

# Resource Requirements for the Large Scale Production of Algal Biofuels

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# Biofuels Challenge: Sustainable Scale-up

**Commodity Crops**  
Sugar, Starch, Oil



**Algae**

**Woody Crops; Ag & Forest Wastes**



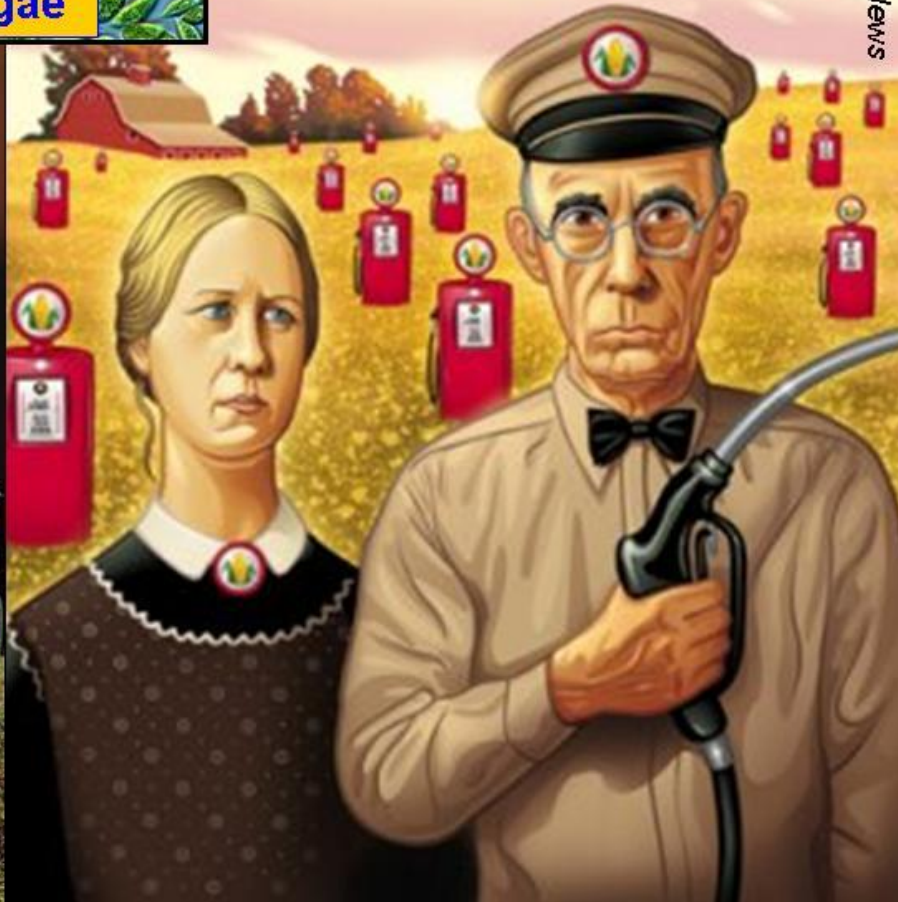
**Cellulosic Biomass**



**Non-Food Energy Crops**  
e.g., Switchgrass

## “Farm Fuel”

Source: Science News



**Rain-Fed vs. Irrigated Feedstock**

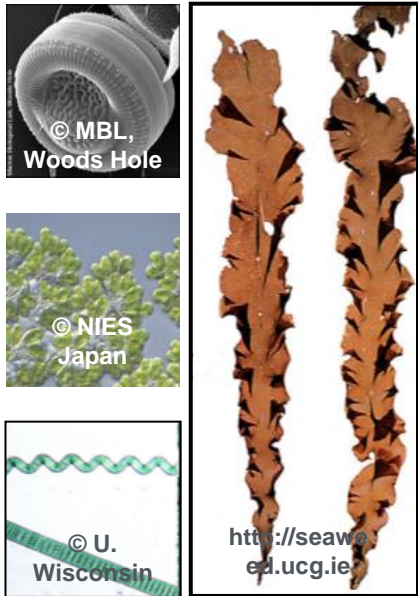
**Food & Feed vs. Fuel**

**Sustainable Resource Utilization**

Land  
Water  
Energy  
Nutrients

**Affordable Production With Reduced Life Cycle GHG Emissions**

# Algal Biofuels ... *Benefits & Challenges*

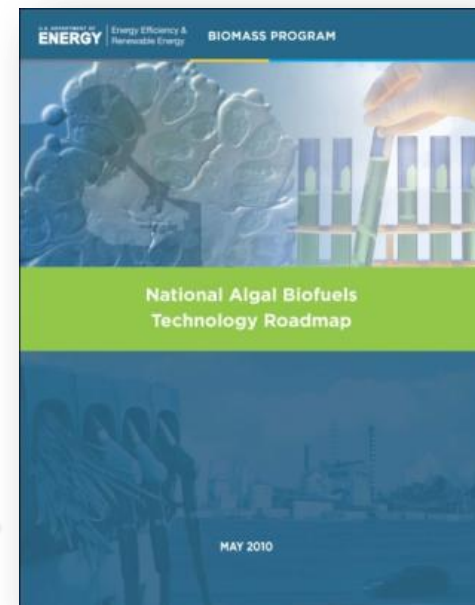


## Benefits of Algal Biofuels

- High productivity potential
- Can minimize competition with agriculture
- Can use non-fresh wastewater and saline water sources
- 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
- Path to fuels also via bio- and/or thermo-chemical processing

## Challenges to commercializing Algal Biofuels

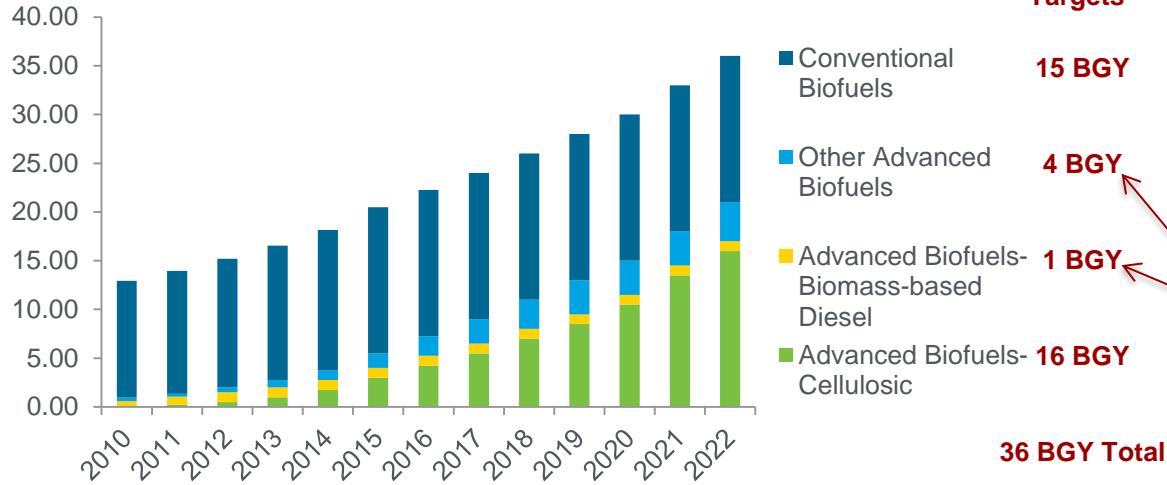
- Affordable, scalable, and reliable algal biomass production
  - Reliable feedstock production & crop protection at scale
  - Energy efficient harvesting and dewatering
  - Extraction, conversion, and product purification
  - Siting and sustainable utilization of resources
- Algal Biofuels Technology Roadmap (2010) by U.S. DOE, to help guide RD&D [http://www1.eere.energy.gov/biomass/pdfs/algal\\_biofuels\\_roadmap.pdf](http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf)



# Current U.S. Policy-Driver for Biofuels

## Within Context of Overall US Transportation Fuel Demand

**EISA RFS2 Renewable Biofuels Production Targets  
In Billions of U.S. Gallons per Year (BGY)**



### Biofuels Policy Mandate:

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

**Categories for Algal Biofuels Contribution**

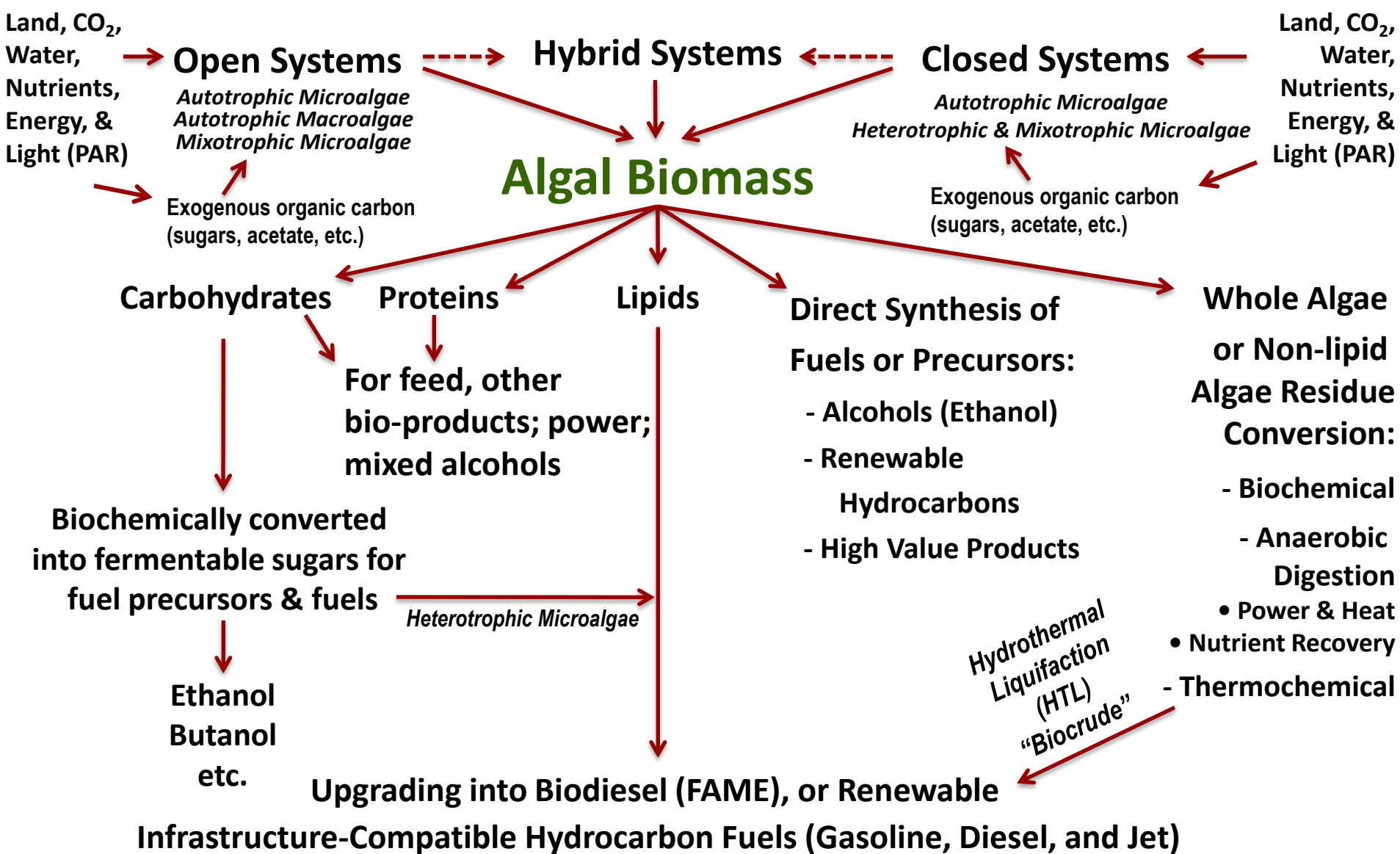


Fuel Type	2008 Demand*	2020 Projection*	2035 Projection*
Gasoline blend (including E85)	8.99 MBD <b>(137.8 BGY)</b> 17.2 Quads	9.42 MBD <b>(144.4 BGY)</b> 18.1 Quads	10.26 MBD <b>(157.3 BGY)</b> 19.7 Quads
Diesel Fuel	3.94 MBD <b>(60.4 BGY)</b> 8.38 Quads	4.24 MBD <b>(65.0 BGY)</b> 9.02 Quads	4.91 MBD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

# Algae Biofuels Pathways Overview

## Production & Conversion to Fuels/Products

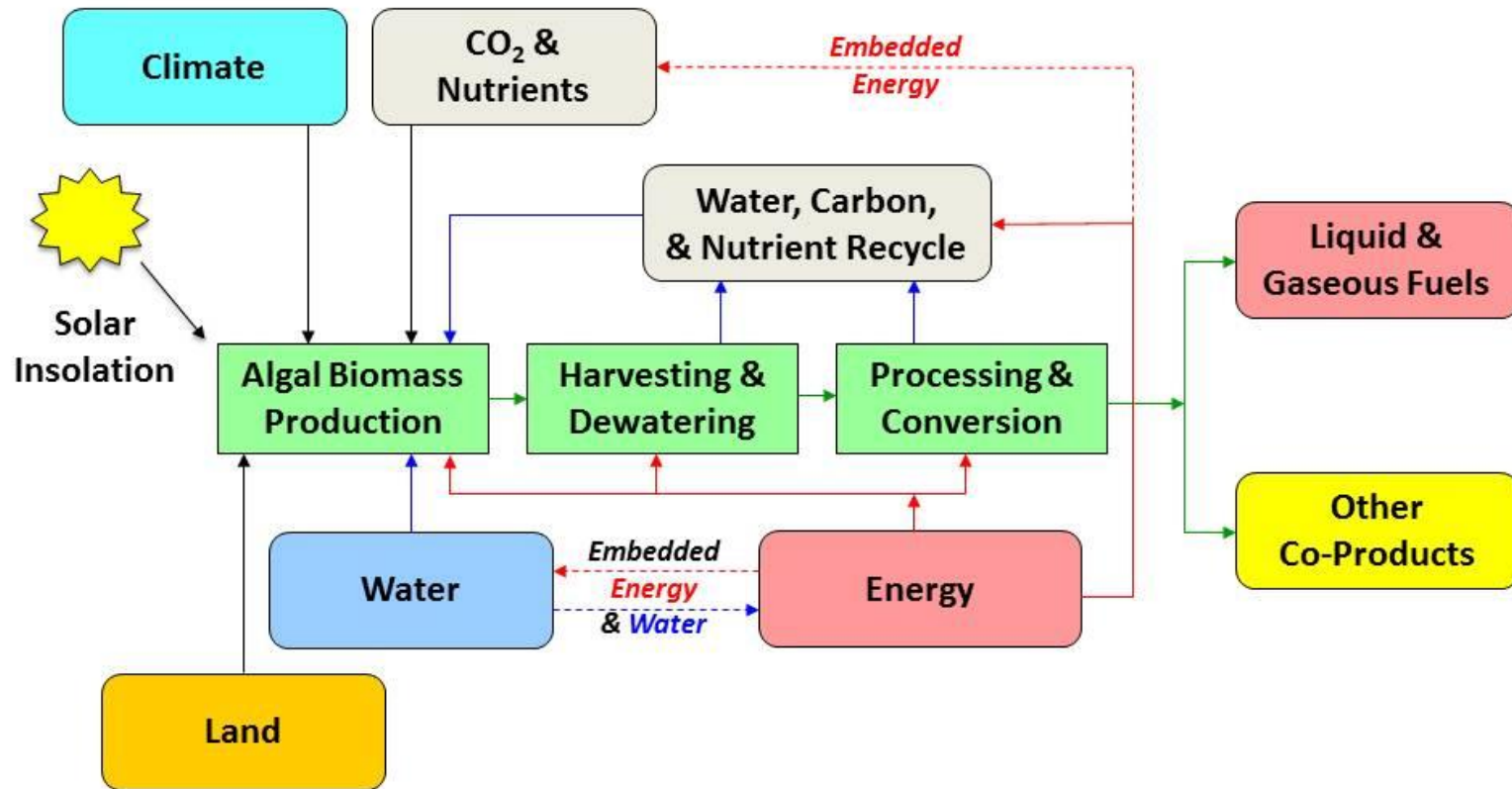


# Passing Comments on Heterotrophic Algae Approach



- **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  $\geq 150$  grams/liter (dry weight)*
  - ... *Oil content of 50% to  $\geq 75%$  (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

# Autotrophic Algal Biofuels Production Processes



## Resources and Environmental Factors and Parameters

### Climate

Solar Insolation  
Temperature  
Evaporation  
Precipitation  
Weather Events

### Water

Surface/Ground  
Location/Access  
Supply/Allocation  
Salinity/Chemistry  
Sustainability

### Nutrients

CO<sub>2</sub>, Organic Carbon\*  
N, P, Other  
Sources/Supplies  
Cost & Availability  
Sustainability  
\* for heterotrophic & mixotrophic growth

### Land

Location/Use Category  
Topography  
Soil type/Ground Cover  
Geology/Hydrology  
Ownership/Access  
Structures & Facilities

### Energy

Electric Power  
Process Heat  
Fuel Resource Use  
Life Cycle Emissions  
Cost & Availability  
Other: e.g., hydrogen & catalysts for fuel upgrading



# Algal Biofuels Resource Requirements

## *High-Level Evaluation by SNL of Autotrophic Microalgal 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 or Liters per Year (BGY or BLY)***
- *What are the most likely resource constraints? ... at what level?*
  - *Focus on land, water, CO<sub>2</sub>, and major nutrients (N, P)*
- *Can limitations be extended or overcome? ... How?*

## **Goals:**

- *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;*
- *To manage expectations for algae biofuels that factors in resource requirements and constraints.*

# Basis for Resource Demand Assessments by SNL <sup>1-3</sup>

*Emphasis here on USA, but approach can be applied globally*



- Consider hypothetical algae production scale-up scenarios
  - Consider target algal oil production levels ranging from 0 to 100 BGY
  - Ignore all systems and processes details ... **assume it exists & works !**
- Assume algae productivities ranging from **Low** to **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<sub>2</sub> and nutrient (N, P) demand based on idealized mass balance with an assumed algal biomass C:N:P composition ratio and 100% utilization efficiency
- Compare projected land, water, CO<sub>2</sub> and nutrient (N, P) demand with estimates for resources available and/or similarly used
- Draw **preliminary conclusions** within limited scenario scope & assumptions

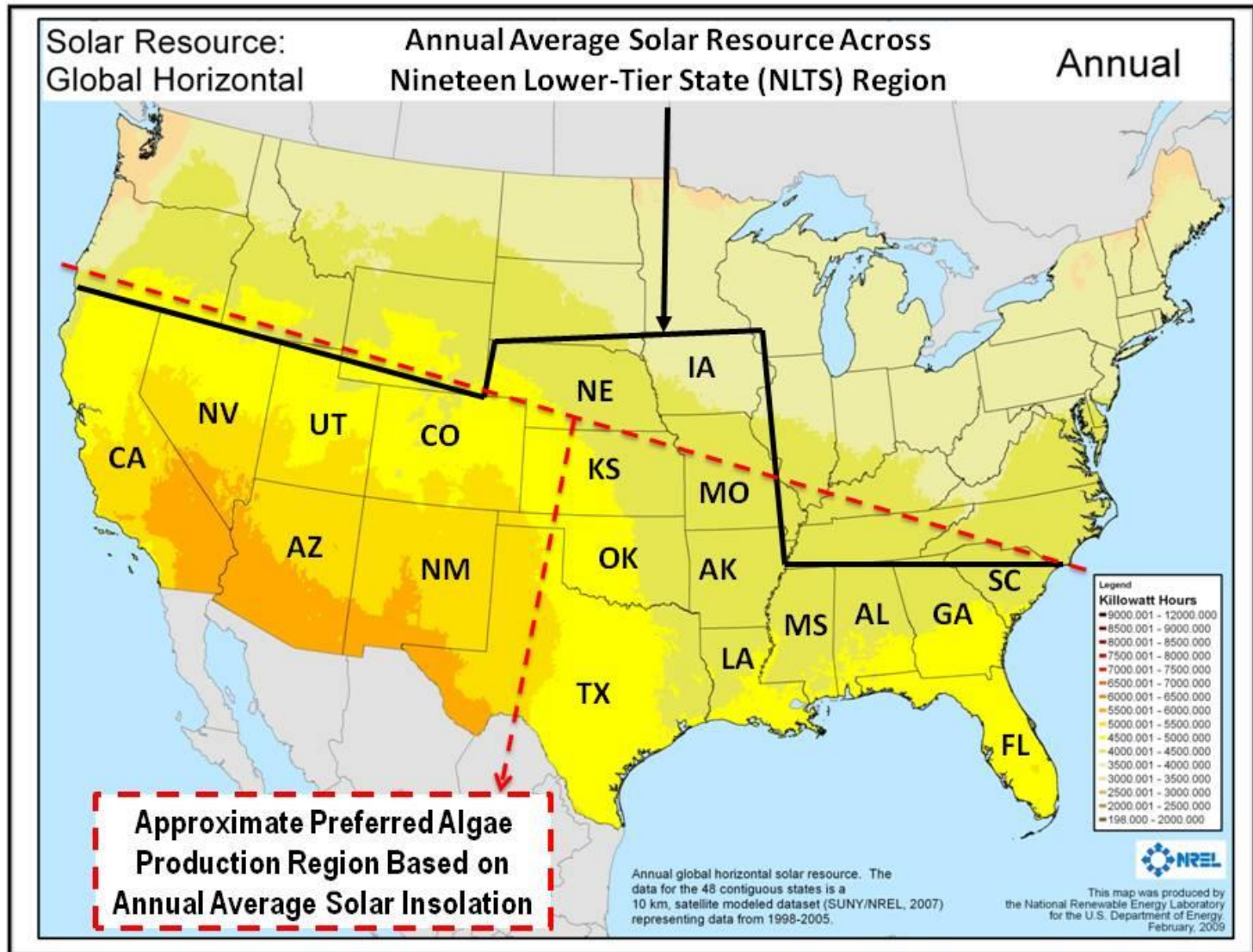
<sup>1</sup> Cooney M.J., Young G., and Pate R. (2011). "Bio-oil from photosynthetic microalgae: Case study", *Bioresource Technology*, v.102(1), 166-177.

<sup>2</sup> Pate, R.C., G. Klise, and B. Wu (2011). "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).

<sup>3</sup> Pate, R.C. (2013). "Resource requirements for the large-scale production of algal biofuels", *Biofuels* 4(4), 409-435.

# Key Factor for Algae Cultivation - Sunlight

## *Drives Focus on Lower Latitude Regions*

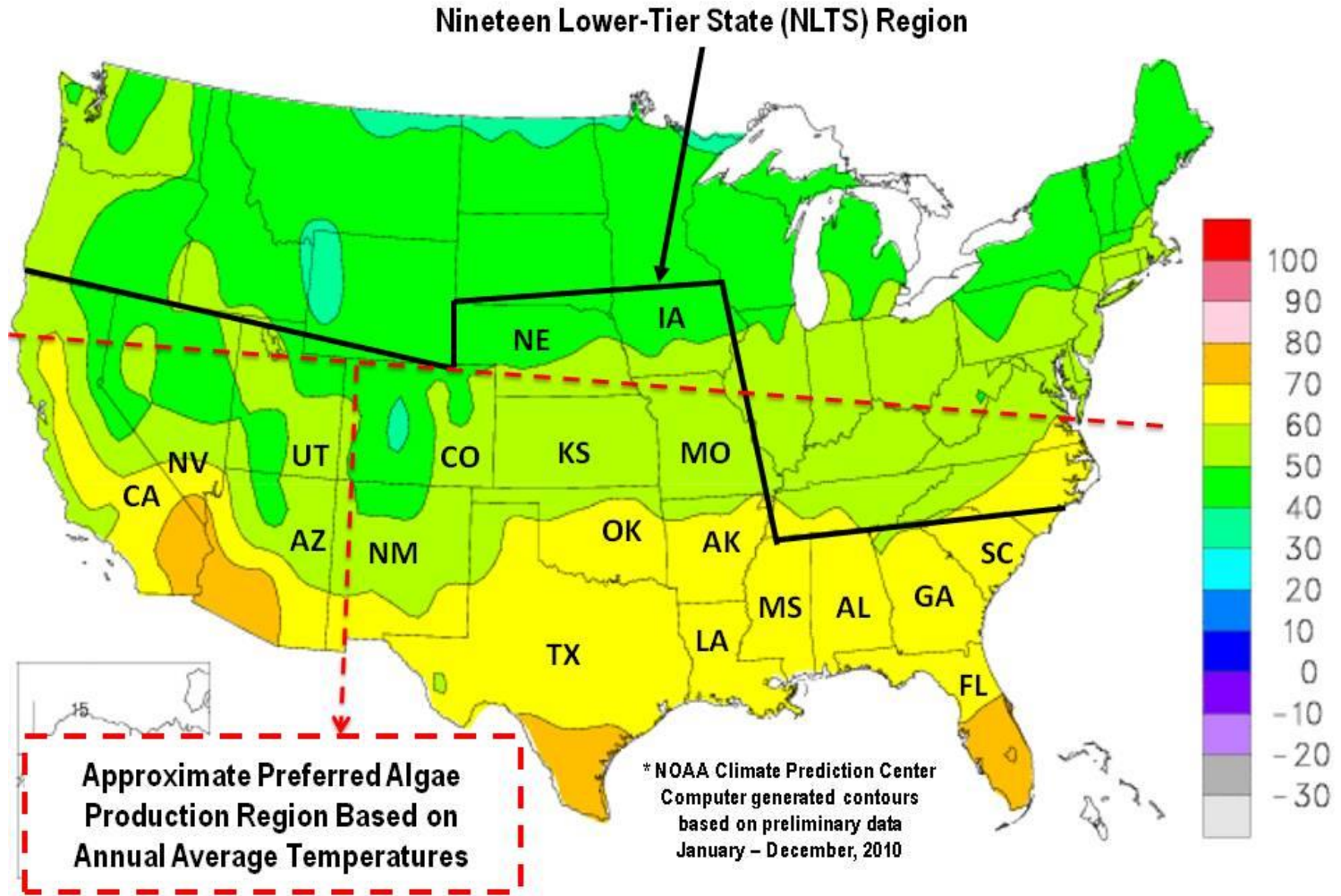


*Solar resource map courtesy of U.S. National Renewable Energy Laboratory (NREL)*

# Key Factor for Algae Cultivation - Temperature

*Drives Focus on Lower Latitude and Lower Altitude Regions*

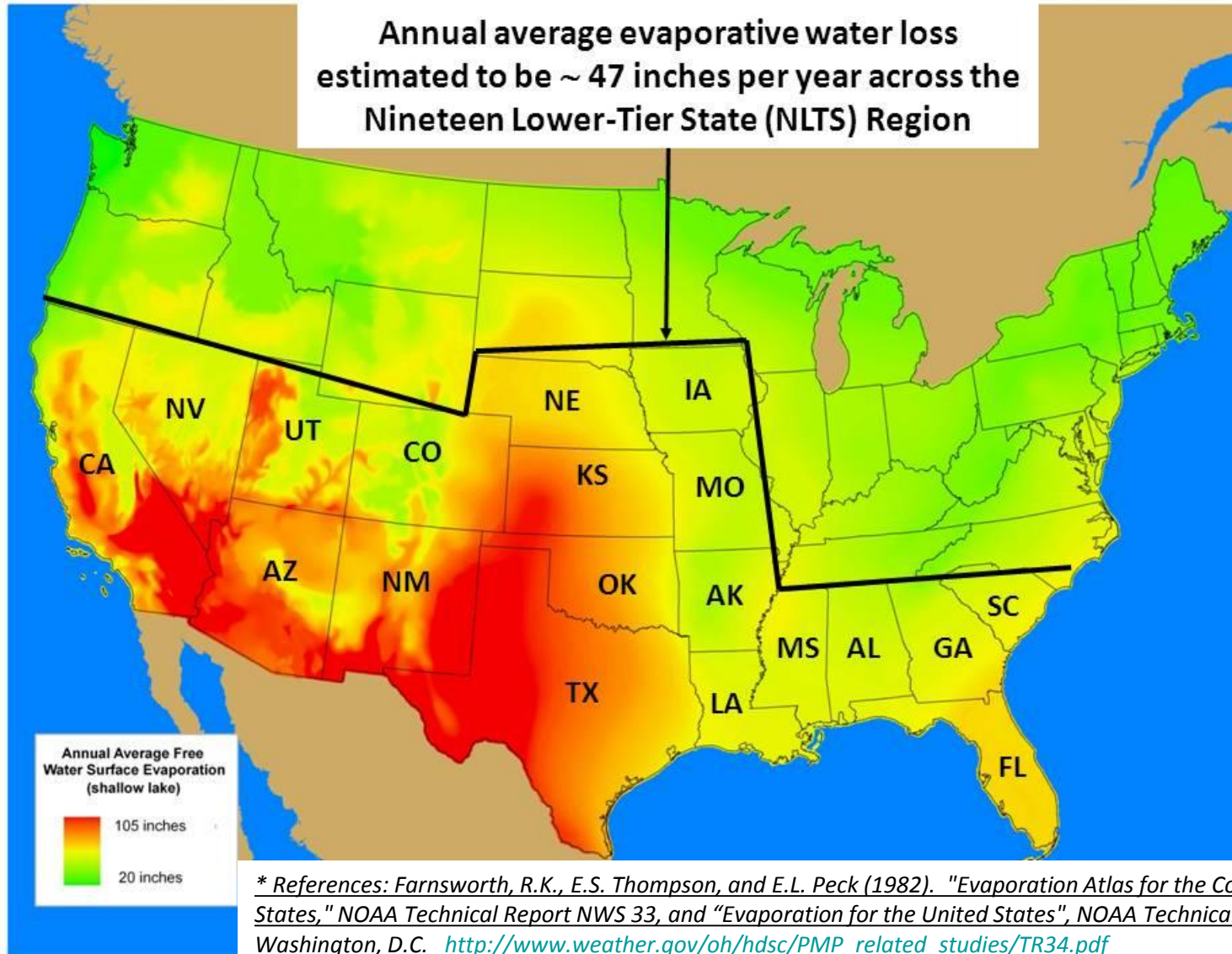
Annual Average Temperatures in °F for 2010 \*



Temperature map courtesy of U.S. National Oceanic and Atmospheric Administration (NOAA)

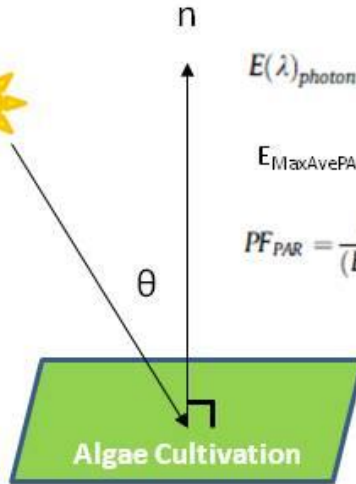
# Key Factor for Algae Cultivation - *Evaporation*

*Assuming Open Systems (fresh water pan evaporation data\*)*



# Theoretical Basis: Solar Energy to Biomass<sup>1</sup>

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



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

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

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

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

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

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

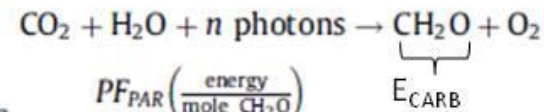
$$S_{EarthPAR} \approx 0.45 \times 9034 \frac{MJ}{m^2 year} = 4065 \frac{MJ}{m^2 year}$$

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

$$E_{MaxAvePAR} = 0.2253 \text{ MJ per mole photons } (\lambda = 531 \text{ nm})$$

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

Photosynthesis:



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

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

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

Assume:  
 $n=10$  photons  
per molecule  
 $CH_2O$

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

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

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

<sup>1</sup> Cooney M.J., Young G., and Pate R. (2011). "Bio-oil from photosynthetic microalgae: Case study", *Bioresource Technology*, v.102(1), 166-177.

# Biomass Energy Density<sup>1</sup> ... 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

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

Where energy content terms are given by:

$$E_C = 16.7 \text{ MJ/kg (for carbohydrate)}$$

$$E_P = 16.7 \text{ MJ/kg (for protein)}$$

$$E_L = 37.4 \text{ MJ/kg (for lipid)}$$

$$E_A = 0 \text{ (for ash)}$$

and where mass terms are given by:

$$M_C = \text{Mass of Carbohydrate [kg]}$$

$$M_L = \text{Mass of Lipid [kg]}$$

$$M_P = \text{Mass of Protein [kg]}$$

$$M_{af} = \text{Ash-Free Biomass [kg]}$$

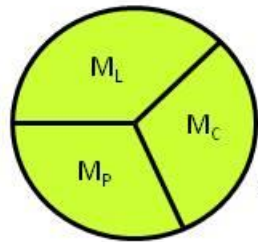
$$M_T = \text{Total Biomass [kg]}$$

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

$$\begin{aligned} E_{BM} &= E_T / M_T = E_C (M_C / M_T) + E_P (M_P / M_T) + E_L (M_L / M_T) \\ &= 0.167 (P+C) + 0.374 (L) \quad [\text{MJ/kg}] \end{aligned}$$

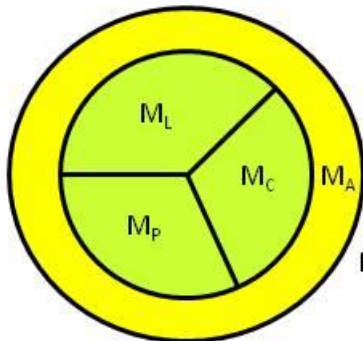
Where A, C, L, and P are the percentage fractions of ash, carbohydrate, lipid, and protein in the composite biomass, and

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



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

$M_{af}$  = 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

<sup>1</sup> Cooney M.J., Young G., and Pate R. (2011). "Bio-oil from photosynthetic microalgae: Case study", *Bioresource Technology*, v.102(1), 166-177.

# Approximate Algal Lipid Production Equations<sup>1-3</sup>

*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:

$$P_{BA} = E_{BCE} / E_{BM} = \frac{52.2}{1 + 0.0124(L) - 0.01(A)} \left( \frac{\text{kg}}{\text{m}^2 \text{ year}} \right)$$
$$P_{BD} = \frac{P_{BA} \left( \frac{\text{kg}}{\text{m}^2 \text{ year}} \right)}{365 \left( \frac{\text{d}}{\text{year}} \right)} = \frac{143}{1 + 0.0124(L) - 0.01(A)} \left( \frac{\text{g}}{\text{m}^2 \text{ d}} \right)$$

Making the further ideal simplifying assumptions that the total lipid content L [%] of the algal biomass can be extracted with 100% efficiency and represents an upper bound for the available lipid-based fuel feedstock, we can then show that the resulting estimated maximum annual lipid production  $P_L$  (proxy for fuel production) can be approximated by:

$$P_L [\text{gal ac}^{-1} \text{ yr}^{-1}] \sim 4.238 \times L [\%] \times P_{BD} [\text{g m}^{-2} \text{ d}^{-1}]$$

$$P_L [\text{l ha}^{-1} \text{ yr}^{-1}] \sim 39.67 \times L [\%] \times P_{BD} [\text{g m}^{-2} \text{ d}^{-1}]$$

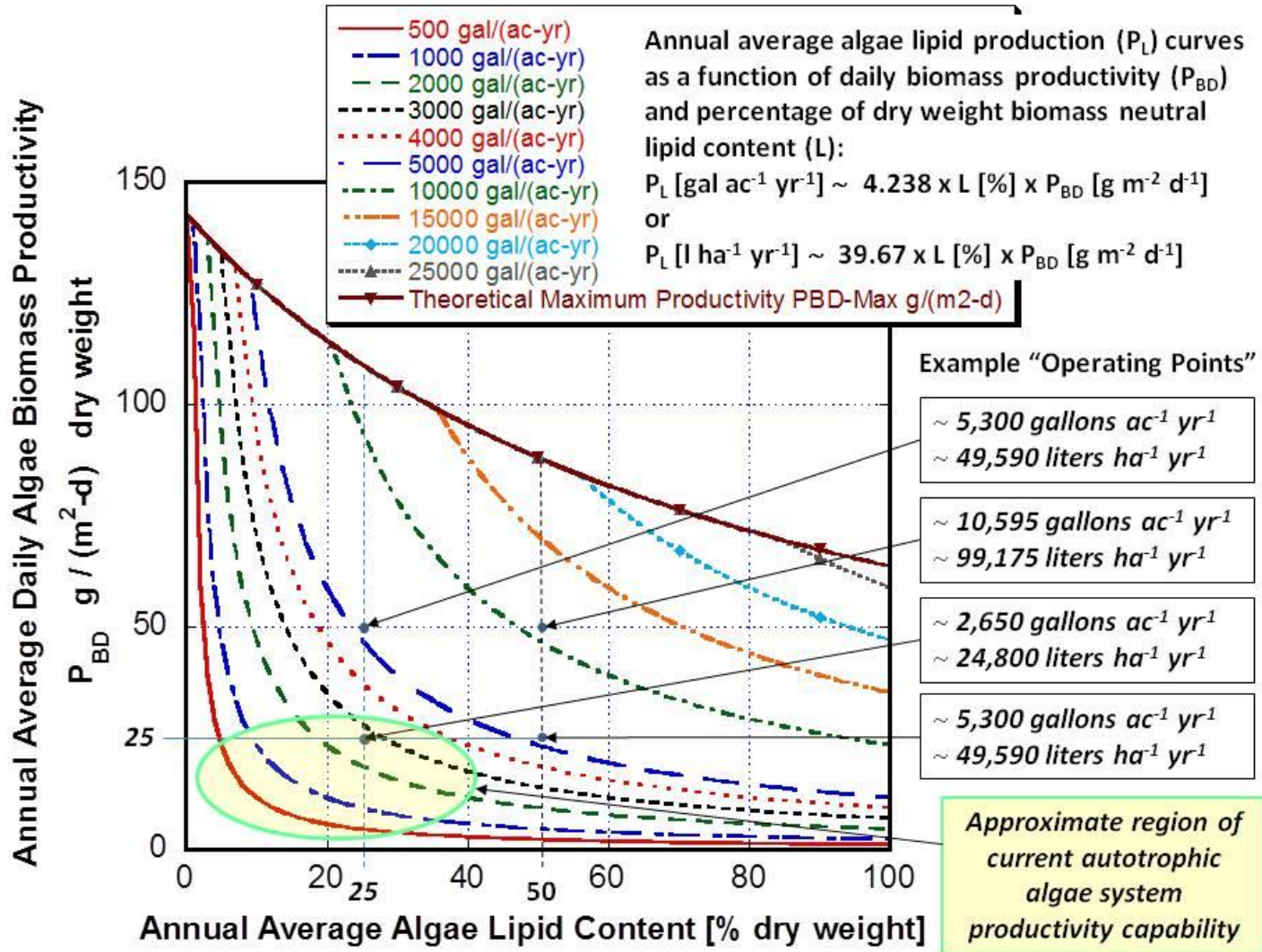
**Approximate annual (upper bound) algal biofuel feedstock production  $P_L$  in U.S. gallons per acre and liters per hectare as a function of lipid content L [%] and annual average daily biomass productivity  $P_{BD}$  [ $\text{g m}^{-2} \text{ d}^{-1}$ ]**

<sup>1</sup> Cooney M.J., Young G., and Pate R. (2011). "Bio-oil from photosynthetic microalgae: Case study", *Bioresource Technology*, v.102(1), 166-177.

<sup>2</sup> Pate, R.C., G. Klise, and B. Wu (2011). "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).

<sup>3</sup> Pate, R.C. (2013). "Resource requirements for the large-scale production of algal biofuels", *Biofuels* 4(4), 409-435.

# Algae Oil Productivity per Acre of Cultivation as Function of Daily Biomass Productivity and Oil Content<sup>1-3</sup>



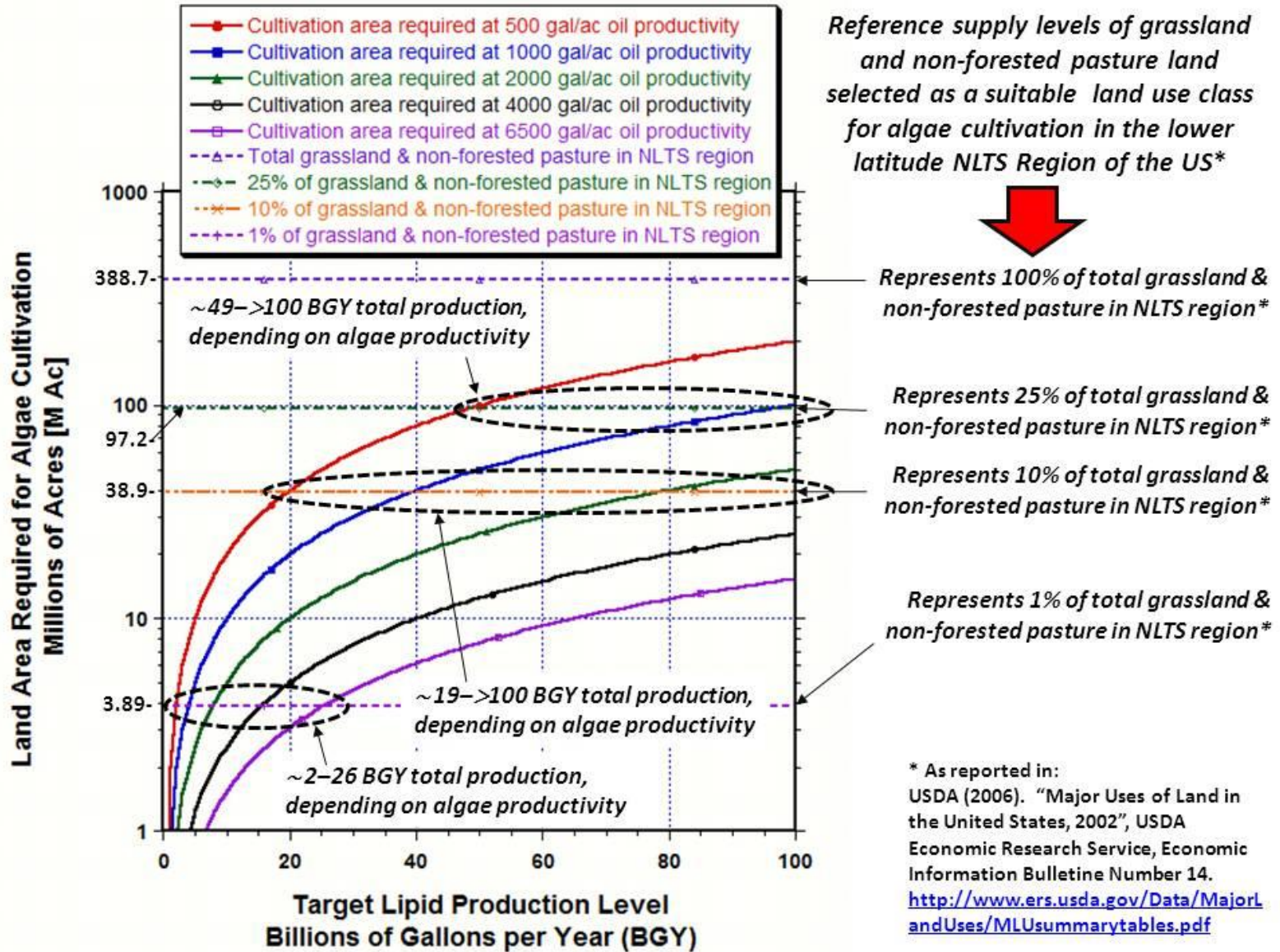
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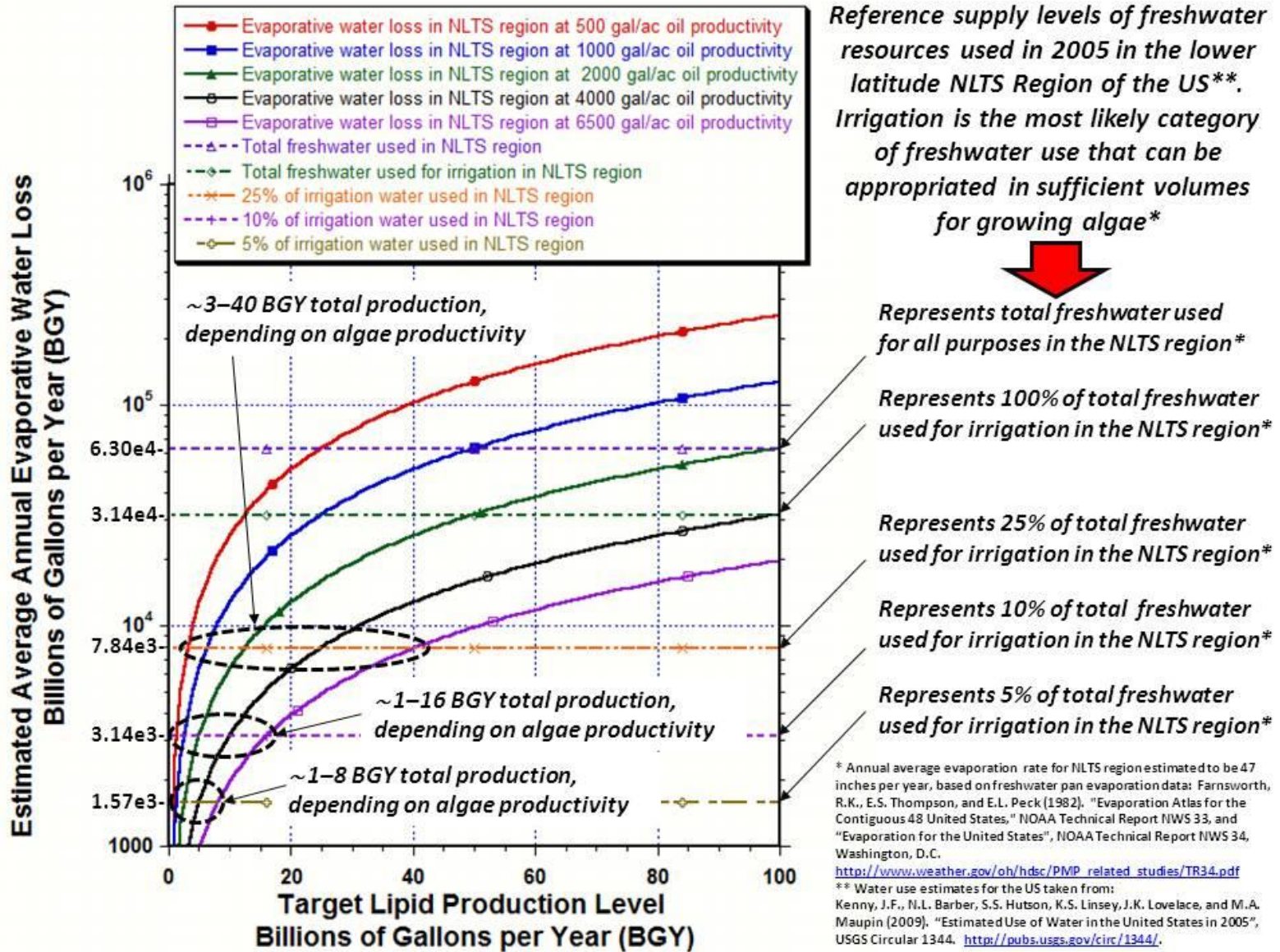
# Estimated Land Area Required for Algae Biofuels

*As function of target production & productivity levels*

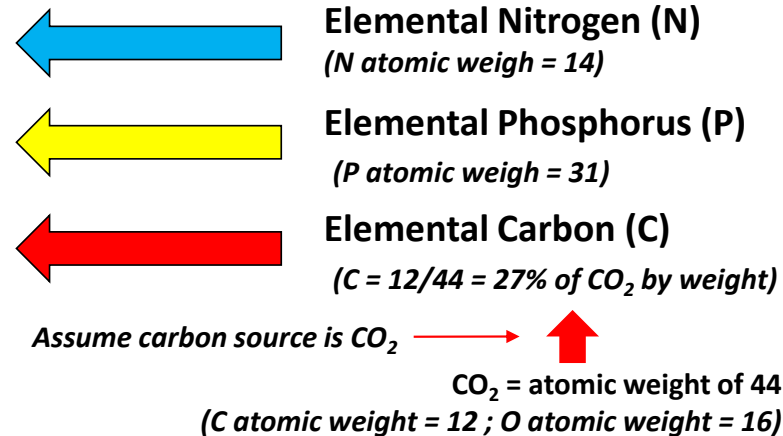


# Estimated Water Required for Algae Biofuels

## As function of target production & productivity levels



# Estimating C, N, and P Demand for Algal Biomass Production Scale-Up



## Idealized mass-balance assumptions and steps for estimating N, P, and C requirements

- 1) Assume inputs of elemental N, P, and C (from  $\text{CO}_2$  sources) are transferred to, and taken up by, algae biomass with no losses and 100% efficiency
- 2) Assume average C:N:P atomic ratio = 106:16:1 (Redfield Ratio) in ash-free dry weight (AFDW) algae biomass with ~ 50% carbon content (by weight)
- 3) C:N:P mass ratio in AFDW algae then becomes:  $(106 \times 12) : (16 \times 14) : (1 \times 31) = 1272:224:31$
- 4) With 50% C content by weight, the C:N:P mass ratio of 1272:224:31 converts to a mass percentage ratio of  $50 : (224 \times 50 / 1272) : (31 \times 50 / 1272) = 50\% \text{ C} : 8.8\% \text{ N} : 1.22\% \text{ P}$

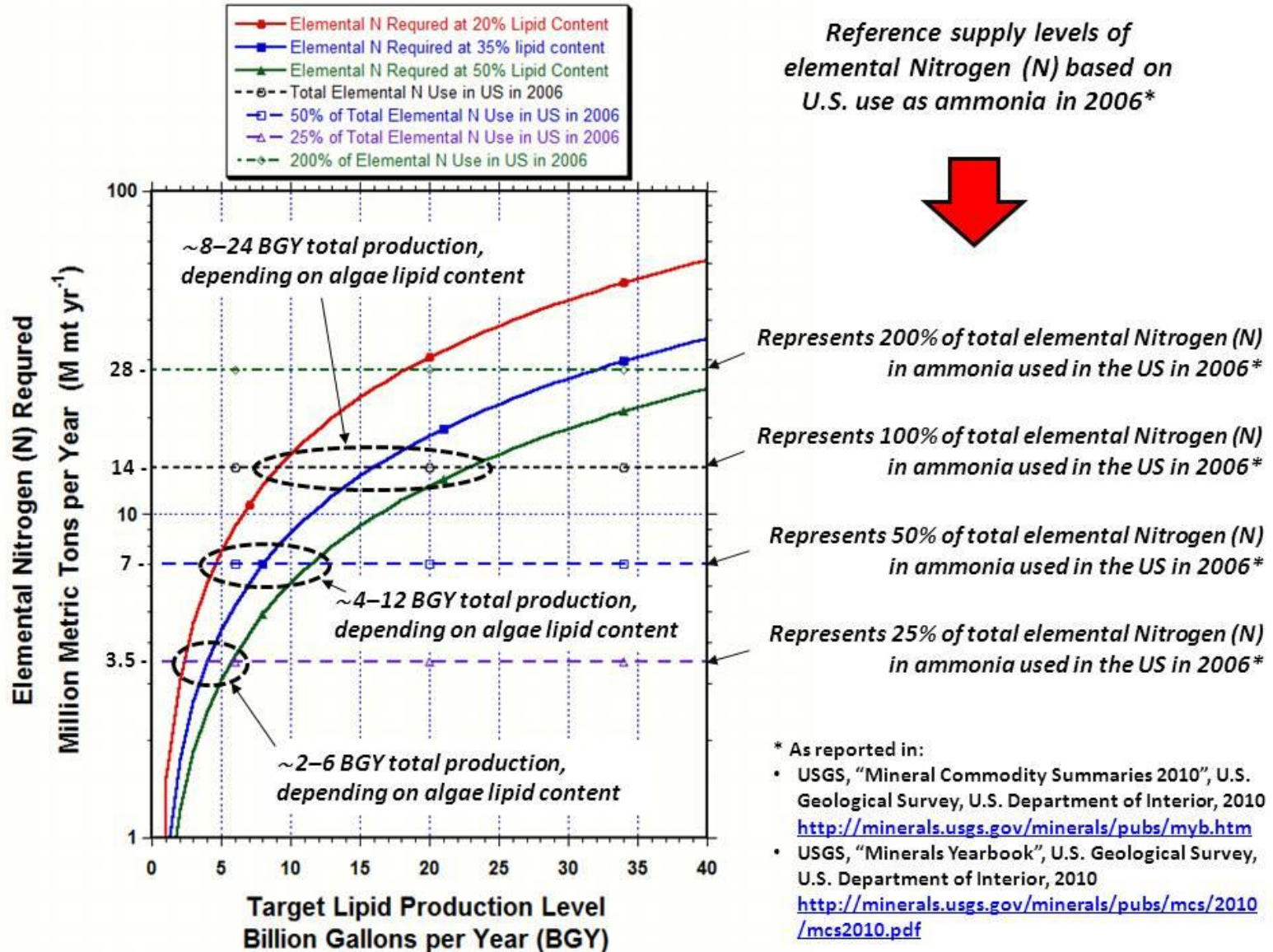
**Resulting estimates:** ~ 88 kg elemental N  
~ 12 kg elemental P  
~ 500 kg elemental C

~ 1830 kg of  $\text{CO}_2$  – Rule-of-thumb: Mass  $\text{CO}_2$  / Mass algae (AFDW) ~ 2

... required for each metric ton (1000 kg) of AFDW algal biomass produced.

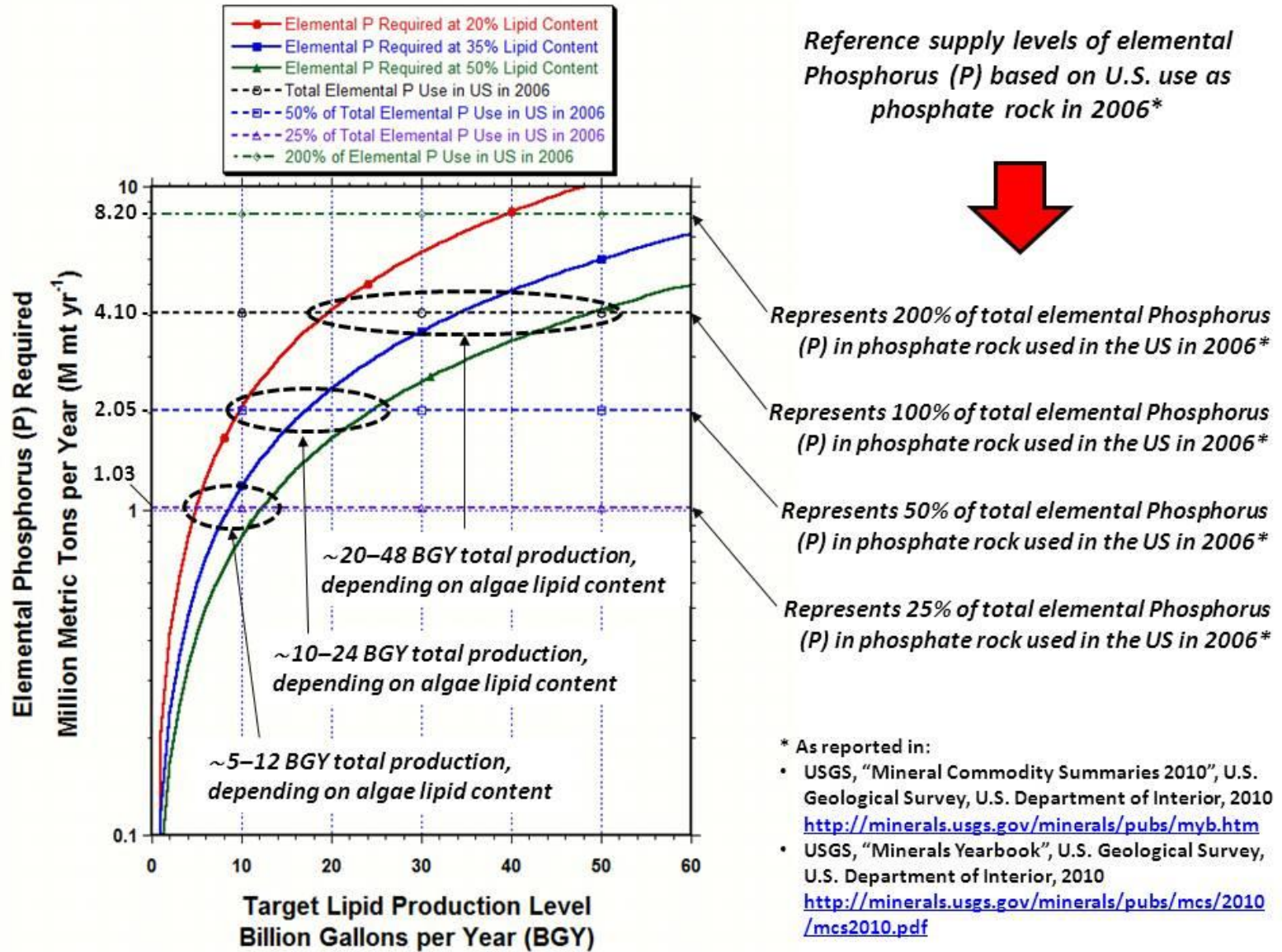
# Estimated Nitrogen Required for Algae Biofuels

*As function of target production & productivity levels*

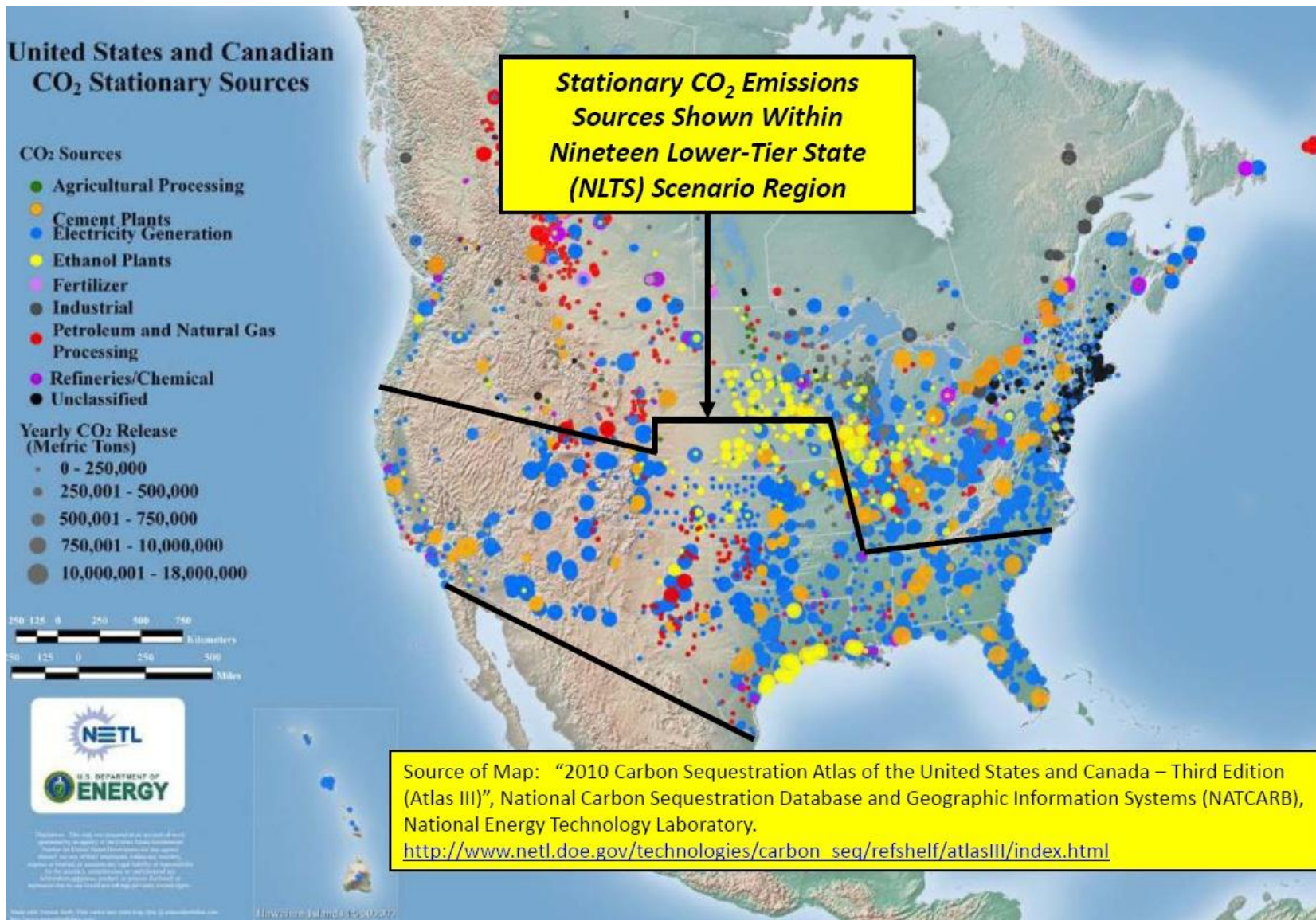


# Estimated Phosphorus Required for Algae Biofuels

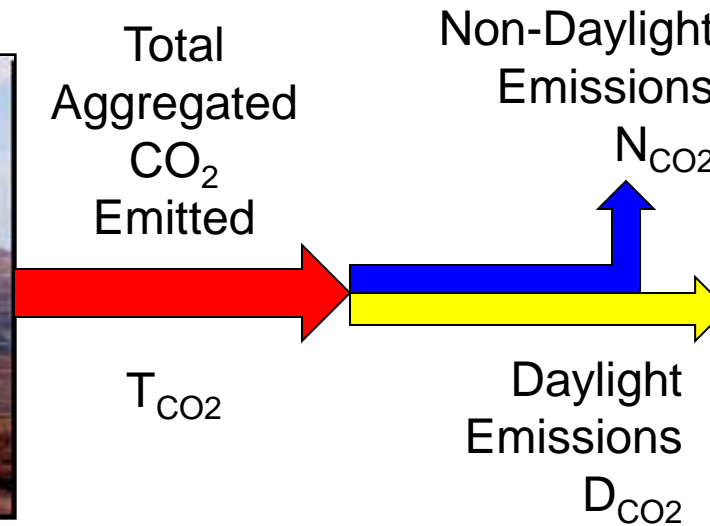
*As function of target production & productivity levels*



# Key Factor for Algae Cultivation – Concentrated Sources of CO<sub>2</sub> to Provide Carbon for Enhanced Algal Production



# Estimating CO<sub>2</sub> emissions during daylight hours\* Availability for use in photosynthetic algae production



Aggregated Emissions from All Stationary CO<sub>2</sub> Sources in Scenario Region

1) Total CO<sub>2</sub> Emissions  $T_{CO_2} = D_{CO_2} + N_{CO_2}$

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

3) Some CO<sub>2</sub> produced by stationary industrial sources will be emitted 24 hours per day, but we assume over half will be emitted during daylight hours; So,

$$0 \leq N_{CO_2} \leq T_{CO_2} / 2$$

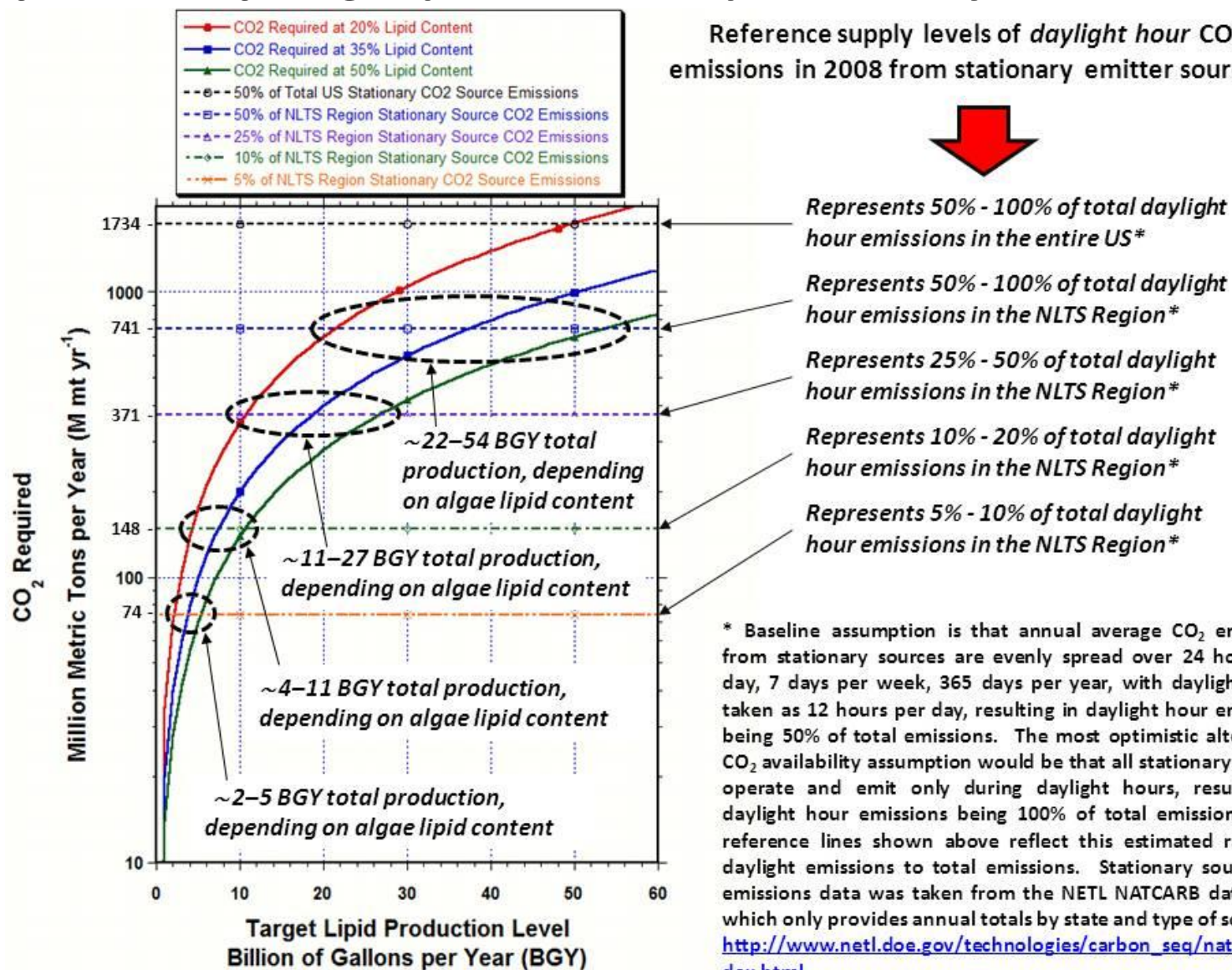
4) It then follows that  $0 \leq T_{CO_2} - D_{CO_2} \leq T_{CO_2} / 2$  and  $D_{CO_2} \leq T_{CO_2} \leq D_{CO_2} + T_{CO_2} / 2$ , resulting in:  $T_{CO_2} / 2 \leq D_{CO_2} \leq T_{CO_2}$

**Thus, we estimate that  $D_{CO_2}$  falls somewhere between 50% to 100% of  $T_{CO_2}$ \***

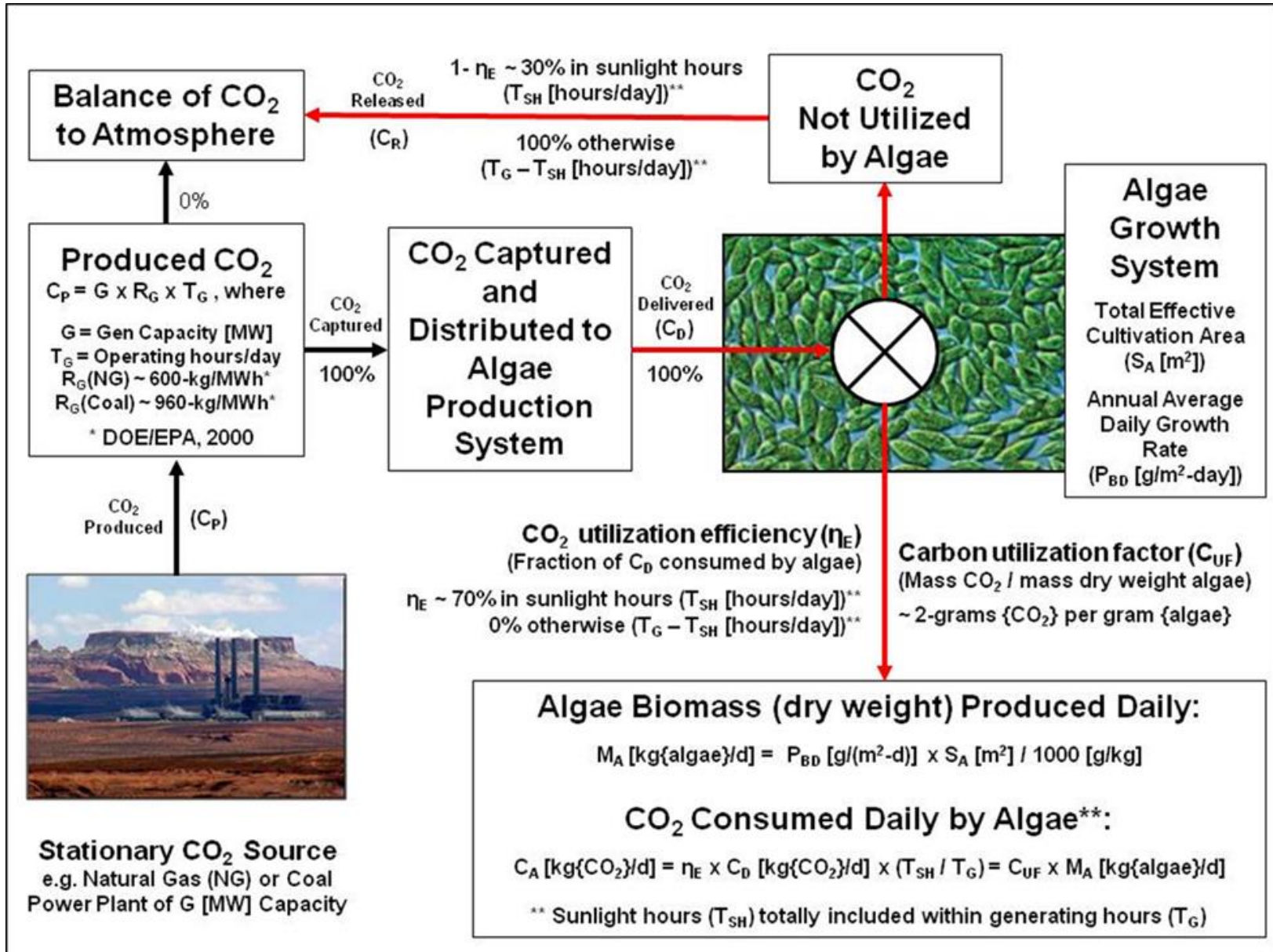
\* Note: CO<sub>2</sub> emissions data is not broken down by hours of the day, or daylight vs. non-daylight

# Estimated CO<sub>2</sub> Required for Algae Biofuels

## As function of target production & productivity levels



# Idealized Utilization of Stationary Source CO<sub>2</sub> for Algae



# Idealized Utilization of Stationary Source CO<sub>2</sub> for Algae

Example showing importance of relative timing of emissions with available sunlight

Idealized estimates of algae cultivation area required to consume CO<sub>2</sub> generated during daylight hours by fossil-fired power plants, and associated gross CO<sub>2</sub> offset, as a function of daily algal biomass productivity, for three scenarios:

A) 50-MW NG peaking plant operating 8-hours per day during sunlight;

B) 50-MW NG semi-base load plant operating 18-hours per day spanning sunlight hours;

C) 1000-MW coal fired base load plant operating 24 h/d.

Daily Algae Productivity (P <sub>BD</sub> ) <sup>1</sup> [g/(m <sup>2</sup> -day)]	Annual CO <sub>2</sub> production (C <sub>PA</sub> ) <sup>2</sup> [mt/yr]	Annual CO <sub>2</sub> used by algae (C <sub>AA</sub> ) <sup>3</sup> [mt/yr]	Algae biomass production (M <sub>AA</sub> ) <sup>1,3,4</sup> [mt/yr]	Algae Area Needed (S <sub>A</sub> ) <sup>3,4</sup> [ha]	Gross CO <sub>2</sub> Offset (C <sub>AA</sub> /C <sub>PA</sub> ) <sup>5,6</sup> [%]
<b>A) Natural Gas Fired Peaking Power Plant: 50-MW operating T<sub>G</sub> = 8-hours/day<sup>6</sup></b>					
10	87,600	61,440	30,720	840	70
20				420	
30				280	
40				210	
50				168	
60				140	
<b>B) Natural Gas Fired Semi-Base-load Power Plant: 50-MW operating T<sub>G</sub> = 18-h/d<sup>6</sup></b>					
10	197,100	61,440	30,720	840	31
20				420	
30				280	
40				210	
50				168	
60				140	
<b>C) Coal-Fired Baseload Power Plant: 1000-MW operating T<sub>G</sub> = 24-h/d</b>					
10	8,409,600	1,966,080	983,040	26896	23
20				13448	
30				8965	
40				6724	
50				5379	
60				4483	
<sup>1</sup> Assuming annual average daily productivities and operation 365 days per year <sup>2</sup> Based on assumed CO <sub>2</sub> production rates of 600-kg/MWh for NG and 960-kg/MWh for coal <sup>3</sup> Based on annual average daily sun hours of T <sub>SH</sub> = 8-h/d and 70% CO <sub>2</sub> utilization efficiency <sup>4</sup> Based on assumed carbon utilization factor of 2-g of CO <sub>2</sub> per gram algae biomass (AFDW) produced <sup>5</sup> Does not include offsets for products and fuels generated from the algae biomass produced <sup>6</sup> Time of operation (T <sub>G</sub> ) assumed to totally include the photo-synthetically active sun hours (T <sub>SH</sub> )					

# Algal Biofuels Scale-Up Assessment Summary



## *Resource Demand Implications for USA*

- **Land** ... requirements probably manageable for high scale-up
- **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 and/or manage evaporative loss impacts*
  - *Open system salinity build-up with non-fresh waters will be issue for inland sites*
- **Nutrients (N & P)** ... significant challenge if recycling is not used
  - *Could seriously compete with agriculture and other commercial fertilizer uses*
  - *Cost and sustainability are issues for commercial fertilizer use*
  - *Approaches needed that enable cost-effective nutrient capture and recycling*
- **CO<sub>2</sub> Sourcing** ... significant challenge ... **perhaps the greatest challenge?**
  - *How much from stationary emitters can be affordably tapped and utilized?*
  - *Co-location opportunities vs. affordable range for transporting concentrated CO<sub>2</sub>?*
  - *Can other sources and/or forms of inorganic carbon be affordably & sustainably used?*
- **Based on Assessment Scenario Assumptions and Trends**
  - ***Resource constraints could emerge in U.S. within the 5 to 15 BGY oil production range***
- **Constraint reduction possible with innovation**
  - *Resource use intensity improves with increased algae productivity & oil content*
  - *How much can this be improved for reliable large scale operations? ... TBD !*

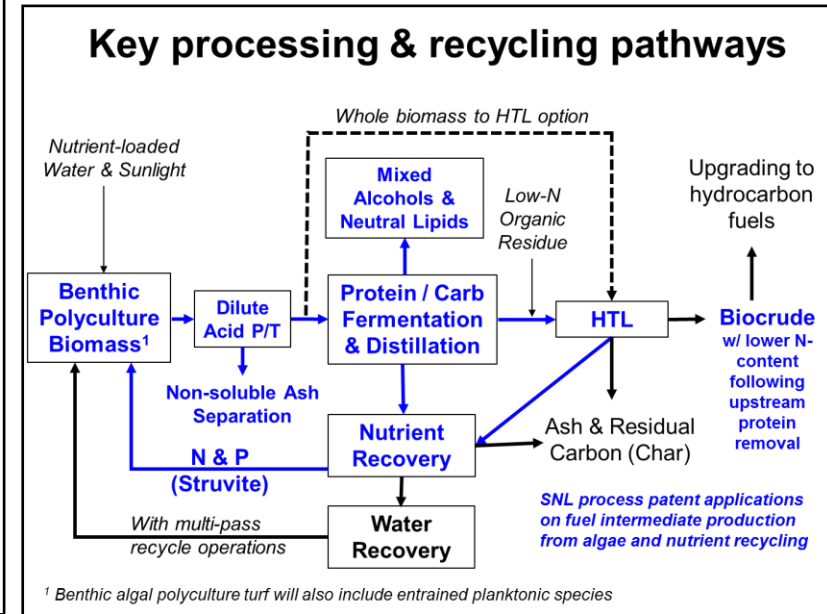
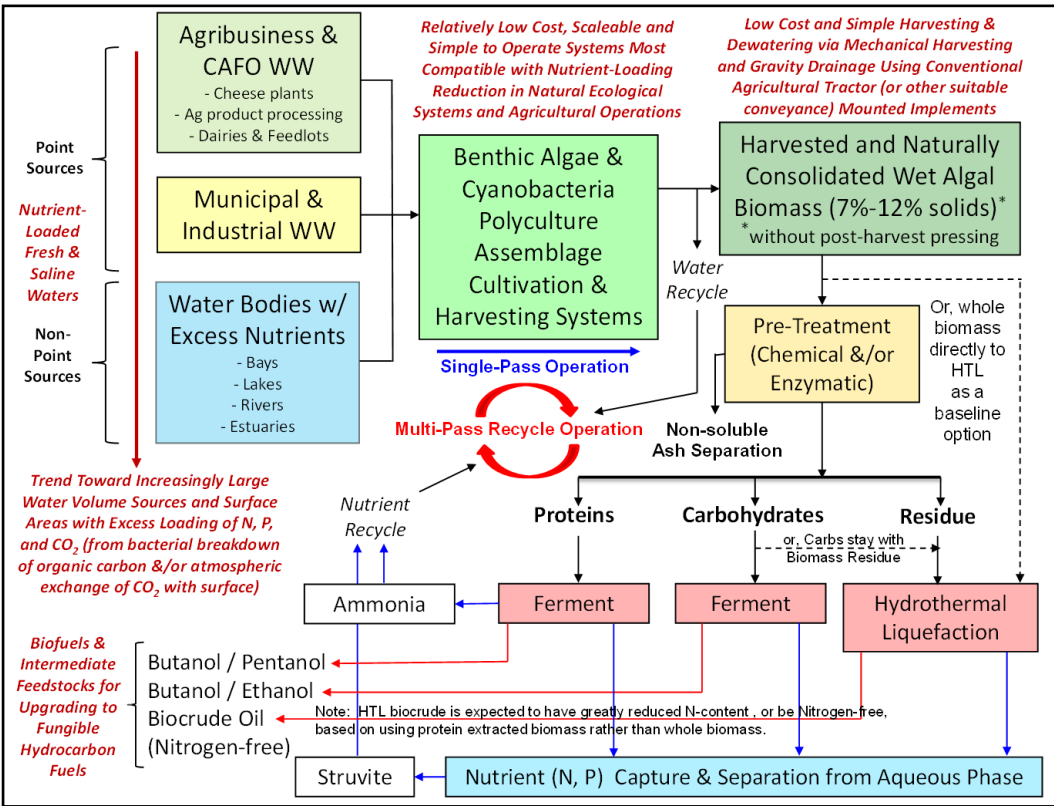
# Example Alternative Approach for Algal Biofuels

## Benthic Algal Polyculture Turf – Has features more like open field agriculture

- Uses pulsed, thin, turbulent gravity flow in planar system configurations
  - Robust, resilient, long-term cultivation productivity at large scales
  - Fresh or saline water – extracts & recycles excess N, P – **big advantage!**
  - Dual-use ... cleans surface waters while producing biomass feedstock
  - **Low neutral lipids – requires biochem and/or thermochem processing**
  - Low energy-intensity harvesting & dewatering – **big advantage!**
  - Supplemental CO<sub>2</sub> not required in single-pass mode – **big advantage!**
  - Relatively high exogenous ash content in non-optimized systems\*
  - Sustainable and affordable scale-up potential under investigation by SNL
- \* Systems designed for water treatment without regard for harvested biomass ash content



Examples of Commercial and Pilot Scale Benthic Algal Polyculture Turf Biomass Cultivation, Harvesting & De-Watering  
 Photos courtesy of Mark Zivojnovich (HydroMentia) and Walter Adey (Smithsonian Institution)



# Thank You !

# Questions ?



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