Assessment of Algae Biofuels Resource Demand and Scale-Up Implications for the U.S.

Exceptional Service In the National Interest

National Nuclear Security Administration

APEC Workshop

On the Resource Potential of Algae for the Sustainable Production of Biofuels in the Asia Pacific Region

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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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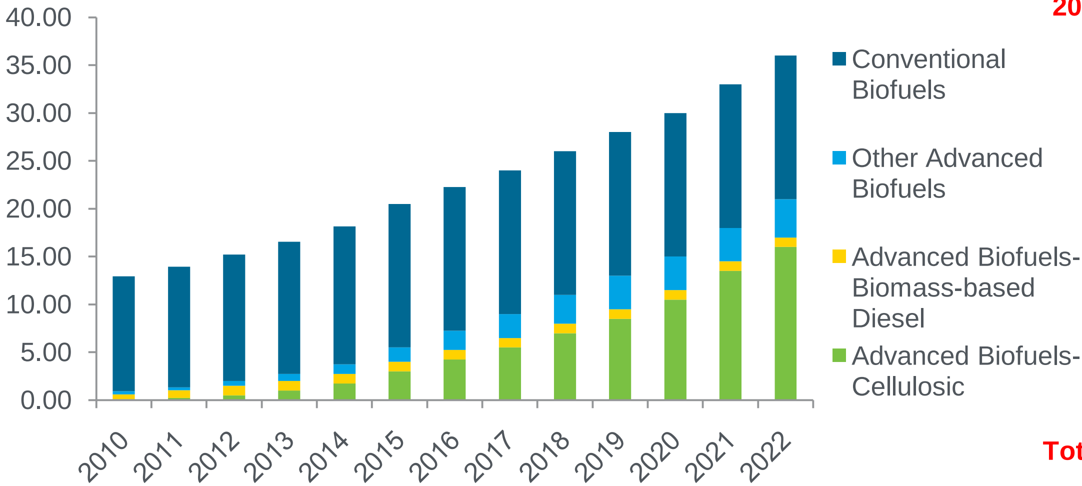
First … Some Background and Context

- Motivation for Biofuels in the U.S.
  - Policy mandate (RFS2) established by EISA 2007
- Trend toward drop-in hydrocarbon fuels
  - Higher energy densities… not all fuels are alike
  - Infrastructure compatibility (handling & end-use)
- Algae biofuels benefits and challenges
- Algae biofuels pathways overview
- Heterotrophic algae – a biochemical conversion path
- Sustainability challenges for algae biofuels
- Algae biofuels scale-up – Key resource questions

Policy Driver for Biofuels in the U.S.

Renewable Fuels Standard (RFS2)

EISA RFS2 Renewable Biofuels Production Targets
In Billions of Gallons per Year (BGY)



2022 Targets

15 BGY

4 BGY

1 BGY

16 BGY

Total: 36 BGY by 2022

Categories for Algae Contribution

Biofuels Policy Mandate*

*** 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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Not All Fuels are Alike

Energy Density Differences and Infrastructure Compatibility

[Yellow box] - Denotes fuels fully compatible with current infrastructure[1]

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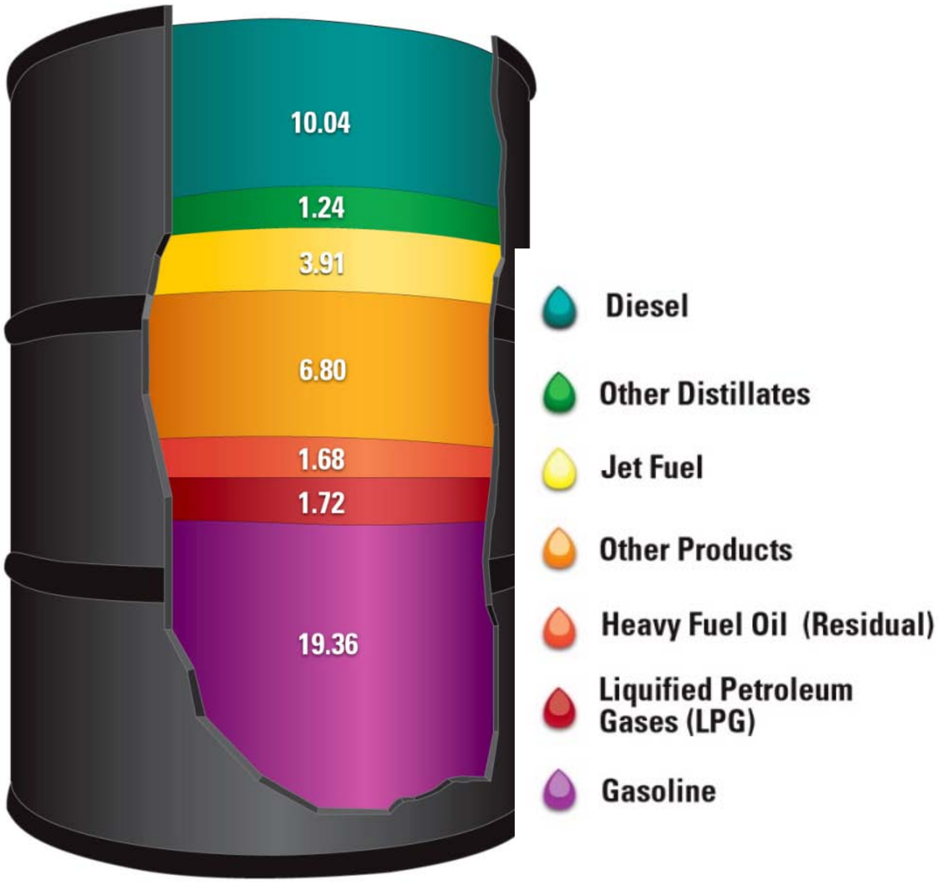
Displacing the Whole Barrel… *Trend Toward Producing Drop-In Hydrocarbon Biofuels & Bioproducts*

Products Made from a Barrel of Crude Oil (Gallons)
(2009)



- **At low % 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.

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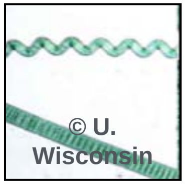
Algal Biofuels … *Benefits & Challenges*

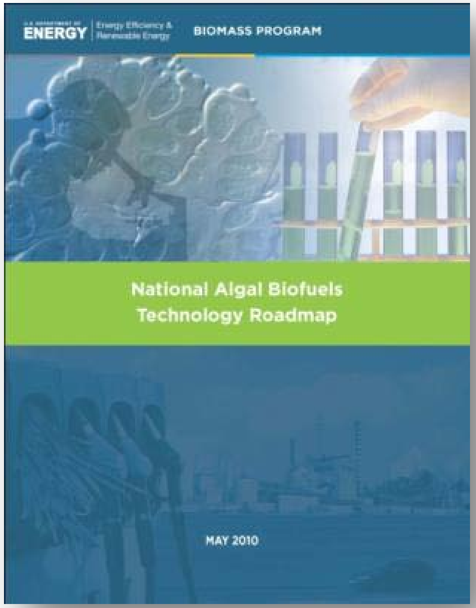


Benefits of Algal Biofuels

- 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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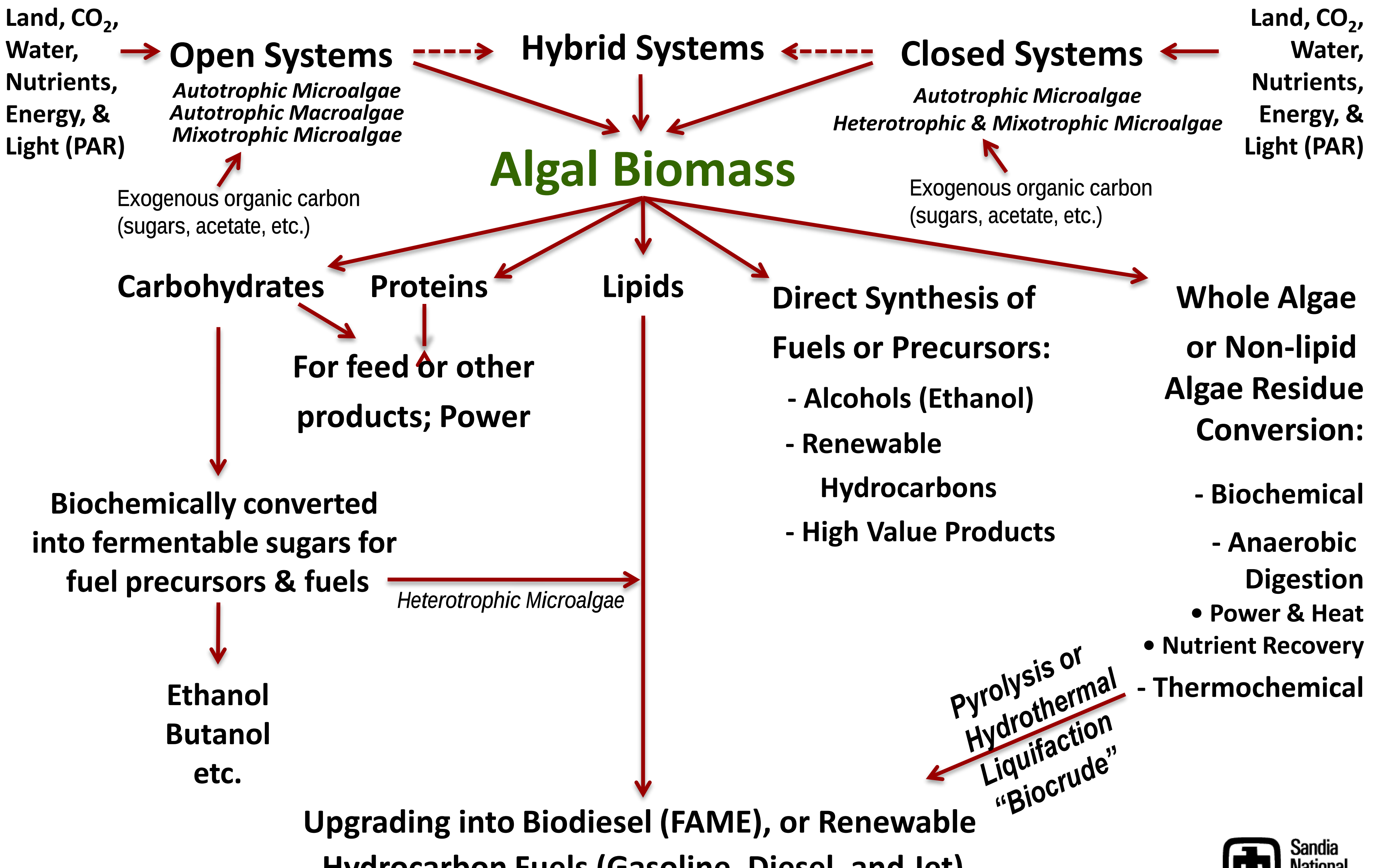
Algae Biofuels Pathways Overview

Production & Conversion to Fuels/Products



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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

  … Current baseline production cost estimates ≤ open pond autotrophic algae

- Has the same “sustainable feedstock” issues as today’s ethanol biofuel

  … Food/Feed vs. Fuel if commodity sugar or starch crops are used

  … Will be most sustainable at large scale using sugar from cellulosic biomass

- Capable of biofuel feedstock oil scale-up in same manner as ethanol production, to extent that affordable feedstock sugars are 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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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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Algal Biofuels Scale-Up
Key Resource Demand Questions

- How far can U.S. algae biofuels be sustainably scaled up?
  - 5 BGY?
  - 10 BGY?
  - 50 BGY?
  - 100 BGY?
  - less? … more?
- Which resource demands are likely to become constraints?
  - Land ?
  - Water ?
  - Nutrients (nitrogen, phosphorus) ?
  - CO_2 ?
- At what level will resource demands likely become constraints?
- How can resource constraints be relaxed and extended?

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SNL Algae Biofuels Scale-up Assessment
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 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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Assumptions in Development of Estimates for Theoretical Photosynthetic Algae Biomass and Bio-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
- 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.

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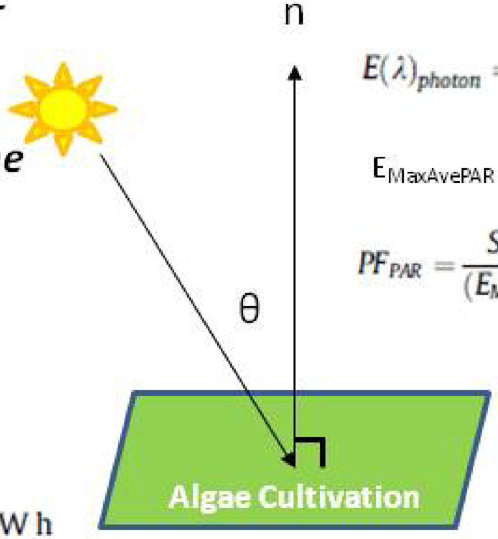
Theoretical Basis for Converting Solar Energy to Biomass

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:

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

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

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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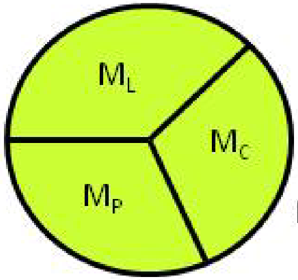
Biomass Energy Density as a Function of Mass Composition

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

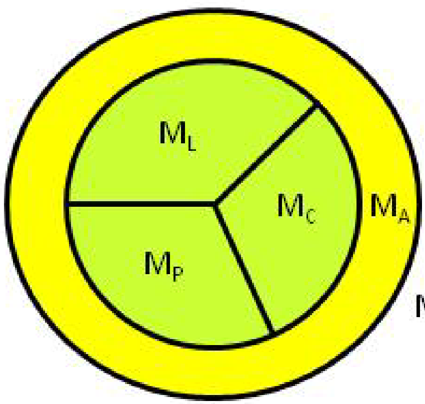
Begin by defining the total energy content (E_T) of biomass having total composite mass (M_T) as:

$M_T = M_C + M_L + M_P + M_A$ 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:

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

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

* 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:

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

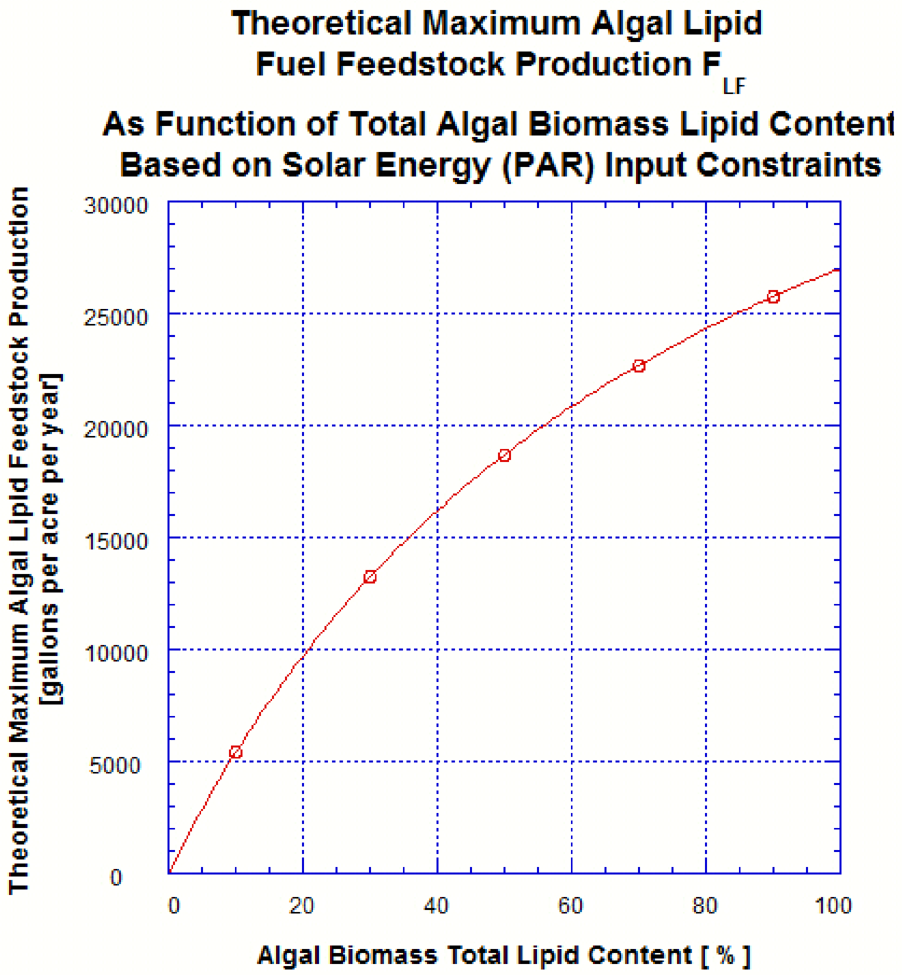
Approximate parametric equation for production of algal oil (or biofuel) in gallons per acre per year as a function of daily biomass productivity and oil content

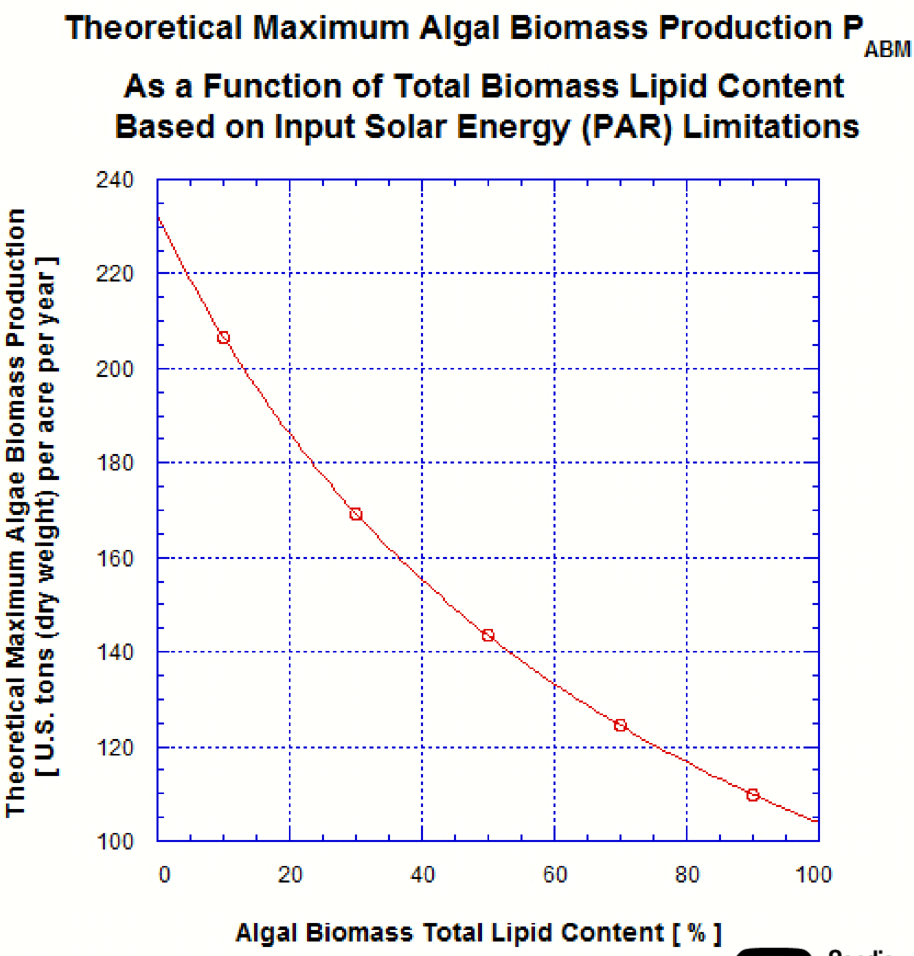
Theoretical Maximums for Photosynthetic Algae

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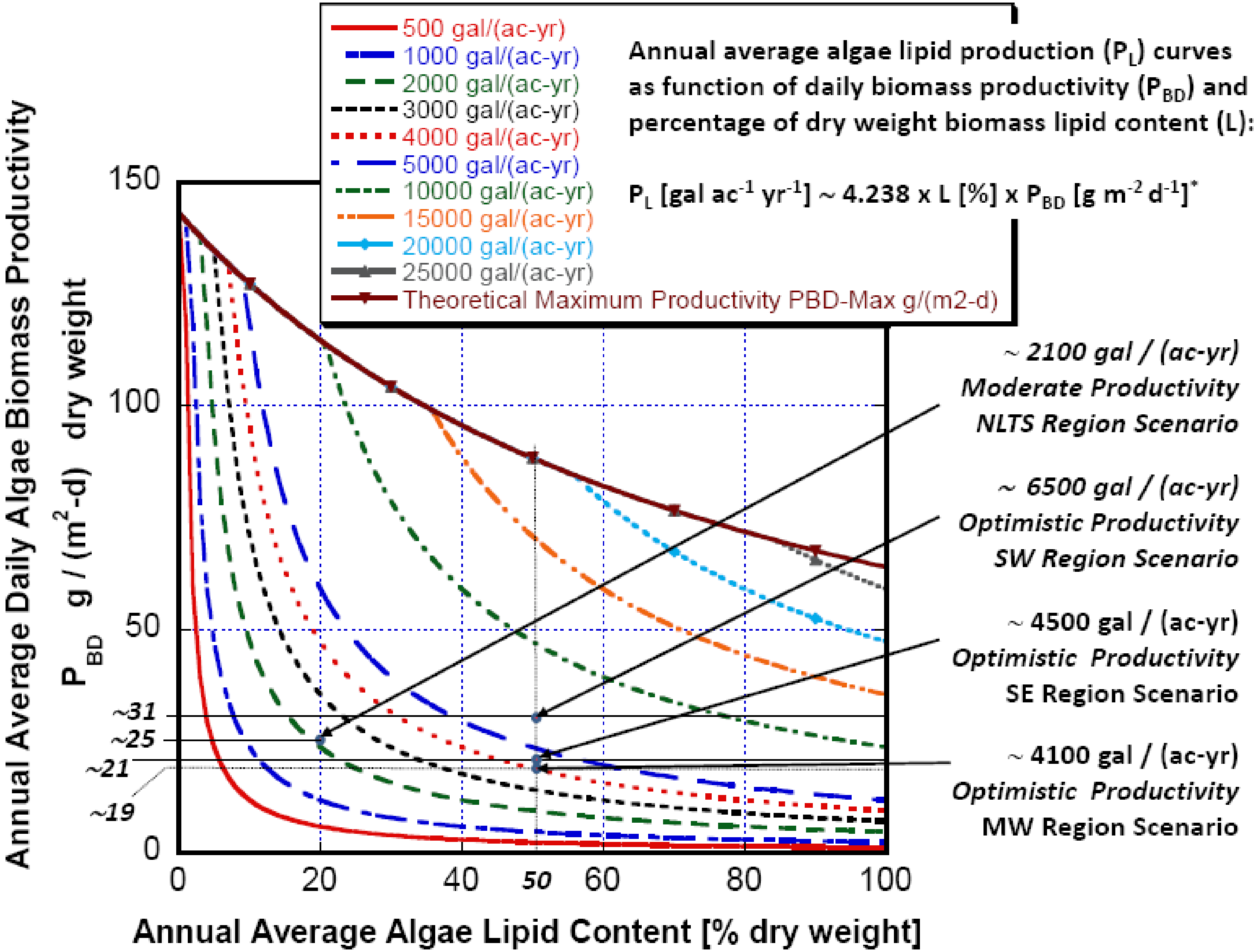
Algae Oil Productivity Curves & Scenario Points
as Function of Daily Biomass Productivity and Oil Content



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

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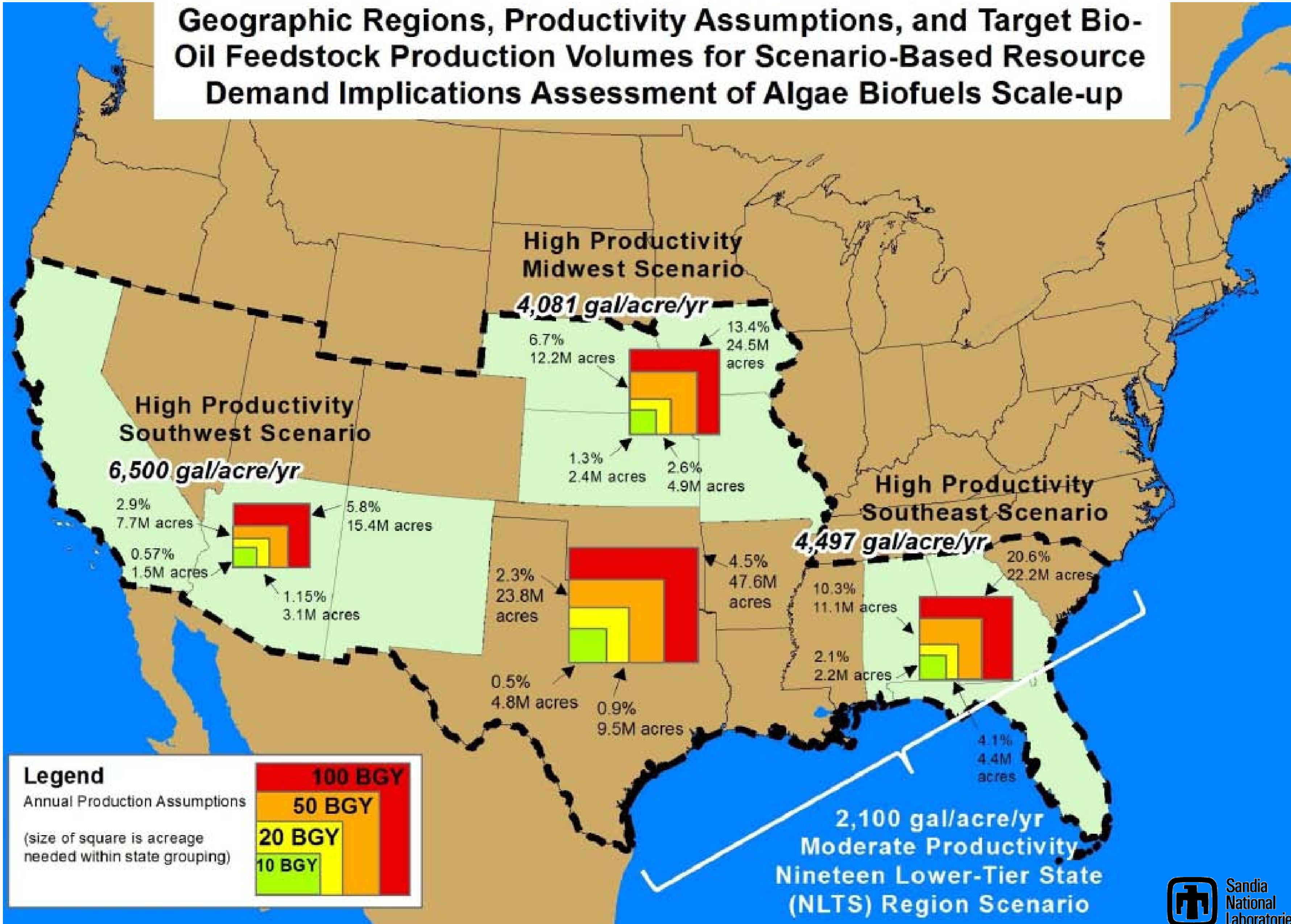
Algae Biofuels Scale-Up Scenarios



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
- Basis of scaling assumptions for CO_2 demand
- Basis of scaling assumptions for N & P demand

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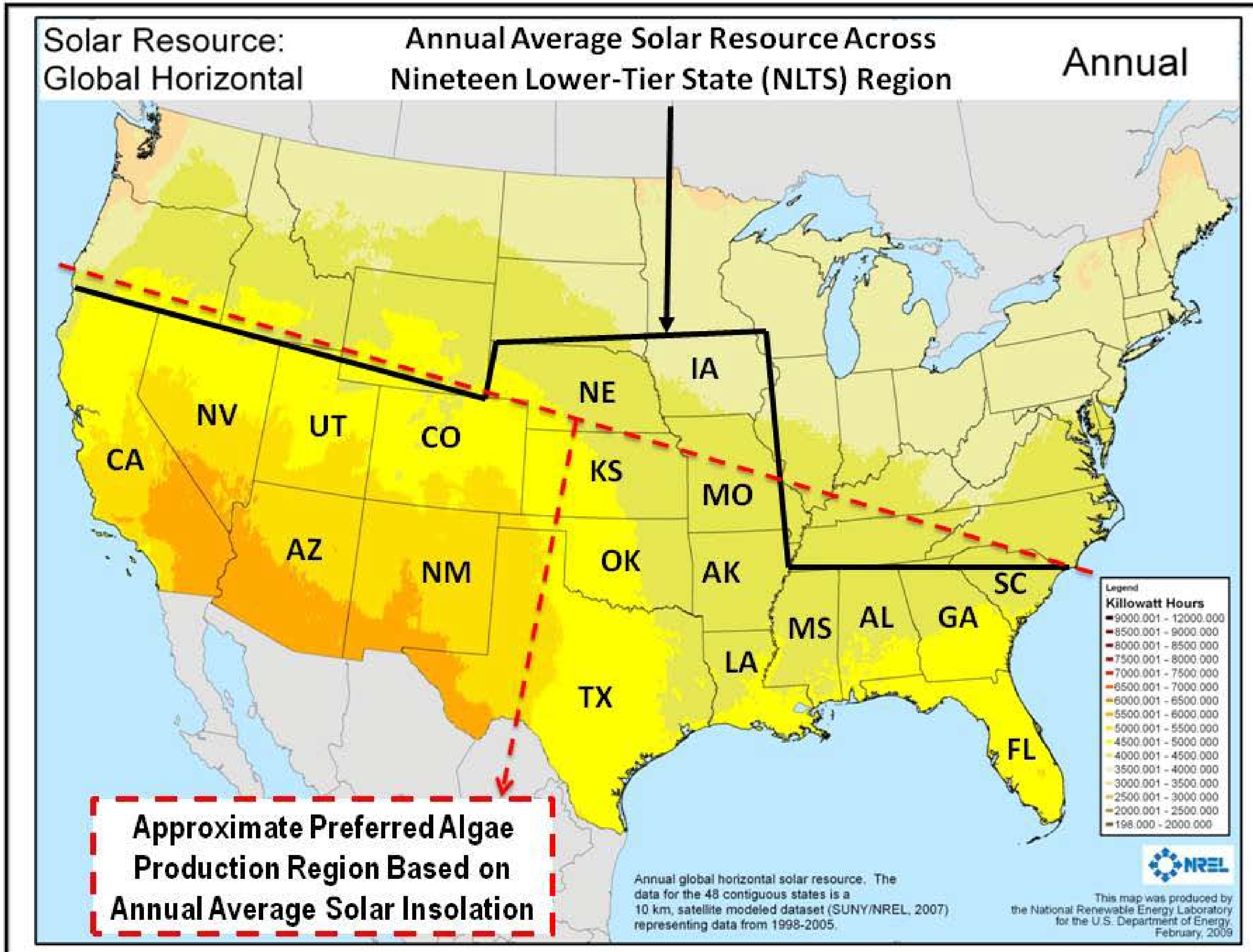
Key Factor for Algae Cultivation - Sunlight

Drives Focus on Lower Latitude Scenario Regions



Solar resource map courtesy of NREL

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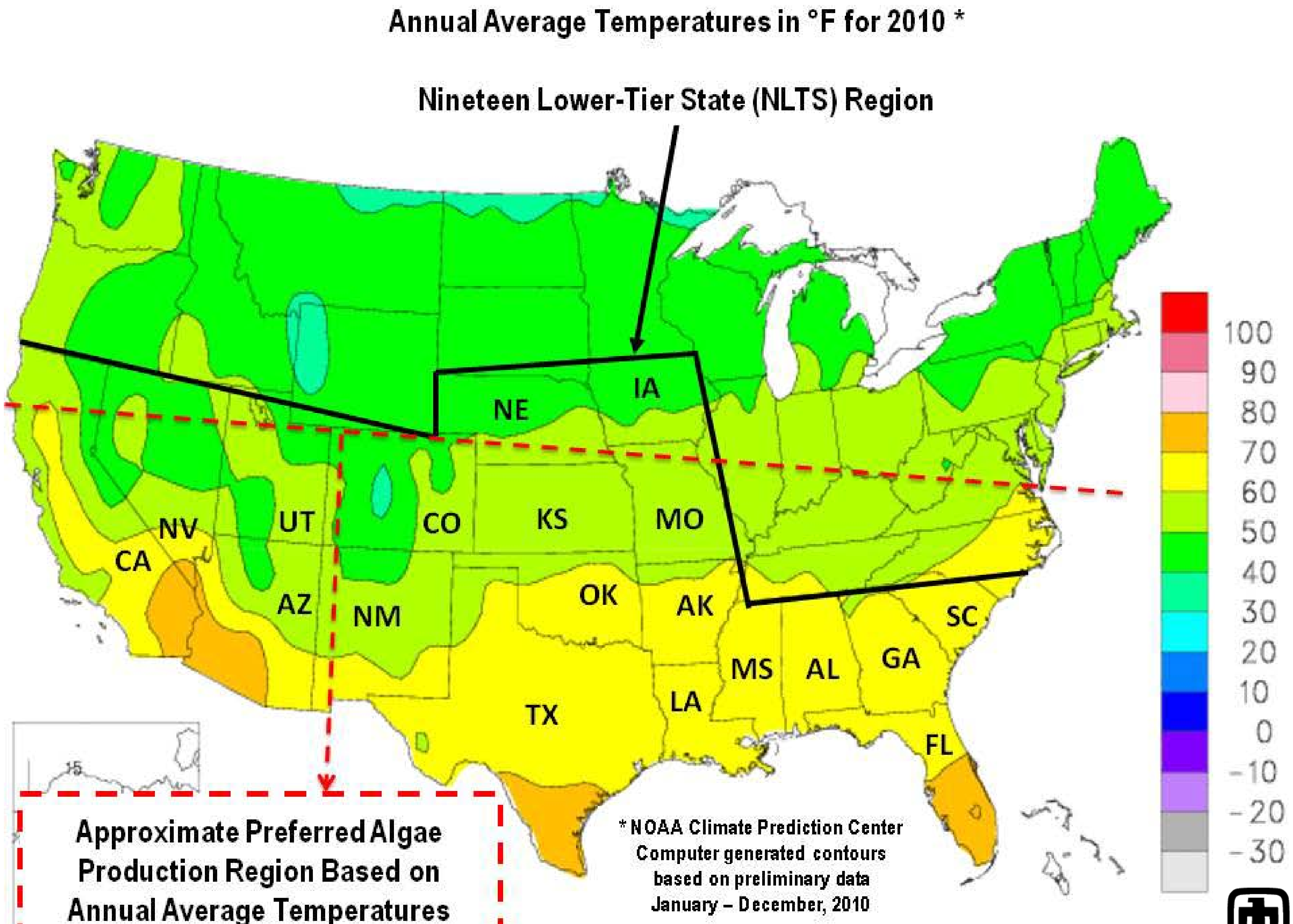
Key Factor for Algae Cultivation - Temperature
Drives Focus on Lower Latitude Scenario Regions



Temperature map courtesy of NOAA

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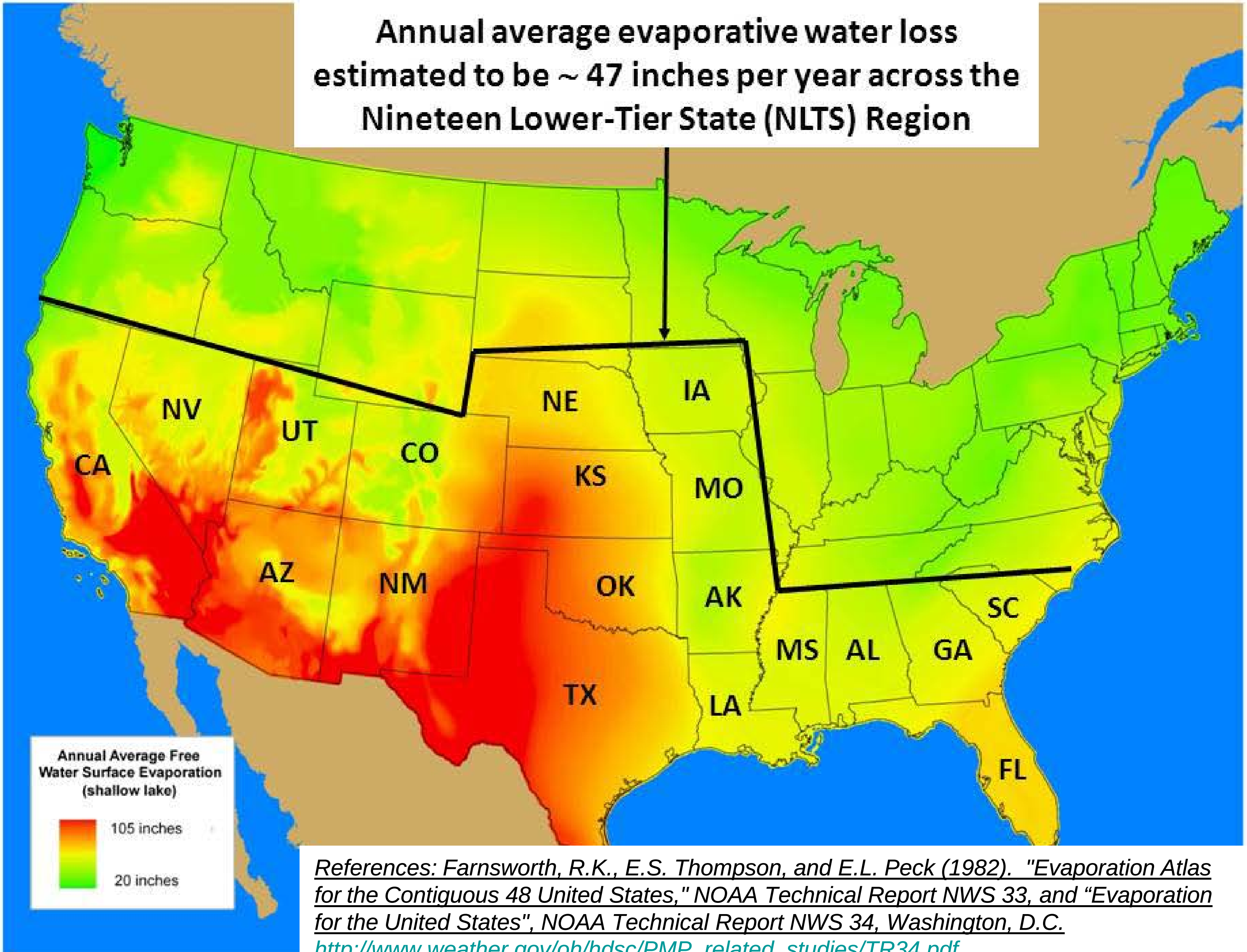
Key Factor for Algae Cultivation - *Evaporation*

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 x 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

Total Aggregated CO_2 Emitted

T_{CO2}

Non-Daylight Emissions

N_{CO2}

Daylight Emissions

D_{CO2}

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,

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

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

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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Projected Algae Cultivation Area Demand
vs. Pasture & Total Land in Scenario Regions

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

LAND USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	Land Required[1,3] (1000s of acres)				Land Required as % of Pasture [2] [% Total] Land in scenario region			
Southwest (SW) CA, AZ, NM	1,540	3,080	7,700	15,400	1.3 [0.6]	2.6 [1.2]	6.8 [3.9]	14 [5.8]
Midwest (MW) NB, KS, IA, MO	2,440	4,880	12,200	24,400	5.5 [1.3]	11 [2.6]	27 [6.7]	54 [13]
Southeast (SE) AL, GA, FL	2,220	4,440	11,100	22,200	28 [2.1]	56 [4.1]	142 [11]	283 [21]
NLTS[3]	4,760	9,520	23,800	47,600	1.2 [0.45]	2.4 [0.9]	6.1 [2.3]	12 [4.5]

[1] Scenarios assume algae lipid productivities of 6,500 (SW), 4,100 (MW), 4,500 (SE), and 2,100 (NLTS) gal ac^{-1} yr^{-1};
[2] USDA (2006): Combination of grassland, non-forested pasture, range, and open grazing land, excluding cropland pasture assumed for this analysis to be the most suitable land category for consideration to avoid conflict with other competing land uses;
[3] NLTS scenario assumes moderate annual average algal lipid productivity of ~2,100 gal ac^{-1} yr^{-1} averaged over nineteen lower-tier states of AZ, AK, AL, CA, CO, FL, GA, IA, KS, LA, MO, MS, NE, NM, NV, OK, SC, TX, & UT .

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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Open Algae System Evaporative Water Loss

vs. Irrigation [& Total] Fresh Water Use in Scenario Regions

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

WATER USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	**Evaporative Water Loss[6] in billions of gallons per year [use intensity: gal water / gal oil]**				**Evaporative Loss as % Fresh Water Used for Irrigation [% Total All Uses] in Each Scenario Region[7]**			
Southwest	2,800 [280]	5,400 [270]	12,100 [242]	22,300 [223]	24 [18]	46 [35]	104 [78]	191 [144]
Midwest	3,300 [330]	6,500 [325]	15,100 [302]	28,300 [283]	72 [32]	141 [62]	328 [145]	615 [272]
Southeast	2,500 [250]	5,000 [250]	12,600 [252]	25,200 [252]	172 [31]	344 [62]	866 [155]	1732 [311]
NLTS	6,070 [607]	12,140 [607]	30,350 [607]	60,700 [607]	19 [10]	39 [19]	97 [48]	194 [96]

[6] Based on annual average freshwater pan evaporation data (Farnsworth, et al. 1982), applied over estimated required algae cultivation (open systems assumed) area by region (likely to be worst-case); For NLTS region: assumed annual average 47-inches evaporative loss;

[7] Water use data by end-use category for the U.S. in 2005, taken from USGS: Kenny, et al. (2009)

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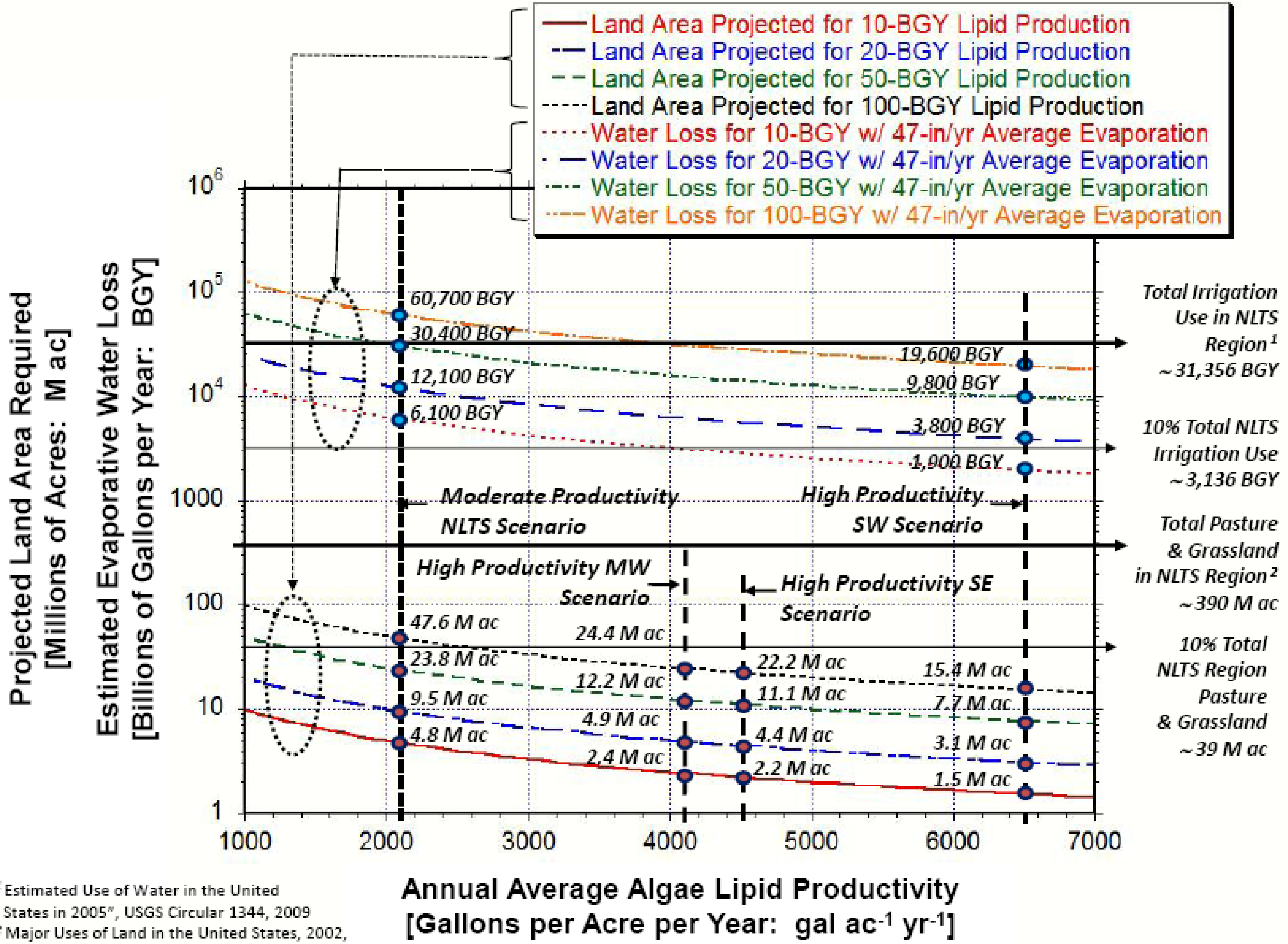
Summary of Land Area & Evaporative Water Loss

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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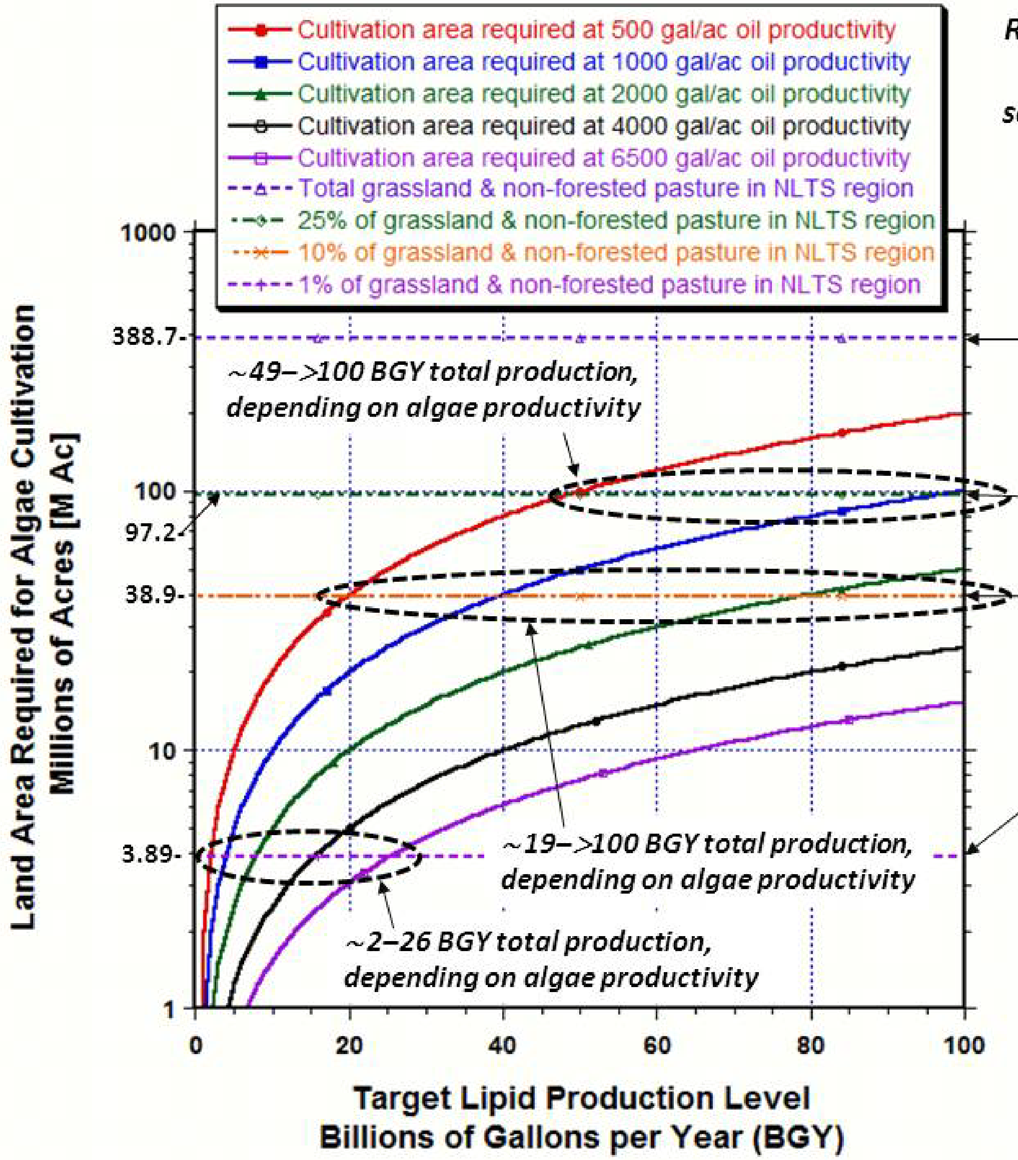
Closer Look at Algae Cultivation Land Area Demand

As function of lipid productivity and target production level



*Reference supply levels of grassland and non-forested pasture land selected as a suitable land use class for algae cultivation in the lower latitude NLTS Region of the US**

*Represents 100% of total grassland & non-forested pasture in NLTS region**

*Represents 25% of total grassland & non-forested pasture in NLTS region**

*Represents 10% of total grassland & non-forested pasture in NLTS region**

*Represents 1% of total grassland & non-forested pasture in NLTS region**

* 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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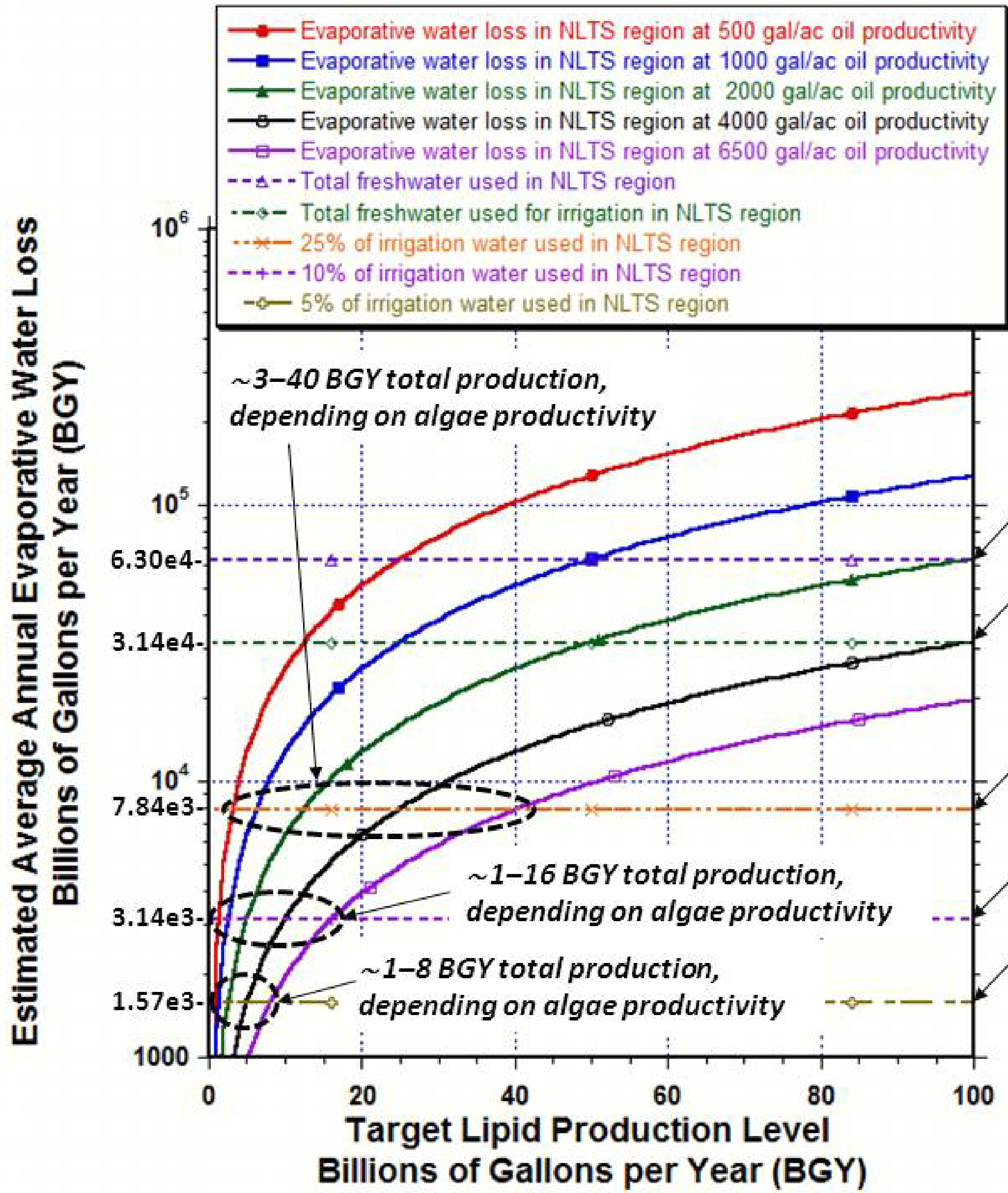
Closer Look at Projected Evaporative Water Loss

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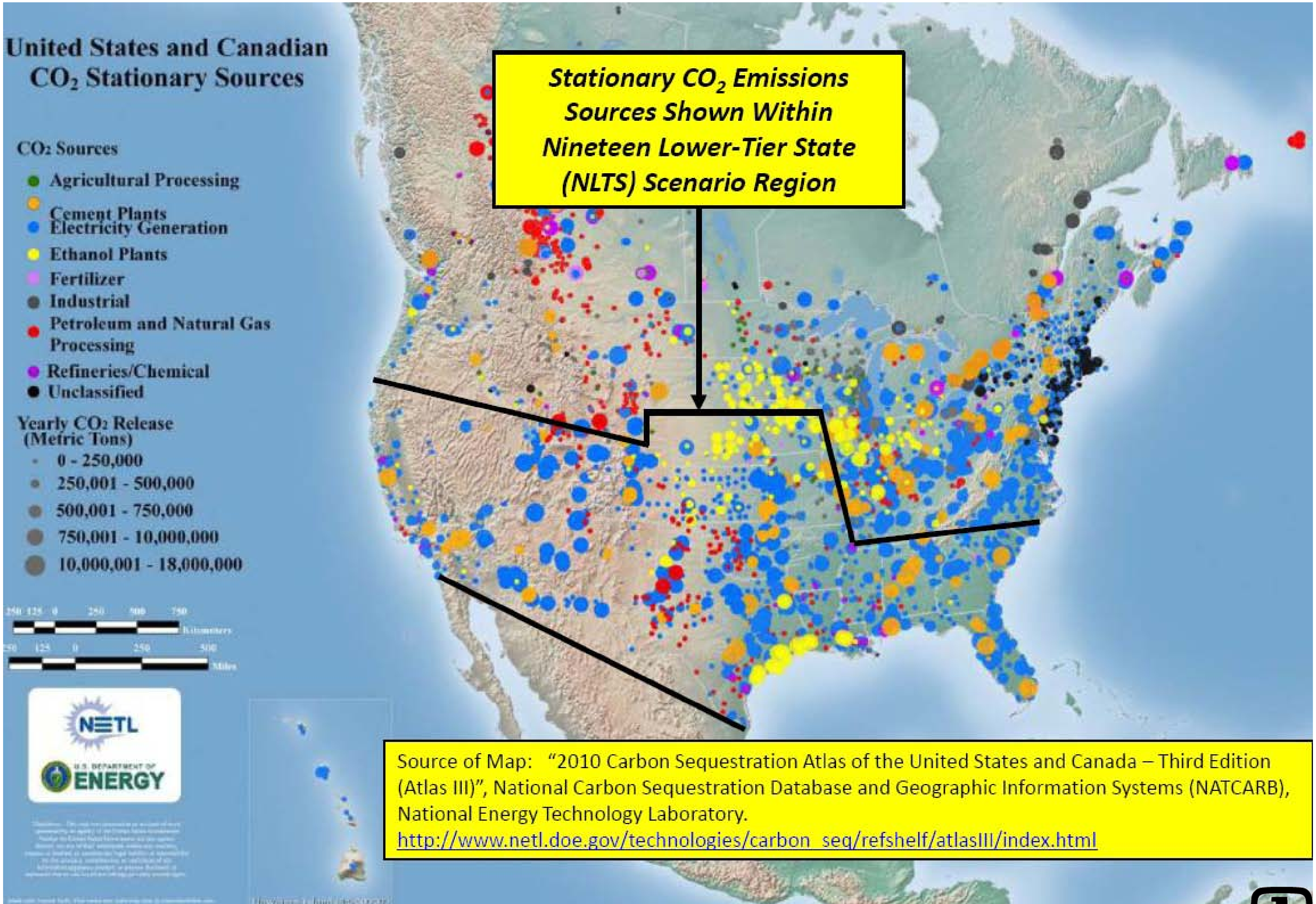
Stationary CO_2 Emission Sources
in Lower-Tier State (NLTS) Scenario Region



Stationary CO_2 sources map courtesy of NETL

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Algae CO_2 Demand as % of Stationary Emissions
for Scenario Regions & Target Production Levels

Shaded Cells signify problem levels for resource availability

CO_2 USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	**Required CO_2 In millions of metric tons [4]**				**% Total [% *Daylight Only*] CO_2 emissions from stationary sources in each scenario region[5]**			
Southwest	140	280	700	1,400	73 [146]	145 [290]	363 [726]	725 [1450]
Midwest	140	280	700	1,400	64 [128]	128 [256]	321 [642]	642 [1284]
Southeast	140	280	700	1,400	45 [90]	90 [180]	224 [448]	449 [898]
NLTS	350	700	1,740	3,490	24 [48]	47 [94]	117 [234]	235 [470]

[4] Based on assumption of two metric tons CO_2 per metric ton of dry biomass with 50% lipid content for the SW, MW, and SE scenarios, and 20% lipid content for the NLTS scenario;

[5] As reported in NETL 2010 NATCARB stationary CO_2 source data base: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html

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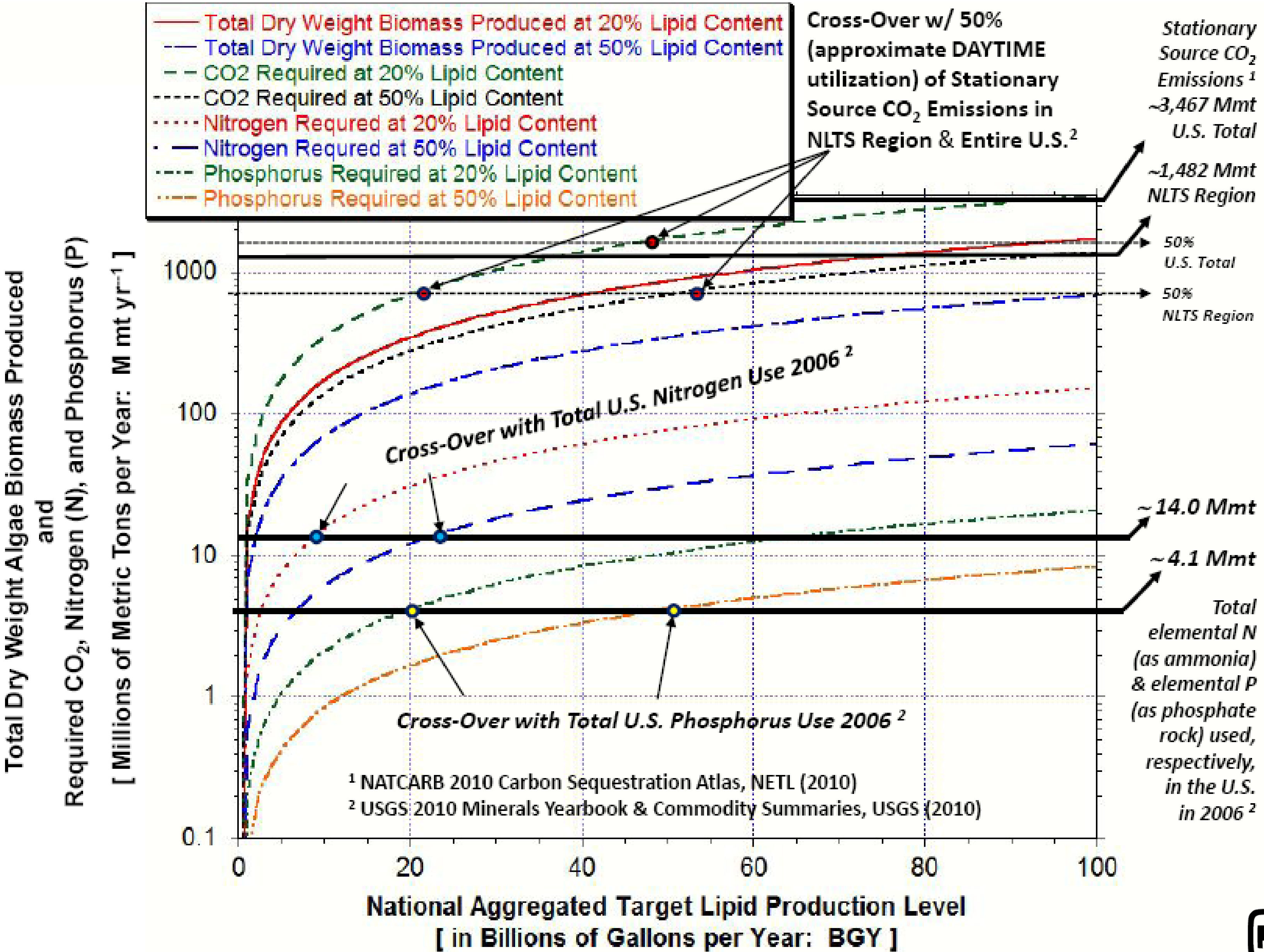
Summary of Biomass Production and Demand for CO_2, N, & P

As a Function of Algae Oil Production Levels & Lipid Content



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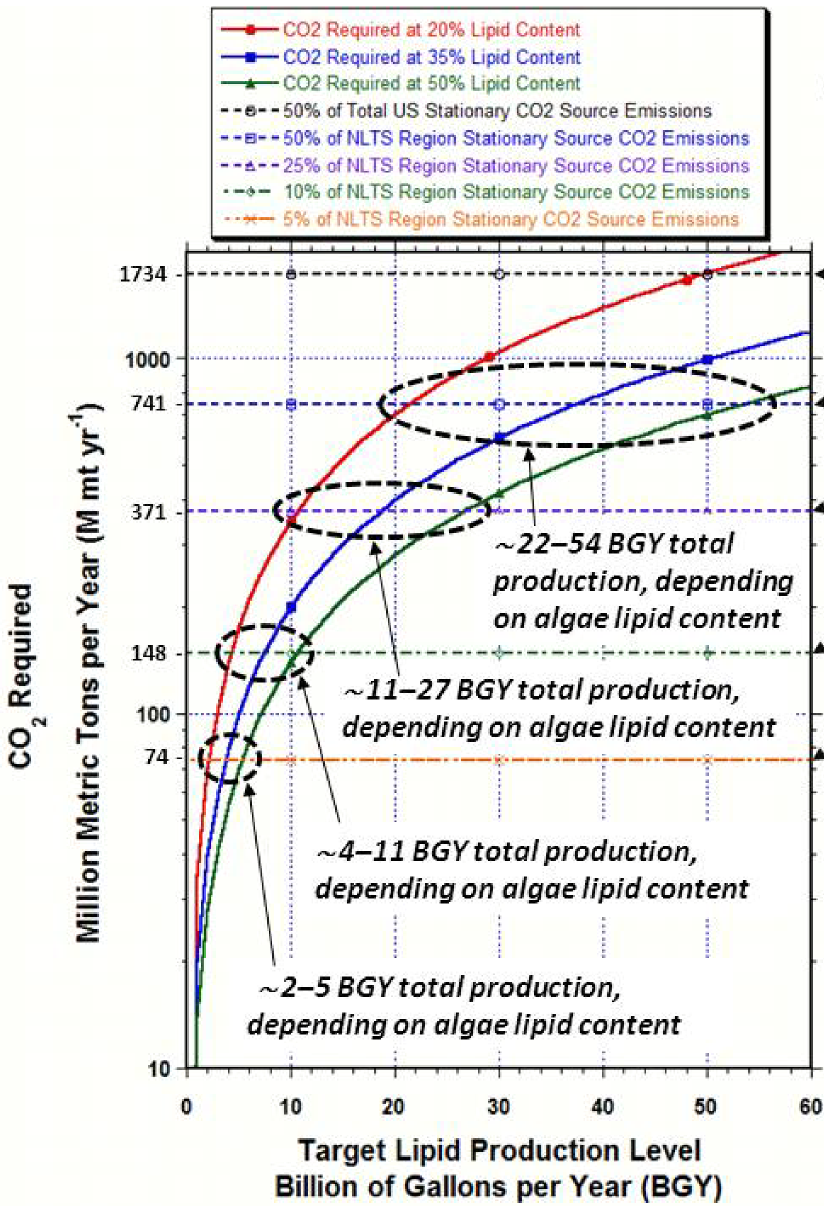
Closer Look at Algae Cultivation CO_2 Demand

as function of algae lipid content and target production level



Reference supply levels of *daylight hour* CO_2 emissions in 2008 from stationary emitter sources*

*Represents 50% - 100% of total daylight hour emissions in the entire US**

*Represents 50% - 100% of total daylight hour emissions in the NLTS Region**

*Represents 25% - 50% of total daylight hour emissions in the NLTS Region**

*Represents 10% - 20% of total daylight hour emissions in the NLTS Region**

*Represents 5% - 10% of total daylight hour emissions in the NLTS Region**

* 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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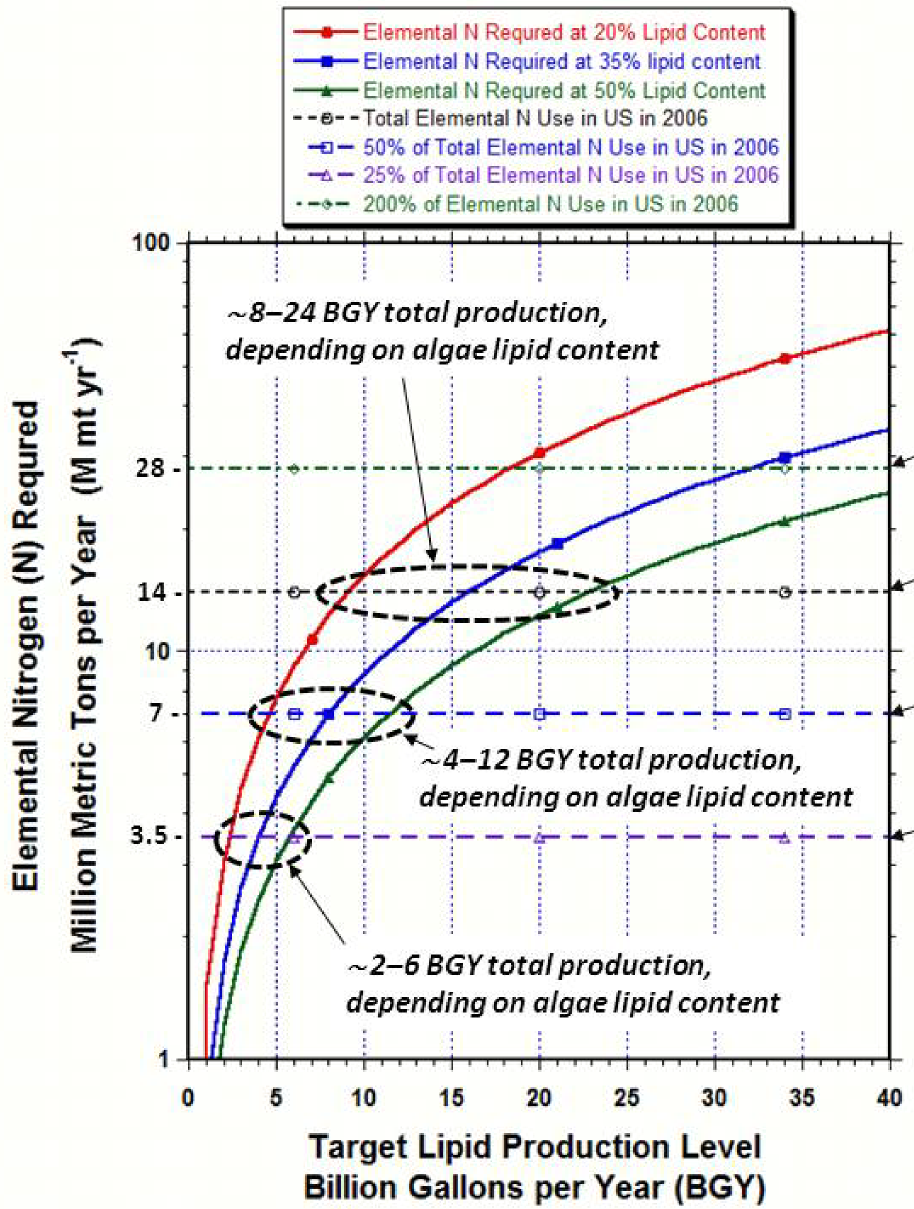
Closer Look at Algae Cultivation N Demand

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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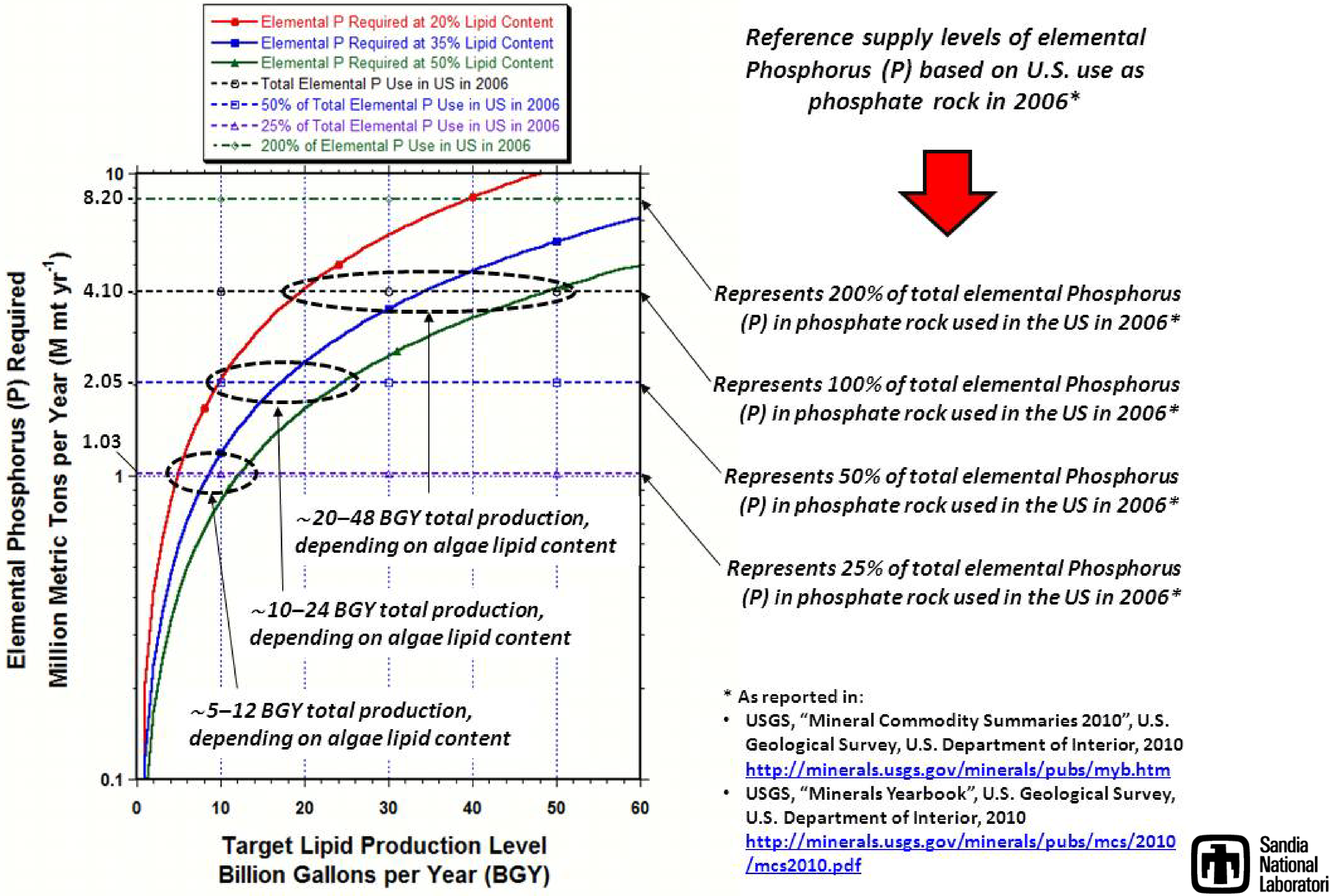
Closer Look at Algae Cultivation P Demand

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**

* 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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Algae Biofuels Resource Assessment Summary

Implications for Algae Biofuel Scale-up

- Resource constraints likely to emerge at the 5-15 BGY oil production range
  - *Based on Assessment Scenario Assumptions and Trends*
- 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 are issues for commercial fertilizer use*
  - *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 evaporative loss (closed systems?)*
  - *Open system salinity build-up with non-fresh waters will be issue for inland sites*
- Land … requirements probably manageable even for very high 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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Conclusions

- Algae is promising feedstock for advanced biofuels, but still faces technical and economic challenges to affordable 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
- Land is probably the least constraining, depending on region
- Needed improvements to partially reduce constraints include:
  - Higher algae oil content and productivity
  - 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

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This work was done under funding support to Sandia National Laboratories from the Office of Biomass Program (OBP) within the US Department of Energy's Office of Energy Efficiency and Renewable Energy. The authors specifically wish to thank Valerie Sarisky-Reed, Leslie Pezzulo, and Joyce Yang from OBP for their encouragement and support.

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Geoff Klise
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Thank You !
Questions ?

Additional Information

The U.S. Department of Energy Biomass Program produces a variety of publications focused on biomass technologies including factsheets, reports, case studies, presentations, analyses, and statistics.

To learn more visit: www.biomass.energy.gov/pdfs/publications.pdf or the Biomass Publication and Product Library at www.biomass.energy.gov/publications.html

Additional Items of Interest

Biomass Program 2011 Peer Review Portal - http://obpreview2011.govtools.us/
Biofuels Atlas - http://maps.nrel.gov/bioenergyatlas
Energy Empowers - http://www.energyempowers.gov
DOE on Twitter - http://twitter.com/energy
Secretary Chu on Facebook - http://www.facebook.com/stevenchu
Biomass Program – http://www.biomass.energy.gov
EERE Info Center - www1.eere.energy.gov/informationcenter
Alternative Fuels Data Center - http://www.eere.energy.gov/afdc/fuels/ethanol.html
Bioenergy Feedstock Information Network - http://bioenergy.ornl.gov/
Biomass R&D Initiative – www.biomass.govtools.us
Grant Solicitations - www.grants.gov
Office of Science - http://www.er.doe.gov/
Loan Guarantee Program Office - http://www.lgprogram.energy.gov

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Supplemental Slides

- Summary Overview of PNNL Algae Resource Assessment
- Comparison of SNL and PNNL Assessments

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PNNL Resource Assessment for Algae Biofuels Production

A National Resource Availability Assessment for Microalgae Biofuel Production

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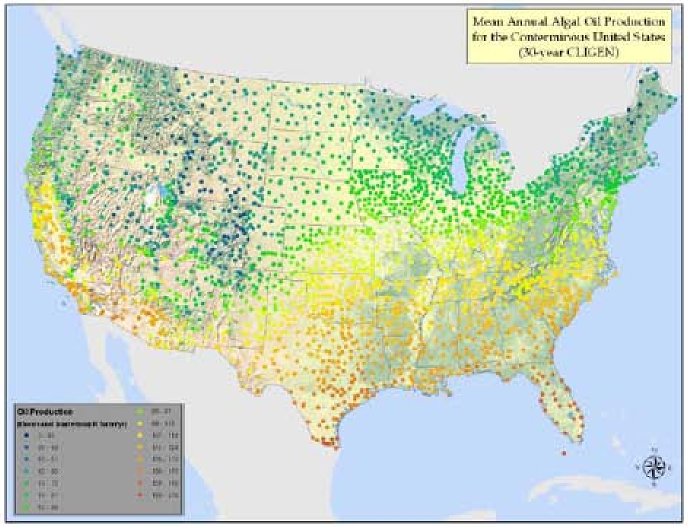

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PNNL-SA-64064

Presentation materials courtesy of PNNL

Overview of PNNL's National Algae Biofuels Resource Availability Assessment

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

- **This project will provide DOE-OBP a systematic national assessment to evaluate the U.S. potential for microalgae biofuel production**
  - algae resource requirements
  - resource availability
  - optimal locations and potential production

- **Compatibility with Bioenergy Knowledge Discovery Framework**
  - software, data, and web services
  - direct integration of data and analysis tools

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Presentation materials courtesy of PNNL

Resource Constraints on Sustainable Large-Scale Algae Biofuel Production

- **Land**
  - 1200 acres of contiguous flat land (slope <= 1 %)
    - "farm scale"
  - exclude cropland, urban, protected, sensitive areas

- **Climate**
  - solar radiation and duration
  - pond water temperature : 15 – 35 C°
  - diurnal variation
- **Water Supply**
  - avoid competition with food production
  - saline groundwater, seawater, other brackish water
  - quantify water use
- **Carbon Dioxide and Nutrients**
  - transportation cost
  - co-location with power plants, refineries, wastewater treatments plants, etc.

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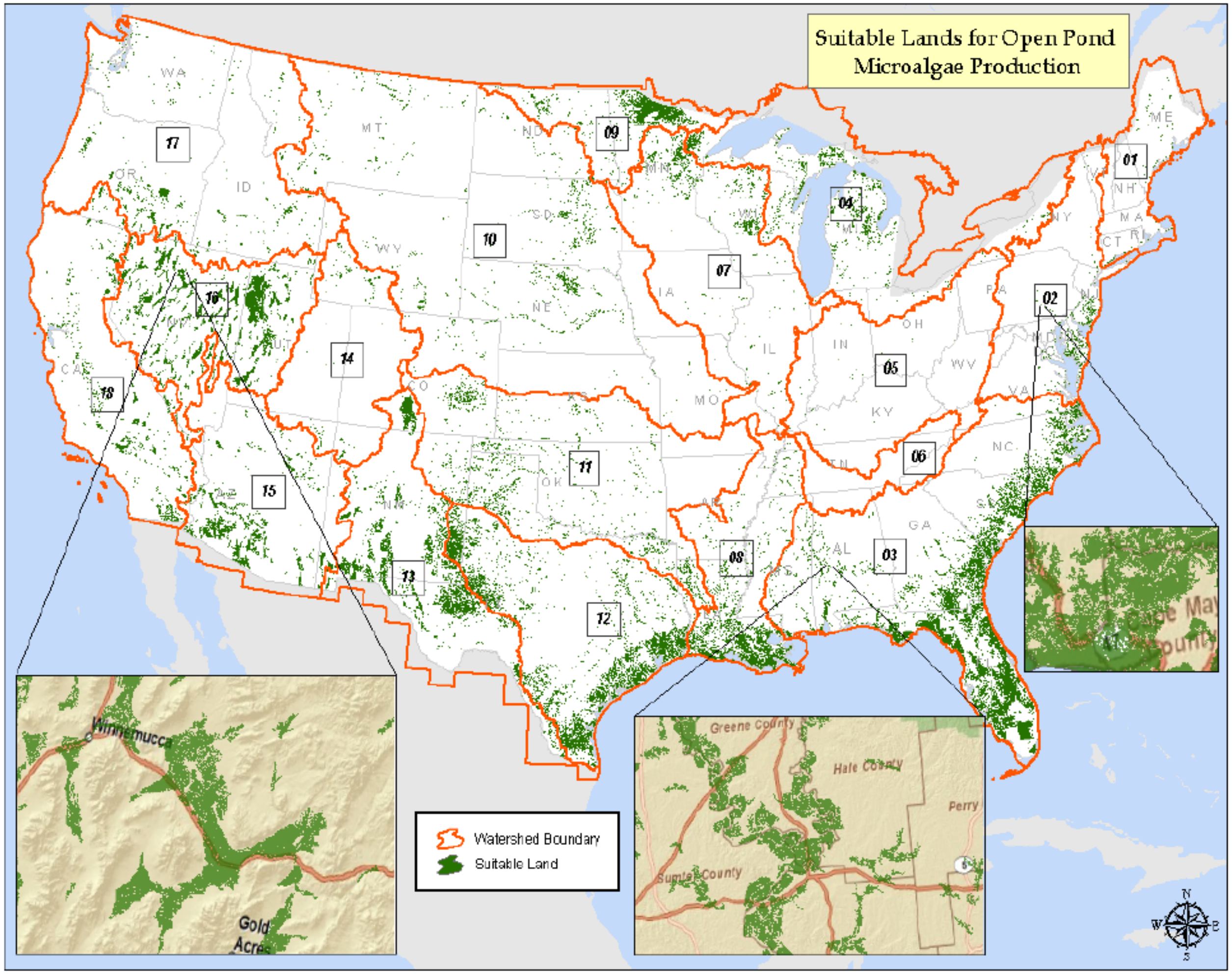
Presentation materials courtesy of PNNL

Suitable Land Resources for Sustainable Large-Scale Algae Biofuel Production



Slope <= 1 %

Exclude:
- Croplands
- Urban
- Open water
- Wetlands
- Riparian zones
- State Parks
- NPS protected
- FS protected
- Wilderness
- FWS protected
- BLM protected
- Military

89,756 suitable areas (i.e. unit farms) totaling approximately 430,830 km^2, or 5.5% of the conterminous United States. (~ 106.4 Million Acres)

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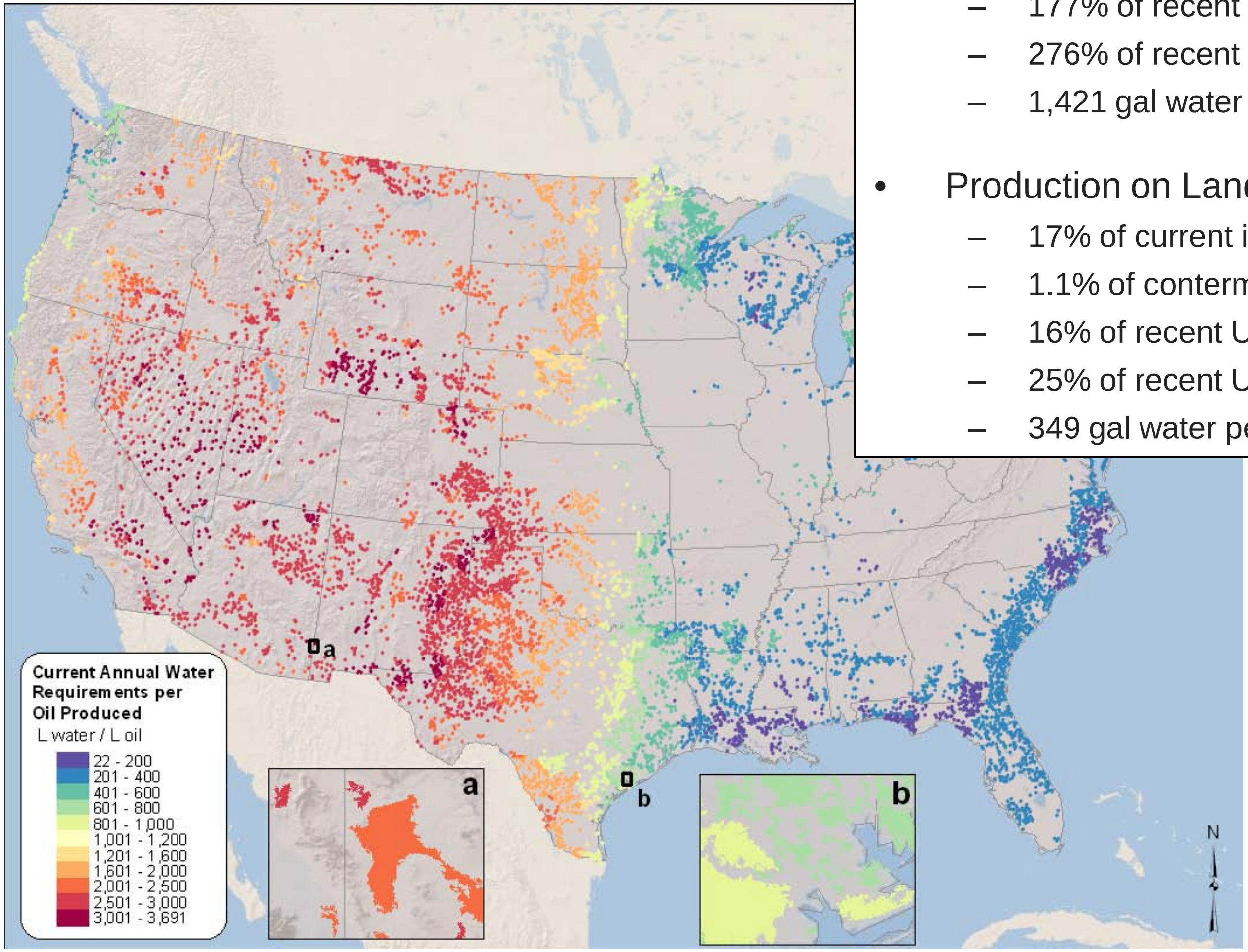
Presentation materials courtesy of PNNL

Optimization of Land Use, Water Use, and Algae Productivity for Biofuels

- Production on All Suitable Land
  - 48% of current imports for transportation
  - 5.5% of conterminous US land area
  - 177% of recent US water withdrawals for irrigation
  - 276% of recent US consumptive water use for irrigation
  - 1,421 gal water per gal oil
- Production on Land Optimized on Water Use Efficiency
  - 17% of current imports for transportation (EISA Target)
  - 1.1% of conterminous US land area
  - 16% of recent US water withdrawals for irrigation
  - 25% of recent US consumptive water use for irrigation
  - 349 gal water per gal oil

89,756 Suitable 480-ha Open Pond Farms



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Presentation materials courtesy of PNNL

Resource Use Optimization for Algae Biofuels

Trade-offs of Land Use, Water Use, and Algae Productivity

Total US Oil Production BGY	Algal Oil Productivity gal ac^{-1} yr^{-1}	Required Land Area M ac	% of Suitable Land Category Used	Water Use [c] BGY	% of Total Water Withdrawn[d] (Consumed)[e] for Irrigation in the US	Water Use Intensity Gal_{Water} / Gal_{Oil}
13.2	639[a]	20.7	19	2974	6.4 (10.0)	225
	745[b]	17.7	17	9950	21.3 (33.3)	753
21.0	598[a]	35.1	33	7320	15.7 (24.5)	349
	709[b]	29.6	28	18379	39.3 (61.5)	875
39.6	562[a]	70.5	66	36982	79.1 (23.7)	933
	648[b]	61.2	57	49491	105.9 (165.6)	1249
58.0	545[a]	106.5	100	82443	176.4 (275.8)	1421
	545[b]	106.5	100	82433	176.4 (275.8)	1421

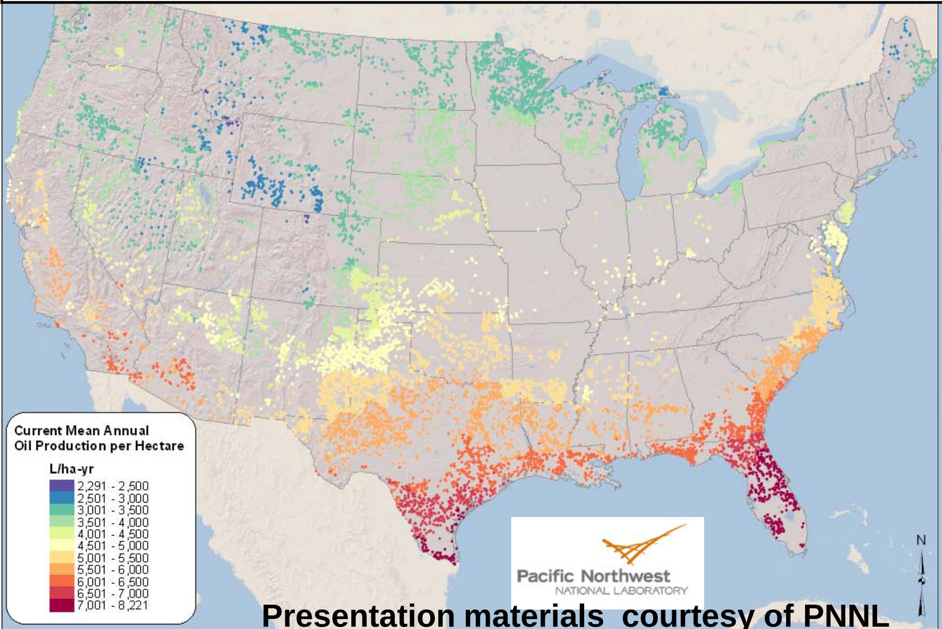
[a] Optimization based on minimizing overall water use ; Oil productivity estimated from model calculations ; as reported in Wigmosta, et al. 2011.

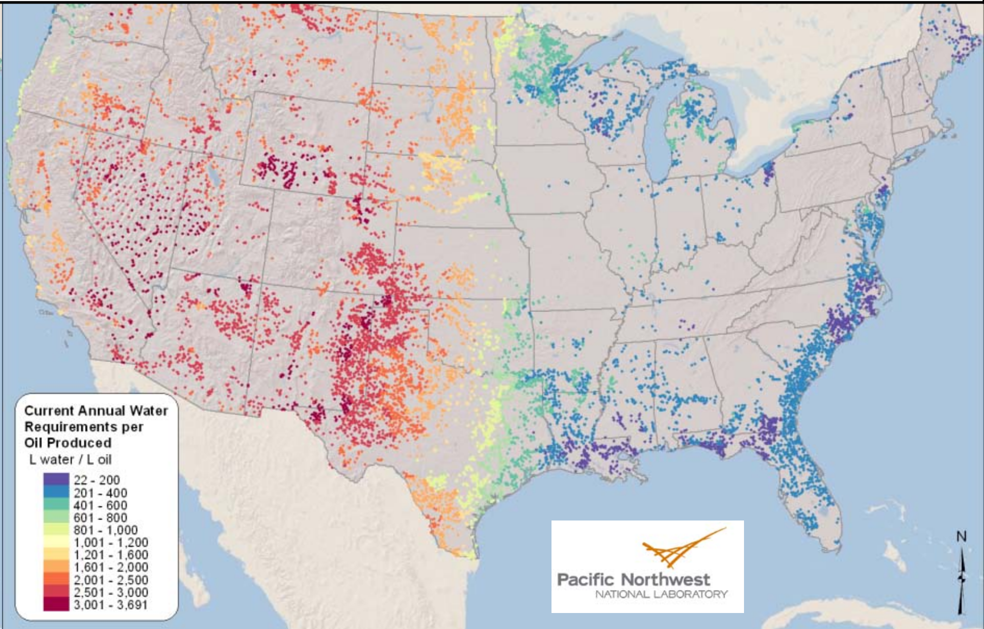
[b] Optimization based on minimizing overall land use ; Oil productivity estimated from model calculations ; as reported in Wigmosta, et al., 2011.

[c] Estimated water consumed through evaporation from open cultivation systems, as reported in Wigmosta, et al., 2011.

[d] Total water withdrawn for irrigation in U.S. in 2005 = 46720 BGY, as reported in Kenny et al. 2009: http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf.

[e] Total water consumed for irrigation in U.S. in 1995 = 29887 BGY, as reported in Solley et al. 1998: http://water.usgs.gov/watuse/pdf1995/html/.





Presentation materials courtesy of PNNL

Algae Biofuels Resource Analyses
Comparison of PNNL & SNL Assessments

Comparison	PNNL Assessment	SNL Assessment
Purpose	High-Resolution GIS-Based Algae Biofuels Resource and Productivity Analysis & Optimization Tool Development	High-Level, Low-Resolution Scenario Analysis to Estimate Resource Demands and Identify Potential Constraints to Inform R&D and Policy
Resolution	High Resolution/Granularity at National Level w/ 30-m Resolution	Low Resolution/Granularity at State Level for Multi-State Regions
Dynamic Modeling	Approximate physics-based growth modeling based on conditions	No detailed physics-based growth modeling – used assumed productivities
Land-Use Filters	**Land-use categories deemed suitable for algae included mix** of shrub/scrub (42%), herbaceous (19%), evergreen forest (14%), pasture (10%), deciduous forest (8%), and other(7%) using MRLC database; **other filters: land with ≤ 1% slope in blocks of ≥ 1200 acres (contiguous), with about 80% algae ponds & 20% overhead**	**Land-use category for algae limited to combination of non-forested pasture, grassland, range, and open grazing (but excluding cropland pasture)** using USDA database; no other land or topological suitability filters applied; **Land area requirements limited to active cultivation area, ignoring overhead land requirements for facilities and logistics**
Solar insolation and other met. data	Incorporated detailed time-series meteorological data, including solar insolation, temperature, other data	Assumed algae productivities scaled loosely to average solar insolation; Temperature loosely factored into selection of geographic regions
Algae Biomass, Algal Oil, and End-Use Biofuel Productivity	Approximate biomass productivity ranging from 30-year national mean of **8.7 g m^{-2} d^{-1}** to maximum of **15.8 g m^{-2} d^{-1}** from growth model calculations and local conditions (solar, temp, etc.), and national mean oil production **617 gal ac^{-1} yr^{-1}** ; **0.8 oil/fuel conversion factor applied** to give biofuel productivity ranging from **214-855 gal ac^{-1} yr^{-1}** , depending on region of the country	Assumed oil productivities per scenario region ranging from very optimistic (**6500 gal ac^{-1} yr^{-1} at 31 g m^{-2} d^{-1}, 50% content**) to modest (**2100 gal ac^{-1} yr^{-1} at 25 g m^{-2} d^{-1}, 20% content**); **Assumed national oil production targets of 10, 20, 50, and 100 BGY, with roughly the same end-use fuel production (neglected the ~ 0.8 oil/fuel conversion factor)**
Water Use Intensity	Calculated freshwater evaporative loss under local time-dependent met. Conditions (consistent with pan evap. Data); processing water ignored; Results: **1421 gal water/gal fuel** (nat'l average) and **350 gal water /gal fuel (with land selected for optimized water use)**	Based on application of freshwater pan evaporation loss rates to active algae cultivation area; other downstream processing water requirements ignored; Results: **240-300 gal water per gal oil for 50% algae oil content; 480-600 gal water per gal oil for 20% algae oil content**
Nutrient (N, P) Use Intensity	**Resource requirements not yet addressed**; Assumed adequate nutrients available for algae growth	**Nutrient demand estimated based on ideal mass balance and uptake efficiencies, assuming dry wt biomass of 50% C and C:N:P = 106:16:1**
CO_2 Use Intensity	**Resource requirements not yet addressed**; Assumed adequate CO_2 available for algae growth	CO_2 demand estimate based on assumed **2 mass units CO_2 per mass unit dry weight algae biomass** (for ~ 50% C content) with no losses
Summary Results	**Total national potential: 58 BGY using total of 106.4 M ac** (5.5% U.S. land area, lower 48 states) **at 1421 gal/gal water use**; **Optimized potential: 21 BGY using about 35 M ac** (1.8% total U.S. land area, lower 48 states) **at 350 gal/gal water use** **Nutrient and CO_2 requirements not yet factored into these findings**	**Land requirements look manageable**, **freshwater use at high production** scale-up above 10-20 BGY (depending on region) **will be challenge**, but **more likely to see nutrient (N, P) and CO_2 resource demand imposing greatest constraints at national production levels approaching 10 BGY, depending on achieved level of algae productivity and lipid content**

Acknowledgement of Contributors

To Supplemental Slide Materials

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