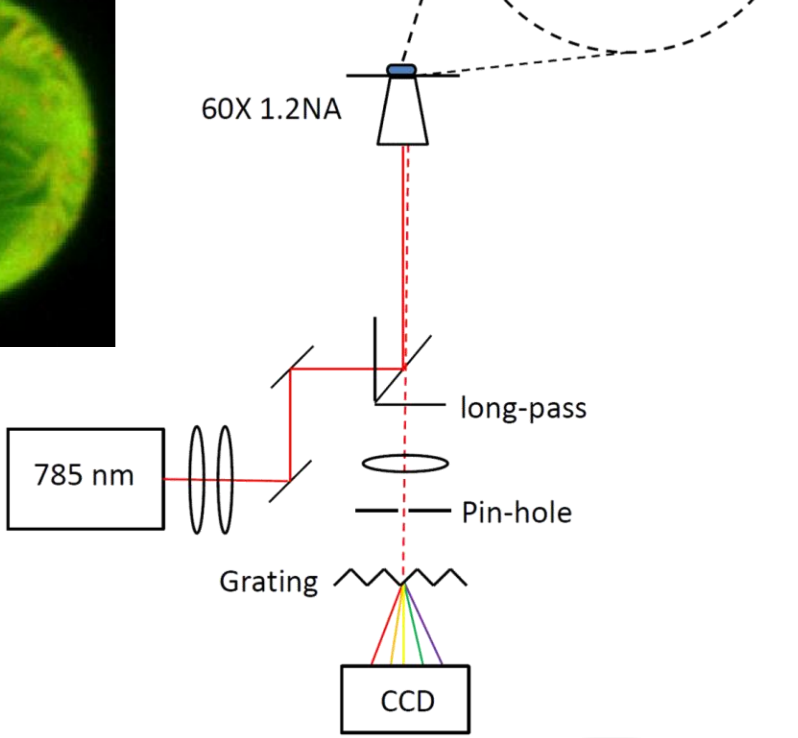
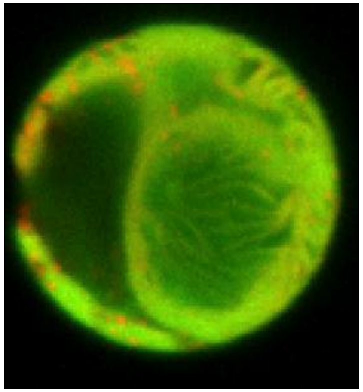
Development and Application of Novel Lipidomics Capabilities to Algae R&D

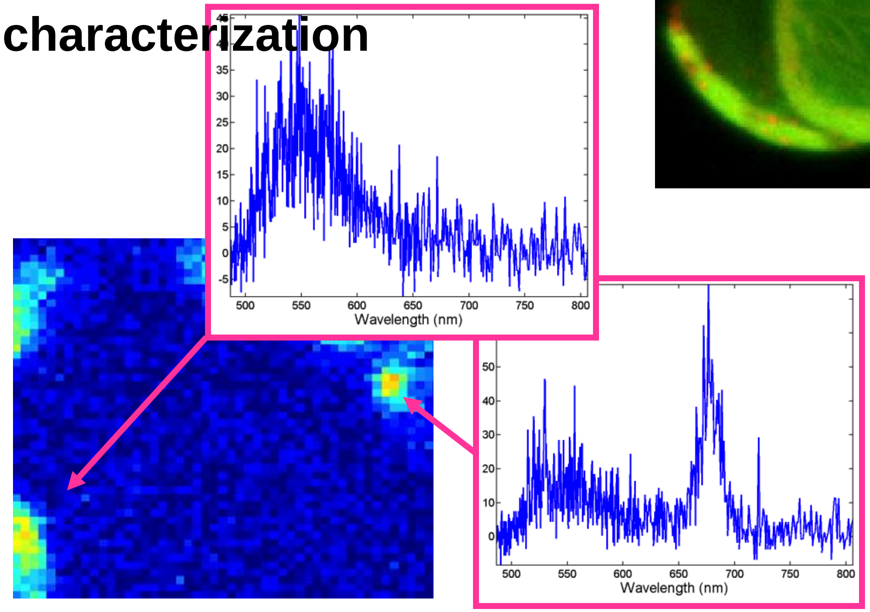
Laser trapping Raman spectroscopy unit for single cell observations of lipid accumulation





Fluorescence hyperspectral imaging for subcellular characterization





PI: Seema Singh

NSF SBIR w/BaySpec

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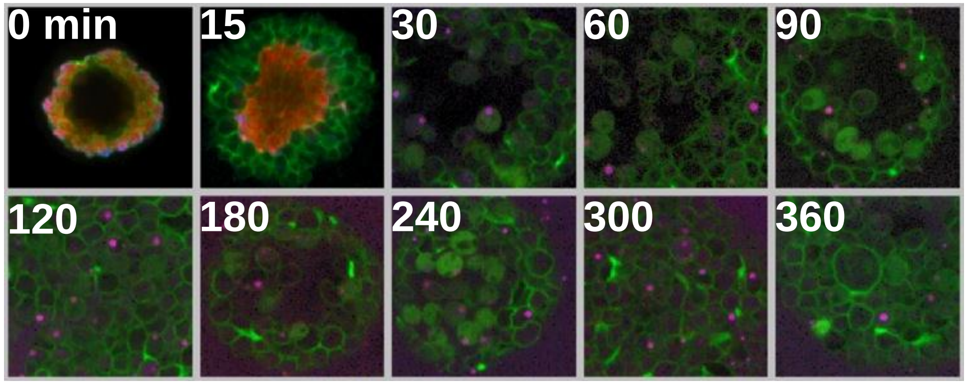
Conversion of algal biomass into feedstock for fermentation-based biofuels

Chlorella in 50 degree C Ionic Liquids

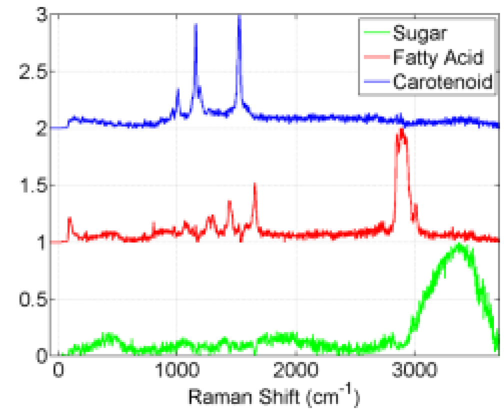


Fluorescence Hyperspectral Imaging

25 μm FOV

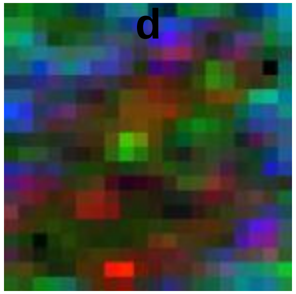
Red – Bound Chlorophyll
Green – Cell walls, carotenoid and carotenoid breakdown products
Blue – Free Chlorophyll

Acid Pretreatment of Chlorella

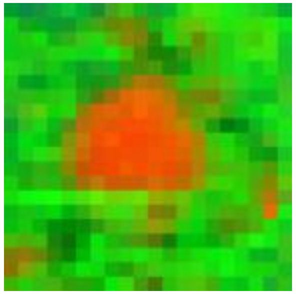


Raman Hyperspectral Imaging

Untreated



Pretreatment



PI: Howland Jones and Masood Hadi

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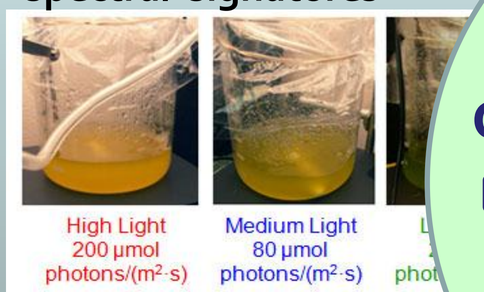
Benchtop to Raceways LDRD

An Innovative, Differentiating Approach

Benchtop Stress Expts

- Basic science on cell level physiological & molecular responses
- Determine cell & culture spectral signatures



Stressors

- CO_2
- Light

Algal Physiology

Molecular Biology

Chemical Imaging / Analysis

Bioanalytical Spectroscopy

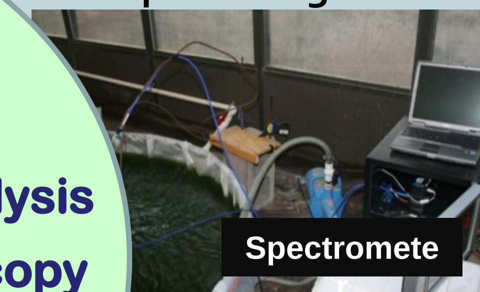
Computational Modeling

Remote Sensing

Statistics

Greenhouse Stress Expts

- Validate algal function at meso-scale outside of lab
- Test spectral signatures



…vay Verification

- …emonstrate validity of approach at raceway scale

Computational Mode…

- Translate experimental work into a scalable mathematical model for *in silico* testing of concepts

$$\frac{\partial}{\partial t}B(\mathbf{x},t) = \left(P - B_M - P_R - W_S\frac{\partial}{\partial z}\right)B(\mathbf{x},t)$$

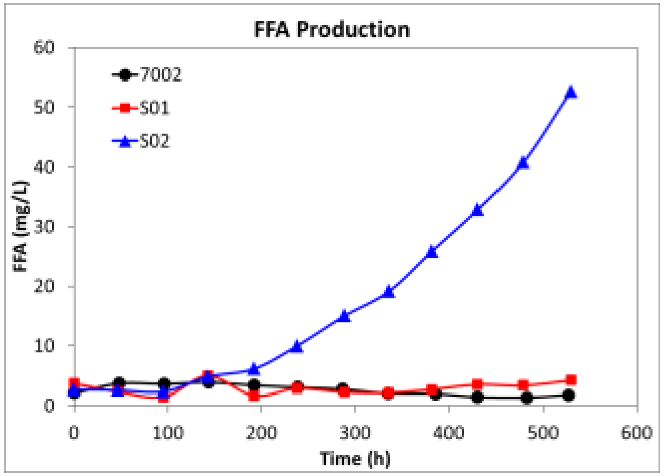
Mechanistic, multi-scale understanding of algal productivity

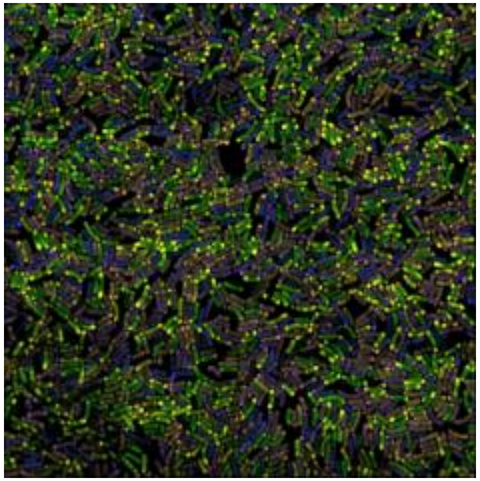
PI: Jerilyn Timlin

Sandia National Laboratories

Genetic Engineering of Cyanobacteria for Biodiesel Feedstock

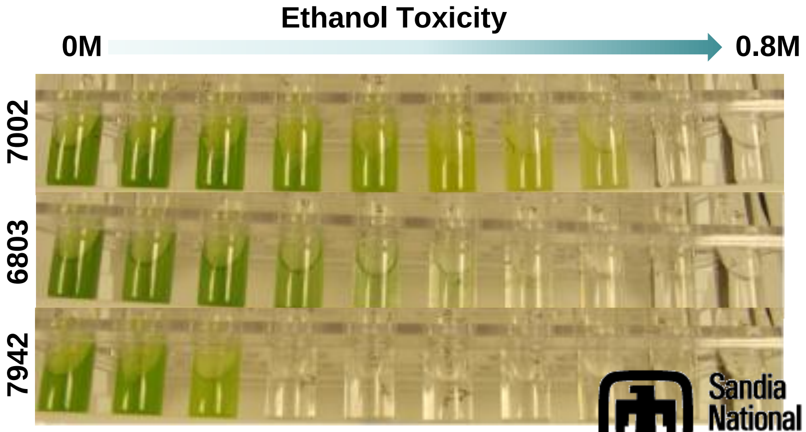
- ***Successfully engineered cyanobacteria for production of biodiesel precursor (FFA – free fatty acids)***





- ***Characterized engineered strains using Sandia's imaging capabilities***

- ***Screened cyanobacterial strains for biofuel tolerance***

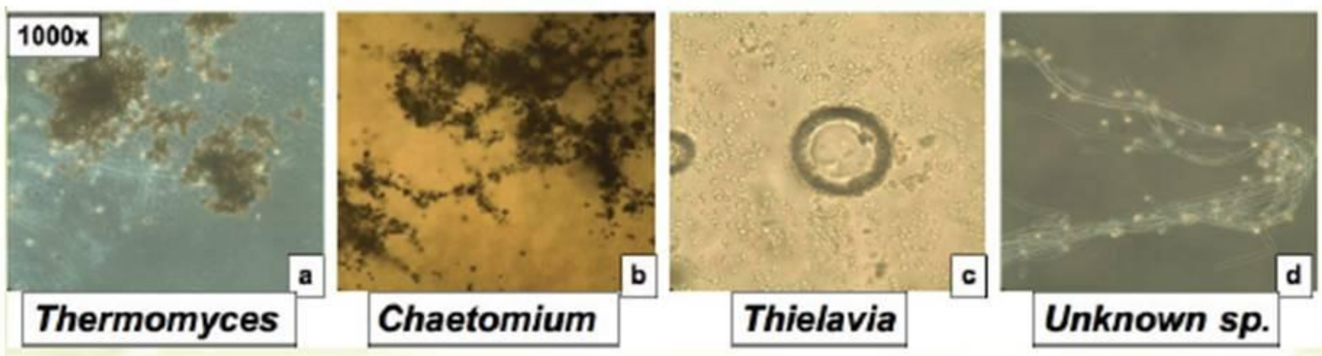


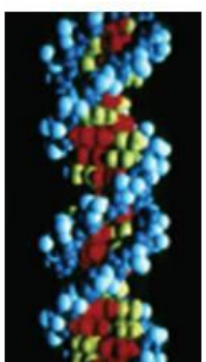
PI: Anne Ruffing

Sandia National Laboratories

Enzyme Discovery & Development For Algae Biomass Processing

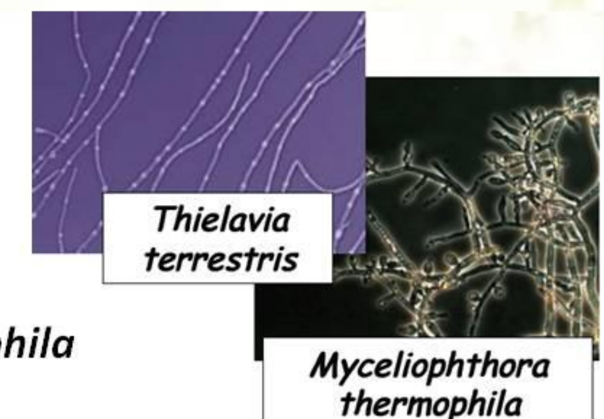
Goal: Use thermophilic fungi & complex microbial communities as enzyme discovery & development platforms to capture new enzyme repertoires for algal biomass processing





Genomic Resources (JGI)

- *Thielavia terrestris*
- *Myceliophthora thermophila*



PI: Amy Powell

Sandia National Laboratories

Sapphire/ Sandia Collaboration

SNL Team: Howland Jones, Tom Reichardt, Scott James, Patricia Gharagozloo, Aaron Collins, Jeri Timlin

Sapphire Team: Craig Benke, Rob McBride, Nicole Heaps

To improve algal culture sustainability through the development of real-time detection and prediction tools…

Field deployment of spectroradiometric methods for real-time monitoring of algal growth. Approach described more fully in: Reichardt, TA, et. al. "Spectroradiometric monitoring of *Nannochloropsis salina* growth", Algal Research, 2012, 1(1) 22-31.

- **Field-test passive spectroscopic tools for real-time characterization of algal growth and pigment properties**
- **Develop computational models to predict algal growth and productivity**
- **Investigate spectroscopic imaging for understanding and possible early detection of chytrid/algal interactions**

U.S. DEPARTMENT OF ENERGY

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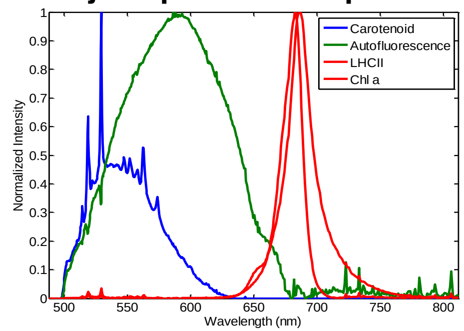
Investigating Chytrid Infection of Scenedesmus:
A Multi-scale Hyperspectral Imaging Approach

Bulk

Goal: Detect chytrid infection using a "bulk-sample-like" fluorescence measurement (i.e. *fieldable*)?

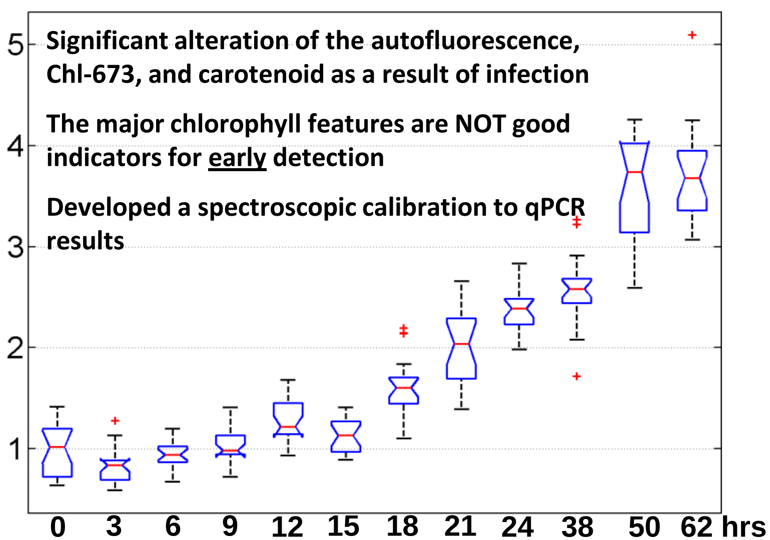
Major Spectral Components



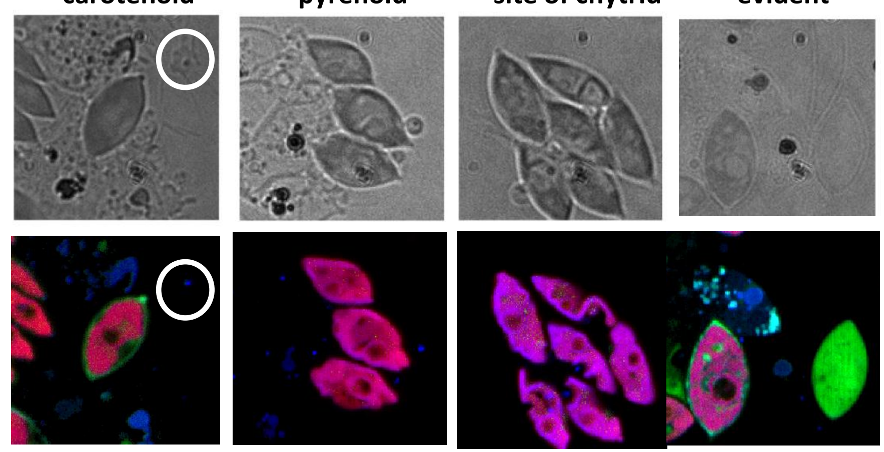
Subcellular

Goal: To develop better *understanding of the mechanism* of infection using chemical, spatial and temporally resolved imaging.

Autofluorescence



Filamentous chytrid w/ carotenoid	Stressed cells show enlarged pyrenoid	Chloroplast retreats from site of chytrid	Variety of stages evident



T= 0 hrs	T= 3 hrs	T= 18 hrs	T= 24 hrs

SNL-Sapphire collaboration

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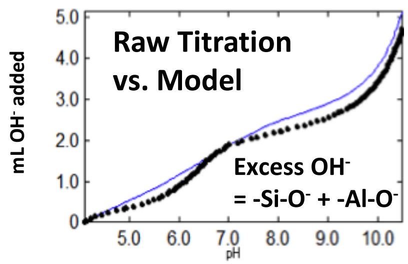
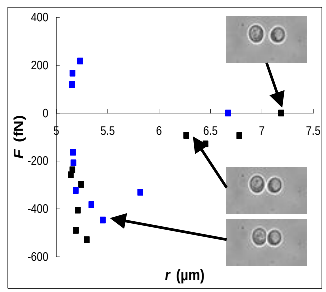
Development of Innovative Algae Biomass Harvesting & Dewatering Technologies

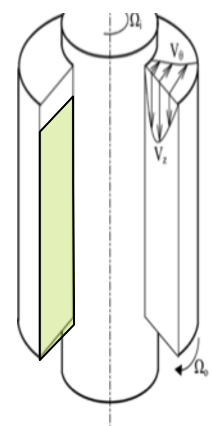
Surface potential measurements

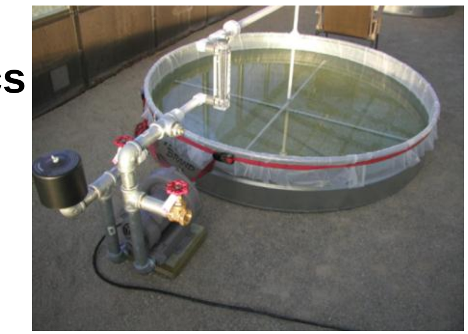


Surface interaction force measurements



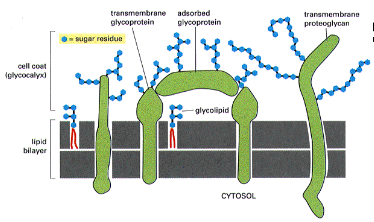
Controlled flow population dynamics measurements



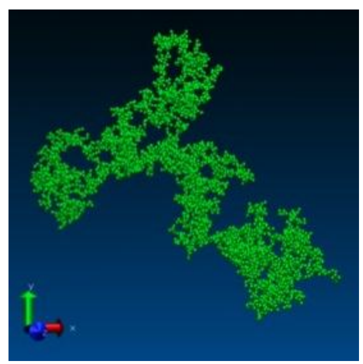


Predicting and optimizing floc dynamics at scale

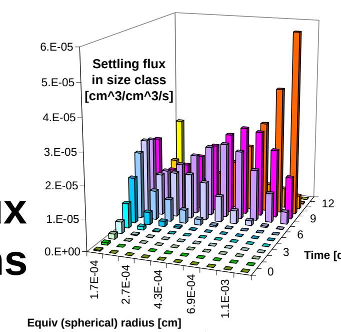
Surface complexation models



Floc aggregation simulations



Predict size and flux distributions



nanometer **micrometer** **millimeter** **meter**

PI: John Hewson

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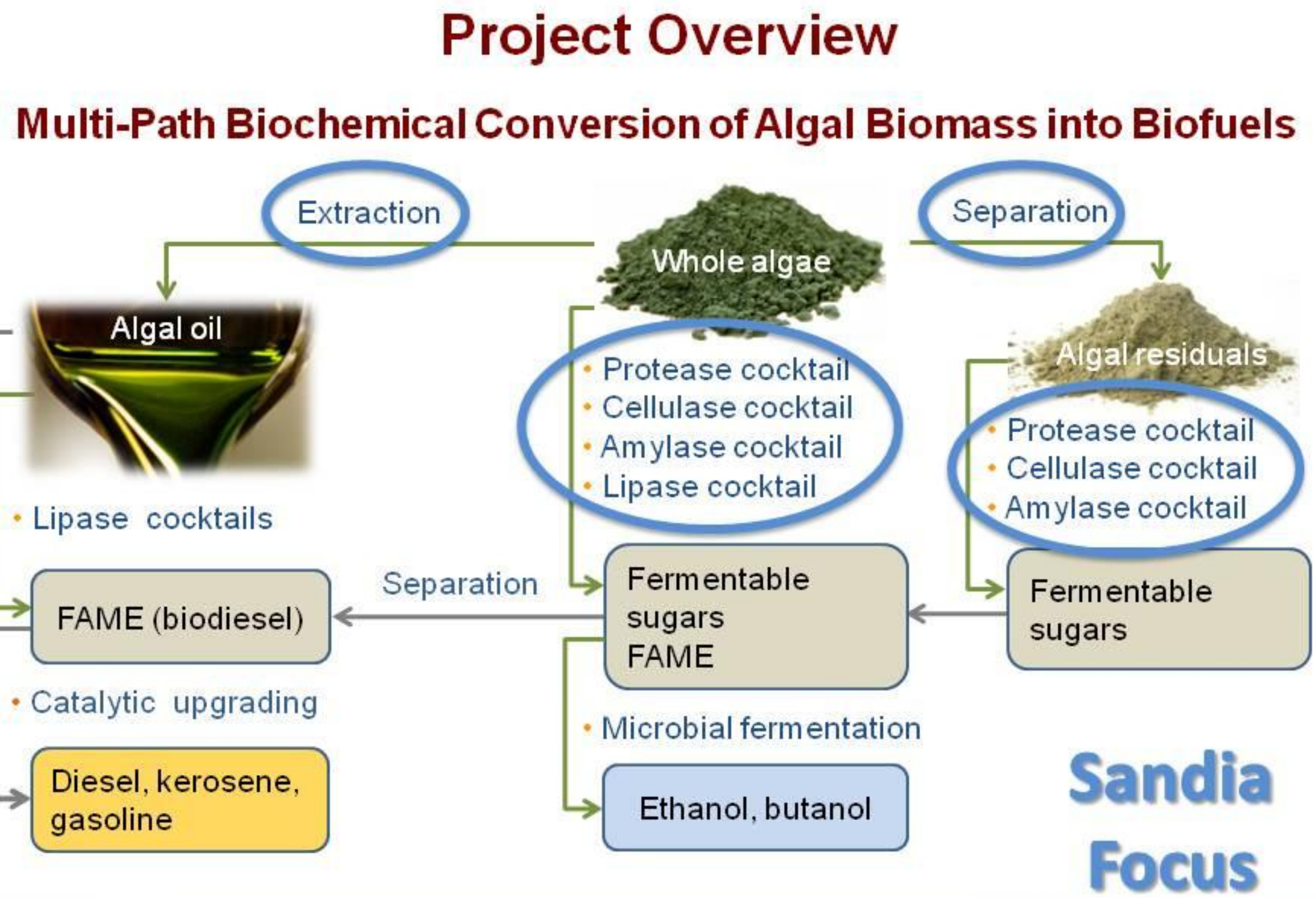
Sustainable Algae Biofuels Consortium (SABC)

$7.5M ($6M DOE Grant) Cost-Shared Project



SNL PI: Ben Wu

Algae Testbed Public-Private Partnership is a national network of testbeds.

ATP3
Algae Testbed
Public-Private Partnership

U.S. DEPARTMENT OF ENERGY

ARIZONA STATE UNIVERSITY

AzCATI
Arizona Center for Algae Technology and Innovation

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CAL POLY
SAN LUIS OBISPO

Sandia National Laboratories

cellana
algae-based products for a sustainable future

SRS ENERGY

Georgia Tech

TOUCHSTONE®

UTEX The Culture Collection of Algae at The University of Texas at Austin

Commercial Algae Management, Inc.

SNL PI: Ron Pate

ATP^3 Vision and Goals

Vision

- Establish a sustainable network of regional testbeds
- Empower knowledge creation/dissemination in algal R&D community
- Accelerate innovation & support algal biofuels industry growth

Goals

- Create geographically diverse network of operating testbeds
  - Leverages existing testbed facilities and experience
- Bring together world-class scientists, engineers and managers
- Increase stakeholder access to high quality facilities
  - Outdoor cultivation
  - Downstream processing
  - Laboratory facilities
  - Managed by a multi-institutional and cross-disciplinary team.
- Support DOE's modeling and analysis activities
  - Techno-Economics
  - Live Cycle Assessment (LCA)
  - Sustainable Resource Utilization and Environmental Impacts
- Close critical knowledge gaps
- Document and promote advancement of state of technology for algal biofuels

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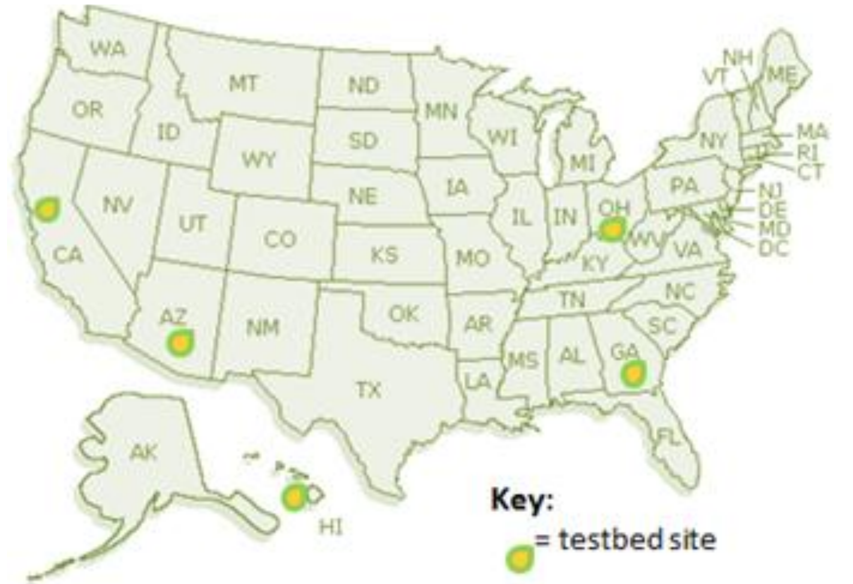
ATP³ Project

Services to include:

- Strain identification & characterization
- Equipment and process testing & validation
- Analytical testing
- Education & training
- Biomass production and supply
- Improved stakeholder access to facilities



Testbed facilities located in:

- Arizona
- Hawaii
- California
- Ohio
- Georgia

Testbed partnership will provide:

- Mutli-regional testbed and analytical lab facilities and operational support
- High quality standardized data collection for algal research community
- Operation of existing open and closed outdoor algae cultivation systems
- Access to real-word conditions for algal biomass production
- Test & evaluation of technologies, processes, and systems
- Performance of long-term cultivation trails.

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Variety of Cultivation Systems
Types and Scale

ATP[3] Partner Site	Cultivation Capacity Total (Liters) (unit scale range)		Annual Production Capacity (AFDW)	Yr. Outdoor Operations Began
	Open Pond	Closed PBR		
ASU (AzCATI)	235,000 (200 - 125K)	21,000 (15 – 1500)	1.5 –2.0 MT	2006
Cellana (KDF)	750,000 (200 - 120K)	300,000 (20 – 24K)	12 – 15 MT	2008
Touchstone (TRL)	450,000 (500-115K)	9000 (75 – 750)	3 – 6 MT*	2012
Cal Poly	100,000 (1000- 10K)	1200 (200-1000)	1.0- 1.5 MT	2007
Georgia Tech. (GT)	6000 (500-1000)	200 (indoor only)	< 0.1 MT*	N/A
Total	1,540,000 L	330,000L	17.5 – 24.5 MT	

* Expected capacity

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Conclusions

- Algae is promising feedstock for advanced biofuels, but faces several technical, economic, & sustainability challenges to affordable scale-up
- Resource demand will impose specific constraints to scale-up
- Site location for sustainable algae production must consider:
  - Available sunlight resource (monthly, seasonal, and annual variations)
  - Available land resources suitable for algae production with minimal use competition
  - Temperature regimes (depending on algae strain and growth system)
    … taking into consideration daily, monthly, and seasonal variations
  - Available water, nutrient, and CO_2 resources… look for co-location opportunities
  - Numerous other required input resources (e.g., energy) and logistical factors
- CO_2 and nutrient (N, P) sourcing will likely impose the greatest overall constraints to scale-up in the U.S.
- Fresh water use can be a constraint, depending on location
  - Non-fresh waste & saline waters are option, but introduce salt build-up & management issues
- Land is probably the least constraining, depending on region
- Improvements needed to reduce costs and constraints:
  - Higher and more reliable algae biomass oil content and productivity
  - Innovations in lower energy intensity harvesting and downstream processing into fuels and co-products
  - Innovations in water and nutrient capture & recycling
  - Innovations in non-fresh water use and reduced water loss during cultivation
  - Innovations in the sourcing and improved use efficiency of C, N, and P
- Other external factors: Cost, availability, & impacts of other fuels
  - e.g., Increased domestic oil and gas production with horizontal drilling and fracking

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Acknowledgement of Contributors

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Thank You !

Questions ?

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Back-up Materials

Not All Fuels are Alike

Energy Density Differences and Infrastructure Compatibility

- Denotes fuels fully compatible with current infrastructure[1] (yellow box)

Ethanol[2]	Gasoline[2]	Biodiesel[2]	Diesel Fuel[2]	Jet Fuel[2]
~84,600 Btu/gal	*~125,000 Btu/gal*	*~126,200 Btu/gal*	*~138,700 Btu/gal*	*~135,000 Btu/gal*
Energy Density (Volumetric) Relative to Conventional Gasoline				
~0.68	*1.00*	*~1.01*	*~1.11*	*~1.08*
Fuel Volume per Quad of Energy Content in Billions of Gallons per Quad (Bgal/Quad)[3]				
~11.8	*~8.00*	*~7.92*	*~7.21*	*~7.41*

[1] Hydrocarbon fuels transport, storage, distribution, and end use (e.g., engines and vehicles)

[2] Higher heating values for the various fuels are taken from:

Davis, et al. (2010). Stacy C. Davis, Susan W. Diegel, and Robert G. Boundy, "Transportation Energy Data Book: Edition 29", ORNL-6985, Oak Ridge National Laboratory, DOE/EERE Vehicles Technology Program, July 2010. http://cta.ornl.gov/data/download29.shtml

[3] Quad = 1-Quadrillion Btu's = 10^{15} Btu, where 1-Btu = 1.055 kJ = 2.93×10^{-4} kWh

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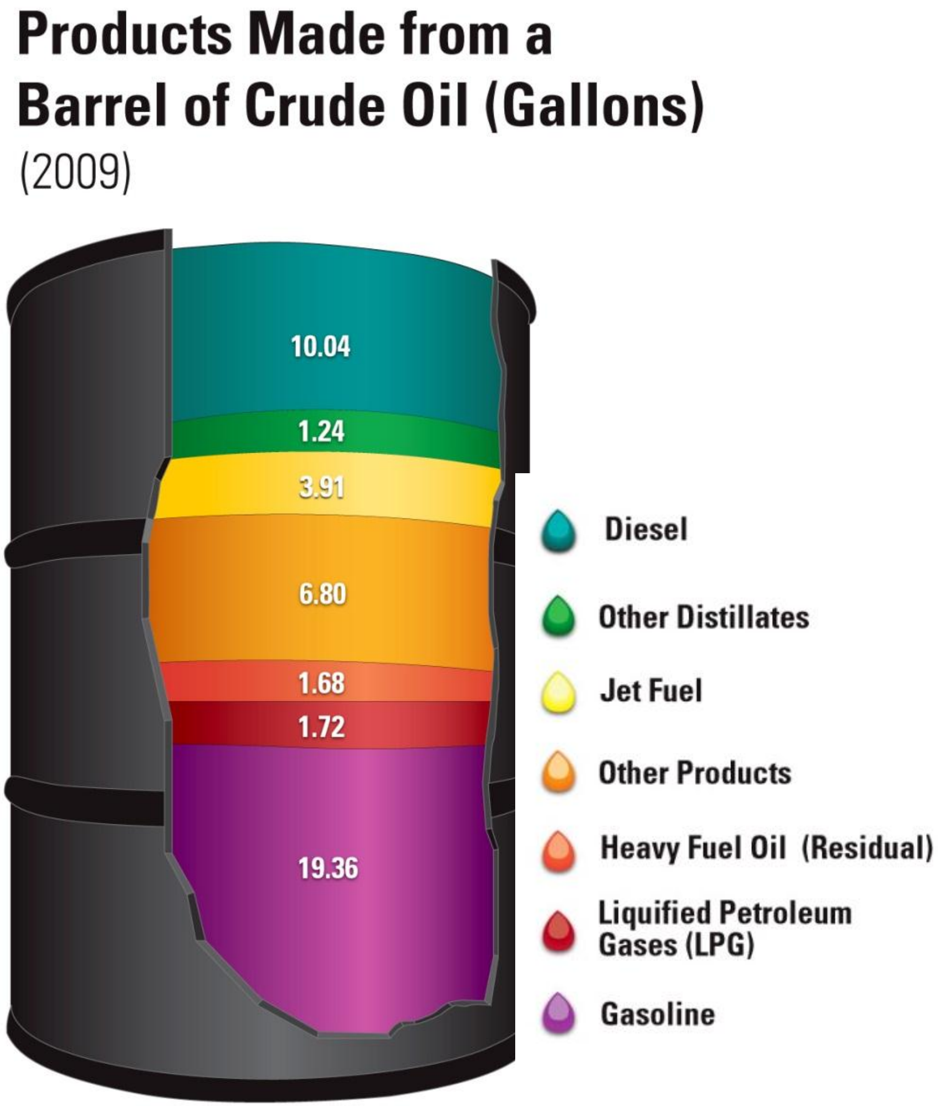
Displacing the Whole Barrel… *Trend Toward Producing Drop-In Hydrocarbon Biofuels & Bioproducts*



- **At low % biofuel blends, refiners can adjust operations to produce suitable blendstocks**
  - **Ethanol, e.g., Vapor Pressure**
  - **Biodiesel, e.g., Cold-Flow**
- **At higher % biofuel, displaced hydrocarbons may be shifted to less-valuable markets**
  - **Gasoline, e.g., to Cracker Feed**
  - **Diesel, e.g., to Fuel Oil**
- **As crude is displaced as a source of one product, there may be shortfalls in other markets**
  - **Gasoline, e.g., Diesel & Jet**
  - **Motor Fuels & Jet, e.g., chemicals**
  - **Aromatics, e.g., hydrogen**

Source: Energy Information Administration, "Oil: Crude Oil and Petroleum Products Explained" and AEO2009, Updated February 2010, Reference Case.

Assumptions in Developing Theoretical Estimates for Photosynthetic Algae Biomass & Oil Production Maxima [1, 2]

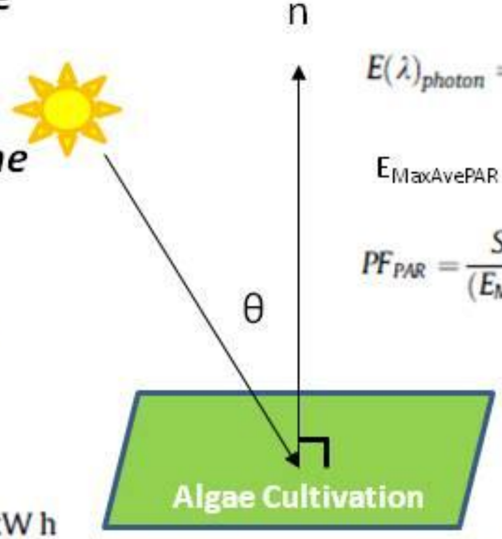
- CO_2 saturation in the water column to support maximum growth
- Sufficient nutrients (N, P, etc.) for maximum biomass growth
- Solar irradiance taken to be I_1 = 1,000 W m^{-2} peak mid-day incidence
- Annual average daylight hours taken to be 12 hours per day
- Clear sunny skies ~ 90% of the year (high solar resource location)
- Photosynthetically Active Radiation (PAR: in wavelength range of 400nm - 700nm) = 45% of incident solar energy spectrum
- Total incident PAR photon flux utilized completely (100% efficiency) for conversion to chemical energy by photosynthesis at the rate of 10-photons per fixed carbon atom (8-photons is theoretical minimum)
- Maximum photosynthetic conversion efficiency between 21-22%
- Chemical energy captured through photosynthesis converted into biomass at 100% efficiency
- Harvest efficiency of 100%
- Extraction efficiency of 100%

[1] Weyer, et al. (2009). K. M. Weyer, D.R. Bush, A. Darzins, and B.D. Willson, "Theoretical Maximum Algal Oil Production", *BioEnergy Research*, 1–10, 2009.

[2] Cooney, Michael, Greg Young, and Ronald Pate (2010). "Bio-oil from photosynthetic microalgae: Case study", Bioresource Technology, 9 July 2010.

Theoretical Basis for Converting Solar Energy to Biomass

Theoretical Maximum Capture of Annual Average Incident Solar Energy on Algae Cultivation on Horizontal Plane at Earth's Surface:



$$I_{hor,avg} = \frac{\int_0^{\pi/2} \left[1000 \left(\frac{W}{m^2}\right) \cos(\theta)\right] d\theta}{\frac{\pi}{2}}$$

$$= \frac{2}{\pi}\left(1000 \frac{W}{m^2}\right) = 637 \frac{W}{m^2}$$

$$E_{solar,daily,avg} \approx 12 \frac{h}{d} \times 636.6 \frac{W}{m^2} = 7.64 \frac{kW\,h}{m^2 d}$$

$$E_{solar,avg} \approx 27.5 \frac{MJ}{m^2\ d} \times 365 \frac{d}{year} = 10,038 \frac{MJ}{m^2\ year}$$

$$S_{Earth} \approx \underbrace{0.9}_{} \times 10,038 \frac{MJ}{m^2\ year} = 9034 \frac{MJ}{m^2\ year}$$

10% loss from clouds, mist, dust, etc. (at sunny locations)

$$S_{EarthPAR} \approx 0.45 \times 9034 \frac{MJ}{m^2\ year} = 4065 \frac{MJ}{m^2\ year}$$

$$E(\lambda)_{photon} = \frac{1.986 \times 10^{-25}\ (J\ m)}{\lambda\ (m)} \quad ;\ \lambda = 400 - 700\ nm\ \text{(PAR Spectrum)}$$

$E_{MaxAvePAR} = 0.2253$ MJ per mole photons (λ = 531 nm)

$$PF_{PAR} = \frac{S_{EarthPAR}}{(E_{MaxAvePAR})} = \frac{4065 \frac{MJ}{m^2\ year}}{\left(\frac{0.2253\ MJ}{mole\ photon}\right)} = 18,043 \frac{moles\ photons}{m^2\ year}$$

Photosynthesis:

$$CO_2 + H_2O + n\ photons \rightarrow \underbrace{CH_2O}_{E_{CARB}} + O_2$$

$$E_{CARB} = \frac{PF_{PAR}\left(\frac{energy}{mole\ CH_2O}\right)}{\left(\frac{n\ photons\ required}{mole\ CH_2O}\right)}$$

Assume:
n=10 photons per molecule CH_2O

$$= \frac{18,043 \frac{moles\ photons}{m^2\ year}\left(0.4825 \frac{MJ}{mole\ CH_2O}\right)}{\left(\frac{10\ photons}{mole\ CH_2O}\right)}$$

$$= 871 \frac{MJ}{m^2\ year}$$ = Maximum chemical energy captured via photosynthesis

Assume 100% conversion of photosynthetic chemical energy to biomass (η_{BA} = 1)

$$E_{BCE} = E_{CARB} * \eta_{BA} = 871 \frac{MJ}{m^2\ year} * (1) = 871 \frac{MJ}{m^2\ year}$$ = Maximum biomass chemical energy produced

$$PE_{total} = \frac{E_{BCE}}{S_{EarthPAR}} = \frac{871 \frac{MJ}{m^2\ year}}{4065 \frac{MJ}{m^2\ year}} * 100\% = 21.4\%$$ = Maximum theoretical photosynthetic efficiency

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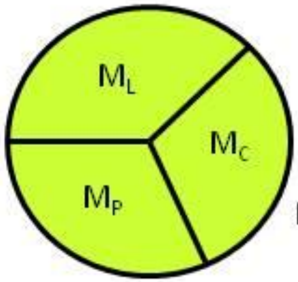
Biomass Energy Density as a Function of Mass Composition

Partition the Theoretical Maximum Captured Chemical Energy into the Major Biomass Constituents of Carbohydrates, Lipids, Proteins, and Ash

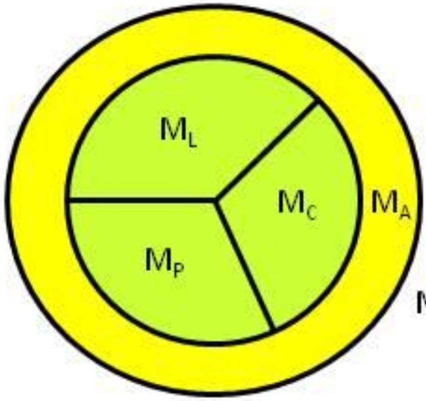
Begin by defining the total energy content (E_T) of biomass having total composite mass (M_T) as:

$M_T = M_C + M_L + M_P + M_A$ and $E_T = E_C \times M_C + E_P \times M_P + E_L \times M_L$,



$M_T = M_C + M_L + M_P = M_{af}$

M_{af} = *Ash-Free Biomass ($M_A = 0$) in units of kg*



$M_T = M_{af} + M_A$

Biomass with ash content ($M_A > 0$) in units of kg

Where energy content terms are given by:

$E_C = 16.7$ MJ/kg (for carbohydrate)
$E_P = 16.7$ MJ/kg (for protein)
$E_L = 37.4$ MJ/kg (for lipid)
$E_A = 0$ (for ash)

and where mass terms are given by:

M_C = Mass of Carbohydrate [kg]
M_L = Mass of Lipid [kg]
M_P = Mass of Protein [kg]
M_{af} = Ash-Free Biomass [kg]
M_T = Total Biomass [kg]

The biomass energy density (E_{BM}) is then given by:

$$E_{BM} = E_T / M_T = E_C (M_C / M_T) + E_P (M_P/M_T) + E_L (M_L/M_T)$$

$$= 0.167\ (P+C) + 0.374\ (L) \quad [MJ/kg]$$

Where A, C, L, and P are the percentage fractions of ash, carbohydrate, lipid, and protein in the composite biomass, and

$$A + C + L + P = 100\ \%$$

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Derivation of Approximate Algae Production Equations*

Partition the Theoretical Maximum Captured Chemical Energy into the Major Biomass Constituents of Carbohydrates, Lipids, Proteins, and Ash

Biomass energy density (E_{BM}) can be expressed as a function of L and A only (by noting that P+C = 100-L-A):

$$E_{BM} = E_T / M_T = 0.167\,(P+C) + 0.374\,(L) \quad \text{MJ/kg}$$

$$= 16.7 + 0.207\,(L) - 0.167\,(A) \quad \text{MJ/kg}$$

Combining the composite biomass energy density (E_{BM}) with the maximum biomass chemical energy (E_{BCE}) produced from photosynthesis gives an estimate for annual maximum yearly and daily algae biomass productivities:

$$P_{BA} = E_{BCE} / E_{BM} \quad = \frac{52.2}{1+0.0124(L)-0.01(A)}\left(\frac{\text{kg}}{\text{m}^2\,\text{year}}\right)$$

$$P_{BD} = \frac{P_{BA}\left(\frac{\text{kg}}{\text{m}^2\,\text{year}}\right)}{365\left(\frac{\text{d}}{\text{year}}\right)} = \frac{143}{1+0.0124(L)-0.01(A)}\left(\frac{\text{g}}{\text{m}^2\,\text{d}}\right)$$

* Cooney, Michael, Greg Young, and Ronald Pate (2010). “Bio-oil from photosynthetic microalgae: Case study”, Bioresource Technology, 9 July 2010.

Making further assumptions that lipids can be extracted with 100% efficiency, and that total lipid content represents an upper maximum feedstock for fuel production, the estimated theoretical maximum annual fuel production (F_{LF}) is approximated by:

$$F_{LF}\left(\frac{\text{gal}}{\text{ac year}}\right) \approx 4.238 \cdot L\,(\%) \cdot P_{BD}\left(\frac{\text{g}}{\text{m}^2\,\text{d}}\right)$$

Approximate parametric equation for production of algal oil (or biofuel) in gallons per acre per year as a function of daily biomass productivity and oil content

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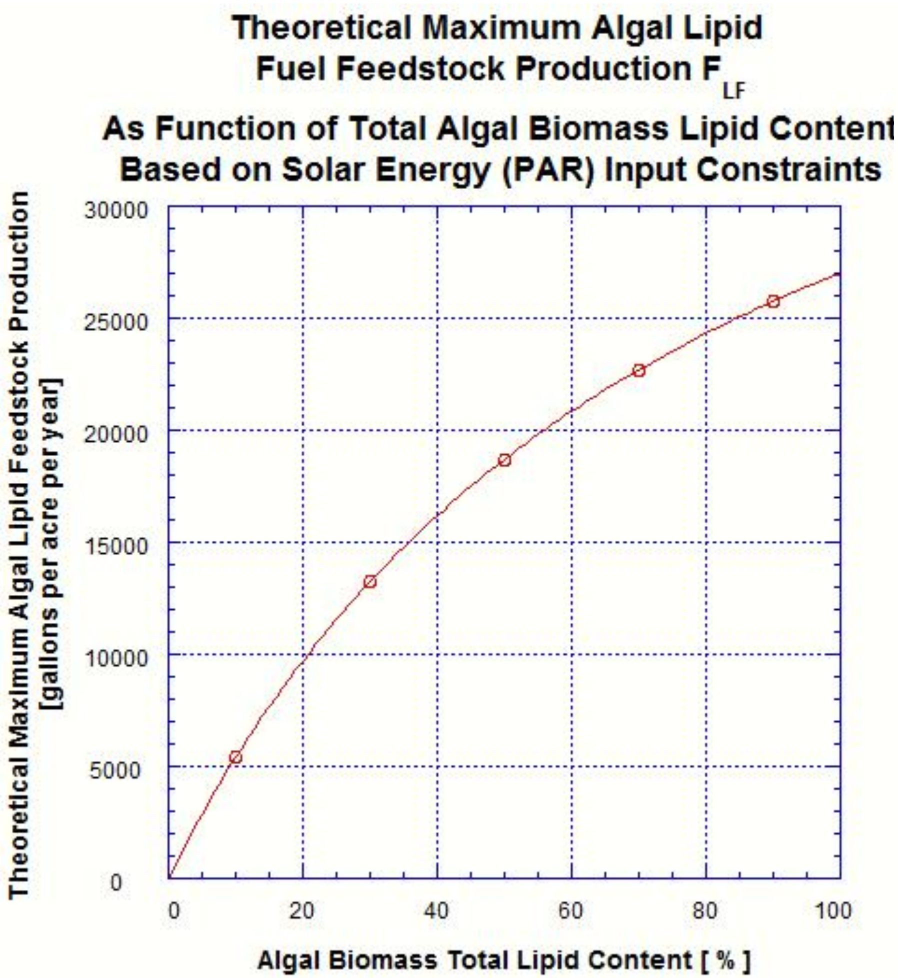
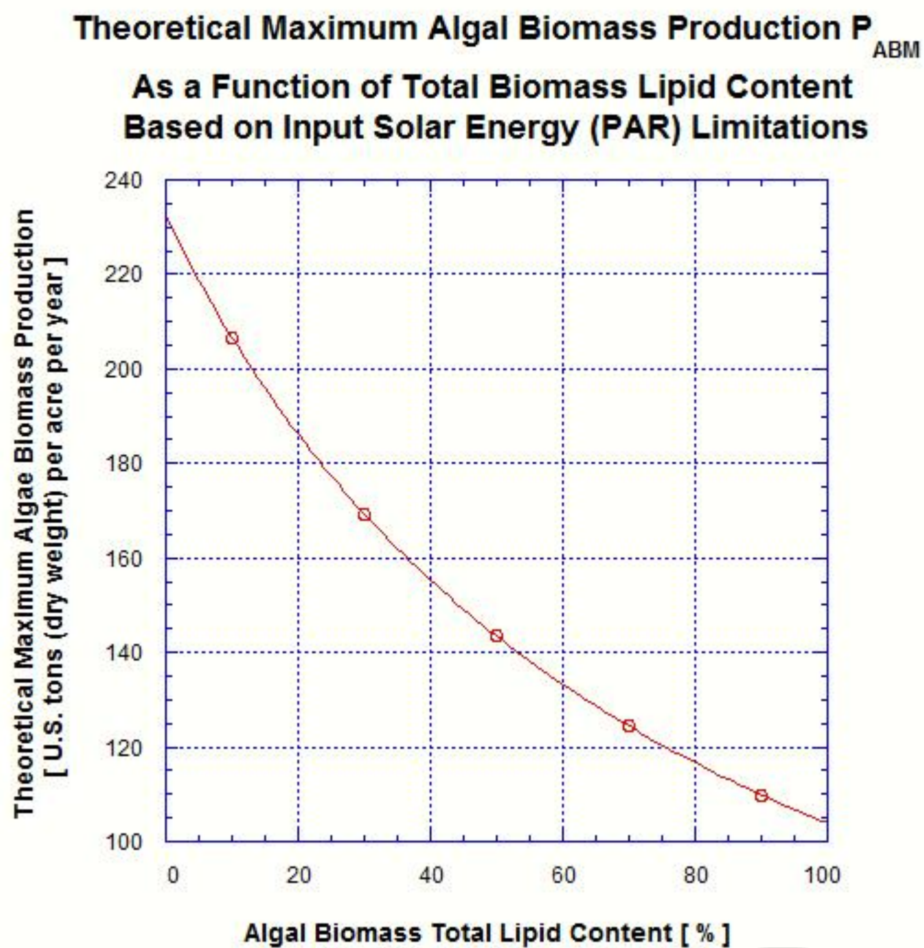
Theoretical Maximums for Photosynthetic Algae

Biomass & Lipid Productivities as a Function of Total Lipid Content

Maximum Total Lipid (gal ac^{-1} yr^{-1})



Maximum Total Biomass (tons ac^{-1} yr^{-1})



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