Design You Own Algae Biofuel Company – Scientific Evidence Packet

a) Regions with annual average climate conditions meeting selected criteria: ≥ 2800 hour annual sunshine, annual average temperature ≥ 55° F, and ≥ 200 freeze-free days

b) Fossil-fired power plant sources of CO_2 within 20 miles of municipal wastewater facilities in the preferred climate region

Figure 1: Areas of optimal climate for growing algae biofuels (figure on the left). The figure on the right shows locations within the optimal climate area that are within 20 miles of a wastewater source and a source of carbon dioxide emissions from power plants (to feed to the algae).

Source: Algal Biofuels Technology Roadmap. 2010. U.S. Department of Energy.

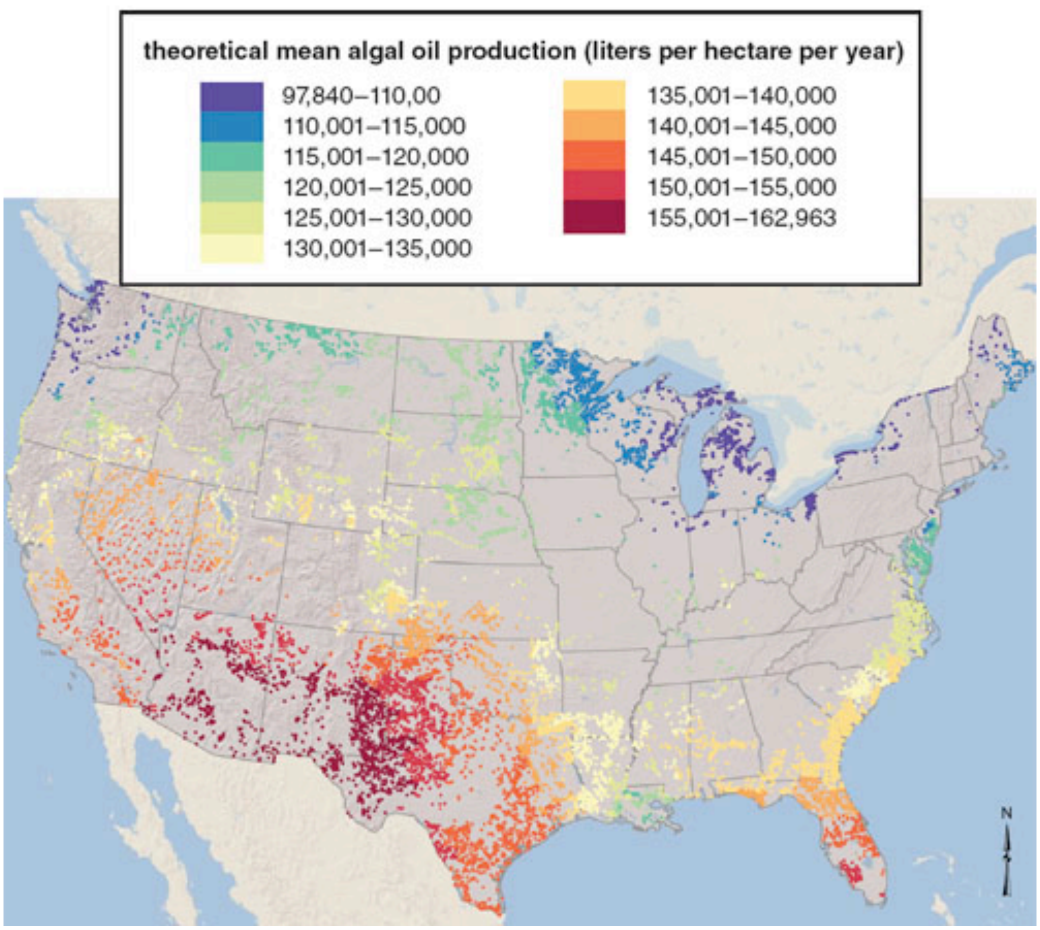

Figure 2: Average annual oil production from algae based on climate and water resources available. These calculations were made by a researcher at the National Renewable Energy Lab, note that this map differs from the map in Figure 1.

Source: "Making Biofuel from Microalgae." American Scientist. 2011. http://www.americanscientist.org/issues/feature/2011/6/making-biofuel-from-microalgae/99999

Figure 3: Examples of closed systems (photobioreactors) for growing algae.

Figure 4: Examples of open systems for growing algae. The systems in these photos are called 'raceway ponds.'

Figure 5: Lipid content of different algae classes (higher lipid content is favorable for algal biofuel production). Red dots indicate algae that are stressed, meaning they are nutrient-starved. Green dots are algae that have plenty of nutrients.

Source: "Making Biofuel from Microalgae." American Scientist. 2011. http://www.americanscientist.org/issues/feature/2011/6/making-biofuel-from-microalgae/99999

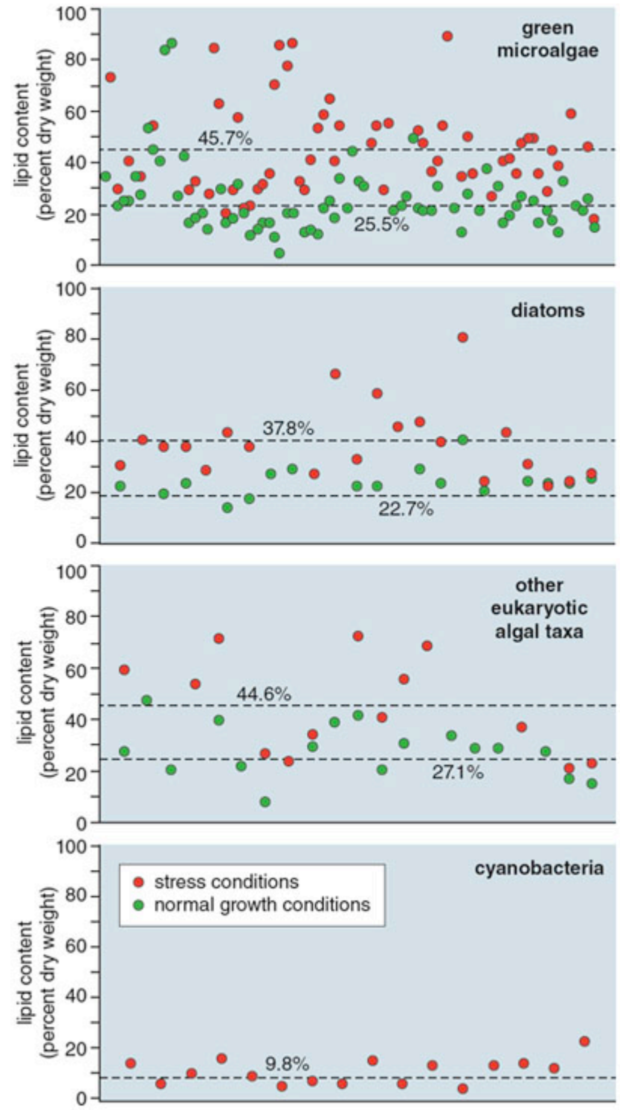

Figure 6: Lipid content of different combinations of algae species. "Species richness" means the number of species of algae that are living together. "Laboratory" means the algae were grown in a laboratory, and "field" means the algae were found in the environment. Do you see a trend between lipid content and the number of algae growing together?

Source: Stockenreiter et al, The effect of species diversity on lipid production by micro-algal communities. *Journal of Applied Phycology* 24, 2012.

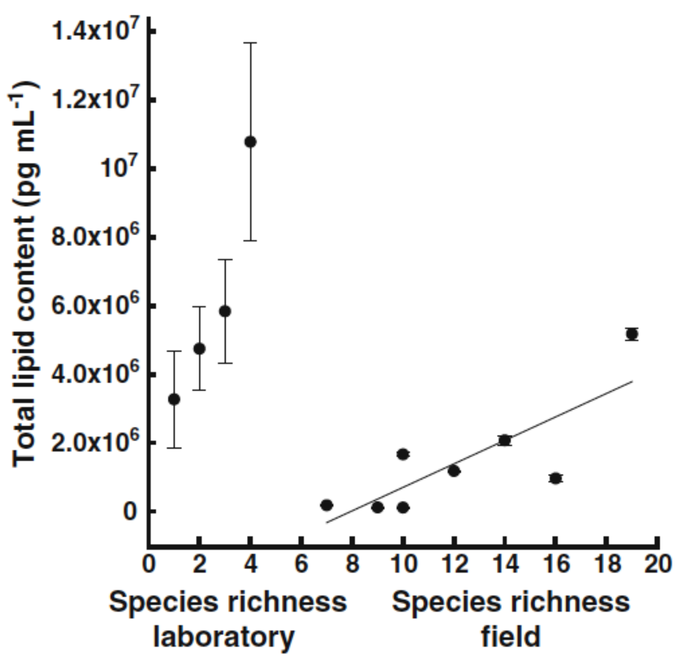

Table 1: Advantages and challenges of growing algae in open and closed systems. "Photoautotrophic cultivation" means growth in which algae use light as an energy source and carbon dioxide as a carbon source. "Monoculture" means that a single kind of algae is growing. Open ponds are difficult for maintaining monocultures because all kinds of organisms can get into the ponds, such as bacteria, other algae, and predators that can harm the algae that you want to grow.

Source: Algal Biofuels Technology Roadmap. 2010. U.S. Department of Energy.

		ADVANTAGES	CHALLENGES
Photoautotrophic Cultivation	Closed Photobioreactors	• Less loss of water than open ponds • Superior long-term culture maintenance • Higher surface to volume ratio can support higher volumetric cell densities	• Scalability problems • Require temperature maintenance as they do not have evaporative cooling • May require periodic cleaning due to biofilm formation • Need maximum light exposure
	Open Ponds	• Evaporative cooling maintains temperature • Lower capital costs	• Subject to daily and seasonal changes in temperature and humidity • Inherently difficult to maintain monocultures • Need maximum light exposure

Table 2: Net Energy Ratio (NER) of algae biomass and oil production in closed systems (photobioreactors) and open systems (raceway ponds). NER is the amount of energy in the algal biofuel divided by the amount of energy used to produce the algae biomass or fuel. Therefore, a NER greater than 1 is desirable (to make more fuel than you use), and a higher number is more desirable. The NER for both open and closed systems was calculated and is given in the bottom two rows.

Source: Jorquera et al. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology* 101, 2010.

Parameter analyzed by the GaBi program	Flat-plate photobioreactors	Raceway ponds
Total energy consumption (GJ/year)	729	450
Total energy content in 100,000 kg biomass (GJ/year)	3155	3155
Total energy content of oil produced (MJ/year)	1155	1155
NER for oil production	**1.58**	**2.56**
NER for total biomass	**4.33**	**7.01**

Table 3: Lipid content of marine algae species (algae that grow in seawater). "% TS" means percent of total solids (total solids is the weight of the algae after they have been dried). This table includes values measured by many different researchers, who are listed in the "Source" column.

Source: Sills, et al. Quantitative Uncertainty Analysis of Life Cycle Assessment for Algal Biofuel Production. *Environmental Science and Technology* 37. 2013.

Species	Lipid (% TS)	Source
Biddulphia	15	Shifrin & Chisholm (1981)[31]
Chaetoceros	28	Benemann et al. (1986)[32]
Chlorella	9	Ben-Amotz et al. (1985)[33]
Chlorella	57	Illman et al (2000)[34]
Nitzschia	37	Smith et al (1997)[35]
Nitzschia	66	Tadros (1985)[36]
Phaeodactylum	23	Thomas et al. (1984)[37]
Skeletonema	25	Shifrin & Chisholm (1981)[31]
Thalassiosira	26	Shifrin & Chisholm (1981)[31]
Dunaliella	9	Ben-Amotz et al. (1985)[33]
Dunaliellia	18	Shifrin & Chisholm (1981)[31]
Nannochloropsis	57	Shifrin & Chisholm (1981)[31]
Nannochloropsis	60	Tornabene (1983)[38]
Nannochloropsis	17	Ben-Amotz et al. (1985)[33]
Nannochloropsis	36	Ben-Amotz et al. (1985)[33]
Nannochloropsis	60	Rodolfi et al. (2008)[39]
Nannochloropsis	53	Benemann & Oswald (1996)[40]
Tetraselmis	15	Laws & Berning (1991)[41]
Hymenomonmas carterae	14	Shifrin & Chisholm (1981)[31]
Isochrysis	26	BenAmotz et al. (1985)[33]
Monallantus salina	57	Shifrin & Chisholm (1981)[31]
Navicula	58	Benemann & Oswald (1996)[40]
Amphora	14	Benemann et al. (1986)[32]
Ankistrodesmus	40	Ben-Amotz et al. (1985)[33]
Boekilovia	36	Benemann et al. (1986)[32]
Cyclotella	42	Tadros (1985)[36]
Monoraphidium	25	Benemann et al. (1986)[32]

Table 4: Ideal characteristics of algae grown for biofuels. "Irradiance" means the rate at which light energy reaches a given area (higher irradiances mean the algae are exposed to more light).

Source: Borowitzka and Moheimani, Algae for Biofuels and Energy. 2013, Springer Science.

Property	Reason	Comments	Selected references
Rapid Growth	Required for high productivity (also reduces risk of contamination by other algae and/or predators and pathogens)	Smaller cells generally grow faster. Single, planktonic cells also generally grow faster than cell 'clumps', colonial or filamentous forms, or cells growing on surfaces	Tang (1995), Kagami and Urabe (2001)
High lipid content (for biodiesel production)	Required for high lipid productivity	For maximum lipid productivity the lipid content should be high in actively growing cells rather than in stationary phase	Griffiths and Harrison (2009)
Temperature optimum	A high temperature optimum and tolerance (at least 30–35°C) is very important.	Temperature in open raceway ponds can reach 30–35°C in summer, and closed photobioreactors can reach even higher temperatures unless cooled.	Belay (1997)
	A broad temperature optimum is desirable.	A broad temperature optimum means a higher productivity over the whole year.	
Maximum temperature tolerated	Avoid possible culture 'crash'	In the case of a breakdown of the culture system temperatures may rise and the ability to withstand high temperatures means that the culture will not die.	
High photosynthetic efficiency	Increases productivity		Richmond (1999)
Ability to tolerate high irradiances	Reduces photoinhibition and photodamage at high irradiances and can increase productivity	The irradiances reached in ponds or photobioreactors at noon can cause photoinhibition and damage to the photosynthetic apparatus	Vonshak et al. (1988), Vonshak and Guy (1992), Raven (2011)
Salinity	For sustainability saline water will have to be used to make up for evaporative losses, especially in open ponds. This will result in increasing salinity in the culture over time	Algae with an ability to grow over a wide salinity range are desirable	Borowitzka and Moheimani (2010)

Table 5: Range of nutrient concentrations in freshwater, seawater, and local wastewater sources. Nitrogen and phosphorus are two of the major nutrients that algae need to grow. Algae can only use nitrogen and phosphorus when they are in certain forms, but the values below give an estimate of the available nutrient concentrations in each water source.

	Wastewater	Freshwater	Seawater
Total Nitrogen (mg/L)	24.4	2.6 – 6.4	0.07 – 0.3
Total Phosphorus (mg/L)	2	0.01 – 0.3	0.001 – 0.3

Source:
Unnithan, Veena V, et al. Mini-review: A priori considerations for bacteria–algae interactions in algal biofuel systems receiving municipal wastewaters. *Algal Research* 4, 2014.