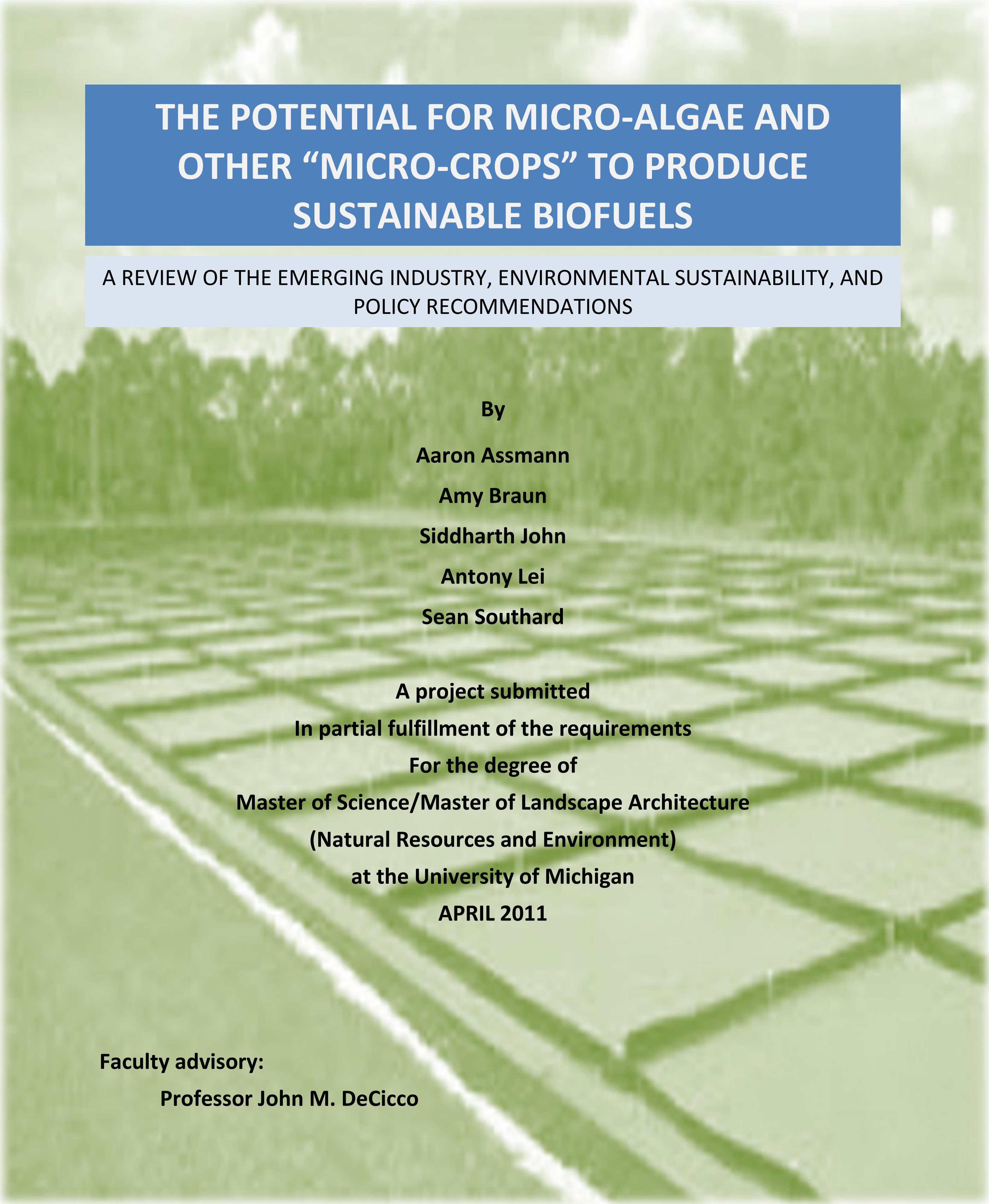

THE POTENTIAL FOR MICRO-ALGAE AND OTHER “MICRO-CROPS” TO PRODUCE SUSTAINABLE BIOFUELS

A REVIEW OF THE EMERGING INDUSTRY, ENVIRONMENTAL SUSTAINABILITY, AND POLICY RECOMMENDATIONS

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EXECUTIVE SUMMARY

INTRODUCTION

Biofuel derived from algae and other micro-crops has been proposed as an environmentally benign transportation fuel. Algae can be cultivated on low productivity lands using low quality water. Interest in algae technology is driven by a national desire for a domestic fuel source that will reduce dependence on fossil fuels. Another motivation is their potential as a high productivity feedstock that does not compete for arable land and so may be less greenhouse gas (GHG)-intensive than biofuels based on plants. This has led to government research grants and private investments of millions of dollars. The following report explores two model systems of algae-based biofuel production, exploring potential economic costs and environmental impacts. Policies derived from these findings will be recommended to ensure that adverse environmental impacts are mitigated and the industry can achieve sustainable growth.

METHODOLOGY

To perform a quantitative and qualitative evaluation of the possible environmental impacts of commercial algae biofuel production, two possible algae cultivation systems were identified and a prospective model of biodiesel production for each cultivation system was created. The two cultivation technologies were (A) an autotrophic system with open pond raceways and seed cultivating photobioreactors, and (B) a heterotrophic system with closed bioreactors. These models estimate industry production levels of one billion gallons of algae biodiesel annually. For System A, total production was split between 84 U.S. Southwest facilities, each producing about 12 million gallons annually. For System B, total production was split between 84 U.S. urban or suburban facilities, each producing about 12 million gallons annually. The existing dairy industry and corn ethanol industry were used as analogs for the autotrophic and

heterotrophic systems, respectively, given their similarities in waste and potential regulatory compliance requirements.

Algae biodiesel technology is closest to commercial maturity and was therefore selected for this study. The production of biodiesel consists of 4 stages: cultivation, harvest, extraction, and conversion. The two studied systems used different technologies for the cultivation stage, but both used gravitational separation and wet hexane extraction as the harvest and extraction methods, respectively. The extracted algal oil is purified and converted to biodiesel by alkaline transesterification with methanol.

To calculate the required amount of algae to produce one billion gallons of algae biodiesel annually, Microsoft Excel and STELLA programs were used. Empirical data from published field tests, as well as localized environmental conditions, were used to estimate cultivation outcomes under these scenarios. For further research, interviews were conducted with government officials, non-profit businesses, and academic researchers. Government policies and programs were reviewed to identify the key drivers of growth and potential regulatory outcomes of commercial algae biofuel production.

The costs of pond-lining and wastewater treatment were also estimated. Five pond-lining options were evaluated by both flexibility and cost-effectiveness. For wastewater treatment, the costs were estimated using an inflation-adjusted cost curve based on an EPA analysis of municipal wastewater treatment plants. Estimated construction costs were adjusted using time and location factors to account for inflation and location-specific conditions, respectively.

KEY FINDINGS

Table ES1 compares the potential environmental concerns identified in the prospective analysis for the two examined systems. Our analysis considers the water quality and quantity, nutrient inputs, land use change, and wastes. Table ES2 compares the identified policy concerns for the two hypothetical systems.

Table ES1. Comparison of the Environmental Concerns under Scenario A and B of Algae Biodiesel Production

Environmental Concern	A. Autotrophic System	B. Heterotrophic System
Water Resource Impact	Open raceway cultivation may be water-intensive, requiring freshwater inputs due to evaporation, with possible impacts to ecosystems across the landscape	Impact may be less than System A due to culture efficiency. However, will have higher indirect water requirements to cultivate organic carbon sources
Land Resource Impact	Smaller than any other first- or second-generation biofuel, but will need large area conversion, with impacts likely to be concentrated geographically	Impact will likely be less than System A due to culture efficiency, however will have higher indirect land use requirements to cultivate organic carbon sources
Waste and Effluents	Large volumes of concentrated blow-down waste material may accumulate in downstream processes	Downstream waste material may have implications for municipal wastewater treatment facilities
Genetically Modified	Open autotrophic systems expose modified algae directly to natural environments and may make containment impossible	Closed heterotrophic systems reduce risk of release, but may not ensure containment of modified algae due to algae mobility and human error

Table ES2. Comparison of the Policy Concerns under Scenario A and B of Algae Biodiesel Production

Policy Concern	A. Autotrophic System	B. Heterotrophic System*
Concerns with Endangered Species Act	Large, possibility of habitat loss due to land conversion that may subsequently increase pressure on wildlife populations, such potential candidates of the ESA like the Dunes Sagebrush Lizard or Lesser Prairie-Chicken	Small, the contained nature of photobioreactors makes protected species “take” less likely
Concerns with the Toxic Substances Control Act	Probable, if genetically modified algae are used	Probable, if genetically modified algae are used
Concerns With NEPA	Yes, if federally funded or on federal land	Yes, if federally funded or on federal land
Direct Land Competitor	Other renewable energy projects, agriculture, and industry	Industrial, residential (if switchgrass is an input, then marginal land as well)
Tribal/Land Siting Concerns	Very large	Small
Clean Air Act Permits	Yes	Yes
Wastewater Discharge Permits	No	Yes
On-site Wastewater Construction and Operating Permits	Yes	No
Pretreatment Permits	No	Yes

* Direct Impacts

CONCLUSIONS & RECOMMENDATIONS

As seen in the key findings of this report, System A and System B each have their own associated costs and benefits. Both systems have improved efficiencies, including land use and nutrient inputs, over corn ethanol. However, adverse environmental impacts must be mitigated to ensure the sustainability of production. After reviewing the technical findings and the quantified environmental impacts of each system, four general policy recommendations were crafted to minimize the potential detrimental impacts of a commercialized algae biofuel industry.

Recommendations:

- By location, perform an extensive environmental risk assessment prior to production to better understand possible environmental consequences, including that of genetically modified algae cultivation, before the species and location of algae cultivation are selected. To do this, create a joint-learning process and foster a collaborative approach by engaging all stakeholders. Continued monitoring and mitigation should also occur.

- Water use must be regulated and controlled. Algae cultivation is water intensive. By incentivizing water recycling and use of lower-quality water for the algae medium, the consumption of the water may be reduced. Further, blow-down must be regulated to ensure that hard metals and nutrients do not contaminate water and soils.

- Incentivizing co-location of production, harvesting and extraction to reduce the carbon footprint of algae biofuels. By investing in technologies that can take advantage of wastewater treatment plants, power plants and centralized extraction facilities, there will be reduced transportation costs, emissions, and land use loss.

- Ensure that economic incentives provided for the algae industry, such as those proposed in Algae-based Renewable Fuel Promotion Act (HR 4168), start-up tax credits, and small-farmer tax credits, include adequate provisions for environmental assessment and the demonstration of sustainable practices.

A technical assessment of an industry – including the technology, economics, and environmental impacts – is a tool to inform decision-makers on how to craft policies to ensure that the societal advantages outweigh the negative impacts. Policymakers can use this paper and the recommendations when assessing the current state of algae biofuel production, and when crafting new policies that affect this production.

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The National Wildlife Federation

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LIST OF ACRONYMS

BCAP	Biomass Crop Assistance Program
BLM	United States Bureau of Land Management
CAFO	Concentrated Animal Feeding Operation
CCI	Construction Cost Index
CWA	Clean Water Act
CO_2	Carbon dioxide
DOE	United States Department of Energy
EIA	United States Energy Information Administration
EISA	Energy Independence and Security Act
EPA	United States Environmental Protection Agency
EPAct	Energy Policy Act
EPDM	Ethylene Proplyene Diene Monomer
ESA	Endangered Species Act
FAME	Fatty acid methyl ester
GHG	Greenhouse gas
GM	Genetically Modified
GMO	Genetically Modified Organism
HDPE	High Density Polyethlene
MCAN	Microbial Commercial Activity Notice
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
NRDC	Natural Resources Defense Council
O_2	Oxygen
PBR	Photobioreactor
PVC	Polyvinylchloride
RFS	Renewable Fuel Standard
TAG	Triglyceride
TDS	Total Dissolved Solid
TSCA	Toxic Substances Control Act
USDA	United States Department of Agriculture
WaTER	Water Treatment Estimation Routine

INTRODUCTION

A confluence of concerns has led the United States Government to create a number of policies to encourage the growth of the biofuel and renewable energy industry. Many political leaders claim that by securing a domestic fuel source, the U.S. will be able to have increased energy and national security. Further, as fossil fuel prices continue to climb internationally, with higher extraction costs and political unrest in exporting countries, renewable fuels become more economically competitive and a geo-political advantage. Lastly, public pressure to find environmentally friendly alternatives to fossil fuels has grown, as more citizens are concerned with environmental sustainability and climate change.

Given this political atmosphere, biofuels have become a focus of scientific research, industry investment, and the government. Within the last twenty years, the technologies of plant-based fuels have progressed to some degree, but at commercial scale remain largely reliant on the efficient technology of fermentation. Recent U.S. policies have fostered increasing use of corn ethanol. However, such crop-based fuels have serious environmental impacts and, outside of the renewable fuels industry itself and its government backers, are not generally viewed as sustainable. For that reason, the development of more efficient second- and third-generation biofuels continues to push forward. Micro-algae and other “micro-crops” (i.e. diatoms, cyanobacters, and micro-angiosperms) can be genetically engineered to optimize their production of lipids that can be converted into one such third-generation biofuel, which has the potential to be used as a drop-in transportation fuel, similar to jet fuel, diesel and gasoline.

Early in 2010, the U.S. Department of Energy (DOE) finalized the “National Algae Biofuels Roadmap”, which was the first detailed exploration of the technical feasibility of the industry –

including the various species, cultivation methods and extraction and conversion techniques. The private sector has also seen potential in algae as a source of biofuel. Exxon Mobil Corporation has promised to invest $600 Million in algae biofuel over the next 5-6 years, and will invest even more if research goals are met. Similarly, BP has invested millions of dollars in a multi-year partnership to explore algae-based biodiesel.

Many lessons can be learned about the role of policy in the renewable fuel field from the advancement of the corn ethanol industry. By creating strong policy incentives, the corn ethanol industry was able to grow significantly in a relatively short time period. Before this growth, however, no wide-scale environmental assessment was performed to predict unintended consequences, resulting in the current debate over the viability of corn ethanol – including food versus fuel, life cycle emissions and its economic impacts.

Learning from these mistakes, the National Resources Defense Council (NRDC) produced "Cultivating Clean Energy: The Potential for Algae Biofuels". The NRDC report was the first step in predicting the environmental consequences of algae biofuels. It enumerates most environmental concerns; however, there is little quantitative analysis of the extent of the impacts based on the technical and economic feasibility of specific models. That report called for additional assessments including prospective lifecycle analysis, in order to anticipate sustainability risks.

The impetus for much of the recent interest in algae biofuels was with the 2007 Energy Independence and Security Act (EISA) revision, which mandated a major expansion of the U.S. Renewable Fuel Standard (RFS), targeting production of 36 billion gallons of renewable fuels by 2022. Part of the RFS includes a requirement for biomass-based diesel fuels, ramping up to one billion gallons by 2012. Currently, most algae fuel development is oriented toward supplying biodiesel type fuels for meeting this part of the mandate. This and similar policies make biofuel development and their associated impacts a ripe issue that must be addressed in a timely manner.

With the extensive research into algae as a biofuel and limited quantification of the environmental impacts, it is the place of this assessment to expand on the existing research by performing a quantitative analysis of all potential environmental impacts. By imagining what a commercial-scale algae biofuel industry would be, if it achieved a capacity for producing one billion gallons of biodiesel nationwide, the economic feasibility and the potential environmental impacts could be quantified and assessed in detail. In this way, this study explores the potential technological realities, economic costs and environmental impacts of a fully commercialized industry. All policies that are relevant to the algae biofuel industry at a commercial scale will be reviewed and there will be assessment of how they fit into a commercial industry.

Data are compiled from existing research from industry and the government. After careful consideration of all the potential environmental problems, the existing relevant policies in place, and economic and technological considerations of a commercial-scale algae industry, policy recommendations are synthesized for the guidance of policymakers. The hope is that with the right policies in place, the nation can ensure that when the algae biofuel industry expands, adverse environmental impacts are avoided so that the promise of a truly sustainable biofuel is realized.

TECHNOLOGY

The processes involved in algae biofuel production and the technologies available for each process are detailed in Appendix Tables 1, 2 and 3. There are associated decision points with each of these processes and potential options available with them. With the first process in algae biofuel production, strain development, the available options that improve strain are bio-prospecting, breeding, and genetic engineering. Selecting the strain would depend on factors such as cost, biomass composition, and environmental conditions.

The second process is cultivation, and the many decision points include: the metabolic pathway chosen, which could be photoautotrophic and heterotrophic (chemo-organic); the cultivation mode, which is whether a monoculture or polyculture is used; and the production mode, which is whether production occurs continuously or in batches. A photoautotrophic algae uses light as an energy source and CO_2 as a carbon source, while a heterotrophic (chemo-organic) algae uses organic carbon, such as simple sugars, for energy and as a carbon source, and cannot use CO_2 or light. Monoculture is the cultivation of a single species or strain of algae, while polyculture is the cultivation of more than one species or strain of algae.

Harvesting which includes the option of biomass recovery, de-watering, and drying, follows cultivation. The extraction process includes the options of using a chemical solvent, using sonification, or simply using mechanical crushing. The final process of conversion into usable fuel components includes the options of producing ethanol by fermentation of polysaccharides, biodiesel by transesterification of triacylglycerols/triglycerides (TAGs).

Selecting the desired technology for each process is the first and foremost step in designing an algae biofuel production system. It depends on the type of fuel produced, cost of production, and many other constraints. Given the number of technologies available for each process, it is clear that a large number of pathways are possible, but for now, only a few are technologically mature enough to be commercially viable. For the purpose of this report, two hypothetical systems with specific design parameters were modeled and their inputs and outputs were quantified.

THE SELECTED SYSTEMS

BIOFUEL

Among the biofuels that can be produced from microalgae, biodiesel is nearest to commercial production. Biodiesel has been widely studied for many years, as it is derived from other feedstocks, such as soybean oil, palm oil, and rapeseed (canola) oil (Argonne National Laboratory, 2008). Biodiesel can be used in the current petroleum infrastructure without expensive modification (National Renewable Energy Laboratory (NREL), 1998). As of 2009, about 500 million gallons of biodiesel were consumed in the U.S. annually (U.S. DOE, 2009).

The EPA classifies biodiesel as a "biomass-based diesel", and must satisfy the following conditions to qualify for the production quotas established by the RFS, which is one billion gallons of biomass-based diesel by 2012 (U.S. Environmental Protection Agency, 2010):

1. Composed of mono alkyl esters of fatty acids and conforms to ASTM 6751 fuel standards, and produced from renewable biomass (ASTM International, 2011).
2. Has life-cycle GHG emissions that must be at least 50% less than the diesel fuel it displaces.
3. Excludes renewable fuel derived from co-processing biomass with a petroleum feedstock.

A biomass-based diesel that satisfies the above conditions is biodiesel, irrespective of which biomass feedstock is used. When methyl groups are the alkyl groups in biodiesel, the biodiesel is known as fatty acid methyl ester (FAME) biodiesel. Biodiesel with other alkyl groups (ethyl) as components are known as "other biodiesel". Another biomass-based diesel is renewable diesel, sometimes known as green diesel, which is composed of non-ester molecules and complies with ASTM D 975 fuel specification (ASTM International, 2011). This is not biodiesel, but instead a biomass-based diesel. A detailed explanation of the different renewable fuels, their definitions, and their volume requirements is found in the *The EPA's Final Rule on EISA* section of the appendix.

Currently, biodiesel is primarily used as a transportation fuel in locomotives, trucks, and automobiles as either a blend with, or as a substitute for, No. 2 petroleum diesel (highway diesel). However, biodiesel has one major limitation. Biodiesel is not fully fungible with other petroleum diesels and biomass-based diesels, meaning that one gallon of biodiesel does not have the same physical properties (temperature stability, energy content, etc.) as petroleum diesel and other biomass-based diesels (National Renewable Energy Laboratory (NREL), 1998). Therefore, biodiesel can only be used interchangeably to a limited extent in the form of blends and in a few engines that are specifically designed to handle pure biodiesel (B100).

The reason for the difference in the physical characteristics is due to the difference in the type of molecules that constitute biodiesel, as compared to that of petroleum diesel. Biodiesel is composed of straight chain hydrocarbon esters, which have one oxygen atom per molecule, while petroleum diesel is composed of non-oxygenated straight and cyclic hydrocarbon chains. Because it is based on compounds that include oxygen, namely esters, it does not meet all of the stability, distribution, and engine requirements of standard diesel fuels. The use of pure biodiesel in existing infrastructure could cause problems during transportation through pipelines and use in engines, but can be managed without substantial monetary costs (McElroy, 2007). For this reason, algae biofuel research (like that for most advanced biofuels) is seeking ways to make fuel components that are fully fungible.

Biomass from algae can be processed into fuels, such as green diesel and other advanced biofuels that have physical characteristics that comply with existing fuel standards such as that of No. 2 diesel and gasoline (U.S. DOE, 2010). Such a fuel is referred to as a “drop-in fuel”, meaning that they can be used in existing engines without any modification, or in other words, is perfectly fungible.

There are a number of studies in the primary literature about algal biodiesel, which makes the hypothetical system design and validation of results easier (Chisti, 2007; Collet et al., 2011; Demirbas, 2009; Jorquera et al., 2009; Lundquist et al., 2010; Lardon et al., 2009).

PRODUCTION CAPACITY

For this report, the national annual production is assumed to be one billion gallons of algal biodiesel, based on the 2012 RFS target for biomass-based diesel (U.S. Environmental Protection Agency, 2010). This equates to approximately 1.8% of the total 55 billion gallons of diesel fuel consumed in the U.S. in 2009 (U.S. DOE, EIA, 2011), and about 200% of 506 million gallons of biodiesel consumed in the U.S. in 2009 (U.S. DOE, EIA., 2009). One billion gallons of algal biodiesel is 6.5% of the 15.2 billion gallons total of the renewable fuel requirement for 2012, and 50% of the two billion gallons total of the advanced biofuel requirement for 2012 and 100% of the one billion gallons total of biomass-based diesel in 2012 (U.S. Environmental Protection Agency, 2010). The one billion gallons of algal biodiesel is less than 2.7% of the 36 billion gallons of total renewable fuel and 4.6% of 21 billion gallons total of the advanced biofuel requirement for 2022 (U.S. Environmental Protection Agency, 2010). The mandate for biomass-based diesel in the RFS for 2013 has yet to be determined; however, one billion gallons of biodiesel is 117% of the 850 million gallons of the projected total FAME biodiesel production in 2022 (U.S. Environmental Protection Agency, 2010).

Only 25% of the installed capacity of biodiesel production is being used to manufacture biodiesel, leaving a capacity of 1.5 billion gallons to be used for algal biofuel production (U.S. DOE, EIA., 2009). Given the existing conversion capacity of biodiesel, the primary constraint to algae biofuel production is the cultivation and harvest of algae itself.

A reasonable estimation of the biodiesel produced from algae is difficult to produce, and there are many short-term and long-term estimates that vary significantly. The 2010 report by Greentech Media Research projected annual U.S. production of six billion gallons of algal biodiesel by 2022 (Kagan, 2010). The 2011 report by Emerging Markets Online projects U.S. production of 100 million gallons of algal biodiesel in 2014 (Emerging Markets Online, 2011). The biodiesel and renewable diesel production targets reported to the EPA by Sapphire Energy is 135 million gallons by 2018 and one billion gallons by 2025. Solazyme plans to produce 100 million gallons by 2012 to 2013 (U.S. Environmental Protection Agency, 2010).

For the purpose of our analysis, we assume a hypothetical algae biodiesel production facility having a capacity of 12 million gallons/yr. This plant scale is based on the median capacity of existing U.S. biodiesel facilities (National Biodiesel Board (NBB), 2011). This plant capacity of 12 million gallons/yr, which is 45,425 m^3/yr, or 33,973,951 kg/yr, assuming density of 884 kg/m^3 (Amin, 2009), or 1,530,971,879 MJ/yr on a higher heating value basis of 39 MJ/kg (Lardon et al., 2009), is what we use as the functional unit when estimating local environmental impacts.

To achieve a production level of one billion gallons would require 84 facilities at the scale of the 12 million gallon per year functional unit we analyze. Therefore, in order to project the level of impacts for an extensive algal biofuel industry, we scale-up our facility level estimates by a factor of 84, resulting in the values we report below as potential national-scale impacts.

ORGANISMS

Chlorella vulgaris and *Chlorella protothecoides* (shown in Figure 1) are two species that have been selected by researchers for lipid production because of their high productivity. Productivity depends on lipid content and growth rate, and both these organisms have a medium lipid content and high growth rates (Singh & Gu, 2010). Both have been studied for lipid production and many strains have been developed that grow in various environmental conditions, where growth parameters are obtained empirically and available in literature. They are unicellular, have a simple structure and are relatively easy to cultivate, study, and modify. The strains considered in this study are genetically modified organisms (GMOs), also known as GM algae.

Chlorella spp. is distributed throughout the freshwater of the world, and can be large component of phytoplankton populations in nutrient-poor waters. *Chlorella spp.* have evolved different nutrient uptake mechanisms, which allows them to grow rapidly and out-compete larger species of phytoplankton in lakes of low to moderate nutrient status. In certain situations, *Chlorella* will form symbiotic relationships with other organisms, called *Zoochlorella* (e.g. the freshwater polyp, *Hydra viridis*) (Bold & Wynne, 1984).

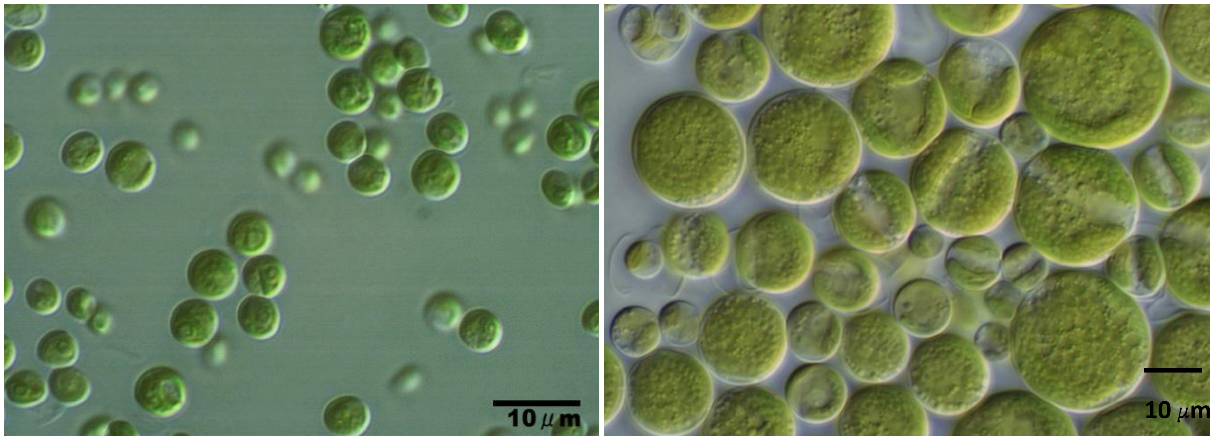


Figure 1. The two species of algae used in this study. *Chlorella Vulgaris* is used in System A and is autotrophic, while *Chlorella protothecoides* is heterotrophic and used in System B.

CULTIVATION

Many of the major companies plan to use an autotrophic algae cultivation system (e.g. PetroAlgae Inc, Sapphire Energy Inc) or a heterotrophic algae cultivation system (Solazyme, Inc), and most academic and industrial research is being conducted on these cultivation systems (PetroAlgae, 2011; Sapphire Energy, Inc., 2011; Solazyme, 2011). More companies and their products are listed in the Appendix. Enough information is available, on which to base an environmental assessment.

Two technologies exist that can be used for autotrophic algae cultivation: photobioreactors (PBRs) and open pond raceways. PBRs are closed-system organism culture vessels where algae can be cultivated in a controlled environment. Currently, conventional PBRs are too expensive to be used to produce large fuel volumes (Ludquist et al., 2010; Mata et al., 2010). Under most models, open ponds have too low of a productivity to provide adequate yield on their own in an economically favorable amount of time (Demirbas, 2009; Jorquera et al., 2009). Although cheaper to operate, open ponds cover larger amounts of land to ensure that the algae get adequate sunlight. Open pond raceways are open systems where the culture interacts with the water and CO_2 of the atmosphere, reducing the necessary inputs, while creating potential for contamination, such as that seen in Figure 2. This system has a net absorption of CO_2, thereby reducing the atmospheric concentration of the GHG at least temporarily, until the fuel is burned. A hybrid system consisting of PBRs to produce the seed for the open pond raceways leverages the advantages of both autotrophic cultivation systems, and is employed by two major algae biofuel companies, Sapphire and PetroAlgae (PetroAlgae, 2011; Sapphire Energy, Inc., 2011).

Figure 2. Aerial photograph of a pilot facility operated by HR BioPetroleum-Cellana, Hawaii. Autotrophic microalgae cultivated in open pond raceways using seawater. (Cellana, 2011)

Despite the high cost of operation for fermenting bioioreactors (Figure 3), they have the benefit of high yields (about 100 times that of autotrophic systems), and do not require light (Brennan & Owende, 2010). They have the potential to provide an alternate pathway to convert organic wastes and lignocelluloses to lipids. The closed system has higher productivity than PBRs, due to higher efficiency of heterotrophy, while allowing controllable growing conditions for the production of high-quality products. Therefore, in a heterotrophic system, fuel is a secondary product, while high-value pharmaceuticals and cosmetics are the primary products. Solazyme uses this technology and claims to start producing algal biofuels within the next two years; therefore, it is worthwhile to study such a system (Solazyme, 2011).

Figure 3. Photograph of three fermenters (bioreactors) that are likely to be used in System B for the cultivation of heterotrophic algae *Chlorella protothecoides*. (topmachinebiz.com, 2011)

SYSTEM DESCRIPTION

This study estimates the environmental impacts of producing one billion gallons of algal biodiesel using two hypothetical systems shown in Figure 4. The algal biodiesel production has four stages: cultivation, harvesting, extraction, and conversion. This report uses two differing cultivation systems, with identical harvesting, extraction, and conversion for both. Table 1 shows the specifications of the two systems and the growth characteristics of the organisms, which are based on the assumption that one billion gallons of algal biodiesel are produced by 84 facilities, with each facility producing 12 million gallons of algal biodiesel annually.

Cultivation systems are similar to that of other biofuel feedstock cultivation, including soybean and corn cultivation, in terms of fertilizer and water input, suitable location with adequate sunlight, and temperature variation. These analogs are further discussed in the *Dairy and Ethanol Production Facility Permitting* section. Similarities in the infrastructure and harvesting of microalgae with the equipment used in the water treatment industry, such as clarifiers, aerators, and process piping involved in moving water is discussed in the *Economics of Mitigation Strategies* section.

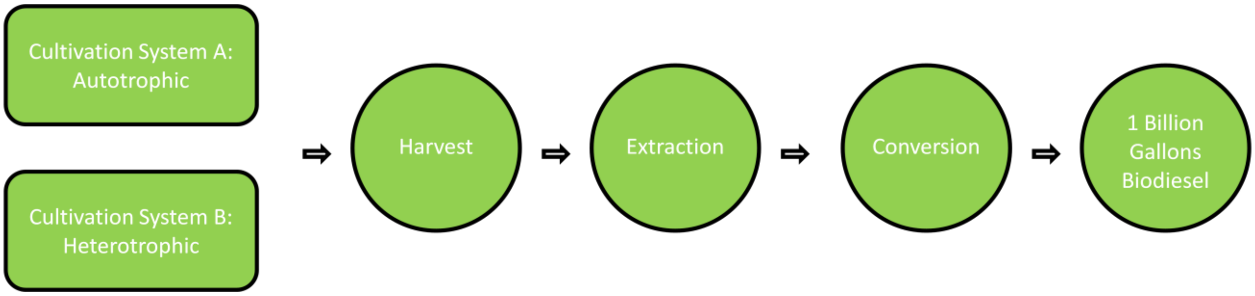


Figure 4. Algal Diesel Production Process Overview

The biomass density and volume productivity were estimated from Lee (2011), Brennan et al. (2010), Jorquera et al. (2009), and Amin (2009). The lipid contents were estimated from Brennan et al. (2010), Mata et al. (2010), Jorquera et al. (2009), Singh et al. (2010), and Hu et al. (2008), while the TAG content was estimated from Chinnasamy et al. (2010) and Hu et al. (2008). Figures 5 and 6 are based on the layout made by Lundquist et al. (2010) and Sheehan (1998), and adapted for a scale of 12 million gallons per year.

The design parameters for the autotrophic cultivation systems are those used by Collet et al. (2010), which are comparable to those used by Lardon et al. (2009), Sheehan et al. (1998) and Clarens et al (2010) but substantially smaller than those used by Lundquist (2010). The design parameters for the heterotrophic fermenters were estimated from those used in the brewing and winemaking industry because their processes are similar to that of heterotrophic algae cultivation. This was done by comparing commercially available fomenters from the Top Machine website, which is a website used for the sale of industrial equipment from various companies (topmachinebiz.com, 2011).

The nutrient sources were assumed as urea, superphosphate and potash fertilizer all of which are commercially available chemical fertilizers and have been used by Clarens et al. (2010) and Collet et al. (2010) in their studies.

Table 1. System Specifications

	System A: Autotrophic Cultivation		**System B[A]: Heterotrophic Cultivation in bioreactors**
	Photobioreactor (Seed Production)	**Open Raceway Pond (Lipid Production)**	
Organism	*Chlorella vulgaris*	*Chlorella Vulgaris*	*Chlorella Protothecoides*
Biomass Density [C,G,D,S] (kg/m^3)	2.5	0.5	3 – 15
Lipid Content [G, T, D, F, U]	14%	35%	45% – 58%
Volume Productivity [C,G,D,S] (kg biomass/m^3.day)	0.60	0.07	14.71
TAG Content [Q,U,E]	20%	85%	80%
Area [J,B,L,M](m^2)	22	1344	6.7
Volume [J,B,L,M](m^3)	1.6	324	20
Length [J,B,L,M] (m)	193	100	3
Breadth/Diameter [J,B,L,M] (m)	0.11	10	3
Depth [J,B,L,M] (m)	N/A	0.3	N/A
Hydraulic residence time (days)	5	5	1
Water Source	Brackish (Aquifer)	Brackish (Aquifer)	Fresh
Water Recycling	No	Yes	No
Location	Southwest	Southwest	Urban/Suburban
Energy Source	Sunlight	Sunlight	Acetate
Carbon Source	Atmospheric CO_2	Atmospheric CO_2	Acetate
Nitrogen source		Urea	
Phosphorus source		Super Phosphate	
Potassium		Potash Fertilizer	
Harvest Efficiency [N]	N/A.	87	90
Lipid Extraction Efficiency [O]	N/A.	70	70
TAG Refining Efficiency [P,Q]	N/A	80	80
Transesterification Efficiency [R]	N/A	97	97
Evaporation (per month)	No	25% -100%	No
Pesticides	No	Yes	No
GMO	Yes		Yes
Waste Management	On-site Storage		Wastewater Treatment Plant

A: O'Grady & Morgan (2011), **B:** Clarens et al. (2010), **C:** Lee (2011), **D:** Jorquera et al. (2009), **E:** Chisti (2007), **F:** Singh & Gu (2010), **G:** Brennan & Owende (2010), **H:** Demirbas (2009), **I:** Lundquist et al. (2010), **J:** Collet et al. (2011), **L:** Lardon et al. (2009), **M:** Sheehan et al. (1998), **N:** Yang (2010), **O:** Lee et al. (2010), **P:** Greenwell et al. (2009), **Q:** Chinnasamy et al. (2010), **R:** Ban et al. (2002), **S:** Amin (2009), T: Mata (2010), U: Hu (2008)

SYSTEM A: AUTOTROPHIC

System A is an autotrophic system where *Chlorella vulgaris* grows on CO_2 and sunlight, through photosynthesis in a hybrid cultivation system consisting of PBRs and open pond raceways. This system is assumed to use brackish water from a groundwater aquifer, so as reduce competition with freshwater for agricultural and human consumption, though brackish water may be used in hydroponic cultivation of certain crops or desalinated for human and agricultural use.

System A has two subsystems, one produces the algal seed, and the other uses the seed to yield lipids. Autotrophic cultivation needs optimum sunlight to have high productivity, so the location chosen is based on the amount of sunlight falling on the land surface. Autotrophic cultivation systems are likely located in the Southwestern United States, rather than the Southeast. Even though they are in the same latitude, the Southeast receives less sunshine on the land surface, due to cloud formation (NREL, 2011).

The detailed design and layout of a facility using an autotrophic cultivation is shown in Figure 5, and the productivity at different levels is listed in Table 2. The seed production is in closed system PBRs, where sunlight is used with abundant nutrients, and optimum growth conditions can be maintained more easily than in open ponds. The optimum conditions of growth are maintained in terms of temperature, pH, CO_2 concentration, and other factors. In optimum conditions, algae reproduce by binary fission and their cell number increases exponentially, while their lipid content does not increase. In the PBR, high cell densities can be obtained through constant mixing. Although using this system of seed production can be energy intensive, only small volumes of culture need to be produced, due to high cell density and growth rate. The energy requirements for this system are detailed below in the *Potential Environmental*

Impacts section. The expectation is that pesticides and selective media would not be used in the PBR because it is a closed system and conditions are well controlled with little opportunity of contamination (Demirbas, 2009).

The mature seed is introduced into the raceways, leaving behind a small volume of seed in the PBR to start the next seed batch. The raceway receives the remaining growth medium (water and nutrients), which may or may not be recycled. When the growth medium is recycled, fresh medium is added when there is a deficit between the volume of the medium that needs to be in the raceway and the volume of recycled media.

The volume of water in the raceway is maintained at a constant by using freshwater to compensate for evaporation loss. 25% to 30% of the water in the open ponds is lost per month for Southern California, near the coast, and 50% to 100% of the water per month in Arizona, New Mexico, and West Texas. These numbers represent the net loss, which is the difference between the water loss due to evaporation and the water gained due to precipitation, each measured in inches. They were calculated from the 15-year average maximum and minimum pan evaporation and precipitation data for the respective regions from the Western Regional Climate Center (Western Regional Climate Center, 2011). The data were converted to a percentage of the volume of the raceway, with the use of a 30 cm depth of the raceway.

50% of the water harvest will be recycled, and the remaining effluent water is stored on-site in ponds with suitable lining to prevent groundwater contamination, and allowed to evaporate. Algae are exposed to the variation in temperature, light levels, etc. and grow on atmospheric CO_2 under nutrient-deficient conditions. To prevent shading and to enable equitable distribution of nutrients, the water is mixed using a paddle wheel, powered by an electric motor. The algae are harvested every five days.

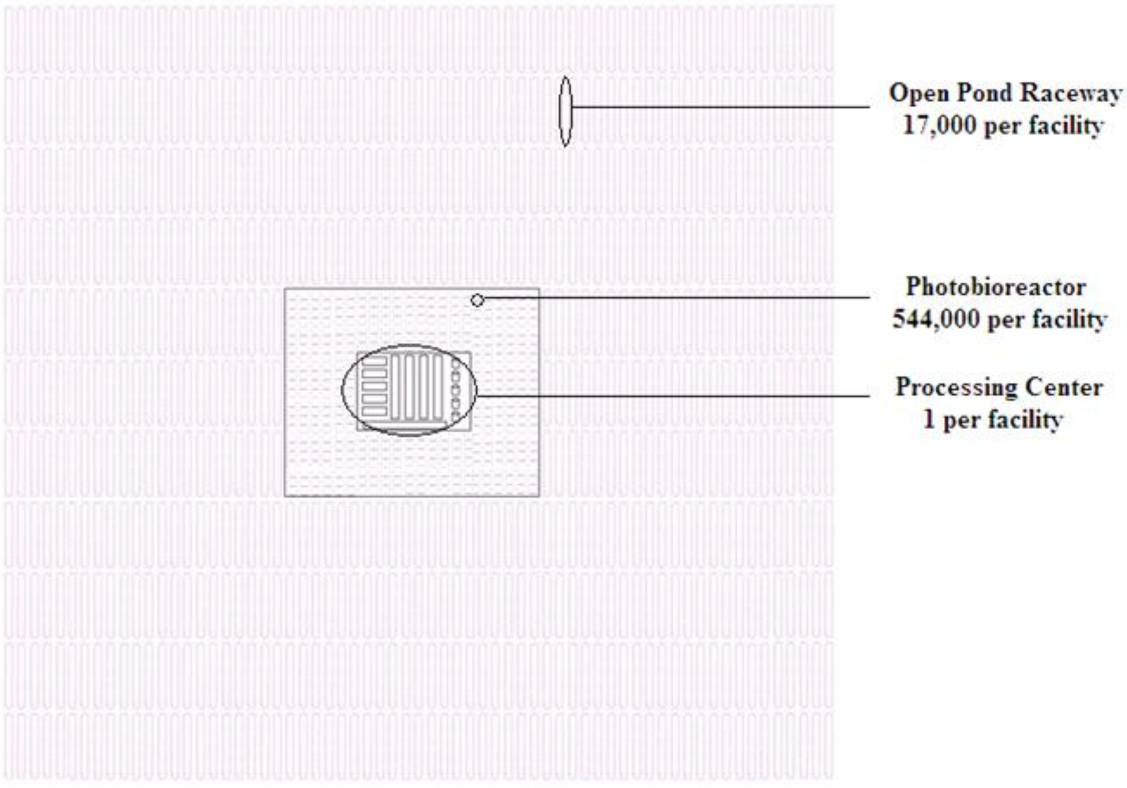
The open ponds use biocides or a selective medium, such as one with high salt content, to control predators and competitors. Very little information was found during the course of this study regarding the use of chemicals to control pests and further research is needed to determine the effect of their use.

Table 2. Biodiesel Productivity (gallons of biodiesel per year) – System A: Autotrophic Algae

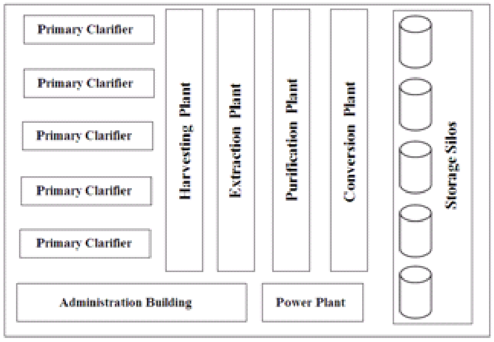
Production Level	Productivity*	Land Area (km^2)#
Pond	≈ 706.3	0.0014
Facility	≈ 12 million	24.5
System	≈ 1 billion	2031

* Assuming each facility consists of 17,000 ponds and the system consists of 84 facilities.

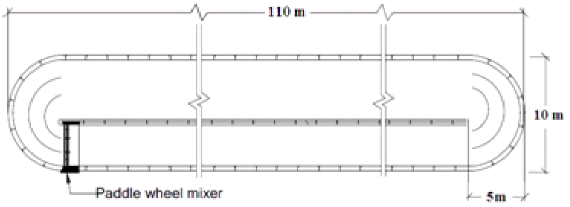
The land area for pond level area is determined by dividing the area of the facility with the number of raceways (16,991), rather than the area of one raceway, which is $0.0013km^2$.



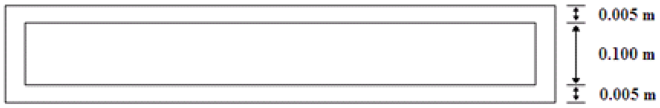
Design and Layout - Facility
- 17,000 Cultivation Ponds
- 544.000 Photobioreactors



Design and Layout - Processing Center



Design and Layout - Cultivation Pond



Design and Layout - Photobioreactor (PBR)

Figure 5. Layout of a hypothetical algal biodiesel facility with autotrophic cultivation system (System A) with an annual capacity of 12 million gallons of algal biodiesel, which has an areal footprint of 24 km^2. This is not drawn to scale.

SYSTEM B: HETEROTROPHIC

System B is a heterotrophic system in which algae use digestible organic carbon (acetate, glucose, glycerol) as a carbon source to produce lipids, instead of CO_2 and sunlight (Lee, 2011). Such carbon sources may be derived from effluents from the agricultural, dairy, and sugar industries. In this study, the carbon source is acetate that is derived from switchgrass. Switchgrass is chosen because it would be valuable to know what the impacts would be if the feedstock were specifically cultivated for feeding algae instead of using organic wastes. Cultivation of lignocellulosic feedstocks, such as miscanthus, switchgrass, convolvulus, etc. has been discussed and presented as an alternative pathway for the production of algal biofuel by Solazyme (Solazyme, 2011).

The growth media is freshwater and nutrients with no evaporation loss, because it is a closed system. The spent water is sent to a water treatment facility before being discharged into surface water, so there is no recycling of water or nutrients. Further discussion of the implications of not recycling water or nutrients and using a water treatment facility is in the *Potential Environmental Impacts*, *Water and Land Permitting Concerns*, and *Wastewater Treatment* sections of this report.

Heterotrophic algae produce CO_2 and hence do not sequester it; up to 70% of the carbon consumed as substrate is lost to respiration, cell maintenance, lysis, etc., resulting in actual yield of about 30%, which is comparable to other heterotrophic microbes (Lee, 2011). The algae are grown in large bioreactors in the absence of O_2, to allow fermentation to occur. While heterotrophic algae can grow in aerobic conditions, this is not considered in this study because data to model such a system is unavailable and a major algae biofuel company, Sapphire Inc., uses a fermentative system. The productivity of heterotrophic algae is higher than autotrophic algae because they rely on a high-energy organic feedstock and the photosynthesis for producing their feedstock (e.g. switchgrass is assumed here) occurs further upstream. Because this cultivation system does not require light, it does not require a large surface area-to-volume ratio, and shading (photolimitation) due to other algae is not a concern allowing high biomass density.

An experimental study by Demirbas (2009) shows that the algae in a heterotrophic system need constant mixing, which requires high-energy use (more than two times that of the open ponds of an autotrophic system, such as System A) due to the large volume. Later, Table 4 describes in greater detail the energy requirements in these two systems, and demonstrates the higher energy requirements of System B.

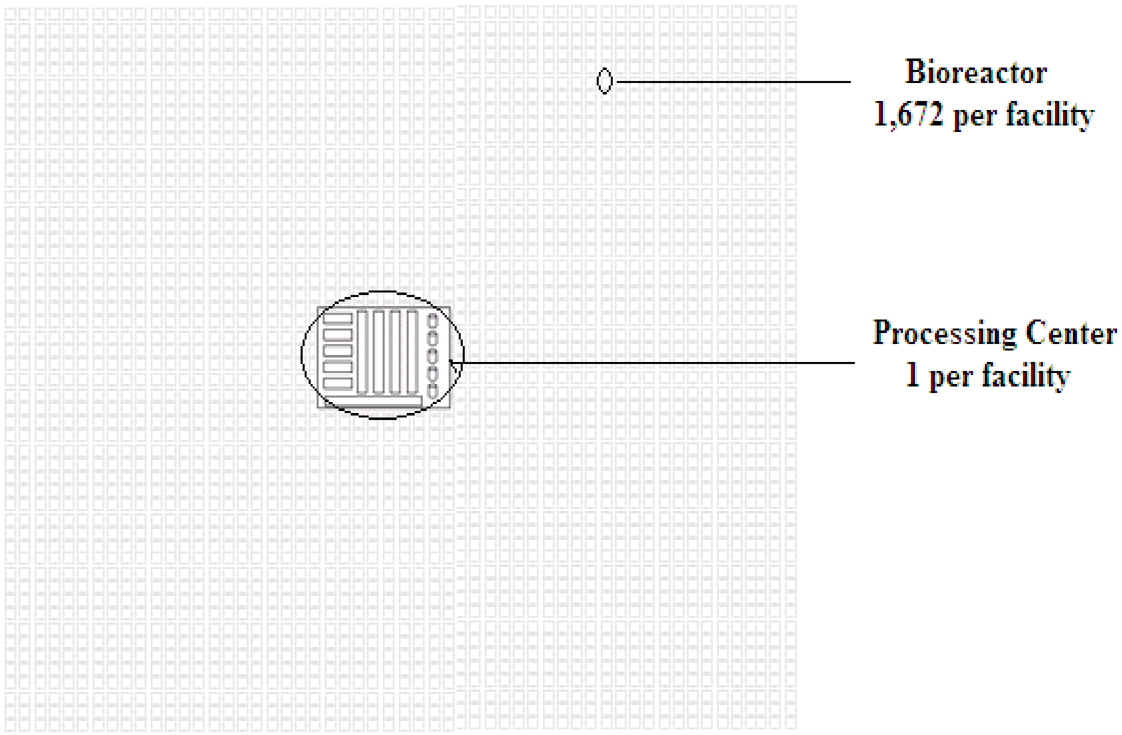
Pesticides are not used because there is little chance of infection or contamination in a closed system where environment can be controlled (O'Grady & Morgan, 2011). Temperature and pH conditions need to be maintained, which adds to operation costs. Fertilizer is used to ensure that adequate nutrients are available for optimum growth conditions. Figure 6 describes the layout of this facility plan and Table 3 shows the productivity at different levels of the system.

Table 3. Biodiesel Productivity (gallons of biodiesel per year) – System B: Heterotrophic Algae

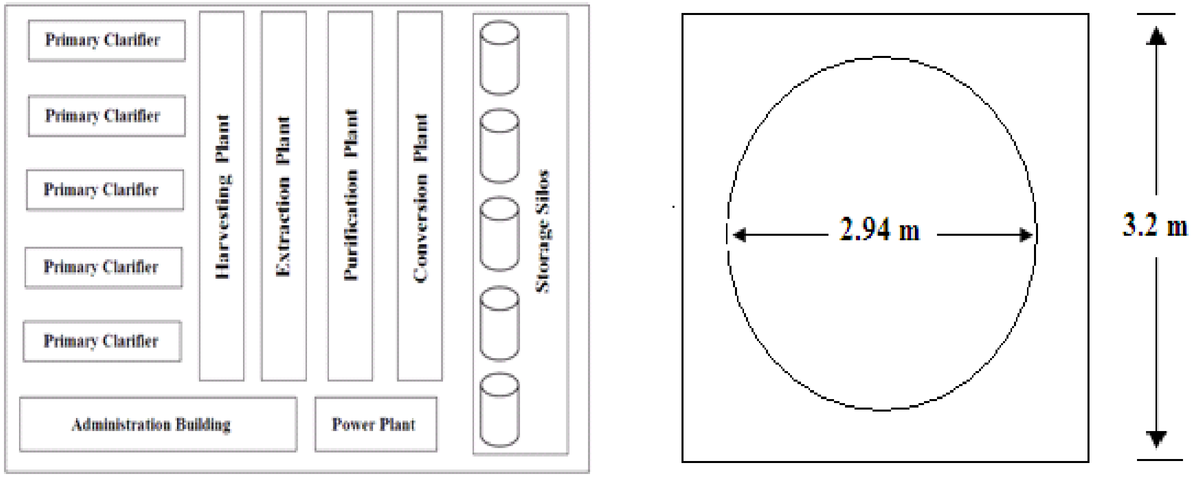
Production Level	Productivity*	Land Area (km^2)#
Bioreactor	≈ 7,378	0.0035
Facility	≈ 12 million	8
System	≈ 1 billion	649

* Assuming each facility consists of 1,626 bioreactors and the system consists of 84 facilities

The land area for bioreactor level area is determined by dividing the area of the facility with the number of bioreactors (556,213), rather than the area of one bioreactor, which is 0.0001km2.



Design and Layout - Facility
- 1,627 Bioreactors



Design and Layout - Processing Center

Design and Layout - Bioreactor

Figure 6: Layout of a hypothetical algal biodiesel facility with heterotrophic cultivation system (System B), with an annual capacity of 12 million gallons of algal biodiesel and a land area of six km^2. This is not drawn to scale.

HARVEST AND DEWATERING

For both System A and System B, algae are separated from the growth medium using gravity settlement in primary and secondary clarifiers, and dewatered using a rotary press. The recovery rate of algae from the growth medium is assumed as 95% and the solid content after harvesting is assumed to be 90% (U.S. DOE., 2010). Even though pilot-scale data on this process were not found, the models developed by Yang et al. (2010) estimate that the reuse of harvest water could decrease the input of the nutrients by 55% and water use by 80%. A comparative life-cycle analysis study of a hypothetical algae facility by Lardon et al. (2009) demonstrates that the harvested algae are not dewatered completely by drying before extraction because wet extraction is likely to be less energy intensive when used for algae grown with limited nitrogen. That study suggests 0.05 to 0.08 MJ/MJ biodiesel is consumed for wet harvesting. This is almost three times lower than that used by Sheehan et al. (1998) and Clarens et al. (2010), because an energy intensive centrifuge is not used, with the resulting cost of reduced biomass recovery. Solar drying is not considered because of the time involved, the limited availability of sunlight of desired intensity, and risk to the stability of the lipid. The product at the end of this stage consists of 90% algal biomass and 10% water. In the case of *Chlorella vulgaris*, the lipid content is 35% of the dry algal biomass, and the TAGs are 30% of the dry algal biomass, while *Chlorella prtothecoides* is 41% of the dry algal biomass.

EXTRACTION

Hexane is used to dissolve the TAGs from the cell and leads to a loss of 30g of hexane per kg of biodiesel produced. The energy requirement for the electric motors of the compressors and pumps are adapted from literature and are not shown separately in a table in this paper (Sturm &

Lamer, 2010; Pfromm et al., 2010). According to the study conducted by Yang et al. (2010), using models from Dominguez-Faus et al. (2009), water use for extraction and transesterification is between 2 to 10 L per kg biodiesel, varying by a factor of five. This variation is due to the steam requirements for the extraction process, which may or may not be recovered and reused from the condenser. These facility process water requirements depend on the geographic and climatic variables associated with the facility, as well as the type of feedstock used (Dominguez-Faus et al., 2009). The energy used in this stage is 0.37 MJ/ MJ biodiesel for wet extraction under low-nutrient conditions (Lardon et al., 2009), while the ratio of the energy content of TAGs to that of the energy input is 2.6 (calculated by dividing HHV of algal oil, 37.2 MJ/kg, by the energy input of 15.3 MJ/kg).

CONVERSION

Biodiesel is made by transesterification of TAGs into mono alkyl esters of fatty acids and complies with ASTM 6751. Methanol is commonly used in the transesterification, and the alkyl group in the ester is a methyl group. Biodiesel is usually composed of FAME. A typical biodiesel recipe (CIRAS, Iowa State University, 2011) is

$$45.4\ kg\ Oil + 9.9\ kg\ methanol + 1\ kg\ KOH = 45.6\ kg\ biodiesel + 4.7\ kg\ glycerol + 4.9\ kg\ methanol$$

The recipe shows that one kg of algal oil produces almost one kg biodiesel. Methanol is added in excess to encourage the complete conversion of algal oil. It is assumed that 98% of the algal oil is converted to biodiesel by using KOH and Methanol (Antolin et al., 2002). It is also assumed that the catalyst KOH and the excess methanol are completely recovered and recycled. Energy used for conversion by transesterification is 0.0024 MJ/MJ biodiesel assuming HHV of 38 MJ/kg algal biodiesel (Lardon et al., 2009).

COMPARISON OF AREA AND ENVIRONMENTAL BURDENS OF SYSTEMS

Table 4 lists the requirements and environmental burdens of System A and System B and compares them with other forms of diesel. Figure 7 shows the total land area required, at both the facility and commercial scale, for commercial algae biodiesel production for the two systems studied here.

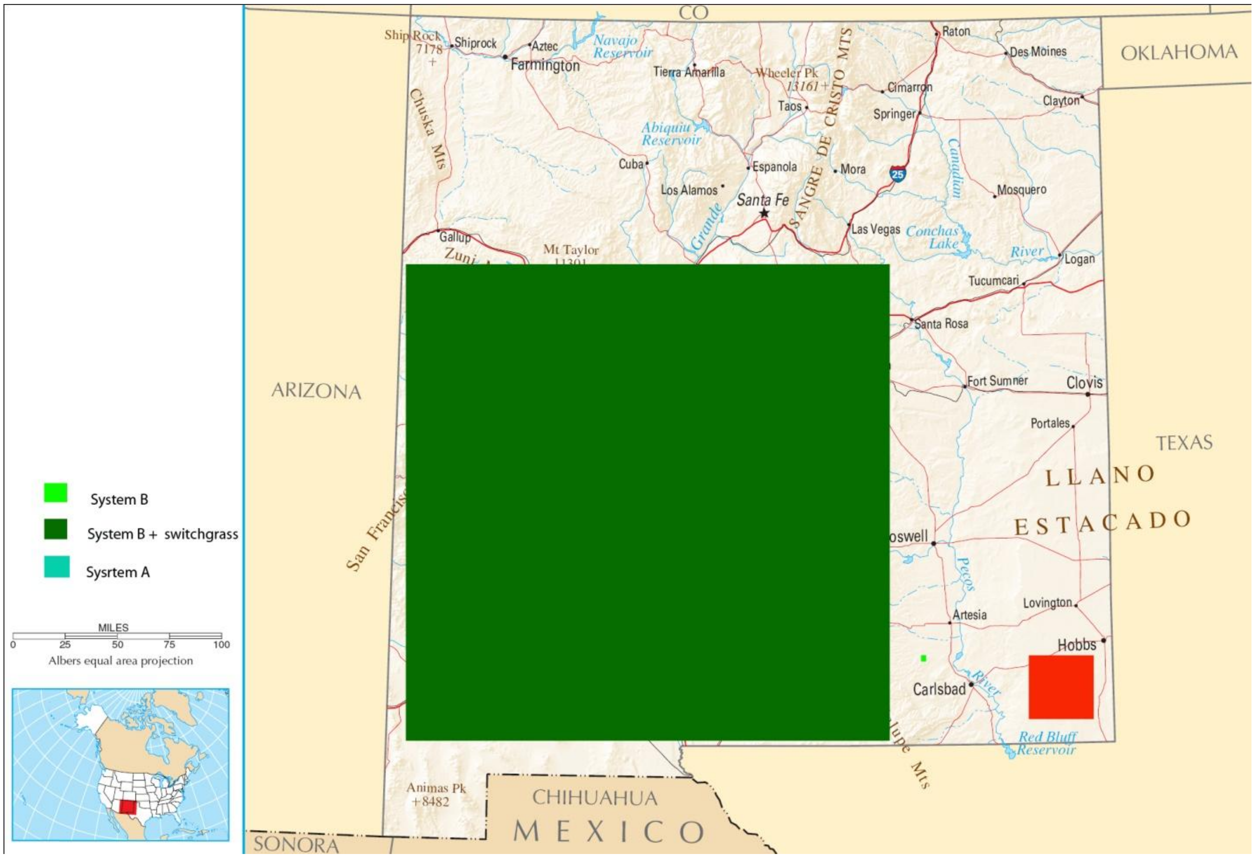


Figure 7: Figure showing the land area for System A (Autotrophic Algae Production, Red Square with side of 46 km, area of in the East) and System B (Heterotrophic Algae Production, Light Green Square with a side of 4 km, Northwest of Carlsbad) and System B with switchgrass (Heterotrophic Algae Production, Dark Green square with a side of 335 km). The squares represent the combined area of 84 facilities with a cumulative annual production capacity of one billion gallons of algal biodiesel. The annual production capacity of one facility is 12 million gallons.

Table 4. List of the various environmental burdens to produce one MJ of energy in the form of algal biodiesel and comparison with other diesels. All numbers without superscripts were results of calculations from the model with specifications listed in Table 1.

Per MJ of Biodiesel per year	Process Energy (MJ)	Water (L)	Fertilizer (g)	Land (m^2)	Net GHG (g CO_2 eq.)	Waste Water (L)
System A (Autotrophic)	0.5	160	5	0.02	27	120
System B (Heterotrophic)	1.15	8	5	0.0001	53	10
System B (Heterotrophic) + switchgrass	3	176	17	0.897	138	140
Soybean biodiesel	0.6^G	32^B	3^E	0.18^H	33^F	0.03^C
Petroleum diesel	0.2^A	0.01^B			94^I	0.007^C

Per 12 million gallons of biodiesel per year	Process Energy (GJ)	Water (m^3)	Fertilizer (x10^3 kg)	Land (km^2)	Net GHG (x10^3 kg CO_2 eq.)	Waste Water (m^3)
System A (Autotrophic)	812,593	274,475,779	7,459	25	40,276	179,005,943
System B (Heterotrophic)	1,715,474	11,933,730	7,459	0.15	79,061	14,917,162
System B (Heterotrophic) + switchgrass	4,475,149	262,542,049	25,359	1,338	205,857	208,840,267
Soybean biodiesel	895,030	47,734,918	4,475	269	49,227	44,751
Petroleum diesel	298,343	14,917			140,221	10,442

National Renewable Energy Laboratory (NREL), (1998)
A: Figure 2, **B:** Figure 11, **C:** Figure 13

Argonne National Laboratory (2008)
E: P 16, **F:** P 40 (T 5-7, biodiesel displacement allocation), **G**: T 4 appendix

H: Miller, (2010) **I:** California Air Resources Board (2009)

POTENTIAL ENVIRONMENTAL IMPACTS

Among the reasons for interest in algae biofuels is the hope that they may have lower environmental impacts than current biofuels and fossil fuels. According to proponents, algae biofuels could be a source of carbon sequestration, require less land, and for some systems, could be produced in arid environments and other areas where their land use would not compete with food crops (Chisti, 2007). However, the benefits of algal fuels will depend on how well their production is managed from a sustainability perspective. Concerns include:

- Water resource impacts and effects to hydrology.
- Direct and indirect land resource impact to natural ecosystems.
- Downstream wastes and effluents.
- Unpredictable interactions of GMOs with natural environments.

In an attempt to predict potential environmental impacts on a commercial scale, an analysis of system inputs, direct facility requirements, and wastes is considered in the following section for both the autotrophic and heterotrophic systems, as summarized in Table 5.

Table 5. Environmental Concerns in Systems A and B

Environmental Concern	A. Autotrophic System	B. Heterotrophic System
Water Resource Impact	Open raceway cultivation may be water intensive requiring freshwater inputs, due to evaporation with possible impacts to ecosystems across the landscape	Impact may be less than System A due to culture efficiency. However, will have higher indirect water requirements to cultivate organic carbon sources
Land Resource Impact	Smaller than any other first- or second-generation biofuel, but will need large area conversion, with impacts likely to be concentrated geographically	Impact may be less than System A due to culture efficiency, however will have higher indirect land use requirements to cultivate organic carbon sources
Waste and Effluents	Large volumes of concentrated blowdown waste material stored in on-site holdings ponds may require specialized treatment	Downstream waste material may burden municipal wastewater treatment facilities
Genetically Modified Algae	Open system may directly expose GMOs to natural environments	Closed system does not ensure containment of GMOs

WATER CONSUMPTION AND IMPACT TO HYDROLOGY

While the Southwestern region of the U.S. has the best solar resources for growing autotrophic algae, water resources are limited and already under pressure from existing residents, agriculture, and industry. A water intense process, such as algae biofuel production will have an adverse impact unless mitigated, and the demands can be projected over a range, while also acknowledging the existence of uncertainties. Water, whether fresh or brackish, extracted by groundwater pumping or obtained through surface water diversion, could further impact desert ecosystem health. The use of non-potable brackish groundwater in autotrophic systems may reduce the demand on freshwater resources, compared to previous generation biofuels. However, algae cultivation systems utilizing open raceway ponds require inputs of freshwater due to the high evaporation rate of some ecosystems. The heterotrophic model system assumes no recycling of water or water loss due to evaporation, and therefore those factors are not included in the analysis of System B. However, heterotrophic systems have large upstream water demand for the cultivation of switchgrass or other organic sugar feedstocks. To account for upstream water consumption, the resource impacts for switchgrass cultivation have been analyzed.

Due to the limited water resources in arid environments, water use by algae biofuel production facilities may be highly contentious from the perspective of environmentalists, communities, developers, politicians and land stewards. If commercial-scale algae facilities are clustered regionally, they may magnify adverse effects on local water resources. To assess the potential impact on water resources, total water consumption has been estimated. Having determined the amount of water input needed to produce one gallon of biodiesel, it is possible to predict implications that commercial-scale autotrophic and heterotrophic algae biofuel facilities may have for water resources (Table 6).

Table 6. Water Consumption Efficiency of System A and B (million gallons per year)

	System A: Autotrophic		System B: Heterotrophic
	50% Recycling	No Recycling	
Evaporation Water Loss	1,700	1,700	0
Direct Freshwater Input	1,800	1,800	100
Upstream Freshwater Input	0	0	59,000
Brackish Water Input	64,000	110,000	0
Total Facility Consumption[1]	66,000	112,000	59,100
Industry Consumption[2]	5,500,000	9,100,000	5,000,000
Water/Biodiesel Ratio[3]	**5,500**	**9,100**	**5,000**

1. Facility consumption: water consumed to produce 12 million gallons of biodiesel
2. Industry consumption: water consumed to produce 1 billion gallons of biodiesel
3. Water/Biodiesel Ratio: how many gallons of water is consumed to produce 1 gallon of biodiesel

Table 6 shows the water consumption of System A and System B. An analysis of on-site water resource consumption shows that System B may consume considerably less water than System A, regardless if System A recycles water (Table 6), largely because heterotrophic systems do not experience water loss from evaporation. Further, since heterotrophic algae are not limited by shading of light, cell concentrations may be grown at higher densities than that of autotrophic systems. Heterotrophic organisms utilize nutrients more efficiently; therefore, experience faster growth rates to produce more biomass in similar volumes of water (Ryan, 2009).

Although System B's direct freshwater consumption is quite low, only 8.6 gallons of water is used per gallon of biodiesel produced, but this is not shown in the table. However, when considering the need of its energy-rich feedstock, the overall system requires nearly as much water as System A. It is important to note that System B operates with only freshwater inputs for both algae and organic carbon source (switchgrass) cultivation. In comparison with System A, due to upstream consumption, the analysis shows that heterotrophic systems have the potential to consume about 32 times more freshwater.

An analysis of System A production shows high direct water use, ranging from about 5,500 gallons to about 9,100 gallons of water per gallon of biodiesel produced, with and without water recycling, respectively. Most water inputs consist of low-quality brackish water, with an addition of freshwater use that is small in comparison. Given the high evaporation rates of the Southwest, open autotrophic systems are subject to high water loss from evaporation. This system is sensitive to cell density and shading effects, causing the open ponds to have larger surface areas, making the pond even more susceptible to evaporation.

Water consumption may be reduced by about 40% in System A if pond water is recycled. This method of water conservation would significantly reduce stress to limited existing water resources in arid environments, and create a more sustainable algae biofuel industry utilizing autotrophic systems.

The quantitative analysis of water use from System A and B are compared to more conventional biofuels, such as corn ethanol and soybean biobiesel, which consume 800 and 80 gallons of water per gallon of fuel, respectively (Appendix C: Figure 1) (Aden, 2007; O'Connor, 2010). In comparison with the model, water use for algae biofuels, regardless of technology, may be higher than traditional biofuels. Assuming 50% recycling of water for autotrophic systems, System A consumes about seven times more water than corn ethanol and about 70 times more than soybean biodiesel. Without recycling, System A consumes about 11 times more water than corn ethanol and over 100 times more than soybean biodiesel. Similarly, heterotrophic System B consumes about six times and about 60 times more water than corn ethanol and soybean biodiesel respectively. However, through the use of low-quality water, potential ecological impacts and stress on freshwater resources by algae biofuels could be mitigated, unlike freshwater irrigation for corn ethanol and soybean biodiesel production.

ECOLOGICAL IMPACTS FROM GROUNDWATER EXTRACTION OR SURFACE WATER DIVERSION

Groundwater used by commercial-scale autotrophic algae biofuel facilities and surface water used by commercial-scale heterotrophic algae biofuel facilities across the landscape has consequences for the hydrology of the Southwest terrestrial, riparian, and aquatic habitats, which may be affected.

HYDROLOGY: IMPACTS TO SURROUNDING HABITATS

Brackish groundwater is found deeper in the Earth than that of freshwater aquifers, and it has greater density of dissolved solids (LBG-Guyton Associates, 2003). Similar to those of fresh groundwater extraction, brackish groundwater extraction may impose similar stresses on the flow of hydrologic systems, such as a reduction or elimination of spring flow. Habitats downstream dependent on spring discharge may be affected. Deeper waters have longer flow routes and discharge into distance surface waters; therefore effects may not be seen locally, but instead in distant habitats (Winter et al., 1998). Ecosystems in arid environments, dependent on groundwater resources, can be particularly sensitive to human groundwater extraction (Patten et al., 2008). Groundwater withdrawals for algae biofuel production that lower an already shallow water table may lead to reduction, or even elimination of spring discharge into surface water. Groundwater in arid environments can be can the most reliable source of water for many desert plant species because annual precipitation is highly variable. Groundwater extraction lowering the water table below root zones could negatively affect groundwater-dependent plant communities (Elmore et al., 2006). As a result, habitats may experience reduced plant species richness, and shifts in plant species composition and vegetation cover (Patten et al., 2008).

Habitat loss or increased habitat fragmentation can further affect animal species. Vegetation loss that results from groundwater extraction for algae biofuel production may increase erosion and sediment run-off due to the fact that plant roots improve the integrity of soil (Laity, 2003). In addition to effects on wildlife, groundwater extraction for algae biofuel production could result in land subsidence in some areas. Excessive pumping of aquifer systems can result in permanent subsidence as soils are extracted of their water and become compacted, thus permanently reducing aquifer size and storage capacity (USGS Georgia Water Science Center, 2011).

In arid environments, aquatic habitats occur infrequently in a scattered distribution across the landscape, likely making them susceptible to impacts from the extraction of groundwater for the production of algae biofuels (Shepard, 1993). Common to all arid regions, depletion of groundwater and the diversion of surface water transform aquatic habitats, causing harmful affects to local species. If the life of a spring or a cluster of springs is compromised by groundwater extraction from algae production, species dependent on the spring may suffer loss of habitat that cannot be mitigated (Kodric-Brown & Brown, 2007).

In isolation, groundwater extraction for the production of algae might not significantly impact aquatic habitats, but groundwater extraction for algae production could exacerbate an already stressed hydrology system. Groundwater extraction that exceeds groundwater recharge or replenishment from precipitation could have long-term consequences for local and or more distant aquatic habitats. Thus, the water demand for algae must be assessed for its cumulative environmental impact in combination with other water demands in regions where production is considered.

WATER QUALITY & EVAPORATION

Algae may be grown in low-quality, non-potable water mediums such as saline, brackish, or brine extracted from groundwater or saltwater bodies, therefore reducing the demand on freshwater resources (U.S. DOE., 2010). Variation in water quality can be described as a measurement of total dissolved solids (TDS) in solution. Dissolved solids can include calcium, magnesium, sodium, chloride, sulfate, bicarbonate, potassium, nitrate, iron, fluoride, as well as other trace elements. TDS can be described as the mass of dissolved solids in milligrams per liter of water or mg/L (see Appendix C: Table 1) (LBG-Guyton Associates, 2003). As water evaporates, TDS condense to form blowdown material (Lundquist, 2010).

Evaporation rates in the Southwest are among the highest in the country. Based on our model, we have assumed water loss due to evaporation, and consequently, additional freshwater is required to continue optimal production (Table 8). Evaporation is dependent primarily on air temperature, relative humidity, and wind; however, evaporation is also dependent on production variables like surface area, depth, and medium density (Yang, 2010).

DIRECT FACILITY REQUIREMENTS

LAND USE EFFICIENCY

The extent of environmental impact of an algae biofuel facility will depend largely on location because environmental characteristics (e.g. species diversity, land cover, and soil composition) vary by location. Facilities developed in desert ecosystems will have variable effects, compared to impacts on forest or grassland ecosystems.

Developing new industry requires new infrastructure. Infrastructure at the commercial scale may require significant land cover conversion for algae biofuel projects developed in previously undisturbed areas. Some production technologies (e.g. heterotrophic methods) can be potentially developed in existing industrial infrastructure, but other technologies, such as PBRs or open raceway ponds, may convert vast areas of undeveloped and relatively level land to accommodate these systems (Luo et al., 2010).

The designed model systems were used to estimate land use requirements to produce 12 million gallons of biofuel at the facility scale and total area required to produce one billion gallons of biofuel annually (Table 7). Subsequently, we estimated production of algae biodiesel per acre by dividing total industry land area by the total industry production of one billions gallons of biodiesel. From these values we are able to compare relative land use requirements for both systems as well as other more conventional biofuels, such as corn ethanol and soybean biodiesel (Appendix C: Figure 2). In a system-by-system comparison, this analysis shows which technology is making better use of the land by producing a greater quantity of fuel per unit of area (acre). From land use estimates it may be determined which algae system might have a relatively "smaller" environmental footprint while still maximizing biofuel production at commercial scale.

Table 7. Land Use Needs of Algae Biofuel Production

	System A: Autotrophic	**System B: Heterotrophic**		
		Direct	**Upstream**	**Total**
Facility Area (Acres)	8,000	0.0003	300	300
Industry Area (Acres)	672,000	0.27	26,000	2,6100
Gallon/Acre[1]	**~1500**	**N/A**	**38**	**38**

1. Gallon/Acre = Industry Production (1 billion Gallon) / Industry Acre

Estimates in Table 7 estimate the production of 12 million gallons of biodiesel for System A at facility scale will require about 8,000 acres. An industry of 84 individual algae biofuel facilities may be needed to produce one billion gallons annually, which may yield a total industry land requirement of about 672,000 acres. Autotrophic systems require more direct land use primarily because shallow ponds with large surface area maximize cell growth (Ryan, 2009). Autotrophic culture densities are limited by shading of light, compared to high-density heterotrophic culture systems not limited by photosynthesis. In order to obtain desired biomass yields, autotrophic systems may require expansive tracks of land to maximize pond surface area across facility and industry scales to produce 12 million and one billion gallons of biodiesel, respectively. Due to the fact that autotrophic systems may be capable of producing algae on non-arable tracks of land, they may reduce land use competition for food production.

Similar to upstream water consumption, heterotrophic systems have upstream land use requirements. Although System B requires less direct land area to culture algae, an analysis of upstream land use to produce organic carbon sources like switchgrass shows an overall increase in land use (Table 7). Model estimates reveal that each facility may have a direct requirement of three acres to produce 12 million gallons of biodiesel annually, subsequently equaling about 274 acres for the entire industry producing one billion gallons of biodiesel. However, combining direct and upstream land use requirements for System B reveals a reduced efficiency of 99.99% per acre. Including upstream land use requirements into land use totals, each facility may require about 311,000 acres, totaling about 26,124,000 acres for 84 facilities at the industry scale. By comparison, this may be about 40 times less efficient than autotrophic systems. Unlike autotrophic systems, which may be capable of producing biomass in arid non-arable environments, switchgrass may need to be cultivated on more productive arable land, and therefore may increase land use competition for food production (Rinehart, 2011). However, heterotrophic systems that utilize municipal green waste as an organic carbon source (not considered in this study) could reduce the demand for switchgrass and therefore become more efficient in terms of land use.

The model system estimates, in comparison with other fuel types, show a reduction in land use for System A compared to conventional biofuel feedstocks (Appendix C: Figure 2). Based on this analysis, System A reveals land use to be about 2.4 times more efficient than corn ethanol, and 8.5 times more than soy biodiesel. In contrast, when upstream land use is considered, System B shows, by far, the greatest land use requirement of any fuel type compared.

Relative to predictions, commercial-scale algae biofuel production may have significant local ecological impacts. However, in comparison, autotrophic algae biofuel systems are predicted to use less land regionally, mitigating competition for arable land and environmental impacts at the landscape level. Heterotrophic systems may have a reverse effect.

ECOLOGICAL IMPACTS FROM LAND USE

Construction of algae biofuel facilities and infrastructure to a commercial scale could result in ecological disturbances, such as habitat loss and fragmentation, causing wildlife displacement and interference in travel corridors for species that cannot effectively traverse these barriers. Species may experience reduced survivorship if vital habitat patches are disturbed or removed for algae production developments, and suitable habitat replacements cannot be found within their range (Smith, 2011).

Ecological impacts of algae biofuel may occur at the facility scale and impacts could thereby be magnified across the landscape if multiple facilities are clustered locally. Further, if additional facility infrastructure is implemented, such as roads, fencing, and transmission lines, natural habitats beyond the scope of algae biofuel production facilities may experience land conversion.

Facility infrastructure could create ecological disturbances within its borders, while also acting as a barrier impeding or completely blocking species migration across the landscape, which could potentially impair species survival, while also creating concerns of limited gene flow (K.L. Penrod, 2009). Further, new developments may remove existing vegetation, increasing edge habitats susceptible to terrestrial invasive plant species (Brooks, 2009).

Grading may occur during construction of ponds, PBRs, roads, and other facility infrastructure that could impact existing soils and result in removal of vegetation. Soil compaction reduces pore space in the soil, causing reduced permeability. Vegetation removal is also a major cause of soil degradation or loss. Both subsequently result in greater surface runoff and erosion (Castillo et al., 1997; Lull, 1953). In some desert ecosystems, sensitive desert soil crusts thrive and contribute to soil stability, dust trapping, and ecosystem water infiltration. Once these desert crusts are destroyed, recovery, if ever, may take decades (Mathews, 2008). Further, in other ecosystems, soil stability and structure is dependent on plant roots and associated hyphae acting as a “sticky string bag.” (Oades, 1993)

PROTECTED SPECIES

Lesser Prairie-Chicken, Photo Credit: UFWS

Due to regulatory constraints under the Endangered Species Act (ESA), algae biofuel facility developments will likely be prepared to follow procedures to prevent incidental take of listed endangered species and their habitat as they create their facilities. However, biofuels have the highest areal impact of any other fuel source and the amount of natural habitat disturbances to occur in the future is contingent on whether U.S. policy continues to incentivize biofuel production. Domestic sources of fuel are becoming more politically popular for boosting agricultural interests and national security. As a result, there will be increased areal changes to natural landscapes. Increased land conversion of natural habitats to produce biofuels may increase habitat loss and subsequently increase pressure on wildlife populations (McDonald et al, 2009).

Species such as the Dunes Sagebrush Lizard (*Sceloporus arenicolus*) and the Lesser Prairie-Chicken (*Tympanuchus pallidicinctus)* have had populations in decline over the past 50 years. This is largely due to habitat loss and fragmentation by oil and gas industry and these species have become listed as Candidate Species for Federal Listing (U.S. Fish and Wildlife Service, 2009; U.S. Fish and Wildlife Service, 2009). The Sand Dune Lizard and Lesser Prairie-Chicken home ranges extend into parts of Southeastern New Mexico and West Texas, which overlap areas of the U.S. as potentially suitable locations for algae biofuel developments. If listed, algae biofuel developments that exist within the home ranges of the Sand Dune Lizard and Lesser Prairie-Chicken may face federal regulatory complications in the future, including putting in retroactive measures to ensure these species are not negatively affected.

If the production of biofuels continues to expand the issue of habitat loss by biofuel production, operations may be highly contentious from the perspective of environmentalists, communities, and land stewards. Biofuel developers and decision-makers should consider conservation policy, such as the ESA, in order to minimize conflicts as biofuel industries expand.

SYSTEM WASTES & EFFLUENTS

BLOWDOWN MATERIAL & WASTE MANAGEMENT

Blowdown wastes consist of unknown materials, primarily because cultivation mediums are considered proprietary information. However, the chemical composition of blowdown material may correlate with the chemical make-up of input water and nutrients for cultivation. Dissolved solids present in low-quality water inputs may consist of calcium, magnesium, sodium, chloride, sulfate, bicarbonate, potassium, nitrate, iron, fluoride and other trace elements, and therefore may also be present in blowdown waste.

The disposal of blowdown waste is of concern because mismanagement of blowdown waste material that accumulates because of evaporation may lead to environmental contamination. The "blowdown" ratio is increased by the loss of water through evaporation and is brought back to equilibrium with an addition of freshwater (Lundquist, 2010).

The autotrophic model system assumes that blowdown waste will be stored in on-site lined holding ponds. The use of liners in on-site holding ponds may mitigate the risk of environmental contamination by waste material. However, over time, holding ponds will become full and proper off-site disposal will be required. Possible solutions are to dump, landfill or bury (deep-well injection) the concentrated substance (Lundquist et al., 2010). This, however, is not sustainable practice because nitrogen, phosphorous and other valuable finite resources remain in blowdown waste. Conversely, the heterotrophic model assumes blowdown material will be sent to municipal wastewater treatment facilities. Using model systems, it is possible to estimate the annual accumulation of blowdown waste material at both the facility and industry scale producing 12 million and one billion gallons of biodiesel, respectively (Table 8). Having generated waste material accumulated for the model systems, a waste production analysis has been done for Concentrated Animal Feeding Operations (CAFOs) and manufacturing industries to provide a comparison with blowdown waste accumulation (Appendix C: Figure 4).

Table 8. Total Annual Blowdown Waste (million tons per year)

	System A: Autotrophic		**System B[*]: Heterotrophic**
	50% Recycling	**No Recycling**	
Total Facility Waste	1.37	2.26	0.02
Total Industry Waste	115	190	1.68

* Assuming no recycling

The analysis of annual blowdown waste accumulation for System A, both with recycling and no recycling, assumes the primary input of brackish water at a TDS concentration of 5000 mg/L. The analysis shows about a 40% reduction in blowdown waste when System A incorporates recycling, at both facility and industry scales. In comparison, System B analysis assumes blowdown waste accumulation using fresh water inputs that are not recycled at a TDS concentration of less than 500-mg/L, and shows blowdown waste accumulation to be substantially less than System A. This is primarily due to the difference in water quality inputs, in terms of TDS.

In an analysis of analog systems, manure production for small- and large-scale CAFOs produce about 2,800 to 1.6 million tons, respectively (U.S. GAO, 2008). In comparison with the values of blowdown waste accumulation for System A (Table 8), large-scale CAFOs may annually produce similar volumes of waste. Further, manufacturing facilities, on average, produce about 105,555 tons of waste per year (Makower, 2008). In comparison to facility-scale algae systems, manufacturing facilities may produce about 13 to 21 times less waste, depending on whether System A recycling is or is not included, respectively. System B waste, in comparison to average manufacturing facility waste, may produce about 5 times less.

As mentioned above, accumulation of blowdown waste materials creates concerns of disposal and management. On-site disposal for System A creates concerns over liner leaks or overflow that may contaminate local soils or hydrologic systems. Once waste material comes in contact with soils, contaminants may percolate through soils and subsequently contaminate hydrologic systems (Winter et al., 1998). Over time, blowdown volumes will fill on-site holding ponds and subsequently require off-site disposal. Additionally, blowdown waste disposal for heterotrophic systems would require pretreatment of waste material before being sent to wastewater treatment facilities. Regardless of technology, blowdown waste management and monitoring will be an important part of any algae production facility, due to the accumulation of large volumes of waste and uncertainty of the chemical composition of blowdown material.

GREENHOUSE GAS EMISSIONS

GHG emissions from fossil fuel combustion and land use change are an area of concern for environmentalists and industry alike. Biofuels being developed as alternatives to fossil fuels, and are promoted as a tool to reduce GHG emissions.

Algae biofuel has been promoted as being potentially carbon negative (Mathews, 2008). To have algae become a carbon-negative fuel, the oil must be extracted, while the protein and carbohydrates of the algae must be sequestered as carbon credits. However, in most existing economic models of algae, the protein and carbohydrates would also be sold, as high value co-product. Given this reality, under the best circumstances, algae biofuel could be a carbon-neutral energy source (Chisti, 2007). This is unlikely, however, due to full life-cycle emissions for the foreseeable future of biofuel production. Emissions can be generated from nutrient inputs (including synthetic fertilizers and pesticides), land conversion, and energy use during conversion and transportation of algae biofuel or biomass. With full lifecycle emissions considered, algae biofuel is not carbon neutral for the model systems evaluated in the report.

Table 9. Net Greenhouse Gas Emissions in g CO$_2$ eq./MJ

		GHG Emissions (g CO2 eq./MJ)
Algae	System A: Autotrophic	27
	System B: Hetertrophic	138
	Soy Biodiesel	33[B]
	Petroleum Diesel	94[A]

A: California Air Emissions Board (2009) **B:** Table 4

By analyzing the two model systems, estimated CO$_2$ emissions can be calculated for comparison. As seen in Table 9, System A and System B have emissions that will contribute to global CO$_2$

concentrations. However, even considering full life-cycle emissions, autotrophic algae biofuels emissions are significantly less than petroleum diesel. In contrast, our analysis of System B predicts heterotrophic systems that cultivate switchgrass in upstream processes as an organic carbon sugar source to have emissions higher than that of any other fuel we considered.

SYNTHETIC BIOLOGY/GENETIC MODIFICATION

Genetically modified (GM) and synthetic algae are commercially enticing because they have the potential to improve oil and protein yields, chemical resistance, and cellular robustness to environmental stress factors such as grazers, salt concentrations, climate, pH and light intensity (Radakovits et al., 2010). Based on our models, GM *Chlorella vulgaris* and *Chlorella protothecoides* are cultivated in open system raceway ponds and closed-system bioreactors, respectively. Regardless of system, GM algae could be released into natural environments intentionally, via wastewater, or unintentionally, via human error.

The ecological safety of the introduction of GMOs is highly contested. The U.S. Government and industry leaders have vigorously supported the safety of these organisms to both human health and ecosystems. Recently, the federal government approved the use of GM alfalfa after rigorously performing the first environmental impact statement of a GM crop (USDA, 2011). Some scientists claim that GM algae are more competitive in culture systems and are likely to be less competitive against their non-GM counterpart in natural environments (Flynn et al., 2010). However, public perception conceives GMOs as deleterious because of unavoidable environmental contamination, high mobility, and the potential for gene flow (Friends of the Earth, 2011). Environmental organizations and others have been vocal about their concern over the unknown consequences of GMOs (Greenpeace USA, 2011; World Wildlife Fund, 2003).

Forecasts based on assumptions and expert opinion cannot predict interactions between GM/synthetic algae and natural environments. Understanding these interactions is essential because containment of GM/synthetic algae will be impossible regardless of cultivation system. Once released, GM/synthetic algae can be transported by humans between aquatic habitats on boats, shoes, and clothes or carried by hydrology flows. Similar to the food industry, GM algae used for biofuel production presents a polarizing debate about both human and environmental safety.

ECONOMICS OF MITIGATION STRATEGIES

Besides the above potential environmental impacts, commercialized algae biodiesel production will cause two immediate environmental problems that must be considered and addressed properly during the phase of system design and facility construction. The first problem is the potential soil and groundwater contamination by the seepage of the shallow ponds, or raceways, of System A. The second problem is the pollution of surface and ground waters by large amounts of wastewater produced during all four major processes involved in algae biodiesel production. The following section will discuss the cost and effectiveness of mitigation strategies aimed to minimize or eliminate these immediate environmental damages.

SOIL AND WATER CONTAMINATION

POND LINING

For any algae biofuel system that uses ponds for cultivating the organisms, the pond lining design will be one of the most important decisions during facility construction. This is the case for the shallow ponds, or raceways, of System A. The ponds must be lined properly to prevent not only the loss of water and various nutrients by seepage, but also soil contamination, groundwater contamination, and floor erosion by wastewater and nutrient growth media. In addition to the costs of lining materials, other considerations in determining what lining material to use, are the cost of water and nutrients added after initial depletion, and local environmental regulations. However, for the purpose of this report, only the costs of materials, the quality of materials, and the corresponding implications on the effectiveness of eliminating or minimizing environmental impacts will be considered.

NATURAL CLAY LINERS

It comes as no surprise that not lining the ponds at all is the least expensive approach, but at the same time, it is also the least effective approach to preventing water seepage, floor erosion, and soil contamination. If not lining at all is the chosen approach, then preventing seepage and contamination will depend on the clay layer of the local soil. There are two important considerations about clay liners. The first important consideration is the thickness of the clay liners. The clay liners must have some minimum thickness because drying out the open ponds, which is often necessary for maintaining the selected algae, will often cause the clay liners to crack (Lundquist et al., 2010). The second important consideration is that, depending on the type of clay liners, this could adversely affect the ponds' effectiveness of maintaining the productivity of the selected algae species, because pond cleaning would be impossible (Lundquist et al., 2010). Finally, In addition to clay liners, the crushed rock layer could also be used to line the open ponds (Weissman & Goebel, 1987), but it is too expensive and not more effective in preventing seepage, erosion, or contamination. In summary, if open ponds are built without being lined, managing the risks associated with seepage, erosion, and soil and groundwater contamination will depend on the clay layer of the local soil, and many site-specific details must be carefully evaluated on a case-by-case basis

PLASTIC AND SYNTHETIC LINERS

Besides clay liners, PVC (Polyvinylchloride), HDPE (High Density Polyethylene), EPDM (Ethylene Propylene Diene Monomer), Fiberglass, and Butyl Rubber are the most common choices for pond liners. Durability, reliability, and other characteristics of lining materials directly determine their effectiveness in managing and preventing soil and groundwater contamination. Each of the five types have advantages and disadvantages in terms of effectiveness in protecting soil and water. In general, the more reliable and effective they are, the more costly are the lining materials. For example, EPDM is long lasting and well resistant to ultraviolet radiation, but it is much more expensive than other options (Just Liners Plus, 2011). On the other hand, although PVC is very inexpensive and easy to use, it is susceptible to ultraviolet degradation, and thus direct sunlight can have a seriously detrimental effect on it. In addition, PVC has a relatively short service life (Just Liners Plus, 2011). HDPE is somewhere in between EPDM and PVC. HDPE is also a less expensive option, but it is famous for toughness and provides a service life of about 15 years (Everything-ponds.com, 2011). Butyl Rubber is as long lasting as EPDM and tends to be thick and heavy. However, Butyl Rubber is toxic to certain animals and thus its installation could cause additional environmental concerns (Everything-ponds.com, 2011). Finally, fiberglass has been used for almost a century and fiberglass pond liner has the best performance in terms of durability and reliability; however, it is very complex to install and most of fiberglass pond liners are pre-formed pond liners, which means that they are not flexible and the ponds must be designed around the liners (Everything-ponds.com, 2011). Table 10 is a summary of the aforementioned five lining materials and Table 11 is the corresponding approximate estimate of lining costs for System A.

Table 10. The Summary of Lining Materials*

Lining Material	Costs	Effectiveness Advantages	Effectiveness Disadvantages
Fiberglass	Very expensive	• Highly durable and reliable	• Not flexible • Complex to install
Butyl Rubber	Expensive	• Highly durable and reliable • Easy to use and install	• Thick and heavy • Toxic to certain animals
EPDM	Less expensive	• Highly durable and reliable • Highly flexible • UV stable • Cold-resistant • Easy to use and install • Aquatic safe • Expandable and contractible	• No significant disadvantage
HDPE	Less expensive	• Highly durable and reliable • Highly flexible • UV stable • Tear and puncture resistant • Easy to use and install • Aquatic safe	• Not cold-resistant
PVC	Very Inexpensive	• Expandable and contractible	• Not cold-resistant

* Just Liners Plus (2011) and Everything-ponds.com (2011)

Table 11. Construction Costs

Lining material	Price[1] (per m^2)	Price[2] (per pond)	Constr. Mult.[3]	Total Costs[4] (per pond)	Total Costs[5] (per facility)	Total Costs[6] (System)
Fiberglass	\$412.65	\$439,884.90	1.6	\$703,815.84	\$10,557,237.60	\$886,807,958.40
Butyl Rubber	\$40.48	\$43,151.68	1.3	\$56,097.18	\$841,457.76	\$70,682,451.84
EPDM	\$8.61	\$9,178.26	1.2	\$11,013.91	\$165,208.68	\$13,877,529.12
HDPE	\$7.11	\$7,579.26	1.2	\$9,095.11	\$136,426.68	\$11,459,841.12
PVC	\$6.11	\$6,513.26	1.2	\$7,815.91	\$117,238.68	\$9,848,049.12

1. Just Liners Plus (2011).
2. Assuming a pond dimension of 100m (L) × 10m (W) × 0.3m (D), which has a covering area of 1,066 m^2.
3. Construction Multiplier: to reflect the installation costs based on the complexity of installation.
4. Total Costs per pond = Price per pond × Construction Multiplier.

5. Assuming a facility consisting of 17,000 ponds.
6. Assuming a system consisting of 84 facilities.

WASTEWATER TREATMENT

All of the four major processes of algae-based biodiesel production, namely cultivation, harvesting, extraction, and conversion, produce large amounts of wastewater. If the wastewater and its contaminants are discharged without proper treatments, they will cause tremendous damage to local environment, especially surface and ground waters. Therefore, both for System A and for System B, on-site proper wastewater treatment facilities are critically important and estimating the associated costs is an essential part of an environmental economics analysis of algae-based biodiesel production.

METHODOLOGY

This report estimates the construction costs of on-site wastewater treatment facilities by utilizing an inflation-adjusted cost curve based on an EPA analysis of municipal wastewater treatment plants (Huan, 1980). This cost curve was developed by looking at 737 treatment plants constructed across the U.S. and is the most complete empirical analysis of construction costs (Huan, 1980). In the cost curve, the construction cost of a particular type of plants is given, versus the designed flowrate of the influent. Therefore, this is a simple method to determine an approximate construction costs for a given type of plants.

However, two additional adjustments must be made: “time factors” and “location factors” adjustments. First, as the determined costs are statistical average costs for the entire U.S. and don’t reflect the site-specific conditions (Huan, 1980), adjustments must be made to account for differences in local markets, called “location factors” adjustments. Secondly, the determined costs are based on the data collected from 1973 to 1978 and reported in 1979 dollars (Huan, 1980), so adjustments to account for the inflation also must be made using appropriate estimates of inflation rates since 1979, called "time factors" adjustments.

This report takes the above-described method of inflation-adjusted EPA cost curve because this method has been widely adopted in the wastewater treatment field. For example, in 2006, the government of Cecil County, MD conducted a study of a reservoir and water treatment plant, which adopted the inflation-adjusted EPA cost curve to estimate the construction cost of water treatment plant (Cecil County Government, 2006). Another good example is a spreadsheet-based tool called Water Treatment Estimation Routine (WaTER), developed by the U.S. Department of the Interior in 1999, which also adopted the inflation-adjusted EPA cost curve to facilitate system cost estimation (Wilbert et al., 1999). And in 2003, WaTER was utilized by the United Nations in a general review of wastewater treatment technologies to estimate the construction costs of various types of wastewater treatment facilities all over the world (United Nations, 2003). Furthermore, the inflation-adjusted EPA cost curve has been widely adopted for both teaching and research purposes in the academic world. For example, in 1999, Syed R. Qasim developed the Qasim Treatment Plant Cost Equations based on the inflation-adjusted EPA cost curve (Qasim, 1999). From 2001 to 2010, in the class of Environmental Engineering Design at University of Colorado at Boulder, the inflation-adjusted EPA cost curve has been adopted in dozens of industry-sponsored projects (University of Colorado, 2011), in order to estimate the construction costs of wastewater treatment facilities (University of Colorado, 2011).

TYPE OF PLANTS

Based on the levels of treatment, there are three general types of plants: secondary treatment plants, advanced secondary treatment plants, and advanced wastewater treatment plants (Huan, 1980). They are further defined in Table 12. In order to minimize the potential environmental impacts of wastewater on local surface and ground waters, we take the type of advanced wastewater treatment plant as the base for the analysis. Additionally, as nitrate and phosphate are used as nutrient inputs in both System A and System B, nitrification and phosphorus removal will be also required for both systems. Therefore, the base wastewater treatment of the analysis is the advanced wastewater treatment with nitrification and phosphorus removal.

Table 12. Definition of Levels of Treatment[*]

Treatment Level	Definition
Secondary Treatment	$BOD_5 = 30$ mg/1
Advanced Secondary Treatment	BOD = 24 mg/l – 11 mg/l
Advanced Wastewater Treatment	BOD $\leq$ 10 mg/l
Nitrification	Ammonia nitrogen $\leq$ 5.0 mg/l
Phosphorus Removal	Total Phosphorus $\leq$ 3.0 mg/l

[*] Huan (1980)

CONSTRUCTION COSTS

According to Figure 8 (Huan, 1980), the equation used to estimate the total construction cost is

$$C = 2.41 \times 10^6 \times Q^{0.92} .$$

In Table 4, we can see the average wastewater burden of producing 12 million gallons of algae biodiesel is about 134 million gallons. Therefore, wastewater is generated at the rate of 134 million gallons per year at each of 84 facilities, which is equivalent to 0.33 million gallons per day. So the total construction costs is

$$C = 2.41 \times 10^6 \times 0.33^{0.92} = 0.87 \times 10^6 \ dollars .$$

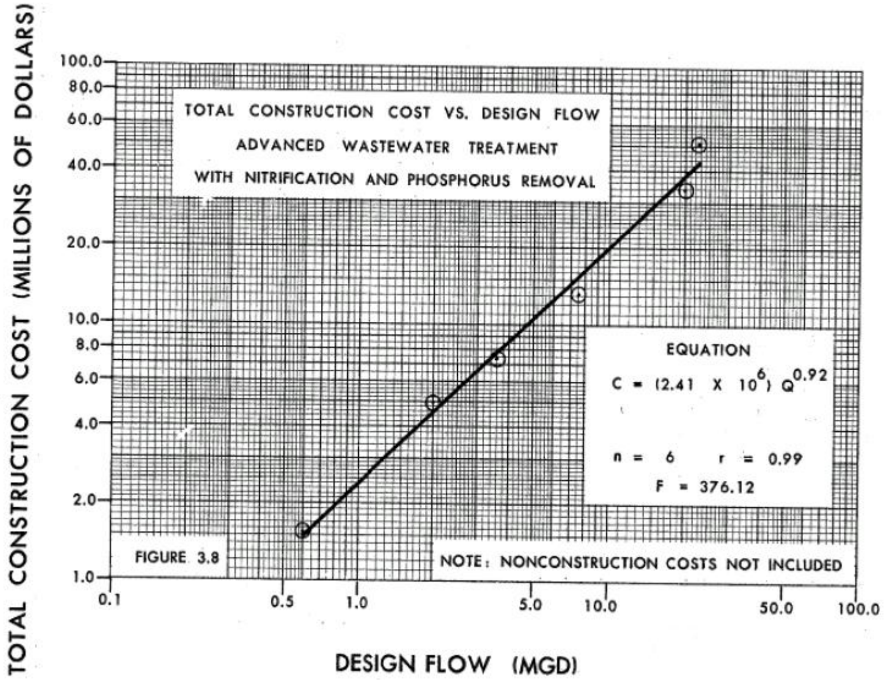


Figure 8. The Relationship Between Total Construction Cost and Design Flow, Based on Regression Analysis[*]

∗ Huan (1980)

ADJUSTMENTS

Location Factor

The location factors published by R.S. Means are different from region to region in the Southwest (RSMeans, 2011), but in general, due to the lower population density and price level, average location factors of 0.85 can be assumed for the cities and regions of the Southwest.

Time Factor

Time factors used to adjust costs for inflation since 1978 are the Construction Cost Index (CCI) Ratio calculated using the historical CCIs supplied by Engineering News Record (McGraw-Hill Construction, 2011). Table 13 lists the most recent CCIs and corresponding time factors.

Table 13. CCI-based time factors

Time	CCI[1]	Time Factor[2]
1978	2,776	1.00
2008	8,310	2.99
2009	8,570	3.09
2010	8,802	3.17

1. McGraw-Hill Construction (2011)
2. $Time\ Factor = CCI\ \ Ratio = \frac{CCI_{date}}{CCI_{1979}}$

In addition to CCI, the general inflation data can also be used to calculate the time factor to adjust the construction costs for inflation. Table 14 lists the most recent inflation rates and corresponding time factors.

Table 14. Inflation-based time factors

Time	Inflation Rate[1]	Time Factor[2]
1978	7.62%	1.00
2008	3.85%	3.30
2009	-0.34%	3.29
2010	1.64%	3.35

1. InflationData.com (2011)
2. $Time\ Factor_n = \prod_{i=1979}^{n} (1 + Inflation\ Rate_i)$

In general, inflation-based time factors are higher than CCI-based time factors because inflation-based time factors are based on the inflation data that reflect the increase of non-construction related material and labor costs.

FINAL COSTS

So given a “location factor” of 0.85, a “time factor” of 3.17 (CCI-based) or 3.35 (inflation-based), and an estimated construction cost of 0.87 million dollars, the final costs of wastewater treatment are listed in Table 15.

Table 15. Final Costs (million dollars)

Final costs	Time Factor	
	CCI-based	Inflation-based
Facility level	2.34	2.48
System level*	196.56	208.32

* Assuming a system consisting of 84 facilities

POLICY AND REGULATORY ISSUES

This section takes all other sections into consideration to examine the policy implications of the two systems that are analyzed. First, the permitting and siting concerns of having commercial algae biofuel production are examined, and summarized in Table 16. Second, there is a review of the policy instruments used in the biofuels sector. Third, these policy instruments and permitting concerns are taken into account in the formulation of four policy recommendations. These recommendations can then be used by policymakers to create a commercial algae biofuel industry, as described in our systems, that reaches for the lower end of potential environmental impacts and is based on a foundation of sustainability.

Table 16. Policy Comparison of Systems

	System A: Autotrophic Culture	System B: Heterotrophic System*
Concerns with Endangered Species Act	Very large	Small
Clean Air Act Permits	Yes	Yes
Wastewater Discharge Permits	No	Yes
On-site Wastewater Construction and Operating Permits	Yes	No
Pretreatment Permits	No	Yes
Concerns with the Toxic Substances Control Act	Probable	Probable
Concerns With NEPA	Yes, if federally funded or on federal land	Yes, if federally funded or on federal land
Permitting Analog	Dairy, renewable energy	Industrial processes, ethanol conversion
Direct Land Competitor	Other renewable energy projects, agriculture, and industry	Industrial, Residential (if switchgrass is an input, then marginal land as well)
Land Siting Concerns	Very large	Small
Use of Tribal Lands	More likely	Less likely

* Direct Impacts

WATER AND LAND PERMITTING CONCERNS

To reduce the burden of environmental externalities, permits are often required to either minimize or relocate these impacts. This is the case with many alternative energy producers, and the governments at the federal, state, and local levels require these energy producers to get permits to site their production facilities. To mitigate the potential harm, a regulatory approach of permitting is used, and it controls the amount and type of environmental externalities in such industries. This is the point where intervention occurs to solve the realized or potential environmental harms from the fledgling industry.

Permit compliance can be costly. There is general uncertainty about the cost of compliance efforts before new processes reach a commercial scale. Presumably, there will be plenty of time and money tied up in reaching compliance, so a helpful exercise would then be to look at permitting and siting in the context of analogs to a commercial algae biofuel industry. Based on analog industries and the government's likelihood for using past precedents in current situations, this would allow for a general sense of what the commercial industry can expect moving forward in the permitting process, and then create recommendations grounded on these expectations.

DAIRY AND ETHANOL PRODUCTION FACILITY PERMITTING AS ANALOGS

An important aspect of commercializing algae biofuel production is to perform a gap analysis and identify the potential gaps in the ability of existing policy to handle impacts in relation to algae fuel production. Therefore, it is necessary to examine the existing permitting requirements of analog industries since they would presumably have similar environmental impacts to a commercialized algae biofuel industry and would face many of the same challenges. It would be prudent to look toward a parallel system that has strict permitting requirements, in order to understand what kind of permitting requirements the commercial algae biofuel industry could face. There are obvious differences between the systems, but the dairy industry proves to be a good analog in that it is a system working with a number of potential environmental harms and many things that could potentially go wrong.

The process to obtain a dairy facility permit varies from state-to-state, with some states being stricter than others, but the federal Clean Water Act (CWA) binds all states. CAFOs are now identified as point sources of pollution under the CWA, thus subjecting them to the National Pollutant Discharge Elimination System (NPDES) program (Dairy Producers of New Mexico, 2007). Most states have the authority to manage CAFO programs and issue the necessary permits. General permit requirements for CAFOs are that they implement a nutrient management plan, submit annual reports to regulating authority, keep records of nutrient management practices for at least 5 years, and keep a current permit at all times of operation (Dairy Producers of New Mexico, 2007).

States also have their own discharge permits. New Mexico, for example, has discharge permits that are issued based on discharge volume, not number of cows, through the New Mexico Environment Department. They also mandate that there must be compliance with public notice requirements. The permit application is not cost-prohibitive, as the filing fee is only $100, but the fee schedule of additional fees is based on discharge volume (Dairy Producers of New Mexico, 2007).

In all upper Midwest states, state-issued permits and approved construction plans are required for the construction of a new milk production facility or for the improvement of an existing facility. In addition to these state regulations, they are also required to participate in other aspects of the permitting process, including public hearings and local government consent. This is an expensive process and the total for engineering and legal expenditures to secure such a permit run from $50,000 to several hundred thousand dollars (Hann, 2003). Many claim, however, these regulations go too far and are too expensive, even for such an environmentally damaging industry (Childress, 2010).

This is, however, not to say that there are not sustainability lessons to learn from the dairy industry, and how such an environmentally harmful industrial process can be conducted sustainably. A 2010 report from Aurora Organic Dairy documents the measures that can be taken to mitigate the potential environmental damage from this industry (Gough et al., 2010). Being a water-intensive industry, water meters installed at particular points in the entire process allows for efforts to be undertaken that increase the water conservation efficiency where possible. This is helpful as a best practice to consider in the algae industry, as well as just generally quantifying water use. The study suggested getting the detailed picture of operational water uses, and of those through its supply chain, thereby looking into best practices for water uses as water scarcity increases, and understand how much of the total life-cycle water use can be made more efficient. Another recommendation was to source inputs from low water stress regions, to reduce the total environmental footprint of the operations.

These lessons are important when we think about algae biofuels and increasing the overall sustainability of operations. Since water use is such a major issue with algae facilities, best practices like those undertaken in this analog industry would be prudent, as well as life-cycle analysis of water use, which allows for efficiency measures to be undertaken at various points of the process that may be inefficient. Also key is to reduce the life-cycle impact by sourcing inputs from areas of low water stress, thereby not increasing the water stress in the desert ecosystem.

Obviously, the dairy industry is a heavily regulated industry and permitting to prevent groundwater or surface water pollution is a huge cost. There are many unknowns for algae biofuel production in these hypothetical systems, and one is the environmental damage that a release of algae, whether they are GMO, exotic, or native, would cause on the ecosystem. The danger of run-off (different from discharge in that it is an unintentional release instead of an intentional release) if there is a large storm that causes the algae ponds to flood into a water source, could cause significant environmental damage. It is reasonable to think that algae biofuel industries will be subject to strict discharge regulations like the dairy industry is. Algae fuel producers would have to invest time and money in securing operating permits for their facilities. It will be important to anticipate discharges from algae facilities and the associated permitting and mitigation requirements for compliance with NPDES. States will face similar situations to those seen in the dairy industry and have their own specific permitting requirements. There will probably be situations like dairy, however, where some states are stricter in their permitting requirements than others. If the algae industry exploits states having less strict environmental requirements, its sustainability may consequently suffer.

This is a similar situation with ethanol, in that states require a number of water quality permits, including the NPDES permits, which need to be addressed when an ethanol production facility is constructed and operated. This is important because permits address all wastewater that will be discharged from an ethanol facility, and applies to all ethanol facilities since zero wastewater discharge facilities don’t exist (Nebraska DEQ, 2006). Additionally, there will need to be notification to local treatment plant officials of these discharges. For ethanol production facilities in Nebraska, for example, the necessary permits include: the NPDES permit, which controls wastewater discharges into the state's surface waters from the facility; a Nebraska Pretreatment Permit, which requires testing designed to meet pretreatment guidelines set by the state; a Wastewater Facility Construction Permit, which must be obtained before constructing any sort of wastewater handling system such as holding ponds or outfall pipes; an Onsite Wastewater Construction and Operation Permit, which is required for onsite wastewater treatment systems and requires an operating permit after this system has been certified; an Underground Injection Control Permit, which requires that it be obtained prior to installing a water injection system; and NPDES Industrial Storm Water Permits and Construction Storm Water Permits (Nebraska DEQ, 2006).

This ethanol facility analog is particularly important to algae and is a good analog to System B, since the wastewater permitting will likely be similar to this described here. System A also has some similarities. Since this autotrophic system will have on-site storage of wastewater, there will need to be permits for the construction of holding ponds and the operation of on-site waste water treatment systems, as well as general NPDES permits. This system will also need permits for injection wells. For System B, there will need to be permits that require pretreatment of the wastewater before it is sent to the water treatment plant. In either case, there will undoubtedly be notification to local authorities of this and confirmation that all state permits have been obtained in time for the construction and operation of the facility.

RENEWABLE ENERGY PERMITTING AS AN ANALOG

It is reasonable to conclude that many of the problems with siting and permitting that other alternative energy producers face, will also apply to algae producers. In this way, we presume that permitting and siting of facilities will be the major problems for expansion.

These problems are likely more intense for facilities that are at the commercial scale we consider in our systems than in smaller-scale facilities. There will be basic infrastructure challenges such as siting a location not too close to residential areas and having adequate access to water, roads, and electricity, as well as the typical “Not In My Backyard” resistance from the local community. Having the characteristic of being a “green” project on itself will not make permitting any easier, as the wind and ocean energy industries discovered many years ago (Kram, 2009).

The system that is commercially developed with algae is important for siting and permitting concerns. In System B, a number of these concerns will be overcome, since the facilities can be regulated like other existing industries such as ethanol or biodiesel plants, and be located in an industrial zone. Even though the permitting for these can still take some time, it would still be considered an industrial facility and probably be regulated like traditional ethanol facilities, which just have air permits and wastewater discharge concerns. According to Peter Mostow, a partner in a law firm that works with clean technology and renewable energy firms, there may not be any special permitting issues with algae PBR facilities, as they will likely just have wastewater discharge permits, and possibly air permits too (Kram, 2009).

System B would have the advantage in the short term over System A with its open pond facilities that cover hundreds of acres. The fragile desert ecosystems must be considered with permitting and siting, and is especially a concern when it is considered that much of the land in this area is federally-owned, and any open pond facility out here will likely at least partly contain some portion of federal land.

There are also concerns that need to be researched by wildlife agencies when hundreds of acres of ponds change an entire area's ecosystem. Concerns for GMO release from open ponds may require an additional layer of government regulation. Algae ponds are also critically different in that they completely change land-use patterns in an area, something that differentiates it from wind power. Since algae cannot act like wind power and allow for leases of small swatches of land from property like wind turbines can, this prevents existing landowners from continuing whichever activity had previously occurred on the property. In this way, algae ponds and solar are similar in that they require the purchase of land for their facilities, rather than leasing development rights from a current landowner, since these industries require facilities that are fully dedicated to production.

Another factor to consider when you look at the desert is that much of this flat and sunny land that is good for an open pond, is also greatly suited for thermal solar electricity production. Since this industry has had more time to work through ideal locations in this area, many of the great locations of flat and sunny land have already been leased by this industry. These are also probably the areas where the concerns of endangering threatened wildlife are less than that of surrounding patches of land, since wildlife assessments have presumably already been done in the permitting process.

A 2010 paper for The Wilderness Society detailed the decision-making process for siting solar energy in a desert setting (Ferdandes, et al., 2010). Solar developers must steer through a complex network of federal and state agencies and processes to receive the necessary permits for building facilities in the California desert. Covering over 260 million acres of public land, the Bureau of Land Management (BLM) is the largest land manager in the nation (The Bureau of Land Management, 2011), and the major agency responsible for approving the siting of new solar facilities. The paper notes that with renewable energy development, current federal administration and policies promote the use of federal land, and although many solar facilities have the choice of leasing or purchasing private land, this is not as attractive of an option as using BLM land. The benefits of using this public land are that it is easier to lease from one federal owner of the land, rather than from purchasing from a multitude of private owners. Additionally, there is the possibility of returning the land to the BLM at the end of the useful facility life, which would be easier than purchasing the land and finding a purchaser interested in highly degraded desert land.

The documented process of development for any proposed solar facility on public land in California would include a Right-of-Way grant from the BLM to develop the land, approval of a power purchase agreement from the California Public Utilities Commission, a license from the California Energy Commission, and to have the California Independent System Operator perform a facility study that includes research into feasibility and system impact. There also needs to be consultation with other federal agencies. Consultation with U.S. Fish and Wildlife Service ensures that the actions that the BLM authorizes do not jeopardize listed species in any way. The U.S. Department of Defense also must investigate any application that is received by the BLM to determine if any proposed interferes with their defense mission. Other key state agencies that would need to be consulted would be the state wildlife offices, state historic preservation offices, and any tribes with cultural ties to BLM lands. The National Environmental

Policy Act (NEPA) analysis would be a key step in this permitting process, as the land leased by the BLM would require it when determining whether a facility receives the Right-of-Way grant. This is an expensive process, as each individual facility is estimated to spend $200,000 to $300,000 in BLM cost recovery fees for the entire permitting process, in addition to monitoring fees accumulated through the life of the project.

There are, however, criticisms of the BLM process in the Fernandes et al. (2010) assessment. They point out that the process that BLM uses does not fully consider all the alternative options available, which could possibly please interested stakeholders, who currently feel left out of the process. It also does not look at the cumulative effect and impacts that multiple projects can have on the ecosystem. These issues will be important to consider from an environmental standpoint as an algae biofuel industry commercializes on federal land.

This is a great analog for System A, in that many of these same issues will be paralleled with the solar industry. Since these are both desert systems, many of the agencies involved in the development of proposed facilities will be the same. The siting and permitting process for algae will likely involve the BLM and the NEPA process, as the majority of public lands in the Southwest are owned by the BLM (The Bureau of Land Management, 2011). Many of the other state and federal agencies involved with solar will be important with algae, as power purchase agreements and similar licenses will be needed for algae. Algae will also need to consult state authorities regulating water use, which is something that is ranked as a great concern by California residents with solar development, and will certainly have exponential growth in this concern once residents realize how many ponds are necessary in this system. The solar industry, however, is a more mature industry and many of the siting and permitting concerns have been worked out, or are in the process of being solved. It remains unknown just how existing policy on solar can handle the impacts of algae biofuels, as there are many impacts in the commercial algae industry that would not be accounted for in existing solar permitting requirements. Recommendations suggested later in this assessment make an attempt to close these gaps in the ability of existing policy to handle impacts in relation to algae fuel production.

Another potential analog industry to algae biofuels in terms of heavy permitting is ocean energy since the oceans are particularly sensitive ecosystems, just as algae facilities run many potential risks in environmentally-sensitive regions, such as in the Southwest desert region we consider in System A. Since the offshore waters are exclusively of federal control, this means that all impacts on every aspect of the ocean ecosystem must be considered. An operating permit would be required, as well as considerations with the ESA, the National Marine Fisheries Service, the Marine Minerals Management Service, and NEPA if the project is considered a federal action. Since the science surrounding this technology is not fully understood, and therefore the impacts cannot be accurately quantified or portrayed, no permits have been issued for this yet (Tran, 2009). This is important for algae, as permits could be delayed until the science surrounding the systems are fully understood and the environmental impacts can be quantified when viewed at the commercial scale of production.

TRIBAL LANDS

With algae biofuel development on the scale we examine, there will need to be huge areas of land needed to develop into open raceway ponds and production facilities. Companies will attempt to get the best land they can for the cheapest price, and with the fewest obstacles. One way to possibly go about all three of these goals would be to lease land on tribal jurisdictions or to have some tribes co-own or operate an algae facility. Not only could this potentially circumvent or streamline some federal permitting requirements, such as NEPA, it could also potentially be great publicity for a company that revitalizes tribal land and a tribe by providing this economic development. What could potentially be a situation that we see would be that tribes allow an algae company to use their land for production.

Studies have previously concluded that Native American tribes are very interested in the development of renewable resources, as long as this occurs without compromising their cultural, social, economic, and political integrity (Acker, 2003). There are sets of strategies and policies that are recommended to tribal leaders for consideration when there is the possibility of a renewable energy project that can act as an economic development for the tribes, while also retaining their tribal sovereignty in the process. However, this pertains mostly to the use of these renewable energy sources by tribes themselves, so that they can make their tribes energy independent and finally provide electricity to all portions of their tribe.

The internal and external factors that a tribe must consider when deciding whether to develop are cultural compatibility of this renewable resource development, as well as access to capital. A tribe that wants to develop biofuels can partner with a company, if the tribe were to have economic development benefits, as well as jobs for tribal members, and some form of co-ownership of the venture with the company (Acker, 2003).

There are also federal statutes, such as the Energy Policy Act (EPAct) of 1992 that allow for various incentives for the creation of renewable energy on tribal lands. One of these is the “Buy Native American” policy that the federal government uses for many instances of procurement, and this could presumably be expanded to be inclusive of the purchase of algae biofuels from a company located on tribal land and co-owned by a tribe.

GENETICALLY MODIFIED ALGAE AND THE TOXIC SUBSTANCES CONTROL ACT

Undoubtedly, the issue of using GM algae to enhance biofuel production will be one that will need to be addressed before the industry grows to the scale in the systems we describe. Potential environmental issues of GM algae do appear great enough, especially in the case of a large release of these organisms into the ecosystems, that some NEPA review procedures, such as the Environmental Impact Statement or Environmental Assessment processes, will be needed when federal funding or leasing tracts of federal land for algae biofuel production. Likely, however, existing policies will be used with biotechnology issues, as has been the case in the past. There has been a precedent with biotechnology that it can be adequately regulated through using the current federal infrastructure and modifying the current laws to fit the regulation of this biotechnology (Belson, 2010).

The Toxic Substances Control Act (TSCA) is the federal statute in place, in which the EPA regulates the chemical substances that are not regulated under other statutes. Since the definition of chemical substance includes “any organic or inorganic substance of a particular molecular identity”, this includes microorganisms (US Environmental Protection Agency, 2010). It is almost certain that using genetically modified organisms of algae to produce biofuels in an industrial application falls under TSCA (D. Glass Associates, Inc., 2010). This is relevant to algae biofuels because any party that seeks to produce GM algae will have to submit information about the microorganism and how they plan on manufacturing or otherwise commercially using this substance, by filing a Microbial Commercial Activity Notice (MCAN). These MCANs have been received by the EPA for GMOs where the organism is intended to be used in the production of cellulosic ethanol, so there is precedent for GMOs in biofuel production, and it should be expected that more MCANs will be filed as the algae industry commercializes (D. Glass Associates, Inc., 2010). Additionally, before these chemicals are used, the parties have to show the potential environmental or human health effects of commercially using these microorganisms. This would then be a relevant risk calculation of the GM algae that will be used, and accomplish one of the main goals of NEPA of reviewing the potential environmental risks of the GMOs being researched or otherwise used (D. Glass Associates, Inc., 2010). It is also imperative to remember that requiring the NEPA process for future funding involving GM algae might become a reality if policymakers point to the fact that government-funded laboratory research on GM algae will someday be used at a commercial scale and that will potentially have a significant environmental impact.

Since there is a history of using the TSCA to establish commercial use of GMOs in biofuels and there have not been unusual risks found with these to the environment or human health (D. Glass Associates, Inc., 2010), it seems that the TSCA process will not be overly burdensome for GM alage producers. Producers should be able to use the past precedent with GMOs under TSCA and be able to successfully use their organisms commercially.

POLICY DEVELOPMENT

In addition to regulatory compliance, it is likely that a commercial algae biofuel industry will be subject to other policy instruments. The development of renewable energy fuels has been a focus of the DOE for decades. Government investment in research and development is considered essential to algae biofuels production. In addition, policy instruments like subsidies have been used to grow an industry to commercial scale. Possible policy interventions for the renewable energy sector can include subsidies, renewable fuel standards, removal of fossil-fuel subsidies, carbon taxes, renewable portfolio standards, low-carbon fuel standards, feed-in tariff, green certificates, concessional loans, and consumer education about renewable energy benefits (The World Bank, 2010). It has long been hoped that such interventions would decrease the time it takes for renewable energy technologies to enter the market and become cost competitive with fossil fuels.

The following is a description of U.S. policy instruments currently being used to promote renewable fuels, which include, or can be expanded to include, algae biofuels. These current domestic policies have allowed the development of first-generation corn ethanol, and will aid second- and third- generation fossil fuels.

TAX INCENTIVES

Since 1978 (Tyner, 2008), there has been a national subsidy written into the EPAct to encourage the development of a biofuels industry within the U.S. Historically, tax credits have been the easiest and most pervasive way to encourage the development of an industry favored by policymakers. The Volumetric Ethanol Excise Tax Credit (VTEEC) has helped corn-based ethanol become more economically attractive, and has been in place since 2004. Therefore, despite vast changes in the price of oil and corn, the subsidy continues to encourage the use of corn ethanol at a large scale (Tyner, 2008). There are a number of tax credits that are currently in place to incentivize biofuels, as seen in Table 17.

Table 17. Current Policy Incentives for Biofuels*

Policy	Authorizing Legislation	Value
Volumetric Ethanol Excise Tax Credit	American Jobs Creation Act of 2004	Up to $.45/gallon
Biodiesel Mixture Excise Tax Credit	Section 40(b) of the Internal Revenue Code	$1/gallon
Small Ethanol Producer Tax Credit/ Small Agri-Biodiesel Producer Tax Credit	Section 40(b)(3) of the Internal Revenue Code	$.10/gallon for up to 15 million gallons (qualifying manufacturers must produce less than 60 million gallons)
Production Tax Credit for Cellulosic Ethanol	Section 40(b)(6) of the Internal Revenue Code	Up to $1.01/gallon
Alternative Fuel Excise Tax Credit	Section 40(b) of the Internal Revenue Code	$.50/gallon for qualifying alternative fuels

* U.S. Department of Energy (2011)

These tax credits are typical examples of economic incentives to stimulate the renewable energy industry. These programs have been implemented independent of in-depth risk assessments to determine the environmental and economic impacts of growth. The first-generation corn ethanol industry has developed with the help of these credits. However, tax credits cannot overcome fundamental technology limitations such as those that plague cellulosic ethanol production, and so its development has not been as fast as many had hoped.

At this time, the status of algae fuels technology is too premature for a tax credit to be beneficial. However, as production increases and algae biofuels become available commercially, a subsidy similar to those of corn ethanol can improve cost-effectiveness and can encourage producers and conversion facilities to enter the market.

ENERGY POLICY

In 2005, the EPAct expanded support for the research and development of biofuels and alternative energy. Incentives for cellulosic ethanol incorporated in Section 942 hoped to stimulate the production of one billion gallons annually by 2015 (Energy Policy Act of 2005). The Bioenergy Program (Section 932) was established to foster cooperation among the DOE, private firms and academia to improve technology and increase price competitiveness of the technology. In Section 941, the Biomass Research and Development Act of 2000 was amended to include four new divisions of research and development. These include:

- Improvements of feedstock production through crop development
- Produce biofuels through recalcitrant cellulosic biomass intermediates
- Improve feasibility of biorefinery fuel production
- Assess the environmental sustainability and security of various biomass technologies (U.S. Department of Energy, 2010).

Unlike corn ethanol, which follows a simple agricultural model, algae cultivation will need highly specialized scientists, engineers and laborers. Through research and development, DOE hopes to amass the knowledge necessary and implement algae cultivation across the U.S.

RENEWABLE FUEL STANDARD

The EPAct of 2005 also created the RFS, which was greatly expanded by the EISA of 2007. The RFS volumetric renewable fuel requirements was 12.95 billion gallons of renewable fuel in 2010; most future expansions of renewable fuel volume must meet a greenhouse gas requirement, as determined by a life-cycle assessment to qualify (U.S. Environmtal Protection Agency, 2010). The RFS includes algae as a renewable biomass, meaning that there will be increased motivation for algae production as an input for biodiesel.

By having a government-mandated renewable fuel goal, private and public investment and research into new technologies will be encouraged. This also ensures farmers that they will have a buyer for the renewable feedstock that they produce. Eventually, the RFS will trigger investment in conversion facilities, which, due to their high capital cost, require price security for biofuel before it is constructed.

USDA'S BIOMASS CROP ASSISTANCE PROGRAM

The 2002 Farm Bill was amended to create the Biomass Crop Assistance Program (BCAP) in Section 9011 of the 2008 Farm Bill. BCAP is a program administered by the Farm Service Agency (FSA) within the United States Department of Agriculture (USDA). This congressional effort was intended to aid farmers and foresters entering the biomass supply chain and to increase the supply of biomass available to produce heat, power, advanced biofuels, and biobased products. In theory, this policy will help increase the supply of biomass needed for biomass conversion facilities to meet the RFS, while reducing the risk associated with switching to biomass crops. Under this program, organic matter, like agricultural waste, vegetative and wood waste, and algae, may qualify for payments from USDA.

BCAP provides a number of financial benefits to bioenergy crop and biomass producers including eligible crop establishment payments (up to 75% of total cost), annual payments for 5 - 15 years, as well as matching payments for the collection, harvest, storage, and transportation of eligible materials (up to $45/dry ton). Over time, funding will likely target establishment and annual payments, which algae biomass producers are eligible to receive; however, algae producers are not eligible to receive matching payments associated with offsetting transportation costs.

However, the current small scale of algae biofuels production puts it a marked disadvantage compared to that of woody and agricultural waste. There are no investments in commercial scale conversion and processing facilities, with which farmers can work and develop BCAP plans. Further, since algae biomass is not eligible for the transportation matching funds, there is no policy to mitigate these opportunity costs. The incentives for this program are mostly based on coupled industries, like traditional agriculture or forestry that can take advantage of established protocols and methods and switch to biomass production. With experts estimating commercial-scale algae production to be available in 10 to 15 years, many of the existing incentive plans that were created in response to RFS will be expired, with the hope that biomass will have reached production levels that it can stand on its own.

POLICY RECOMMENDATIONS

National environmental policies operate at the intersection of what an industry *can* do and what they *should* do. A well-crafted policy will be influenced both by science and politics, with a goal to maintain environmental protection without limiting industrial growth or individual rights. A technical assessment of an industry – including the technology, economics, and environmental impacts – is a tool to inform decision-makers on how to craft policies to ensure that the societal advantages outweigh the detrimental impacts. As explored in this assessment, System A and System B each have their own costs and benefits. Both systems have improved efficiencies, including land use and nutrient inputs, over corn ethanol; however they still have negative environmental impacts that must be mitigated to ensure the sustainability of the fuel. The quantified impacts that are of highest concern include the use of GMOs, water use and resources, land use loss, and nutrient inputs.

The NRDC report identified the environmental challenges that may persist until an algae biofuel industry is developed at scale, and provided several recommendations to encourage commercialization of an algae biofuel industry in a sustainable way (Ryan, 2009). This report takes the NRDC's findings a step further, and brings together the economic, technical, policy, and environmental ramifications of a commercialized algae biofuel industry, by examining two model systems that give a picture of what a commercial scale algae biofuel industry will look like. After reviewing the technical findings and giving careful consideration of the quantified environmental impacts and the issues they raise, four general policy recommendations are synthesized after the previous examination of the two analyzed scenarios. These are proposed to protect and manage against environmental impacts by aiming to reach the lower range of potential environmental impacts of a commercial algae industry, if and when it reaches such a large scale. Policymakers can then use these recommendations immediately and into the future as points to keep in mind and actions to perform when critical decisions are needed that affect algae biofuels production.

RECOMMENDATION 1 – ENVIRONMENTAL RISK ASSESSMENT

By location, perform an extensive environmental risk assessment prior to production to understand possible consequences of GM algae cultivation and examine potential environmental impacts before the species and location of algae cultivation are selected.

The potential environmental impacts of algae biofuels that have been quantified in this study are concerns that a number of environmental groups share. The most widespread apprehension is the unknown consequences of non-native species, biodiversity, and water use on a large scale. Although the human health concerns that are prevalent with GM food crops are not a concern with algae used strictly for fuels, the potential environmental impacts of GMOs and non-native species introduction are diverse and unknown. With this in mind, it is essential that legislation should restrict the use of GM and non-native algae until a risk assessment has been performed, following the precautionary principle. The assessment will consider the environmental impacts of algae biofuels through a comparative risk assessment of the status quo. To create a successful process, there are a number of areas that must be included.

Create a collaborative joint-learning process

In previous research on environmental impacts, there has been heavy debate on the validity and credibility of the research. By creating a collaborative risk assessment, stakeholders are more likely to trust data and results generated by the assessment. For example, hazardous waste siting conflicts have been settled through this approach, despite the varying interests and scientific opinions (Rabe, 1994). This model can be applied to algal fuels production due to the similar nature of the siting concerns and varying opinions on what the impact can be. It is essential for all interested parties to be represented during the collaborative process. In the case of algae biofuels, the parties would include government agencies that are participants either through land ownership or environmental compliance, industry representatives, non-governmental organizations and concerned and informed members of the affected community. By assessing the potential impacts of the system in this way, it is more likely that a long-term, sustainable solution can be formed, as seen many times in the field of conflict management (Wondolleck & Yaffee, 2000).

This collaborative approach should include all key stakeholders, including the affected industry, state government departments like Fish and Wildlife and Environmental Protection, federal government agencies including U.S. Geological Survey, and interested non-governmental organizations with a stake in the outcome, like National Wildlife Federation and local advocate groups. By assembling this educated group during the siting process, they can work together to find the best site and method of algae biofuel production, based on important economic factors and sustainability goals.

Non-governmental organizations, research facilities, government agencies and private firms will all benefit from the summation of knowledge on the complex environmental systems that must be monitored. Bringing in multiple sources of data - qualitative and quantitative - will lead to more reliable results. This collaborative process should determine the impacts to be measured. These matrices might include species migrations, endangered species, critical habitats, biodiversity protection, non-native species introduction and water levels and contamination. It is important to acknowledge that these matrices do not nullify the uncertainty associated with the assessment. The complexity of the environmental systems that will be affected is immense. By incorporating this risk, decision-makers are better able to make informed choices and consider likely relationships independent of their statistic significance (U.S. Environmental Protection Agency, 2010).

Create flexible, iterative and adaptive risk assessment process

The relevance of environmental risk assessments is subject to the data available. It is essential that the assessment structure is flexible to the level of details that are available. "The Cartagena Protocol on Biosafety recognizes that the information required for any particular risk assessment will vary in nature and in level of detail depending on many factors. […] What is important is not whether there is a pre-determined number of steps or a particular methodology, but rather that risk assessors understand that it is appropriate to increase the level of detail of any assessment depending on the results of preliminary analyses, the nature of the decision to be supported, and the limitations of available data (U.S. Environmtal Protection Agency, 2010)." Further, the results should be reassessed based on the changing data and conditions. By looking back, we can validate or adjust assumptions that were made in the original assessment. Through an iterative and adaptive approach, the credibility of the assessment will be maintained as further legislation or products are introduced.

Monitoring

A crucial step in any successful assessment is to ensure continuous monitoring and mitigation of any unexpected adverse impacts. Through the risk assessment, key factors should be identified that will need monitoring as the algae biofuel industry expands and evolves. From the environmental impacts recognized in this report, water use and discharge quality is vitally important to assessing ecosystem effects. Further discussion on water resources are discussed in Recommendation 2. Land use change will also need to be monitored to determine adverse impacts to wildlife, air quality, and the ecosystem. The technical experts within the aforementioned collaborative can execute monitoring. State and national government agencies already monitor a number of these factors on a large scale and their information can be adapted to determine the affects of algae biofuel production. Non-governmental organizations have skill sets that can highlight concerns over specific impacts, such as wildlife disturbances and habitat change. By distributing the workload of monitoring among these groups, the data will be more reliable and there will not be undue burden to one group.

Environmental law compliance

Any federal action, including a federally funded project, will have to comply with NEPA. NEPA requires an Environmental Assessment or Environmental Impact Statement, which will include a collaborative process to determine possible adverse impacts of the project, as well as a comment period for public responses. NEPA also includes a site-specific component to ensure that local impacts are considered and mitigated. This will address the concerns discussed in the proposed environmental risk assessment.

It is recommended that all projects involving GM algae fall under the requirements of the TSCA. As noted earlier, TSCA also requires a risk assessment. This act gives authority to require any "any organic or inorganic substance of a particular molecular identity" to be assessed in this way. By gathering this information, mitigation efforts can be tailored to the ecosystem and the type of operation that exists at the site.

RECOMMENDATION 2 – WATER REGULATION

Water use must be regulated and controlled. Algae cultivation is water intensive. By incentivizing water recycling and use of lower-quality water for the algae medium, the consumption of the water may be reduced. Further, blowdown and other waste material must be regulated to reduce the risk of water and soil contamination.

As evaluated in the *Environmental Impacts* section, water use has the potential to be high, which will be especially taxing in the Southwest, where water availability is limited. Based on current technology and economic conditions, open ponds seem to be the most commercially viable form of algae production. A commercial production facility of this kind would require enormous amounts of water. Large-scale production in the Southwest would almost be cost-prohibitive unless water costs are mitigated. This can, and should, be done in two ways. First, water recycling should be implemented. By recycling water, the facilities will reduce their water footprint and have the potential to retain nutrients, decreasing input costs.

Second, algae should be produced in low-quality water, including brackish water. Brackish water availability is higher than freshwater in the Southwest. The cost for brackish water is low and has the potential to improve the life cycle sustainability of algae biofuel. To ensure that this is a priority consideration for the commercial industry, it should be regulated. Using existing water regulations and crafting incentive policies to reduce total water consumption can mitigate the potential adverse impacts of these facilities. The CWA can be used to ensure that any discharges from these facilities are regulated and controlled. There is risk of water overdraw, and to avoid problems associated with this, incentive policies can be used to provide benefits for producers to encourage water recycling in facilities and to use the lowest-grade water possible. One example of such a policy would be to create cost-sharing incentives, as seen in non-point source pollution mitigation in traditional agriculture (Feather & Cooper, 1995). This voluntary effort would encourage producers to invest in recycling technologies or infrastructure for using brackish water by giving monetary incentives, which would reduce the cost of establishing these practices.

Another area that will need to be regulated by various policies is the blowdown and other waste material that these facilities produce with their leftover water that has numerous materials in it. This will need to be regulated so that the heavy metals and other leftover nutrients do not contaminate water sources. The CWA and Safe Drinking Water Act will be implemented, but it is essential that continued monitoring and assessments of aquifers and soils occur to ensure that discharge is being done safely. This monitoring can be done through facility self-certification as well as periodic monitoring from state and national government agencies.

RECOMMENDATION 3 – CO-LOCATION INCENTIVES

Incentivize co-location of production, harvesting and extraction to reduce the carbon footprint of algae biofuels. By investing in technologies that can take advantage of wastewater treatment plants, power plants, and centralized extraction facilities, there will be reduced transportation costs, emissions, and land use loss.

Co-location is vital to improving the sustainability of algae biofuels, by decreasing environmental and economic costs of inputs, transportation, and land use loss. As previously noted, the process of cultivating algae and turning that into biofuels is a multi-step process. This requires companies that invest in these biofuels to scale-up their laboratory-scale processes on a much larger level. As is the case with many other industries, it is likely more economically-efficient for algae biofuel companies to go with a vertical integration model of business. Numerous companies may have already experienced the increased costs of business as their facilities grew in size and they need to provide many inputs to various parts of the algae biofuel process at an industrial scale, rather than at a laboratory scale, as had likely been the case.

For example, to provide the basic input of CO_2 and other nutrients to the cultivation process, this may not seem to be a problem at a smaller scale, but this becomes difficult when done at a large scale. In many areas, these nutrients may be prohibitively expensive in large quantities or not entirely available altogether, so this makes the vertical integration strategy and co-location of algae facilities with other facilities, such as coal-fired power plants, that can readily provide these nutrients for algae in large quantities. This benefits the power plants in that they will reduce their emissions by providing to algae production instead of paying for emission credits in the future or other costly means of reducing these emissions.

Co-location could also include municipal wastewater treatment plants, since algae production utilizes many of the nutrients such as phosphorus and nitrogen that are in the water that comes from these plants. This nutrient-rich water is environmentally safe, but putting it to use with algae production creates a smaller environmental footprint than using these nutrients for fertilizer sales (Fischetti, 2010). In System B, where carbon is a vital input to growth of the algae, co-location of algae facilities where carbon is available will eliminate the need for switchgrass as a feedstock. Without this, the indirect land use impact will drop considerably and make algae biofuels much closer to carbon neutral.

Vertical integration would also include the co-location of the harvesting and extraction processes as well, with the goal in mind to reduce the carbon footprint of algae biofuel, and because there are many other benefits to vertical integration. There are benefits in that vertical integration allows for better communication among researchers at all steps in the algae biofuel production process. Industrial learning will be essential to progressing the industry and ensuring its economic viability. Facilitated communication allows for all researchers of a company to be closely located and to effectively exchange ideas with other researchers at the other end of the production line so they can work together to produce the highest quality product possible. This almost assuredly allows for greater quality control as all steps of the process will be in the same area, and the chances of something going wrong along the way is minimized.

In addition to aforementioned benefits, greenhouse and other emissions can be further reduced through transportation emissions that would normally be associated with transporting the materials through the various parts of the process. This will not only reduce costs, it also ensures that there will be no danger of losing product as it is transported over long distances. Along the same line, is the benefit of reduced land use when all of these facilities can be located on one centralized location, instead of requiring more land and affecting multiple ecosystems, and create additional siting and permitting concerns.

RECOMMENDATION 4 – TIE ECONOMIC SUBSIDIES TO ENVIRONMENTAL PERFORMANCE

Ensure that economic incentives provided for the algae industry, such as those proposed in Algae-based Renewable Fuel Promotion Act (HR 4168), start-up tax credits, and small farmer tax credits, include adequate provisions for environmental assessment and the demonstration of sustainable practices.

Tax incentives targeting algae biofuels would ensure their competitiveness with other biofuels. Currently, the plethora of tax credits, both for quantity of output and facility upstart, are targeted toward first- and second-generation biofuels, including corn and cellulosic corn ethanol. It has been recommended that current corn ethanol subsidies should be phased out because they perpetuate an industry with adverse environmental impacts (Brooke et al., 2009). Third-generation biofuels like algae, however, currently do not receive any incentives to drive demand, leaving them at a competitive disadvantage. This discourages investment for both farmers and corporations who are looking to enter the market. HR 4168, known as the Algae-based Renewable Fuel Promotion Act of 2010, was proposed to take the first steps to rectifying this inequality.

The bill created tax credits for algae biofuels similar to those of cellulosic corn ethanol, while expanding the definition of cellulosic biofuel in the cellulosic biofuel producer tax credit to include algae-based fuel. Further it created a 50% bonus depreciation of property used to produce algae-based biofuels (GOP.gov, 2010). With a total of $1.01 per gallon production subsidy, this credit was meant help bolster the industry further down the line as it markets to individual consumers. Although this bill never became law, it provided a guideline on the possible incentives needed to grow an algae biofuels industry. It is the opinion of this report that incentives, both to subsidize capital investment and at-the-pump costs, are necessary to aid the development of algae biofuels. However, any incentive should require environmental safeguards. For instance, to receive the tax incentives, a company must continuously monitor to ensure that there is no negative impact on water resources and local biodiversity. Any cash grants should require that sustainability not only be considered, but actually incorporated in facility start-ups. Another option would be to include a requirement that ten percent of profits are dedicated to research on sustainability measures. By putting safeguards into the incentive itself, there is a higher likelihood that all stakeholders have a vested interest in environmental impacts.

Similarly, although BCAP might not be a major incentives policy for algae biomass, a parallel policy that incorporates the economic realities and the biomass availability constraints of this emerging biofuel could be quite beneficial. A dependable source of biomass is essential as commercial-scale facilities are being constructed. It is the opinion of this assessment that, environmentally, having algae production localized on small farms is preferable. By incentivizing biomass production for small farming tracts through BCAP or a similar program, the local economic and environmental benefits that algae biofuels have over corn can be more easily achieved. Algae biomass policies must recognize and incorporate these ideas while acknowledging the amount of research and development that still must be done to ensure economically feasibility.

By giving these types of incentives, as they have for solar and wind projects (Witkin, 2010), the government can encourage the proliferation of algae biofuels. However, it is essential that these projects are done properly and all environmental impacts are not just considered (as is required through NEPA), but are a qualification of obtaining the funds. Further, these funds should encourage the co-location of facilities to reduce the land use and GHG emissions impact.

AREAS FOR FUTURE RESEARCH

Throughout the process of writing this report, there have been many instances where assumptions were made due to the lack of information about algae biofuels and their potential environmental impacts. In order to make reports such as this one more effective, there are areas on interest that require future research to fill informational gaps about algae biofuels. Those areas include, but not limited to:

- Quantified data on interactions of GM algae and natural environments.
- Chemical composition of downstream waste material and best practices and standards for the treatment of solid and liquid wastes.
- Life-cycle analysis and GHG abatement analysis of algae biofuel production.
- Detailed mapping of ideal locations for algae biofuel production.
- More extensive algae species classification and native ranges description.
- Information on toxicity of algal biomass growing in wastewater due to bioaccumulation of toxic substances.
- Information on biocide use in cultivation for the control of predators, pathogens, and competitors. Also, their effects on the environment and best practices for use.
- Studies using physical systems exposed to real world conditions of light, temperature, and nutrient fluctuations to determine growth parameters of algae and allow this to be public information.
- Information on differences in pesticide and nutrient use in monoculture and polyculture.
- Processes for recycling nutrients, bioavailability of nutrients, biocompatibility of recycled water in order to reduce inputs.

CONCLUSION

Interest in algae biofuels has waxed and waned over time, depending on the availability and price of fossil fuels, as well as public pressure for an environmentally friendly fuel source. Recently, this interest has peaked once again, causing investment in algae biofuel by private firms and through government research. The first assessments of the biofuel have garnered support from stakeholders and fostered a sense of optimism about the future of algae biofuel production. Many have a desire for this production to be as sustainable as possible before going to a commercial scale. This assessment examines these issues by modeling two hypothetical algae biofuel systems, imagining what they would look like at a commercial scale, and quantifying any potential environmental, economic, or technological impacts. In this way, our paper brings other research a step further and gives a quantitative basis around the formulation of policy recommendations that can mitigate any potential environmental impacts of these hypothetical systems.

Our research shows the potential environmental consequences of a fully commercialized algae biofuel industry, and has found impacts greater than previously described in literature. Under the parameters defined in this assessment, biodiesel from algae can be quite water-intensive and concentrated in areas that are acutely sensitive to water management concerns. Although there are GHG benefits compared to corn ethanol, the proposed carbon-neutrality is highly unlikely. GHG emissions have the potential to be greatly reduced if co-location is incentivized. Lastly, algae biofuel can produce significant volumes of waste, on the scale similar to CAFOs. Waste concerns can be mitigated through regulatory compliance.

However, it must be reinforced that this industry is in its infancy; meaning that technology has yet to be defined and impacts cannot be known at this time. Given this, creating subsidies to scale-up algal fuels cultivation systems are premature. Policymakers should focus funds and grants on fundamental research to create a more robust, sustainable industry. During this process, it is vital to look at lessons learned from other biofuel and agricultural industries to predict potential environmental impacts. These analogs can help policymakers predict what to expect as an algal fuels industry develops and identify relevant environmental policy concerns. Further, as the industry comes to fruition, costs of mitigation strategies to handle water demand and wastes may greatly impact the economic feasibility of algae biofuel production. Research into better algal systems that can lower the need for mitigation is critically important to the commercialization of algae biodiesel production.

Lastly, it is the conclusion from our research that existing policies are not adequate to protect against all environmental concerns and need to be adjusted as this new industry expands. Strong environmental safeguards should accompany the incentive policies that foster the growth of the industry. Our proposed recommendations are intended to guide policymakers in their decision-making processes and encourage sustainability. Each recommendation is independent and will have a wide range of benefits, as discussed in this assessment. All are vital to protecting against ecological degradation, while allowing innovation and expanding our renewable energy options. These recommendations need to be followed in order to hit the lower estimate of environmental impacts of a commercial algae biofuel industry, and effectively mitigate the potential environmental harms that come at that scale by pointing out where there needs to be special consideration paid. With effective use of these recommendations, the algae biofuel industry will commercialize at levels of sustainability not yet seen in the existing biofuels industry.

APPENDIX A | ADDITIONAL TECHNOLOGY

ALGAE DEFINITION

Phycology, or the study of algae, is a complex field. Since “algae” is not a taxonomic name/rank and the organisms that comprise it are not closely related genetically (Bellinger & Sigee, 2010). Algae are not monophyletic and their classification is unnatural. These organisms range in type (prokaryotes or eukaryotes), physiology (autotrophs or heterotrophs) (Bold & Wynne, 1984), phototrophic or chemotrophic (Bellinger & Sigee, 2010), morphology (some with cell walls or flagella), size (from 0.5µm to 200m). They can even be mixotrophic with the ability to shift from using one source of energy or carbon to another; they can store energy as starches, glycogens or lipid; they live in fresh or salt water, on wet/moist surfaces, in soil, on rocks or another organisms and over a wide range of temperatures from glaciers to hot springs (Bold & Wynne, 1984).

Despite their wide range of attributes, all organisms known as algae have the following characteristics (Trainer, 1978; Lee, 2008; Hoek et al., 1995):

- Have at least chlorophyll a or have recently evolved from organisms bearing chlorophyll a. Hence, some do not have photosynthetic pigments, while others in addition to chlorophyll a, have pigments such as chlorophyll b, chlorophyll c, and chlorophyll d, Carotenoids, Xanthophylls, and Phycobilins, and do not always appear green in color.
- Occur as unicellular organisms or as multicellular colonies and thalli (do not have true leaves, roots and stems). The nonvascular thalli may have tissue that superficially resembles leaves, roots and stems. Multicellular colonies and thalli may be macroscopic or microscopic, while most unicellular algae are microscopic, but a few can be macroscopic, eg. *Dicotomosiphon.*
- Have simple reproductive organs, which are not protected with a covering of sterile cells. Unicellular algae may be gametes themselves, while in multicellular algae, the gametes are produced in each of the unicellular or multicellular gametangia.

Algae Systematics: The following are the list of phyla/divisions to which the different algae are classified under (Graham et al., 2008). The taxonomy of the algae is in constant flux and any list is likely to change (Lee, 2008).

- Cyanophyta/Cyanobacteria/bluegreen algae
- Glaucophyta
- Rhodophyta/red algae
- Chlorophyta/green algae
- Dinophyta/Dinoflagellates
- Euglenophyta
- Apicomplexa
- Cryptophyta
- Heterokontophyta
- Prymnesiophyta/Haptophyta

The classes Bacillariophyceae and Phaeopyceae are commonly known as diatoms. Brown algae are classified under the phylum Heterokontophyta. Cyanophyta is classified under the prokaryotic domain Bacteria while the rest of the algae are eukaryotes. The above characteristics are consistent with those used by the U.S. EPA to define algae. Some scientists define algae as eukaryotic organisms distinct from prokaryotic cyanobacteria, but the popular view held by phycologists is to consider cyanobacteria as algae.

Tables 1 to 3 list the processes involved in algae biodiesel production, and give the key decision points available with them, and the option at each of those points. Table 4 lists some of the organisms termed as "micro-crops" for the production of advanced biofuels.

Table 1. Key Decision-Making – Strain Development

Process	Decision Point	Options
Strain Development	Improve Strains	• Bio-prospecting • Breeding • Genetic Engineering[1]
	High Throughput Screening	• Growth Rate • Product of interest content • Halotolerability • Harvestability
	Strain Selection	• Biomass Composition (Product of interest) • Environmental Conditions • Cost

1. Rosenberg et al. (2008)

Table 2. Key Decision-Making – Cultivation

Process	Decision Point	Options	Sub-Options
Cultivation	Metabolic Pathway	• Photoautotrophic	• Open System ▪ Natural water bodies ▪ Raceways ▪ Circular ponds ▪ Open containers • Closed System ▪ Various shape options ○ Flat plate ○ Tubular ○ Annular ▪ Sunlight or artificial light
		• Heterotrophic	• Organic compound input ▪ Acetate ▪ Glycerol
		• Mixotrophic	• Organic compound and sunlight
	Conservation/Recycling	• Yes/No	
	Synergy	• Singular • Hybrid • Integrated	
	Cultivation Mode	• Monoculture • Polyculture	
	Production Mode	• Batch • Continuous	

Table 3. Key Decision-Making – Post Cultivation Processing

Process	Option	Sub-Option
Harvesting	• Biomass Recovery	• Flocculation[1,2] ▪ Bioflocculation ▪ Chemical flocculation • Sedimentation ▪ Centrifugation ▪ Gravity • Filtration • Ultra sonic aggregation • Bio-harvesting ▪ Shrimp ▪ Fish
	• De-watering	• Draining • Mechanical Press
	• Drying	• Sun drying • Shelf drying • Drum drying • Other options
Extraction[3]	• Mechanical crushing • Chemical Solvent • Super critical fluid • Direct secretion • Sonification • Osmotic shock • Enzymatic	
Conversion	• Heat/electricity by combustion • Syngas by gasification • Ethanol by fermentation of polysaccharides • Biodiesel by transesterification of TAG • Bio-oil, Bio-char by pyrolysis[4] • Heavy oil by thermochemical liquefaction • Methane (biogas) by anaerobic digestion • Hydrogen by photobiohydrogen production	

1. Bilanovic et al. (1988)
2. Knuckeya et al. (2006)
3. Lee et al. (2010)
4. Miao et al. (2004)

APPENDIX B | BIOFUELS BACKGROUND

Fossil fuels mostly exist underground and their carbon compounds rarely come in contact with the atmosphere. Humans utilize the energy potential of fossil fuels through combustion. This releases the carbon into the atmosphere in the form of CO_2, thereby increasing the concentration of CO_2 in the atmosphere. This is the major cause of climate change (IPCC, 2007). Fossil fuels are formed over millions of years, when organic matter exposed to high temperature and pressure in the absence of oxygen. This happens when bodies of biological organisms are buried underground. The rate at which fossil fuels are being consumed is much greater than the rate at which they are being generated, and therefore is not a sustainable resource. In theory, they be a renewable resource, but given a time scale of a few hundred years they can be considered to be nonrenewable resources.

Plants use CO_2 from the atmosphere to produce biomass by photosynthesis. The biomass feedstock can be converted to biofuels, which are then burned to provide energy for human use (Bende, 2000; Demirbas, 2006; Kamm et al., 2006; Stevens & Verhe, 2004). The carbon in biofuels comes from the atmosphere, and not from underground sources. When biofuels are burned, the carbon in the biofuels is released back into the atmosphere as CO_2 (Ari & Anthony, 2007). Therefore, the burning of biofuels does not directly increase the amount of CO_2 in the atmosphere, thereby reducing the harmful effects of climate change. The price of infrastructure changes needed for the immediate large-scale use of biofuels is minor compared to that needed for other new energy carriers such as hydrogen (Service, 2004). Biomass used for biofuels feedstock can be grown locally and reduces dependence on foreign sources for energy, as well as provide social benefits like increased employment (Demirbas, 2009).

However, the use of biofuels increases the amount of CO_2 in the atmosphere indirectly because fossil fuels are used in every stage of the biofuels life cycle. For example, agricultural equipment such as tractors use fossil fuels to grow and harvest biofuels crops (Pamela et al., 2009) and the use of chemical fertilizers for crop cultivation releases other GHGs (Snyder et al., 2009). CO_2 emissions also occur when forests are cleared to grow biofuels crops, known as land use and land cover change (Johnson, 2008; IPCC, 2008). The net increase of CO_2 in the atmosphere could be significantly reduced by replacing fossil fuels with biofuels as our primary source of energy (Green & Byrne, 2004; Larson, 2005; Zah et al., 2007).

Biomass can be created with sunlight and nutrients. Sunlight is a renewable resource and nutrients (including CO_2 and water) can be recycled in a short time. Biomass can be regenerated in the order of a few months and can be considered a renewable resource. Fuels derived from biomass (biofuels) can be generated within a short time from and can be considered renewable.

TYPES OF BIOFUELS

The biomass feed stock utilized in the first-generation of biofuels is made from grains and sugar, such as ethanol from sugar cane and corn grain. There is growing concern regarding their impact on the biodiversity and land use competition with global food crops (Naik et al., 2010).

Second-generation biofuels are produced from lignocelluloses, which can be obtained from cheap and abundant nonfood materials like crop residue, perennial grasses and other non-food stock (Naik et al., 2010). Cellulosic corn ethanol is an example of second-generation biofuels. However, if non-food crops such as switch grass are grown for biofuels production on cleared forestland and on agricultural or irrigated land, biodiversity and food production may be adversely affected (Koh & Ghazoul, 2008).

The processes being developed to improve algal oil yields are broadly referred to as third-generation biofuels technologies (Gressel, 2008). Microalgae have high lipid content and grow in aquatic environments, and hence would not compete for farmland and the global food supply chain. Fourth-generation biofuels produce hydrogen or electricity by "photosynthetic mechanisms, directly, or by embedding parts of the photosynthetic apparatus in artificial membranes, or using algae to produce sugars, and yeast or bacterial enzymes to produce electrochemical energy." (Gressel, 2008)

Examples of biofuels include plant biomass, such as wood and animal biomass, including cow dung, which can be used as fuels directly by combustion to produce heat. Biomass can be processed using thermochemical techniques such as gasification, pyrolysis, and hydroprocessing into various solid, liquid, and gaseous fuels such as bio-char, bio-oil and syn gas. Biogas is produced from anaerobic digestion of biomass. Alcohols are produced from fermentation of biomass. Charcoal is produced from the destructive distillation of wood. Other thermochemical technologies include those which produce various fuels, depending on the type of biomass used.

THE EPA'S FINAL RULE ON EISA

The EPA's final rule on the ESA provides strict definitions for various biofuels that are classified as renewable fuels. Renewable fuel is defined as "fuel produced from renewable biomass and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel." (U.S. Environmental Protection Agency, 2010)

Renewable fuels must be made from feedstocks that qualify as ‘‘renewable biomass’’ which limits the types of biomass as well as the types of land from which the biomass may be harvested. The definition includes (U.S. Environmental Protection Agency, 2010):

1. Planted crops and crop residue from agricultural land cleared prior to December 19, 2007 and actively managed or fallow on that date. (EPA defines ‘‘agricultural land’’ as land from which crops and crop residue can be harvested for RIN-generating renewable fuel production as including cropland, pastureland, and land enrolled in the Conservation Reserve Program (U.S. Environmental Protection Agency, 2010))
2. Planted trees and tree residue from tree plantations cleared prior to December 19, 2007 and actively managed on that date.
3. Animal waste material and byproducts.
4. Slash and pre-commercial thinning from non-federal forestlands that are neither old growth nor listed as critically imperiled or rare by a State Natural Heritage program.
5. Biomass cleared from the vicinity of buildings and other areas at risk of wildfire.
6. Algae.
7. Separated yard waste and food waste.

‘‘Transportation fuel’’ is defined as used in motor vehicles, motor vehicle engines, non-road vehicles or non-road engines (except for ocean-going vessels). “Also renewable fuel now includes heating fuel and jet fuel.” (U.S. Environmental Protection Agency, 2010)

“Advanced biofuel is a renewable fuel other than ethanol derived from corn starch, and for which lifecycle GHG emissions are at least 50% less than the gasoline or diesel fuel it displaces… It includes other types of ethanol derived from renewable biomass, including ethanol made from cellulose, hemicellulose, lignin, sugar or any starch other than corn starch, as long as it meets the 50% GHG emission reduction threshold.” (U.S. Environmental Protection Agency, 2010)

Cellulosic biofuel is renewable fuel derived from any cellulose, hemicellulose, or lignin, each of which must originate from renewable biomass. It must also achieve a life-cycle GHG emission reduction of at least 60%, compared to the gasoline or diesel fuel it displaces. Cellulosic biofuel in general also qualifies as both “advanced biofuel” and “renewable fuel”. (U.S. Environmental Protection Agency, 2010)

‘‘Biomass-based diesel’’ includes both biodiesel (mono-alkyl esters) and non-ester renewable diesel (including cellulosic diesel) and must satisfy the following parameters:

1. First, EISA requires that such fuel be made from renewable biomass.
2. Second, its lifecycle GHG emissions must be at least 50% less than the diesel fuel it displaces.
3. Third, the statutory definition of ‘‘Biomass-based diesel’’ excludes renewable fuel derived from co-processing biomass with a petroleum feedstock.

Any fuel that does not satisfy the definition of biomass-based diesel because it is co-processed with petroleum will still meet the definition of “Advanced Biofuel”, provided it meets the 50% GHG threshold and other criteria for the D code of 5. Similarly it will meet the definition of renewable fuel if it meets a GHG emission reduction threshold of 20%. In no case, however, will it meet the definition of biomass-based diesel. (U.S. Environmental Protection Agency, 2010)

“The production of biodiesel (mono alkyl esters) does require the addition of methanol, which is usually derived from natural gas, but which contributes a very small amount to the resulting product. We do not believe that this was intended by the statute’s reference to ‘co-processing’ which we believe was intended to address only renewable fats or oils co-processed with petroleum in a hydrotreater to produce renewable diesel." (U.S. Environmental Protection Agency, 2010)

The EPA's definition of renewable fuels is such that other forms of diesel that are not included under biomass-based diesel can qualify as cellulosic biofuel (cellulosic diesel made by Fischer-Tropsch biomass to liquid process with at least 60% reduction in GHG emissions) and advanced biofuel (cellulosic diesel with at least 20% reduction in GHG emissions) (U.S. Environmental Protection Agency, 2010).

Figure 1 describes the summary of the classification of renewable fuels according to the EPA's final decision on the EISA. Numbers in percentages represent the minimum reduction in GHG emissions by the fuel as compared to the fuel they replace. NC refers to "not co-processed with petroleum feedstock". Table 5 describes the renewable fuel requirements of the RFS in billions of gallons per year. Table 6 describes the cultivation systems and biofuels and products produced for the major algae biofuel companies in the U.S.

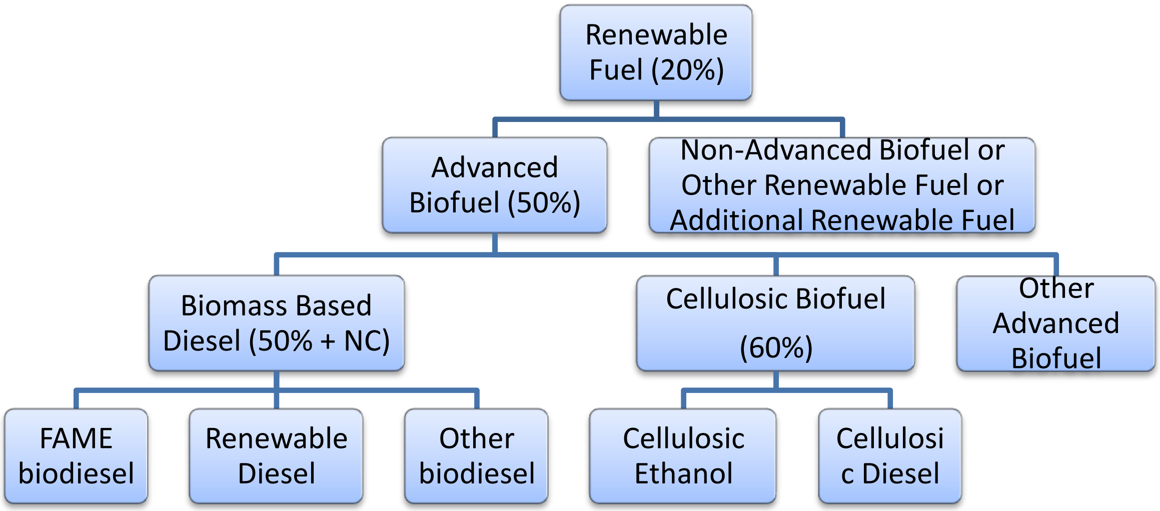
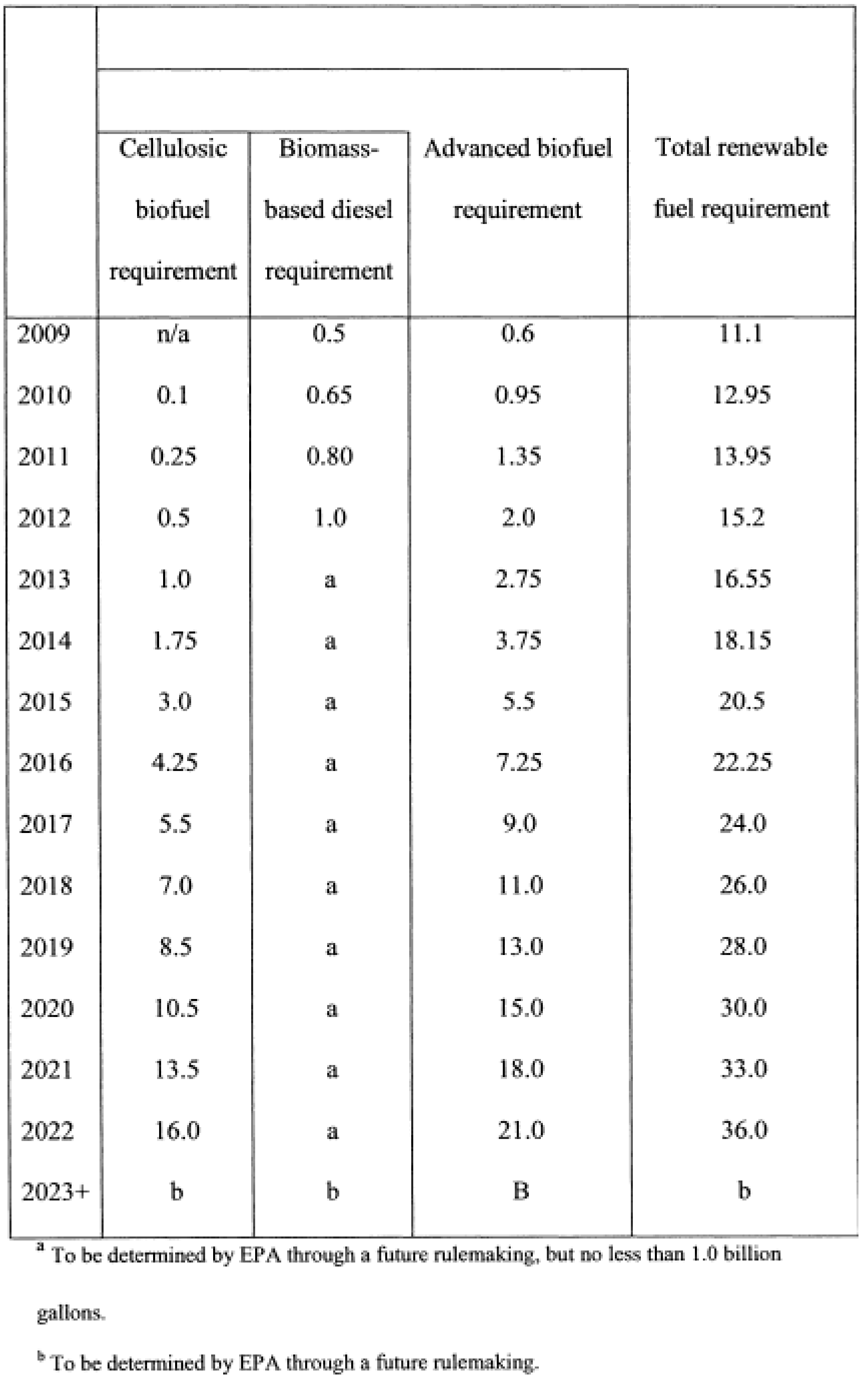


Figure 1: Classification of renewable fuels according to the EPA's Final Decision on the Energy Independence and Security Act.

Table 5. The renewable fuel volume requirements for the RFS2 in billions of gallons (U.S. Environmental Protection Agency, 2010)



	Cellulosic biofuel requirement	Biomass-based diesel requirement	Advanced biofuel requirement	Total renewable fuel requirement
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.5	1.0	2.0	15.2
2013	1.0	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0
2023+	b	b	B	b

[a] To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.

[b] To be determined by EPA through a future rulemaking.

Table 6. List of prominent algal biofuel companies in the U.S. with their cultivation system and the type of biofuel they produce.

	Cultivation System	Product
Saphire Energy, Inc.	Hybrid (open pond + PBR)	Green crude
PetroAlgae, Inc.	Hybrid (open pond + PBR)	Biocrude
Aurora Biofuels	Open pond	N/A
PetroSun Inc.	Open pond	Algal oil
Phycal R&D L.L.C.	Open pond	N/A
Algenol	Photobioreactors	Ethanol
Solix, Inc.	Photobioreactors	Biocrude oil
Solazyme, Inc.	Fermenting bioreactors with a variety of plant-based sugars	Tailored oils, Pharmaceuticals Cosmetics
SolenaFuels	Gasification, Liquifaction	Gasoline, diesel, jet fuel
Cellana and HR BioPetroleum	Hybrid (open pond+PBR)	Oil, cosmetics, proteins

APPENDIX C | EXTENDED DATA

Table 1: Water quality as a measurement of total dissolved solids (TDS)*

Water Type	Total Dissolved Solid (TDS)	Water Quality
Drinking Water	<500 mg/L	*High*
Fresh	<1,000 mg/L	*Medium*
Brackish	1,000 to 10,000 mg/L	*Low*
Saline	>10,000 mg/L	*Low*
Brine	>35,000 mg/L	*Very Low*

* LBG-Guyton Associates (2003)

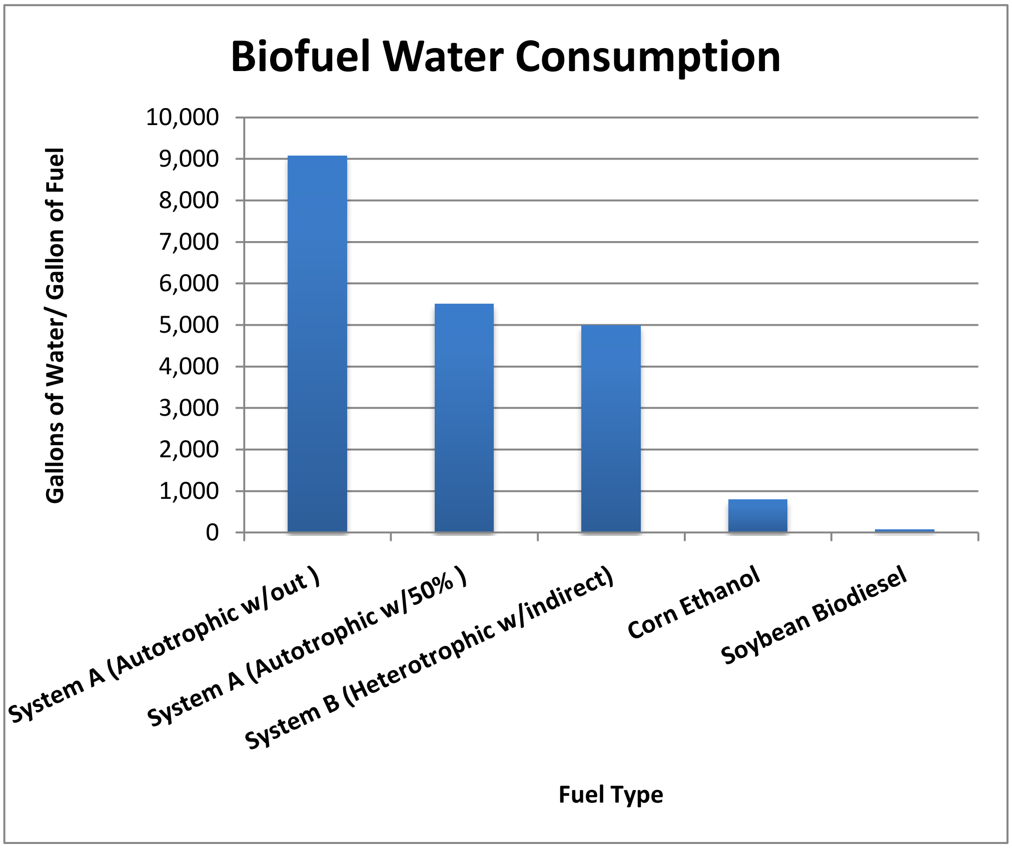


Figure 1: Gallons of water to produce one gallon of biodiesel for algae in comparison with conventional biofuels.*

***** Aden (2007) & O'Connor (2010)

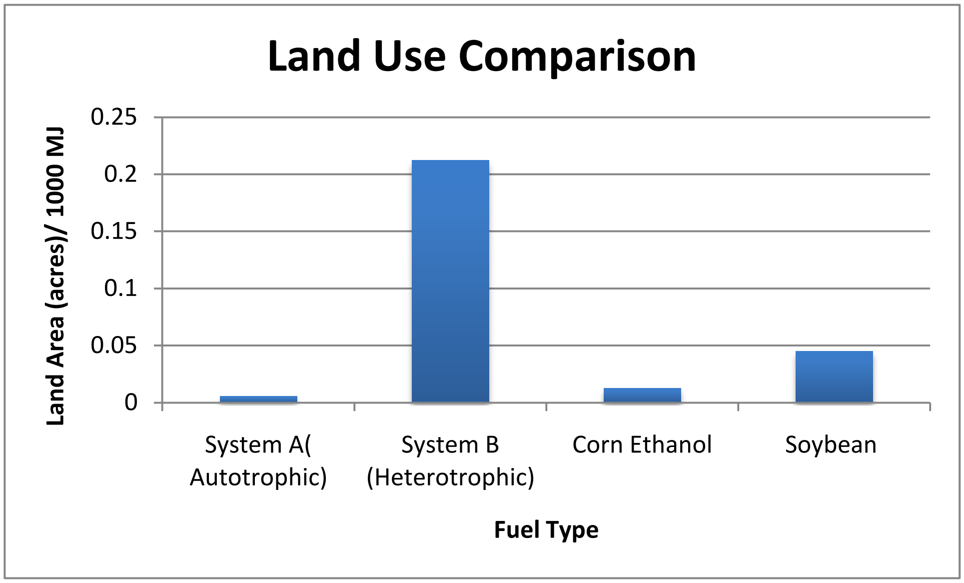


Figure 2: Acres of land needed to produce 1000 MJ in comparison with conventional biofuels.*

***** Miller (2010)

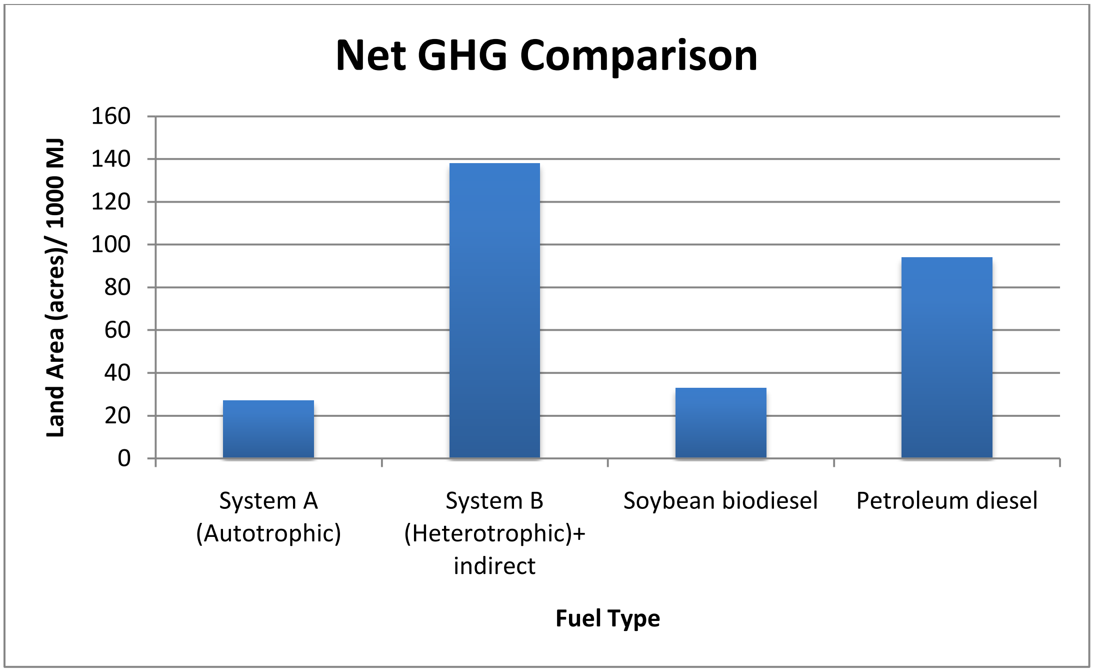


Figure 3: Net greenhouse gas emissions (GHG) of CO2 equivalent per MJ*

* California Air Resources Board (2009)

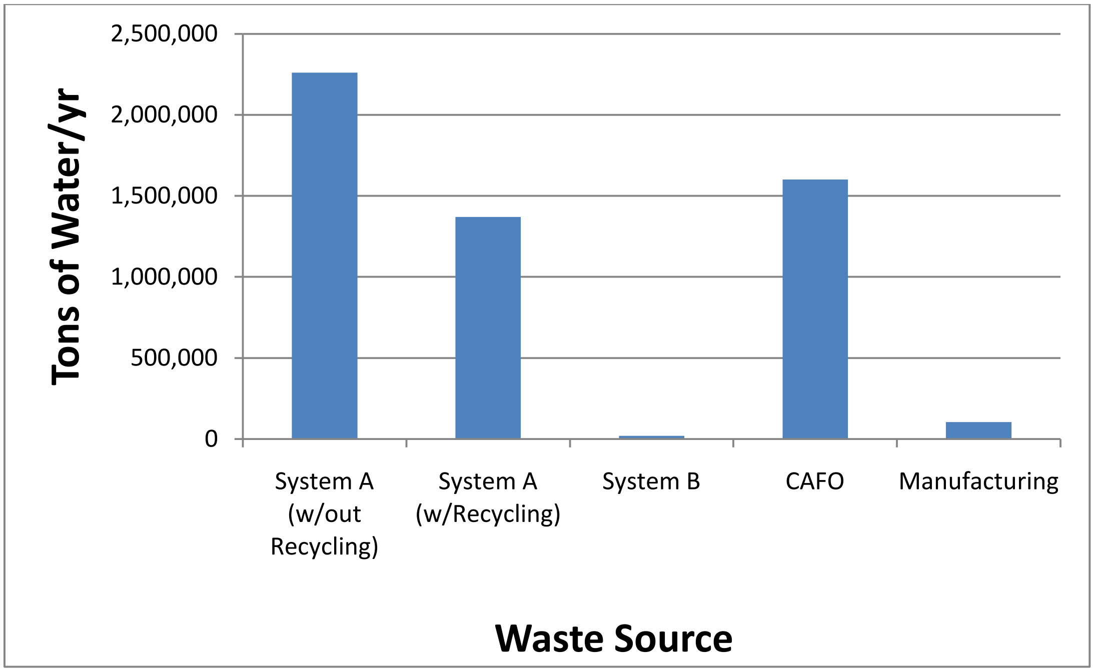


Figure 4: Tons of annual waste per facility*

* Makower (2008) & U.S. GAO (2008)

APPENDIX D | EXTENDED POLICY

VOLUMETRIC ETHANOL EXCISE TAX CREDIT (VEETC) AND VOLUMETRIC BIODIESEL TAX CREDIT

VEETC was created as part of the American Jobs Creation Act (2004), incentivizing oil and energy companies to blend ethanol (domestic or imported) into their gasoline for passenger vehicles. Under the original act, the credit included 42 cents per gallon for E85 and 5.1 cents per gallon of E10, totaling 51 cents (American Coalition for Ethanol, 2010). The current (2010) subsidy level is at 45 cents per gallon and is authorized through December 31, 2010 (Friends of the Earth, 2010). Legislation introduced by Representative Pomeroy (D-ND) and Representative Shimkus (R-IL) in the House of Representatives (H.R. 4940) proposes to extend this credit for five years.

Similar to the VEETC, the Volumetric Biodiesel Tax Credit incentivizes oil and energy producers to blend biodiesel into their diesel fuel. This credit, however, does not allow the use of imported biodiesel (Friends of the Earth, 2010). The credit totals $1.00 per gallon of agro-biodiesel and 50 cents per gallon of waste-grease biodiesel (U.S. Department of Energy, 2009).

SMALL PRODUCER TAX CREDIT

Within the EPAct of 2005, Section 1347 allows small ethanol and agri-biodiesel producers to obtain a tax credit (Friends of the Earth, 2010). This 10 cents per gallon credit is available to all producers with a production capacity of up to 60 million gallons, for up to the first 15 million gallons (U.S. Department of Energy, 2010).

PRODUCTION TAX CREDIT FOR CELLULOSIC ETHANOL

Cellulosic Ethanol producers are able to gain an additional tax credit under EPAct. This gives producers $1.01 per gallon total support. This is first met through the payments provided by the VTEEC. The additional monies are available to cellulosic ethanol producers to encourage investment in this technology.

ALTERNATIVE FUEL INFRASTRUCTURE TAX CREDIT

Section 1342 of the EPAct of 2005 creates a tax incentive to create alternative fuel infrastructure. The tax credit is equal to 30% of the cost alternative refueling property, up to $30,000. The qualifying fuels include ethanol, biodiesels of greater than B20, natural gas, hydrogen and propane. The taxpayer may claim a credit of 50% of the cost of a refueling property if is used in trade, business or at their primary residence. This credit has been in effect from December 31, 2005 to January 1, 2010 (American Coalition for Ethanol, 2010).

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