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Consequence Assessment for U.S. Algae Biofuel Feedstock Production Scale-up

Scenario-based look at land, water, CO_2, and nutrient demand and availability for large scale biomass and bio-oil feedstock production using photosynthetic microalgae

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Purpose:

To address the following high-level questions …

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

Scenario-based Approach

- Consider hypothetical algae production scale-up scenarios & locations in the U.S.
  - o *Set annual target algal oil production levels of 10, 20, 50, & 100 BGY*
  - o *Ignore all algae production systems and processes details …* ***assume it exists & works !***
- Assume range of scenario algae oil productivities
  - o *Moderate (2100 gal ac^{-1} yr^{-1}) to Very Optimistic (6500 gal ac^{-1} yr^{-1})*
  - o *Land requirements based on cultivation area needed for assumed productivity*
- Assume open system cultivation (subject to evaporative water loss)
  - o *Water demand estimates limited to evaporative loss only (ignore all other)*
  - o *Water loss 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 dry weight algae biomass C:N:P ratio of 106:16:1, with provision of sufficient C, N, and P during cultivation for maximum productivity with 100% utilization efficiency
  - o *Approximately two metric tons of CO_2 required to produce each metric ton of dry weight algae biomass, based on 50% carbon content algae on a dry mass basis and 100% utilization efficiency*
  - o *Approximately 88 kg of elemental N and 12 kg of elemental P required to produce each metric ton of dry weight algae biomass, based on 50% carbon content algae and C:N:P = 106:16:1 on a dry mass basis with 100% utilization efficiency*
- Compare projected land, water, CO_2 and nutrient (N, P) demand under algae biofuels production scale-up scenarios with estimates for resources available and/or similarly used for other purposes within the scenario regions, or the U.S. as a whole in the case of N and P, as shown in Table-2 and Figure-3
- Draw ***preliminary conclusions*** within limited scenario analysis scope & assumptions

Context within U.S. fuel demand:

- High fuel use demand in the U.S., as shown in Table-1;
- Scenario production levels used in the analysis were selected as significant volumes of fuel feedstock relative to US fuel demand;
- 10-BGY in oil feedstock could displace about 17% of the petroleum-based diesel fuel currently used in the US;
- 20-BGY in oil feedstock could displace about 33% of the petroleum-based diesel fuel currently used in the US;
- 50-BGY in oil feedstock could displace about 83% of the petroleum-based diesel currently used in the US;
- 100-BGY in oil feedstock could displace roughly all of the petroleum-based diesel and jet fuel currently used in the US.

Table-1*. US Fuel Demand*

Fuel Type	2008 Demand	2035 Projection*
Gasoline Blend (including E85)	8.99 MBD (137.8 BGY) 17.2 Quads	10.26 MBD (157.3 BGY) 19.7 Quads
Diesel Fuel	3.94 MBD (60.4 BGY) 8.38 Quads	4.91 MBD (75.3 BGY) 10.4 Quads
Jet Fuel	1.54 MBD (23.6 BGY) 3.19 Quads	1.84 MBD (28.2 BGY) 3.81 Quads

* Based on EIA (2010)

Results and Implications for Algae Biofuel Scale-up

- **Resource constraints likely to emerge at the 5-15 BGY oil production range**
  - o *Based on scenario assumptions and resource demand trends with autotrophic algae scale-up*
  - o *Fuel production volumes would still be a significant contribution to U.S. fuel supplies*
  - o *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**
  - o *How much from stationary emitters can be affordably tapped and utilized?*
  - o *Co-location opportunities vs. affordable range for transporting concentrated CO_2?*
  - o *Can other sources and/or forms of inorganic carbon be affordably used?*
- **Nutrients (N & P) … significant challenge**
  - o *Could seriously compete with agriculture and other commercial fertilizer uses*
  - o *Cost and sustainability issues likely to arise with commercial fertilizer use at large algae scale-up*
  - o *Need approaches enabling cost-effective nutrient capture and recycling*
- **Water … significant challenge with limited freshwater resources**
  - o *Can't plan on big national scale-up using freshwater with evaporative loss*
  - o *Need approaches that use marine and other non-fresh waters*
  - o *Need Inland approaches that can reduce or better manage evaporative loss (closed systems?)*
  - o *Open system salinity build-up with non-fresh waters will be issue for inland sites*
- **Land … likely manageable even for very large scale-up, depending on algae productivity**
- **Some resource demand constraint reduction/relaxation is possible with innovation**
  - o *Resource use intensity improves with increased algae productivity & oil content (see Figures 3&4)*
  - o *Resource use intensity improves with capture and recycling of water and nutrients*
  - o *How much can this be improved for reliable large scale operations? … TBD !*

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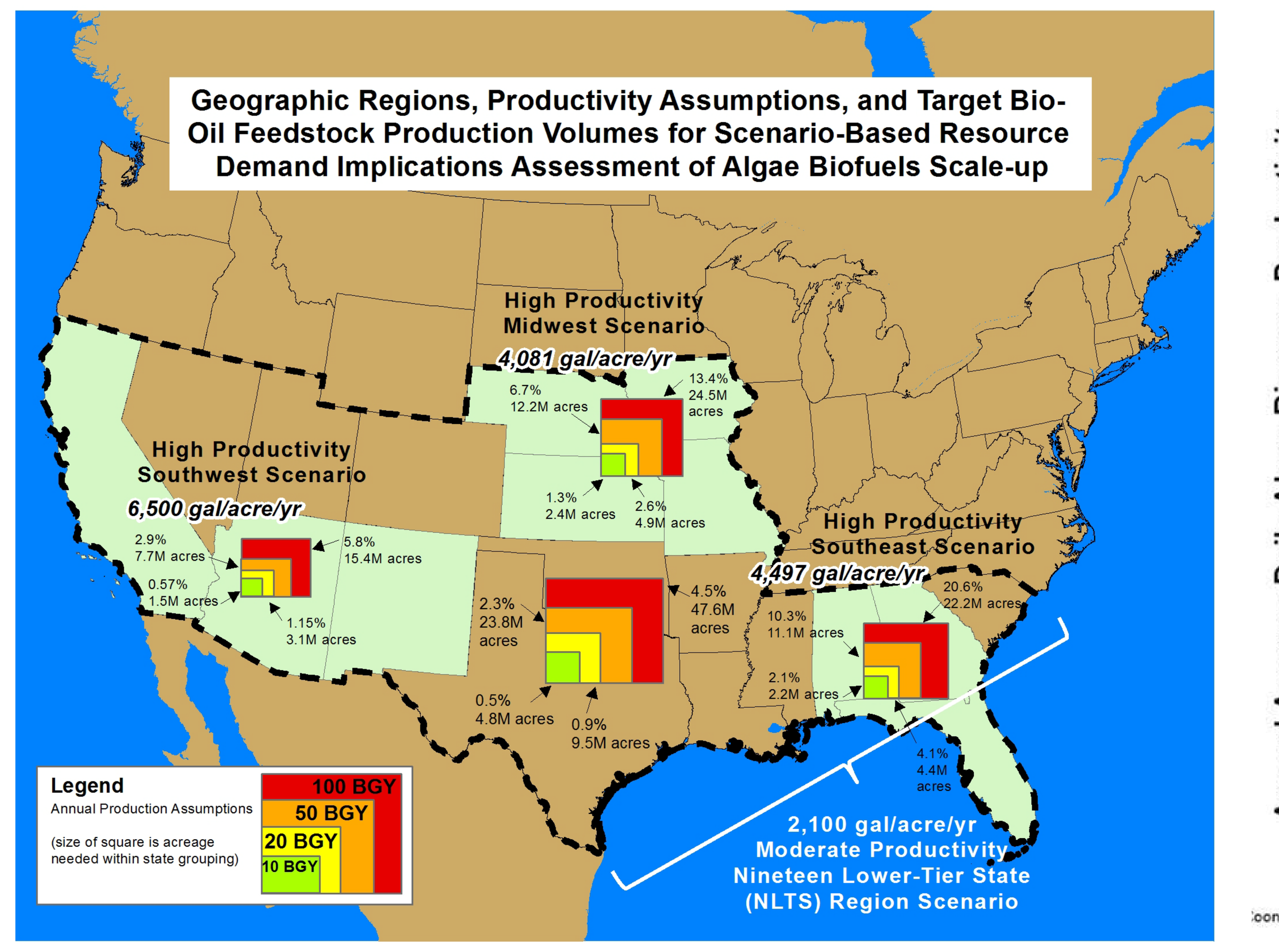

Figure-1*. Projected land areas, shown in acres and in percentage of total land in the four scenario regions considered. Algal productivities are optimistically high in the Southwest (SW), Midwest (MW), and Southeast (SE) regions, with more moderate productivity assumed for the combined Nineteen Lower-Tier State (NLTS) region.*

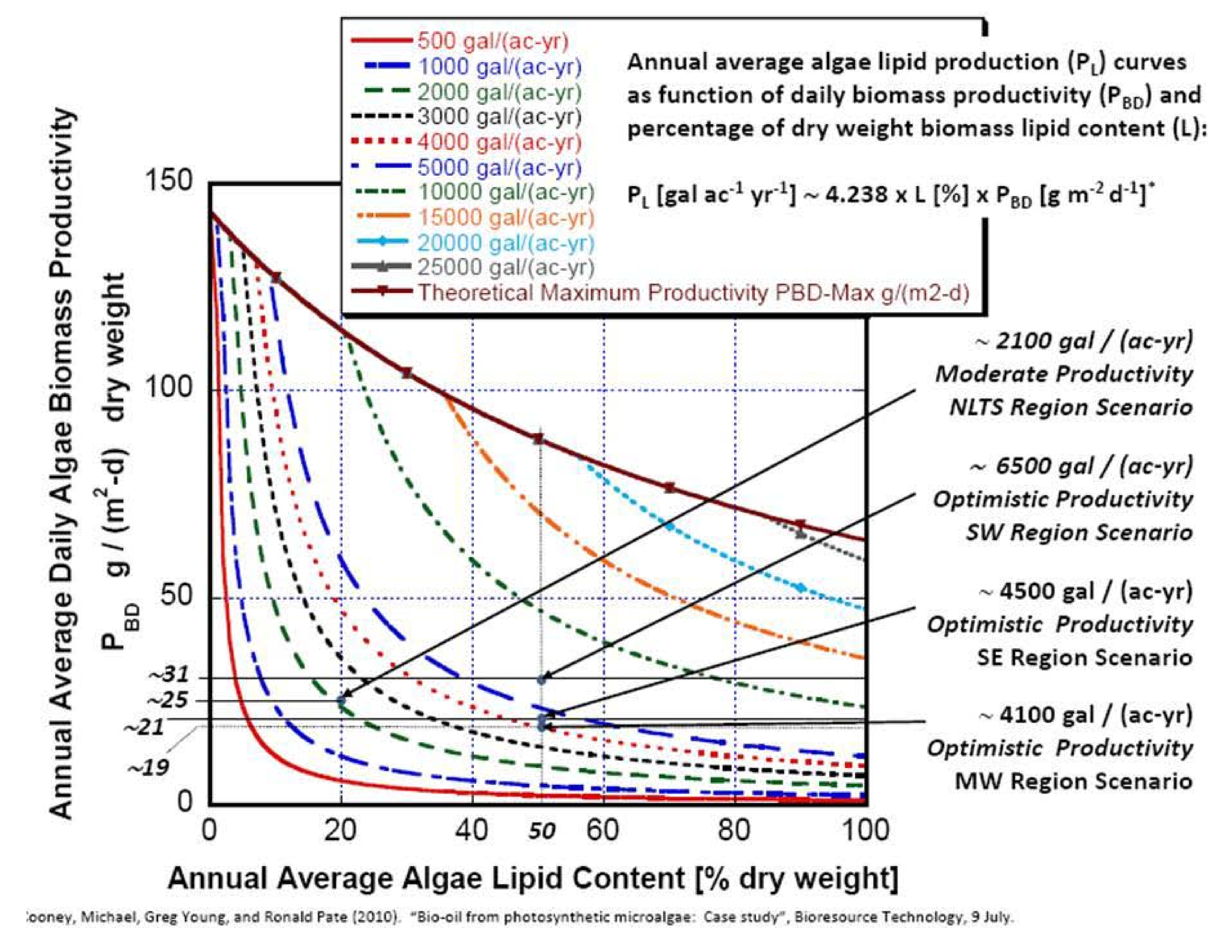

Figure-2*. Mapping of algal oil production curves in gallons per acre per year as a function of annual average daily algal biomass productivity, in grams (dry weight) per square-meter per day, and algal neutral lipid (~oil) content as a percentage of dry weight biomass. (Cooney, et al. 2010)*

Table-2*.* ***(a)*** *Projected resource requirements for land, CO_2, and water compared with the resource profiles existing in each of four multi-state regions of the US: Southwest (CA, AZ, NM), Midwest (NE, KS, IA, MO), Southeast (Al, GA, FL), and Nineteen Lower-Tier States (NLTS) for four hypothetical target algal oil production levels of 10 billion gallons per year (BGY), 20 BGY, 50 BGY, and 100 BGY.;* ***(b)*** *Comparison of resource requirements land, CO2, water, and nutrients (N, P) with relevant resource data for each scenario region. Shaded cells on right-hand side of table signify problem levels for resource availability.*

(a)

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] Land use data for 2002 from: USDA (2006)
[2] Assuming algae lipid productivities of ~6500 (SW), ~4100 (MW), and ~4500 (SE) gal ac^{-1} yr^{-1} at 50% lipid content
[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 w/ annual average lipid productivity of ~2,100 gal ac^{-1} yr^{-1} at 20% lipid content across the states of AZ, AK, AL, CA, CO, FL, GA, IA, KS, LA, MO, MS, NE, NM, NV, OK, SC, TX, & UT

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

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,

[10] Water use data for the U.S. in 2005, from USGS: Kenny, et al. (2009)
[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

(b)

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)				% of Selected Land Classes[2] Considered for Algae Production [% of Total Land] in Scenario Region			
Southwest (SW)	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)	2,440	4,880	12,200	24,400	5.5 [1.3]	11 [2.6]	27 [6.7]	54 [13]
Southeast (SE)	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] With scenario algae lipid productivities of ~6,500 (SW), ~4,100 (MW), & ~4,500 (SE) gal ac^{-1} yr^{-1} at 50% lipid
[2] Combination of grassland, non-forested pasture, range, and open grazing land, excluding cropland pasture
[3] NLTS scenario assumes moderate annual average algal lipid productivity of ~2,100 gal ac^{-1} yr^{-1} at 20% lipid content 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

CO_2 USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	Required CO_2 (millions of metric tons)[4]				% of 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 [1150]
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	1740	3490	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 2010 NATCARB stationary CO_2 source data base: NATCARB (2010)

WATER USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	Evaporative Water Loss[6] (BGY)				Evaporative loss as % used for irrigation [% of all uses total] in each scenario region[7]			
Southwest	2,800	5,400	12,100	22,300	24 [18]	46 [35]	104 [78]	191 [144]
Midwest	3,300	6,500	15,100	28,300	72 [32]	141 [62]	328 [145]	615 [272]
Southeast	2,500	5,000	12,600	25,200	172 [31]	344 [62]	867 [156]	1733 [312]
NLTS	6,070	12,140	30,350	60,700	19 [10]	39 [19]	97 [48]	194 [96]

[6] Based on annual average freshwater pan evaporation over cultivation area by region (likely to be worst-case)
[7] Water use data by end-use category for the U.S. in 2005, taken from USGS: Kenny, et al. (2009)

NUTRIENT USE	10 BGY	20 BGY	50 BGY	100 BGY	10 BGY	20 BGY	50 BGY	100 BGY
Scenario Region	Total Biomass (BM) Produced & Projected Nitrogen (N) and Phosphorus (P) Needed[8] in millions of metric tons per year [M mt yr^{-1}]				Nitrogen and phosphorus use for algae 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 14.0M metric ton elemental N consumed as ammonia and 4.1M metric ton elemental P consumed as phosphate rock, from Mineral Commodity Summaries 2010 & Minerals Yearbook (USGS 2010).

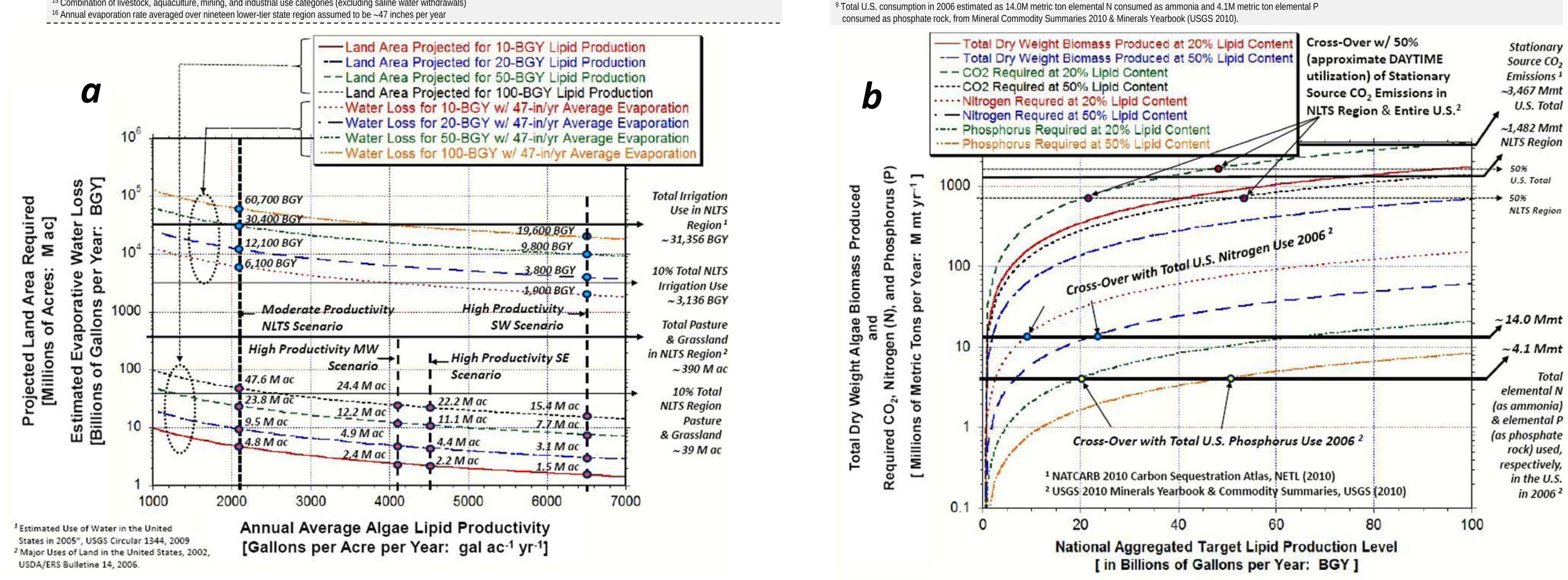

Figure 3*.* ***(a)*** *Projections of land area and associated evaporative water loss (assuming fresh water pan evaporation, which is likely a worst-case estimate) with open systems for target oil feedstock production levels as a function of annual average algae neutral lipid (oil) productivity;* ***(b)*** *Production of dry weight algal biomass (for 20% and 50% oil content) and requirements for CO_2, N, and P as a function of target oil production level.*

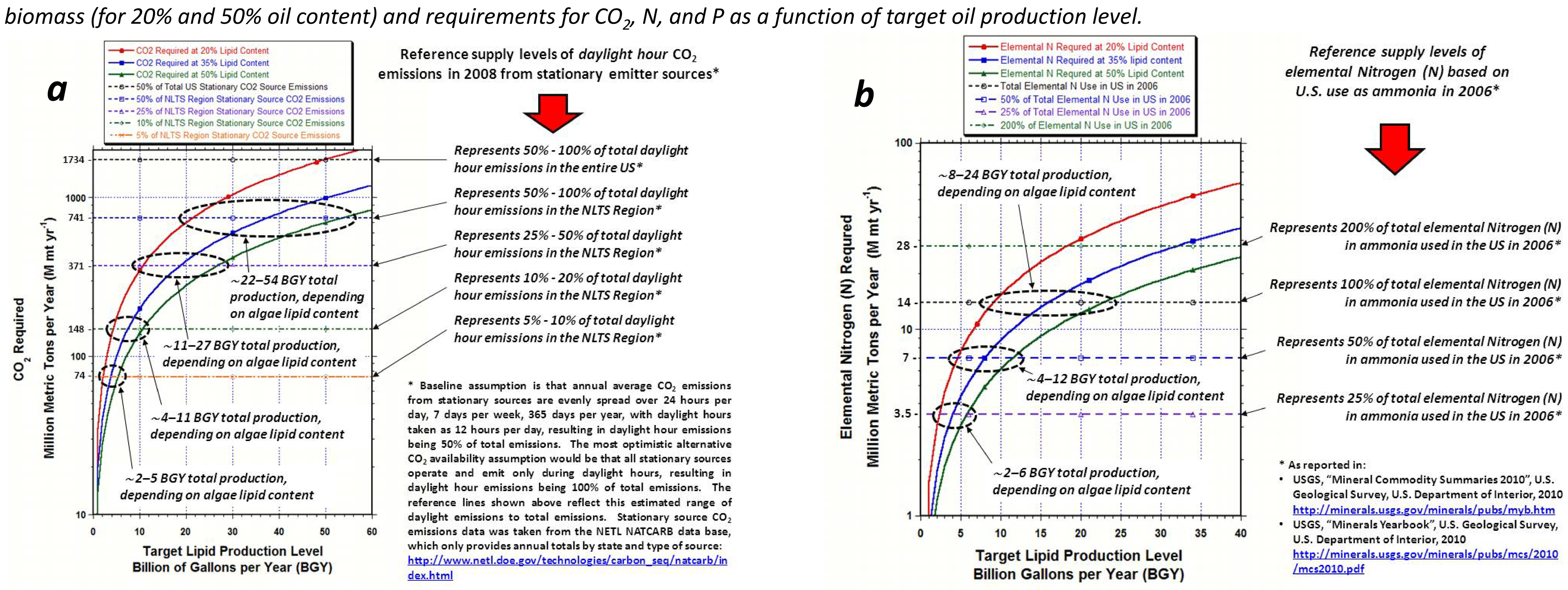

Figure 4. A closer look at the sensitivity of resource demand for algae oil production scale-up as a function of algae oil content: ***a)*** *CO_2 and* ***b)*** *elemental N*

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