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# Multicriteria Site Suitability for Algal Biofuel Production Facilities

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## Abstract

*The use of algae as a feedstock for the production of advanced biofuels has tremendous potential because of its short growth cycle, high productivity, lack of competition for agricultural lands, ability to use a variety of water sources and recycle $CO_2$ and nutrient emissions, and compatibility with existing fuels chains with minimum process changes. However, to make significant contributions to biofuel targets, optimal locations must be identified to ensure production facilities are economically viable. This study presents a framework which leverages Geographic Information Systems (GIS) to help identify optimal locations and a web application which can help stakeholders identify areas that are suitable for production test facilities in the state of Florida. It also presents an example output based on a single configuration of the multicriteria suitability model from this framework. The total area identified as suitable in the resulting data layer is consistent with similar studies though the accuracy of the model is difficult to assess without further studies. Nonetheless, this research builds on previous national and regional scale analyses which offer a more prescriptive view of potential locations based on a narrower set of inputs and suggests new opportunities to develop a practical toolset for site selection moving forward.*

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# Introduction

In 2007, the United States passed the Energy Independence Act, setting a goal of 21 billion gallons of advance biofuel production capacity by 2022. Corn and switchgrass are already established feedstocks for producing biofuel but microalgae can be cultivated on marginal lands while producing more energy per unit of area, making it a promising replacement to land based organisms. For algal feedstocks to make a significant contribution to meeting the advanced biofuels goals of the 2007 Energy Independence and Security Act, large scale test facilities must first be developed. These test facilities must be in areas which maximize production efficiency to ensure economic viability while advancements in bio- and systems engineering are being developed, allowing the expansion to less suitable regions of the country.

One of the primary areas of research interest in the field of microalgal biofuels relates to locating optimal sites which can consistently maximize yields throughout the year. Locating optimal sites is a highly spatial problem and requires the management and analysis of a diverse set of inputs which is perfectly suited for the use of geographic information systems (GIS).

There is already a great deal of research for microalgae production facility suitability in the American southwest, probably as a result of its high insolation rates and the fact that Sandia National Laboratory is there. However, Florida has a lot of the same characteristics which make it highly suitable for algal production without some of the drawbacks. For instance, it experiences similarly high insolation but is much less arid than the American southwest. This results in good growing conditions but lower evaporation rates across the state, potentially conserving water resources which are vital to open raceway algae ponds. Furthermore, Florida is quite flat. As building new facilities on sites with slopes greater than 2% would be prohibitively expensive, this is a comparative economic benefit. Being quite southerly and bordering the warm waters of the Gulf of Mexico, Florida is also warm and experiences few freeze days that might halt production. For these reasons, Florida is a good candidate to employ GIS analysis in order to locate optimal algal biofuel production facilities that can help fulfill the advanced biofuel requirements set out in the U.S. Energy Independence Act.

# Objective

The aim of this study is to provide a GIS methodology and toolset that can help stakeholders identify the ideal areas for biofuel feedstock cultivation in Florida. There are number of geographic characteristics that help determine whether algae can be grown economically and at scale, which makes locating these sites especially challenging. These needs are addressed through a multicriteria suitability model that considers proximity to $CO_2$ point sources, wastewater treatments plants, and roads, as well as precipitation, evaporation, temperature, and hurricane and flood risk. Slope and land use will also be included in the model.

The output of this study will be a geographic data layer indicating optimal locations in Florida based on one configuration of the suitability model. In addition, a web application containing this data layer will be constructed for users to interactively locate and measure potentially suitable areas from the analysis.

# Background

## Overview

Title II of the Energy Independence and Security Act of 2007 is devoted to ensuring US energy security through the increased production of biofuels. It states that by 2022 the US energy profile must contain at least 36 billion gallons of renewable fuel, of which 21 billion gallons should be advanced biofuels. In the same text, advanced biofuels are defined as renewable fuels whose production and use result in 50% the greenhouse gas emissions (GHGs) of traditional fuels. The use of algae as a feedstock for biofuels has been of interest to academics and the US government since the 1960s (Oswald and Golueke 1960; Benemann et al. 1982; Sheehan et al. 1998.) and have reemerged in a number of publications by academics and government funded laboratories as an advanced biofuel candidate (U.S. DOE 2010). Using algae for biofuel feedstock is potentially advantageous because of its short growth cycle, high productivity, lack of competition for agricultural lands, ability to use a variety of water sources and recycle $CO_2$ and nutrient emissions, and compatibility with existing fuels chains with minimum process changes (U.S. DOE 2010, p. 2). That said, there are significant hurdles which need to be overcome if algal biofuels are to be commercially viable. Many of these problems are related to siting and their spatial nature make them suitable for analysis with GIS. In particular, GIS can assist in locating land and water resources, optimal climates, $CO_2$ point sources and nutrient supplies, existing fuel processing, transport and storage infrastructure as well as modeling evaporation loss (U.S. DOE 2010, p. 100).

Until now, most research devoted to identifying resource supplies and subsequent production potential for algal biofuel production has been on a national scale (Quinn et al. 2013; Venteris et al. 2012; Wigmosta et al. 2011) or focused in the American southwest (Lundquist et al. 2010, Lansford et al. 1990). High insolation periods in California, Nevada, Arizona and New Mexico are ideal for autotrophic algae cultivation as light energy is essential for photosynthetic growth of biomass.

Broadly, there are two types of microalgae, heterotrophic and photoautotrophic. Heterotrophic algae are grown without the need for light and require a carbon food source in order to grow, while photoautotrophic require light to grow new biomass (U.S. DOE, p. 29-30). Although the use of heterotrophic algae strains has been suggested as a biofuel source because of their independence from climatic conditions for growth, they are generally viewed as poor candidates. Lignocellulosic sugars used for biomass growth are already used in other biofuel production systems, driving up costs from competition, while the production of these feedstocks has heavy land and fertilizer requirements, reducing or potentially eliminating any environmental advantages in using algal biofuels (U.S. DOE, p. 30). As a result, photoautotrophic algae strains have become the de facto candidates for fuel production, limiting production areas with abundant solar radiation, explaining the emphasis on the American southwest.

Unfortunately, water is also an essential resource for algal growth, processing, and the diluting of blowdown effluents from facilities, raising significant concerns over the appropriateness of creating large scale projects in the southwest where water resources are already stretched thin (Lundquist et al. 2010, p.40). Concentrations of blowdown effluents like algal biomass, salts or other chemicals, and residual nutrients are all increased with evaporation (Lundquist et al. 2010, p.56). Some studies suggest that saline aquifers and recycled industrial and agricultural wastewaters can be used to supply cultivation ponds but there has been no research supporting either production potential and environmental impact in saline conditions, or the availability of industrial and agricultural wastewaters as the sole water supply for large scale facilities. Issues relating to the disposal of effluent in the absence of a freshwater supply remain a problem as well (Venteris 2013; Lundquist et al. 2010, p. 59). Lundquist et al. 2010, in a report assessing the realistic potential of algal biofuels which includes a GIS assessment of California, goes so far as to say areas around the Gulf of Mexico are better suited to provide necessary land and water resources for algal biofuel production (p.44-45). Florida, as one of these states, has nearly as much insolation potential as the American southwest, with the advantage of having a more favorable water supply. This paper hopes to shift the focus from the water limited southwest to Florida, which has received little attention outside of nationwide analyses of potential locations to cultivate algal biofuels.

## Photoautotrophic Microalgae

Algae are characterized as a group of mostly aquatic unicellular and multicellular organisms that have simple cell structures (Hine and Martin 2015). Heterotrophic strains have been proposed as feedstock candidates because of their ability to grow in light constrained conditions and relatively high oil yields, but their reliance on terrestrial crop carbon sources and proneness to batch contamination have made them unpopular choices for scale-up models. Photoautotrophic strains have lower oil yields but are considered better candidates because of their ability to convert sunlight energy and $CO_2$ to chemical energy, while being relatively less susceptible to contamination (Amaro et al. 2011, p. 3405).

Interest in using microalgae as a biofuel feedstock stems from its short growth cycle, high productivity, lack of competition for agricultural lands, ability to use a variety of water sources and recycle $CO_2$ and nutrient emissions, and compatibility with existing fuels chains with minimum process changes (U.S. DOE, p. 2). Oil yields for algae are estimated to be between 1000 and 6500 gallons/acre/year as opposed to leading terrestrial biomass feedstocks palm oil at 635 gallons/acre/year and jatropha at 202 gallons/acre/year (U.S. DOE, p. 3; Christi 2007). Water footprint estimates compared to terrestrial crops vary, but with recycling systems implemented algae cultivation is competitive if not better than terrestrial crops in terms of water usage (Pate et al. 2011, p 3382). The lack of competition with existing agricultural lands and an ability to fix carbon and convert solar energy into chemical energy at a much higher rate than land-based biomass sources establish microalgae as prime candidates for feedstocks (Wigmosta et al. 2011, p. 2).

In both heterotrophic and phototrophic algae, the goal in cultivation is maximizing the organisms' lipid content, mostly in the form of triacyglycerols (TAGs). TAGs are the major precursors to biodiesel and their abundance is directly related to the amount of energy which can be produced per area. The pathways of converting carbohydrates in an organism to lipids are poorly understood but in certain strains nutrient or light starvation may lead to increased TAG accumulation, while in others lipid production occurs naturally (U.S DOE, p. 11-13). The production of methane and ethanol fuels from algal growth have also been suggested, but the conversion of TAGs to biodiesel for transportation fuels is the most promising pathway for biofuel production, and is most prevalent in recent models and analyses (Sheehan et al. 1998, p.6 - program summary).

High TAG producing algae strains are known as oleaginous algae. TAGs from oleaginous algae are converted into fatty acid methyl esters (FAME) using transesterification, which can then be used as a cleaner burning alternative to petroleum derived diesel (Sheehan et al. 1998, p. 1 - Technical review). These strains are capable of producing 20% lipid dry cell weight under normal conditions and up to 50% under conditions of environmental stress. Theoretical yields based on growing potential and photosynthetic efficiency estimate that more than 200 barrels of algal oil per hectare can be produced, which is 100 times more productive than soybean feedstock (Hu et al. 2008, p. 622). However, recent studies have acknowledged that total lipid content is not a good representation of oil production as suitable lipids for biodiesel production constitute only half of the total (Rios et al. 2013, p. 620). Total lipid yields of up to 75% have been achieved in the laboratory and significant savings in production costs could be achieved if these yields were achieved in a multi-hectare cultivation system (Christi 2007, p. 296). There is a need for research in bioengineering of algal strains and production methods to meet the theoretical potential established in lab conditions, but optimizing facility locations through GIS analysis can similarly reduce operations costs, making them more competitive with conventional petroleum based diesel.

There are two primary types of production systems for growing the types of phototrophic algae outlined above, ponds and enclosed photobioreactors. There are several types of open pond systems, but the raceway mixed ponds have been shown to be most productive. Closed photobioreactors can generate high yields of algae growth but require considerable hardware, the costs of which do not scale economically when moving out of the prototyping phase (Lundquist et al. 2010, p 13). For these reasons, the open raceway pond is the production facility type that is considered in the site suitability analysis which follows.

## Algal Biofuel Production Facility Site Suitability Criteria

It is important to consider the contour of a site when determining its suitability for an algal biofuel production facility. The issue was first considered by Benemann et al. in their report for the U.S. Department of Energy's Office of Energy Research (1982, p 108). They stated a maximum of 0.5% slope for channeled algae ponds, requiring land as near to flat as possible. According to their report, as the overall slope exceeds 1% costs for grading the site or pumping water through channels becomes increasingly prohibitive, establishing the figure as an upper limit for site selection. This has been upheld in some current land availability assessments (Venteris et al. 2012, p. 491; Wigmosta et al. 2011, p.4); however, a number of other recent studies suggest larger threshold values. Most recently, Quinn et al. 2013 cites a number of sources in asserting that a 2% slope should be considered the maximum value for a site to be considered economical (p.2).

In addition to slope, land use is also a major consideration when selecting a potential site for biofuel production. One of the benefits of using algae feedstocks as opposed to terrestrial feedstocks is that cultivation centers can be located on marginal lands unsuitable for growing other agricultural goods. The value of these types of lands are typically less expensive and therefore more economical when factored into life cycle assessments for possible plants. Therefore, in any land use analysis active agricultural lands must be excluded from the study area. Furthermore, forested, open water, urban, wetland and federally protected conservation areas are also typically excluded for practical, environmental or cost reasons (Murphy and Allen 2012, p. 5863; Quinn et al. 2011, p. 53; Wigmosta et al. 2011, p. 4; Fortier and Strum 2012, p. 11429; Venteris et al. 2012, p. 484).

Another issue related to land suitability is the total area of the site. To achieve economies of scale which would make advanced biofuels more competitive with petroleum products production facilities require a land area of several hundred hectares (Benemann and Oswald 1996, p. 179; Lundquist et al. 2010, p. 4). Wigmosta et al. (2011) suggest an area of 490ha as a minimum while Quinn et al. (2013) offer a threshold value of 400ha, most likely derived from the work done at this scale by Benemann and Oswald (1996). However, current production figures suggest that even with scaled-up facilities algal biofuels are not an economically viable option to conventional oil and gas (US DOE 2010, p.65-67). Therefore, it is necessary to develop multi-hectare test facilities to perform long term analysis which would benefit development towards commercially viable operations (National Research Council 2012. p. 100).

Proximity to roadways is another consideration for locating algal biofuel production facilities. After crude or refined biofuels are produced, they must be transported to refineries or distribution centers. Facilities constructed in isolation from roadways would incur significant costs in developing transportation infrastructure, making locations close to existing roadways more suitable.

One of the principal components in any photosynthetic process is carbon dioxide. Microalgae is no different, requiring absorbable $CO_2$ in order to grow and create lipids used for biofuels. Economic analyses of microalgae production systems demonstrate that in order to maximize lipid potential for a given area, $CO_2$ must be in abundance to maximize growth rates (Lundquist et al. 2010, p.79). The requirements for optimizing biofuel production could be met using bicarbonate (NaHCO3) but the relatively low amount of $CO_2$ usable by organisms render it an uneconomical choice for supplementation. Commercially delivered $CO_2$ could also be used in algal ponds but was similarly deemed too expensive (Benemann et al. 1982, p. 75, 81). Flue gas from heavy emitting point sources like power plants, industrial furnaces and cement plants is comprised of 10-15% $CO_2$ and is produced in enough quantity to satisfy the needs of a multi-hectare scale microalgae production facility (Kadam and Sheehan 1996, p. 496). For this reason, it is considered the leading candidate to supply $CO_2$ requirements of algal biofuel systems.

In addition to optimizing cell growth, using flue gas from $CO_2$ emitters has the added function of mitigating greenhouse gas emissions, while offsetting captial costs required for the capture and distribution of $CO_2$ to production facilities. Industrial (14%) and electrical (38%) plants generate 52% of $CO_2$ emissions in the United States, constituting a significant portion of world greenhouse gas emissions (EPA 2014). $CO_2$ is released when burning biofuels but capturing emissions from power plants doubles the amount of energy that can be used per unit of $CO_2$, having an obvious positive environmental impact (Kadam and Sheehan 1996, p. 502). With new incentives for emissions abatement being developed in the policy sphere there is also potential for economic benefits (IEA 2012; Lewandowski et al. 2004). Although fluctuations in carbon pricing are great with current emissions often priced under $10 per metric ton of $CO_2$, there is global political will to maintain prices within $40-80 per metric ton through the Paris Agreement within the United Nations Framework Convention on Climate Change (World Bank, Ecofys and Vivid Economics 2017, p.11). With a rate of capture up to 50% of flue gas, the environmental advantages and ability to offset costs through microalgal $CO_2$ mitigation are clear whatever carbon offset incentives are developed in the near future (Li et al. 2008, p. 817).

Collocating heavy $CO_2$ emitters with biofuel production sites is necessary if cheap and consistent supplies are to be maintained. In initial studies a distance of 4.8km was considered for a direct flue gas distribution system from $CO_2$ emitters to algal biofuel facilities (Benemann et al. 1982, p. 129). Delivery systems where gas is released into low velocity raceway ponds through sumps exhibit high levels of $CO_2$ retention (Davis et al. 2011, p.3526; Benemann and Oswald 1996, p. 57,120). The capture, concentration into monoethanolamine (MEA) and transport of $CO_2$ over a distance of 100km was later considered, greatly increasing the catchment areas for $CO_2$ sources (Kadam and Sheehan 1996, p. 494). Although this method exponentially increased the number of available point sources, later studies found this method undesirable due to increased costs associated with MEA production from sources with lower production capacities (500MW power plant was used in the economic model) and lack of consideration for transporting the $CO_2$ source (Benemann and Oswald 1996, p. 123,135). A more recent study investigating the ability of MEA to increase cell growth rate in certain autotrophic microalgae strains may prove Kadam's method more economical but lack of technoeconomic analysis using the new findings prevent its consideration as a $CO_2$ source in this study (Choi et al. 2012). A reduction of the distance of $CO_2$ point sources from 4.8 to 2.5 km saw the overall distribution costs drop by 50%, clearly demonstrating that shorter the distance flue gas must be pumped the more economical a system will be (Benemann and Oswald 1996, p. 135). Increased biofixation of carbon from $CO_2$ in higher lipid yielding microalgal strains being developed will substantially increase a facility's $CO_2$ needs (Kadam and Sheehan 1996, p. 499-500). This augments a system's ability to mitigate emissions, potentially offsetting capital costs, but puts a greater importance on reducing costs associated with transporting and distributing flue gas. Thus, although it is important to locate as many potential flue gas sources as possible, economic advantages favor locations in greater proximity to these point sources (Lundquist et al. 2010, p.51).

According to Benemann et al. (1982), a 36,000-acre open raceway algae pond would require 2,000,000 tons of $CO_2$ delivered per year. Simple calculations reveal that a 100 ha pond would require 13,728 tons per year if the pond were able to utilize 100% or $CO_2$ flows. However, in the favored direct flue $CO_2$ delivery systems night storage is not available and only 50% of emissions are assumed to be consumed (Kadam 2001, p. 17). To compensate for this, the $CO_2$ supply must be doubled, resulting in a figure of 27,456 tons per year.

Aside from $CO_2$, Nitrogen and Phosphorus are the main nutrients required for autotrophic microalgae growth and thus comprise a significant potential cost if they come in the form of chemical fertilizers (Benemann et al. 1982, p. 141). In 1987, these costs were estimated to be 6-8% per gallon of biofuel produced (Benemann and Oswald 1996, p. 147), a figure which has most likely gone up considering phosphate supplies are limited (Vaccari 2009). Based on a conservative 10 billion gallon per year national production figure (less than half of the target amount in the Energy Independence Act), N and P fertilizer requirements would be 107% and 51% of total U.S. consumption in 2006 terms (Pate et al. 2011, p. 3385). The amount of N and P required for even minimal biofuel production would put stress on nutrient supplies, let alone meeting production levels set forth in the 2007 Energy Independence and Security Act. Although recycling N and P from residual algae after lipid extraction is possible, it is not possible to recover 100% of the nutrients consumed so a sustainable production system will still require external supplies (Lundquist et al. 2010, p. 43-45). Furthermore, the production of N and P in chemical form emits $CO_2$, eliminating the carbon sequestering potential of microalgal biofuel systems (Christi 2013, p. 204). The addition of ammonia (NH3) and superphosphate ($P_2SO_4$) to meet stoichiometric requirements for algal growth leads to a production system which is up to 2.5 times more energy intensive as producing conventional diesel (Shirvani et al. 2011, p. 3773,3777). Utilizing these nutrient supplements would exclude microalgae as a feedstock for advanced biofuels, as they are required to reduce greenhouse gas emissions by 50%.

Water is also an important issue when considering wastewater effluent as a potential resource. Although certain models estimate the water footprint for cultivating microalgae would be lower than for terrestrial crops, if a significant contribution were made towards meeting the advanced biofuels targets in 2022, high levels of water stress would occur (Pate et al. 2011, p. 3382). Water consumption would be 2.75 times than currently used in irrigation nationally if all suitable lands in Wigmosta et al.'s study were converted to biofuel production facilities (2011, p. 11). The likelihood of algal biofuel production reaching their estimate is admittedly low, but is representative of overall water needs. A more specific regional study estimates that for the southeast U.S., where water sources are considerably more abundant, a 10 billion gallon a year industry would require 170% of total water currently used for irrigation (Pate et al. 2011, p. 3883). For algal biofuel to be considered a viable alternative to petroleum based energy sources, an alternative to chemical nutrient supplements and freshwater resources must be found to overcome issues of supply, cost and environmental impact.

Municipal wastewater treatment plants may offer an opportunity to secure reliable N, P and water resources at minimal cost with a potential to diminish the nutrients' pollutive effects in waterways. It has been shown that growing algae in wastewater can reduce freshwater usage by 90% and N needs by 94% while completely fulfilling P requirements (Rawat et al. 2013, p. 1767). Utilizing wastewater leads to significant cost avoidance while removing N and P which could have otherwise made its way into waterways leading to eutrophication and the lowering of oxygen supplies vital for aquatic ecosystems. This state of oxygen deprivation, known as hypoxia, is a serious environmental concern in the Gulf of Mexico, increasing the importance of mitigation potential in the study area (Mitsch et al. 2001).

Considering its ability to supply resources and positive environmental impact, the use of municipal wastewater is a vital component in meeting advanced biofuels targets. In their investigation of the feasibility of collocating wastewater treatment plants with algal biofuel facilities for the state of Kansas, Fortier and Strum estimate that up to 29% of the states transportation fuel needs could be met with existing wastewater resources. If a system for collecting agricultural runoff were developed, this number could be expanded substantially (2011, p. 11432-3). It is unlikely that wastewater can fulfill all of the nutrient and water requirements for production of 21 billion gallons of advanced biofuels but it is essential to the viability of first generation commercial systems.

Supplies of nutrients in the form of $CO_2$, nitrogen and phosphorus are not the only concerns in selecting locations for algal biofuel production facilities. Climatic variables like temperature, precipitation, and evaporation must also be considered as these characteristics vary considerably across the United States (U.S. DOE, p. 75). The biomass output of a production system is directly related to the incidence of solar radiation as well as the pond temperature and length of the growing season at a site (Maxwell et al. 1985, p. 9). Precipitation and evaporation levels are also especially important when we consider our focus on open pond production facilities, with areas experiencing high precipitation rates and low evaporative loss being most desirable to limit the impact on water resources. An optimal location would have a long growing season, high solar radiation incidence and a low net evaporation loss though most locations must compromise on one or more of these characteristics, since areas of high precipitation tend to experience less insolation due to cloud cover (U.S. DOE 2010, p. 77)

As mentioned above, solar energy is converted to chemical energy in photoautotrophic algae in the form of lipids and other forms of algal biomass. Thus, the amount of solar energy converted to TAGs and subsequently FAMEs and biodiesel is directly related to the amount of solar incidence where algae is being cultivated (Weyer et al. 2010, p. 205). Therefore, it is critical that production sites are located in regions with high annual insolation rates. Furthermore, the temperature of the pond should remain between 20 and 30 degrees Celsius during the growth season (Christi 2007, p. 297). For this reason, areas with low elevation and latitude are most desirable due to their consistently warm temperatures and relatively high incidence of solar radiation, limiting cultivation regions to the American southwest and southeast. It should be noted that the Gulf Coast region in the southeast experiences lower rates of insolation than those found in the southwest but projected productivities remain high, possibly due to moderate annual average temperatures (U.S. DOE, p. 76). Areas with extreme heat and humidity increase water temperatures outside of the optimal 20-30 degree zone, inhibiting biomass production, similar to that brought on my photoinhibition, where extreme light intensity limits biomass productivity rates (Lundquist et al. 2010, p. 36; Christi 2007, p. 302).

Photobioreactor systems use water more efficiently and have higher production potential than open pond systems, but their extreme cost and inability to be scaled leave open ponds as the only real candidate for algal biofuel production (Lundquist et al. 2010, p.13). As a result, regional variation in precipitation and evaporation become more important in creating a site model due to the significant water resources required to cultivate and process algae. It is true that the American southwest has the highest insolation rates, though this may have a limiting effect in some areas due to photoinhibition. Furthermore, states like California, Arizona and New Mexico have high evaporation rates. For example, Death Valley, California experiences losses of 350mm/month whereas Landsville, Pennsylvania, on the east coast, has a mere 120mm/month evaporative loss. The southeast U.S. experiences a relatively large amount of rain compared to the arid southwest. The combination of this and having less evaporative losses leads to more available water resources and better suitability for location algae cultivation facilities (Lundquist et al. 2010, p.40; U.S. DOE 2010, p.77). Florida, located at the southern tip of the American southeast, exhibits these characteristics and has a warm climate as a result from its low elevation and latitude which are some of the reasons it has been selected as the area of interest for this study.

Although low evaporative loss and abundant precipitation are generally considered positive traits for algae cultivation in open raceway ponds, Florida's rainy climate presents a different set of risks. According to the Earth System Research Laboratory, Florida averages 1.39 meters of rainfall per year, putting it fourth in the U.S. rankings (Earth System Research Laboratory 2018). With its mostly level terrain, this creates a potentially disruptive flood risk. Furthermore, from 1851-2017 there have been 121 hurricanes which have touched down in Florida. The total hurricanes which made landfall in the entire U.S. over that same period was 344, with hurricanes in Florida alone constituting more than a third of that figure (National Oceanic and Atmospheric Administration 2018). The states susceptibility to hurricanes and flooding may be important factors in deciding where to locate facilities.

# Methods

To generate a multicriteria suitability model locations across Florida were individually assessed on their desirability as they relate to proximity to $CO_2$ point sources, wastewater treatments plants, and roads, as well as precipitation, evapotranspiration, temperature, hurricane and flood risk, slope, and land use. The result of these analyses is a set of geographic data layers which communicate a locations desirability according to these the variables. The data layers were then incorporated into a weighted overlay analysis which integrates the different variables to produce a single suitability layer indicating preferred locations for algal biofuel production. The methods below describe the creation of these data layers and the multicriteria suitability model which integrates them.

## Software Used

Most data management and analysis workflows were performed using ArcMap 10.3 (Esri 2014) and layout and publishing workflows for production maps and web layers leveraged ArcGIS Pro 2.0 (Esri 2018b). Automated analytical tasks were scripted using Python 2.7 and the 10.3 ArcPy libraries (Esri 2014). To generate the web application, local data was published as web layers to ArcGIS Online where they could be configured into web maps Finally, the web application was built using the Web AppBuilder framework in ArcGIS Online (Esri 2018a).

## $CO_2$ point sources

In order to ensure adequate supplies of $CO_2$ for production test facilities, only those point sources from the EPA's 2011 Greenhouse Gas Emissions reporting program which met or exceeded the 27,456 tons of emissions per year were included in the $CO_2$ supply analysis (U.S. EPA 2014). This threshold value represents the minimum output that would supply a 100ha facility as outlined above. To account for the fact that the closer facilities are to $CO_2$ point sources, the lower the capital and production costs will be, 1km buffers were generated around the selected point sources to a maximum distance of 10km (Benemann and Oswald 1996, p.123). The decision to extend the radii past 5km was to include areas with sufficient $CO_2$ supplies, albeit at higher costs. Buffered areas closer to $CO_2$ point sources were weighted as more desirable (0-1 km = 10) and those further away were weighted as less desirable (9-10km = 1). The result is a data layer which represents areas within 10km of $CO_2$ point sources that could supply a 100ha test facility and assigns areas closer to the $CO_2$ emitters higher values (Figure 1).

1km buffers around CO2 Point Sources, > 27,456 tons/yr

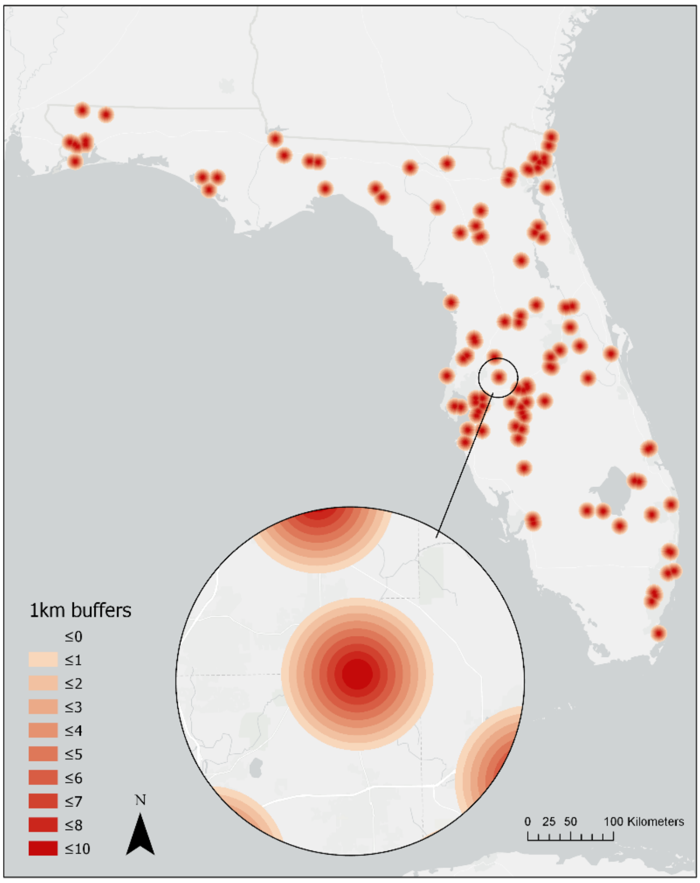


*Figure 1 – 1km buffers around suitable $CO_2$ point sources with relative suitability scores. Higher values represent more desirable locations closer to $CO_2$ supplies.*

Areas close to suitable $CO_2$ point sources are well distributed throughout the state of Florida, though there is some clustering in the center of the state. The total area within the 10km buffer zone is 248,445 hectares.

## Wastewater Treatment Plants

The handling of waste water treatment data from the Clean Water Sheds Needs Survey of 2008 (U.S. EPA 2016) was similar to what was performed for $CO_2$ emissions data. To determine a suitable threshold flow rate for wastewater treatment plants (WWTPs) to supply a 100 ha open water raceway facility, flow rates for a plant in Andover, Kansas were extrapolated. In a study, the facility produced 4364 cubic meters per day of effluent and was able to supply a 3,072,000 m2 pond system with a 0.4138m/year evaporative loss (Fortier and Strum 2012, Supporting Information). A 100 ha system would require a flow rate of 1422m$^3$/day if it experienced an evaporative loss of 0.4138m/year; however, the average rate for stations across Florida was 1.68m/year. Therefore, the base flow rate was determined to be 5523 m3/day.

The same economic considerations in locating algal production facilities near $CO_2$ point sources are relevant to the position of wastewater treatment plants. According to Lundquist et al., the $CO_2$ distribution and supply system would account for roughly 32.5% of capital and

53.5% of operating costs per year, while piping and pumping of surface water (which includes effluent from wastewater treatment plants) amounts to 21.6% and 11.6% (2010, p.54). Although the amortized cost over the lifespan of the facility is less than that for $CO_2$, the increased expense in capital and operational costs incurred by transporting water over greater distances supports proximity to wastewater treatment plants as a factor in any economic model. Nonetheless, if increased production potential through greater supplies of water and nutrients is a higher priority than cost, locations further away from nutrient and water point sources are still valid in a production model. For these reasons, the same workflow of generating 1km buffers up to a of 10km perimeter around nutrient sources was used. The result is a data layer which represents areas that are within 10km of adequate nutrient supplies and a supplemental water resource (Figure 2).

**1km buffers around WWTP Point Sources, > 5523.5 m3/day**

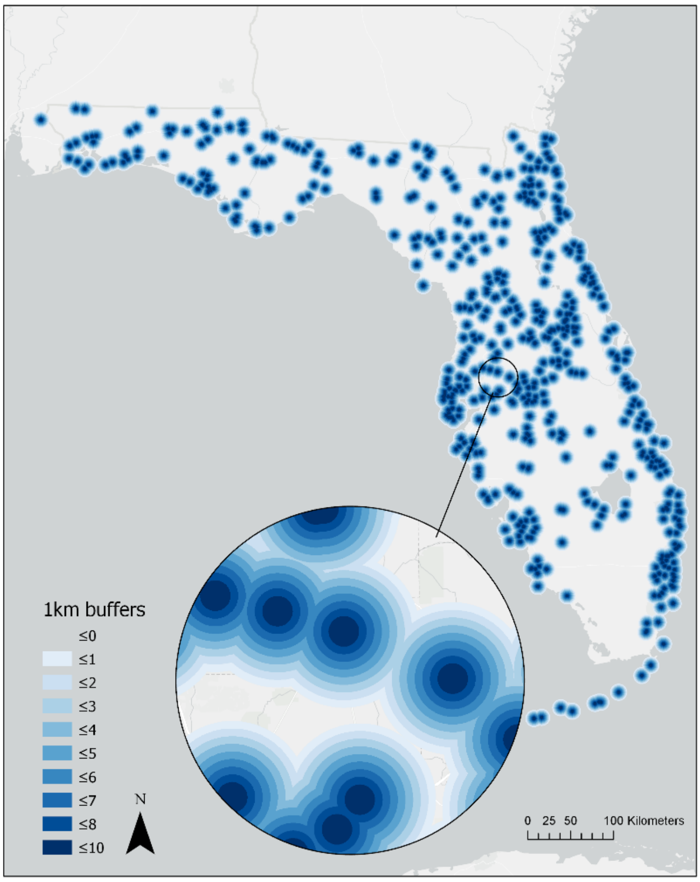


*Figure 2 - 1km buffers around suitable Waste Water Treatment Plants with relative suitability scores. Higher values represent more desirable locations closer to water and nutrient supplies.*

There are considerably more suitable waste water treatment plants that could supply potential operations with water and nutrients than there are $CO_2$ point sources as seen in Figure 2. The total area within 10km of these facilities is 856,287 hectares, more than triple the area represented in the $CO_2$ data layer. The distribution of WWTPs is aligned with human population, with large numbers of facilities along the coasts and in central Florida along the corridor between Tampa and Orlando.

## Transportation

To reflect the desirability of locating production facilities near major roadways, 1km buffer zones up to 10km were created around primary and secondary roads in Florida using a data from the US Census Bureau for 2013 (U.S. Census Bureau 2013). When converted to a raster, the polygon buffers were assigned values from 10 to 1, descending from the innermost buffer zone. The resulting layer displays areas close to primary and secondary roads and values those areas which are closest (Figure 3). The transportation data layer was limited to a 10km buffer to limit potential expenditures for building out new road networks to transport biofuels or feedstocks (Lundquist et al. 2010, p. 51).

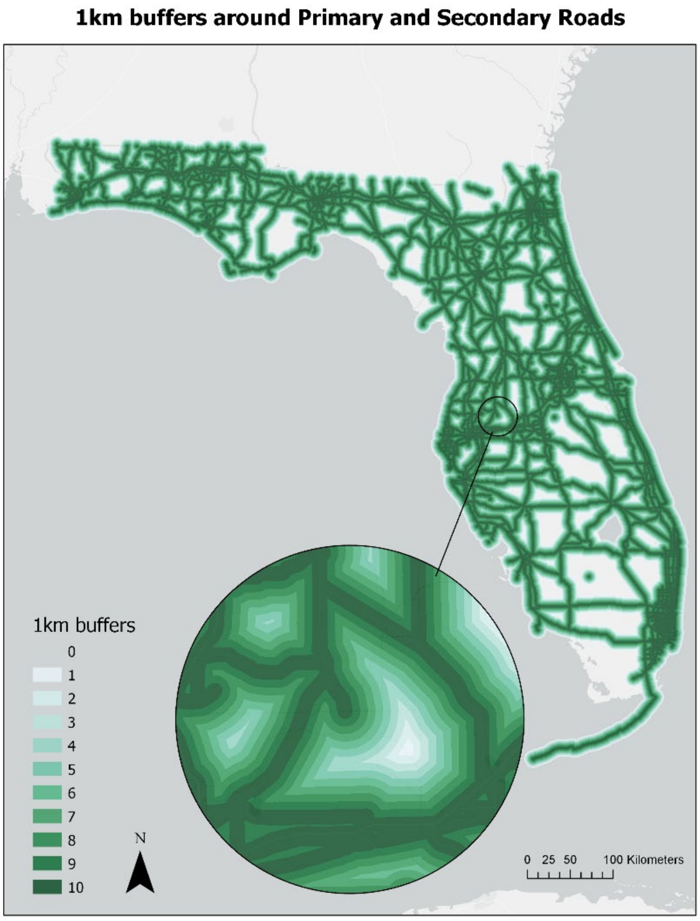


*Figure 3 – 1km buffers around primary and secondary roads. Areas closer to roadways are assigned higher suitability values.*

Florida's primary and secondary road network covers most of the state. There are holes around protected areas like the Everglades National Park at the southern tip of the state, but a large part of the state is within the 10km of major roadways. The total area represented in the data layer is 1,552,476 hectares.

## Climate

Climatic variables were also used in the suitability model because of their impact on growth rates, growth season, and water supply issues (Lundquist et al 2010). Climatic data was sourced from the Florida Automated Weather Network (FAWN) FTP data server (University of Florida Institute of Food and Agricultural Sciences, 2018a). Daily summaries for precipitation, evapotranspiration, and temperature from 2003-2012 were used in this model. Although, climate generally refers to weather patterns as defined over a 30 year period, the local 10 year dataset was favored because it has better spatial distribution over the area of interest (NASA 2005). Figure 4 displays the different weather stations in the Florida Automated Weather Network with each location labeled with its station ID. Methods and results for the different climate variables in the model are addressed below.

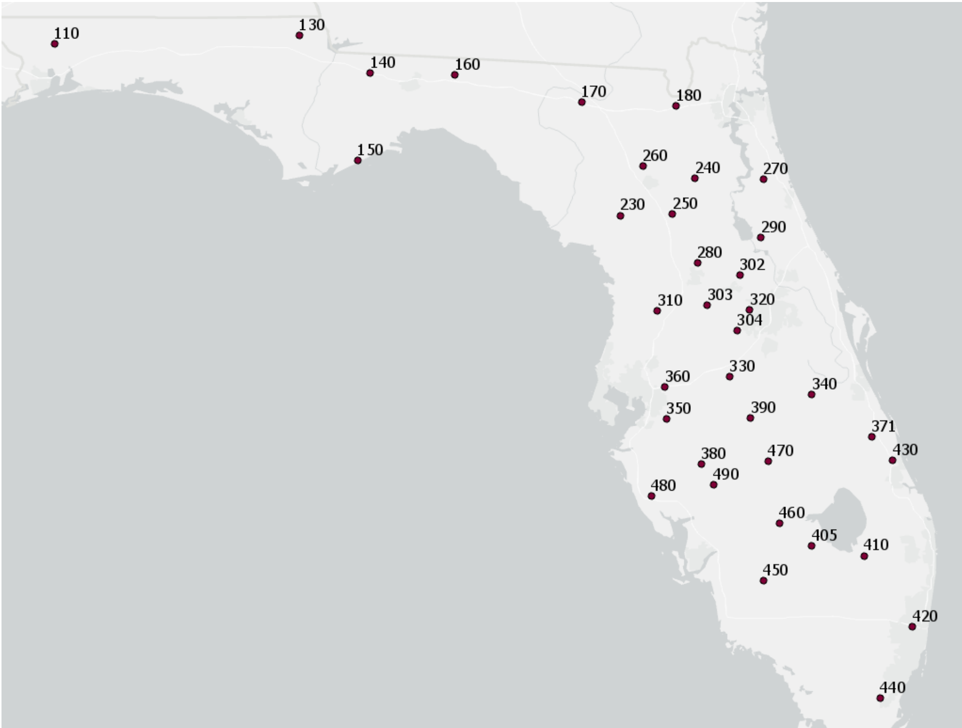


*Figure 4 – Locations of weather stations whose observations were used to create suitability coverages for climatic variables.*

### *Precipitation and Evapotranspiration*

Precipitation and evapotranspiration data are important because of their impact on the availability and long term sustainability of water resources (US DOE 2010). Ideally, pan evaporation data would have been used to generate a surface which represents evaporative water loss. However, known datasets for pan evaporation have sparse coverage for Florida. For this reason, evapotranspiration data from the FAWN climate stations was used as a proxy. These values were derived using the FAO Penman-Monteith algorithm which uses radiation, soil heat flux, average air temperature, wind speed, as well as saturation and actual vapor pressure which should provide an accurate indication of potential for evaporative loss (University of Florida Institute of Food and Agricultural Sciences, 2018b). Generating a surface which could be included in the suitability model was a multistep process. First, annual daily averages for both precipitation and evapotranspiration were calculated for a 10 year period for each of the FAWN climate stations. Then values were appended to a spatial data layer representing the locations of the climate stations where these values were recorded. It is assumed that precipitation and evapotranspiration values from these stations follow Tobler's First Law and are spatially autocorrelated because of Florida's relatively flat elevation profile (Tobler 1970). For this reason, the 10 year annual averages at each location were then interpolated using the inverse distance weighting tool with a distance exponent of 2. This resulted in a coverage with a 30m resolution over the area of interest which provides estimated values for the areas between climate stations. The output precipitation and evapotranspiration rasters were then reclassified into 10 equal interval segments.

For the precipitation raster, the values 1-10 were distributed over equal intervals between the recorded maximum and minimum, with the higher values being assigned to areas of high precipitation (3.96- 4.12mm/day = 10) and the lower values, lower precipitation (2.51-2.67mm/day = 1) (Figure 5). This reflects the desirability of having more precipitation to offset water resource needs.

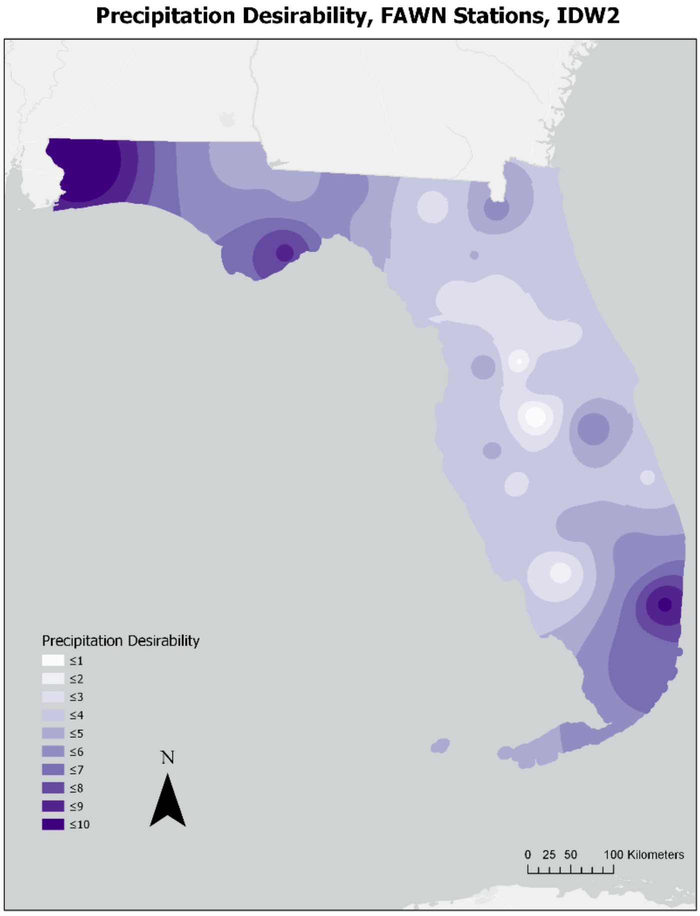


*Figure 5 – Precipitation desirability map generated from reclassified interpolation of rain observations.*

Stations in the northwest and southeast of the state had the highest annual daily averages resulting in areas with a high desirability around these areas.

When assigning values to the equal interval reclassification of the evapotranspiration data was inversed to reflect the strain on resources conditions of high evapotranspiration can have, (2.76- 2.81mm = 10, 3.23 - 3.28mm = 1) (Figure 6). The desirability scores for the evapotranspiration layer had a very different distribution. Stations with lower records of evapotranspiration, and thus higher desirability, are in the northern part of the state, with the exception of station 420 in the southeast.

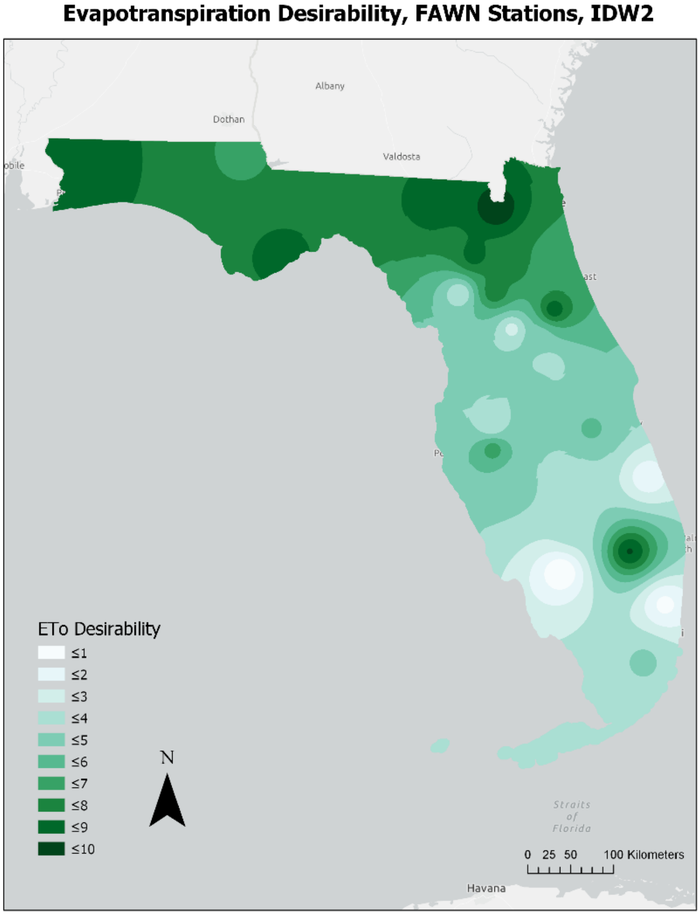


*Figure 6 - Evapotranspiration desirability map generated from reclassified interpolation of evapotranspiration observations.*

## *Temperature*

According to the Sandia National Laboratory, the average daily temperature for optimal algae production should be above 13 degrees Celsius (U.S. DOE 2010, p. 76). All of the climate stations across the state met this requirement, but the number of freeze-days must also be considered. Fewer freeze days indicate a longer potential growth season which is highly desirable from an algal biofuel production perspective. Maxwell 1985 claims that the number of freeze-free days for an area is directly related to the annual production period for a potential microalgae production facility (p. 60). Similar to the precipitation and evapotranspiration data, averages over the 10 year period for the number of freeze days experienced per year were appended to the geographic data for the climate stations. Spatial autocorrelation between the values was also assumed for the number of freeze days so they were interpolated using the inverse distance weighting tool with a power of 2 and the raster was reclassified using the same process for the previous climatic variables. As a lower number of freeze days is preferable, cells with the lowest number of freeze days were assigned higher values (3.4 – 6 days/year= 10) and those with a higher number were assigned a value lower values (28.9 - 32.6 days/year = 1).

Unsurprisingly, areas with a lower number of freeze days and thus a higher growing season desirability score increased as you move south towards the equator as seen in the map in Figure 7. Stations in the north that had significantly higher number of freeze days are concentrated in a relatively small area. When the equal interval classification was applied to the interpolated raster it created a relatively wide range of values though areas with highest desirability score (10) covered 39% of Florida.

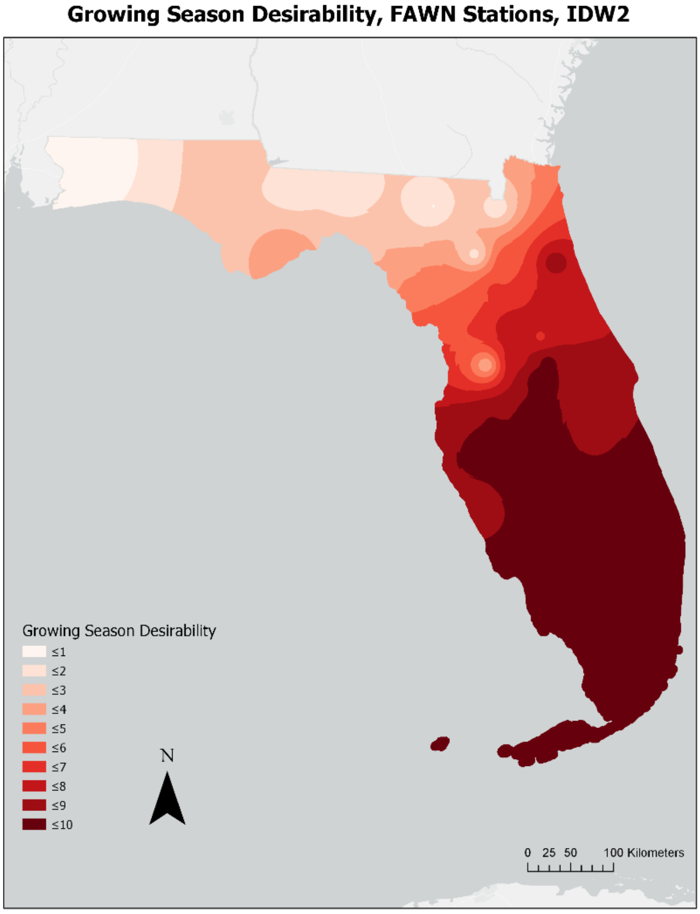


*Figure 7 – Growing season desirability map generated from reclassified interpolation of temperature observations.*

## Hurricane and Flood Risk

Hurricane and flood risk were also incorporated into the suitability model to account for the potential damage that could be sustained from these types of events. Data layers representing risk for these factors were used from FEMA's National Disaster Study (US DOT 2017a). Both datasets were generated to assess the level of exposure to physical infrastructure from respective natural hazards. They originally represented risk on a scale from 0-100, which were then reclassified to a scale of 0-10 and inverted to represent the desirability of low risk in the suitability analysis (US DOT 2017b and 2017c).

As Florida is prone to hurricane events and there are relatively few areas that were considered low risk. The map in Figure 8 shows that those areas with low risk and relatively higher desirability were concentrated in small tracts in the north of the state. 96% of the state occupies the highest two risk categories and thus lowest two desirability classifications.

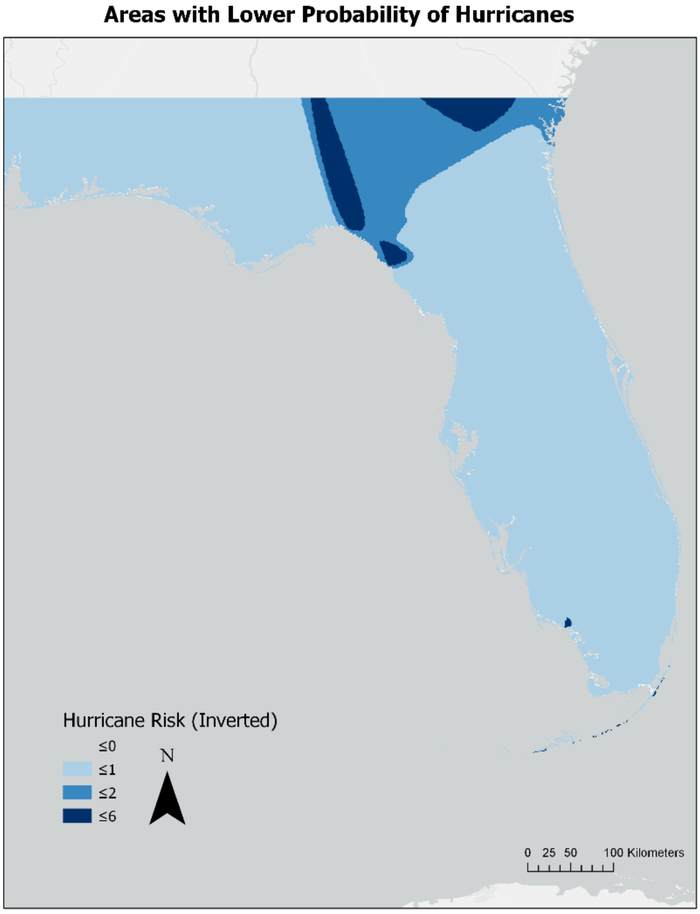


*Figure 8- Hurricane probability map with areas of relatively lower hurricane risk assigned higher suitability values.*

The flood risk data layer in visualized in Figure 9 had a broader distribution of classifications but the proportion of values is again clustered on one side of the curve. 60% of the area had an original flood risk values between 10 and 20, translating to a desirability score of 9. The bottom half of the scale, areas with desirability scores between 1 and 5, made of 37% of the distribution and are generally found along Florida's inland waterways.

**Areas with Lower Probability of Flooding**

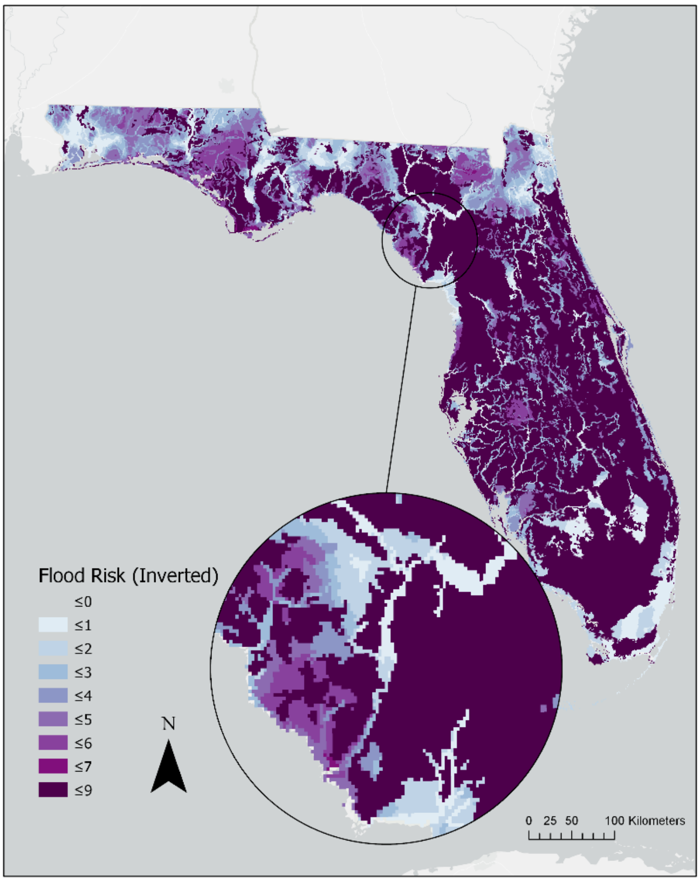


*Figure 9 - F lood probability map with areas of relatively lower flood risk assigned higher suitability values. Original values were dervied from the National Pipeline Hazard Index.*

## Slope

To function efficiently without excessive costs associated with pumping water in open raceway ponds a relatively flat facility site is necessary. Considering this, areas with a slope greater than 2% were excluded from consideration in the study area as they would require prohibitively expensive land excavation to achieve the desired contour (Benemann et al 1982; Lansford et al 1990; Muhs et al 2009; Quinn et al 2013). A digital elevation model was required to determine areas with suitable slopes.

Elevation data was sourced from the USGS using the National Map Viewer (USGS 2013). The raster dataset has a 10m resolution and an extent which encompasses the entire state of Florida. A slope coverage was created using the Slope tool in the ArcGIS Spatial Analyst toolbox with the percent rise option enabled. The coverage was then reclassified so that only those cells with a percent rise value less than or equal to 2 were reassigned a value of 1, and all others given a value of 0. The result of this analysis was a layer which was used later in the suitability model as a mask to exclude any locations with a slope of more than 2% rise (Figure 10).

**Areas with Less Than 2% Slope**

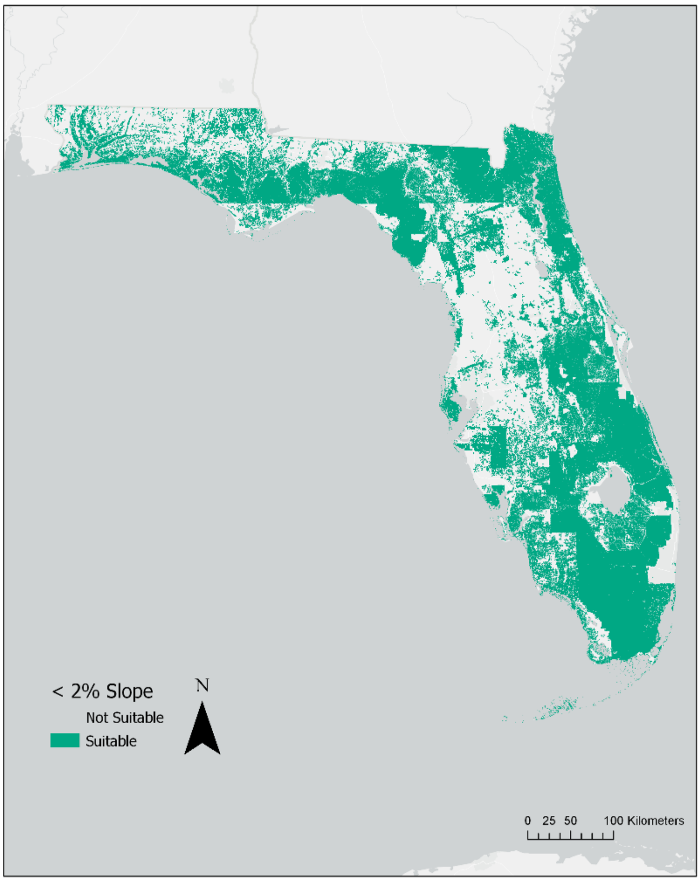


*Figure 10 – Elevation suitability map with desirable areas indicated in green.*

## Land Use

The fact that algae feedstocks can be grown on marginal lands is a big advantage (Murphy and Allen 2012, p. 5863; Quinn et al. 2011, p. 53; Wigmosta et al. 2011, p. 4; Fortier and Strum 2012, p. 11429; Venteris et al. 2012, p. 484). The value of these types of lands are typically less expensive than active agricultural areas and therefore more economical when factored into life cycle assessments for possible plants. Until recently, the Multi-Resolution Land Characteristics Consortium's National Land Cover Database has been used for land cover screening (Quinn et al. 2011; Wigmosta et al. 2011). It offers 30m resolution and covers the entire conterminous United States, but the most recent available data layer is from 2006. The Cropland Data Layer created by the National Agricultural Statistics Services offers the same 30m resolution but has the added advantage of being updated every year (USDA 2014). For this reason, it is the preferred data layer in Venteris et al.'s 2012 study and will be utilized here. Only areas which were classified as Fallow/idle cropland, Developed/open space, Barren, Shrubland, and Grassland/pasture were selected. These were assigned a value of 1 whereas all other areas were given a value of 0. The result is a land use mask that is used later to filter out locations with unsuitable land types in our multicriteria suitability model. Figure 11 shows areas with suitable land use broken down by category.

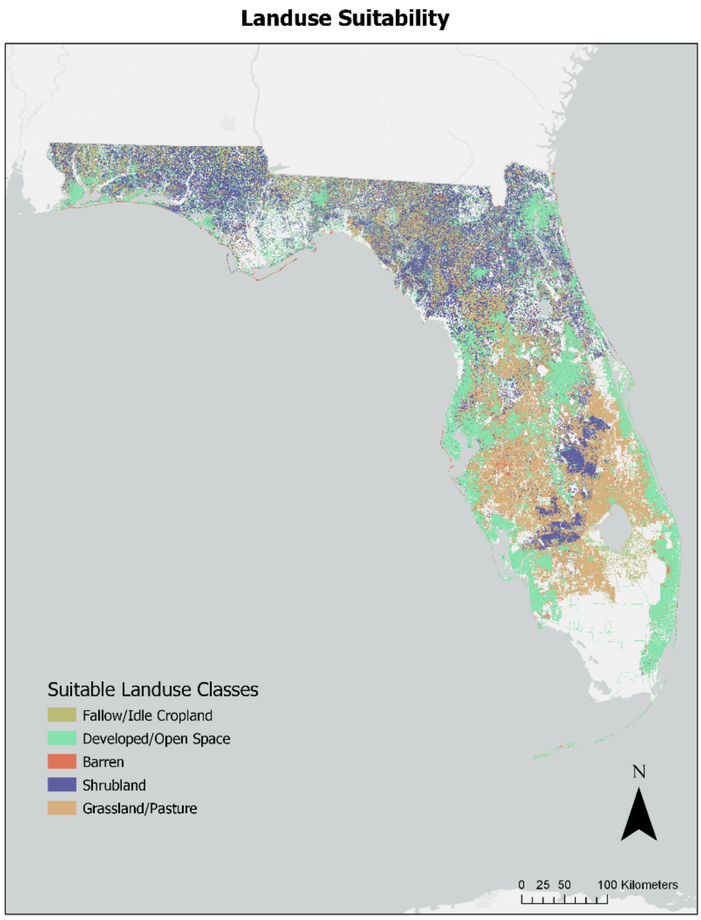


*Figure 11 – Land use suitability map with suitable land use classifications broken down by category.*

In total, there are 391,280 hectares of land that is suitably marginal to locate algal biofuel production facilities. Areas classified as Developed/Open Space, Shrubland, and Grassland/Pasture make up the majority of the suitable areas, constituting 96% of the total.

## Multicriteria Suitability Model

In each of the previous sections raw data was processed into individual data layers that represent suitability values for single characteristics. Each of these data layers are useful in their own way but using a multicriteria suitability model provides unique insight into where algal biofuel production facilities should be located in Florida according to the interests of different stakeholders. This is achieved by assigning different weights to the data layers in the model that account for their relative importance to the stakeholder. There are virtually endless ways to weight the model depending on which characteristics one believes to influence suitability, Table 1 offers one such permutation.

| *Characteristic* | *Relative Weight (%)* |
|---|---|
| *Proximity to Suitable $CO_2$ Point Sources* | 30 |
| *Proximity to Suitable Waste Water Treatment Plants* | 30 |
| *Precipitation* | 10 |
| *Evapotranspiration* | 10 |
| *Freeze Days* | 5 |
| *Hurricane Risk* | 5 |
| *Flood Risk* | 5 |
| *Proximity to Roads* | 5 |

*Table 1 – Configuration of the multicritera suitability model.*

Proximity to $CO_2$ and waste water point sources were give the highest weights in this configuration of the model because, in addition to sunlight, $CO_2$, nitrogen, and phosphorous are the primary components required for autotrophic microalgae growth (Benemann, 1982).

An assumption was made that water would be widely available throughout Florida, though the need to recharge open raceway ponds can be mitigated by higher precipitation and lower evapotranspiration conditions at facilities. Less water use results in lower costs and considering water supply is necessary in algae cultivation, these factors were also weighted heavier.

The number of freeze days has an impact on the growing season for algae, but as all of Florida has recorded daily averages well above the recommended 13 degrees Celsius this data layer was given a relatively low weight (U.S. DOE 2010, p. 76).

Although hurricane and flood events are likely in many parts of Florida, their cycles can be long and there is no certainty that an event will affect a facility which is why less weight was given to these layers.

Lastly, proximity to roads was also given a relatively low weight. In a weighted scheme proposed by Lundquist et al, 2010, proximity to roads was only valued at 1% (p. 54). However, in his cost breakdown he fails to acknowledge operation and maintenance costs and he only considers areas within 1.5 miles from existing roads in the study area for California (p. 51, 54). In the scheme proposed above, proximity to roads was given a weight of 5% to account for the assumption that roads will have operation and maintenance costs just like other capital investments and for the possibility that road construction could amount to a larger capital expense due to the increased distance from existing roads in this analysis (0-10km vs 0 – 1.5 miles).

Once the weights for the different datasets was determined, they were converted into fractions which add up to 1 when added together (30% = 0.3). Each layer was then multiplied by its relative weight and added together, generating an overall suitability data layer. This effectively combined the different data layers into a single weighted overlay whose output maintains the 1-10 suitability classification that went into each of the original suitability assessments.

It should be noted that the slope and land use data layers were not included in this weighted overlay. As mentioned in the previous sections, binary classifications were assigned to these two layers, 1 = suitable, and 0 = not suitable. The final output of the suitability model was obtained by multiplying the weighted overlay by the slope and land use data layers, filtering out areas with more than 2% slope and those that did not meet the land use criteria set out above.

In order to facilitate the use of this data layer in the web tool which will be covered later, steps were taken to optimize the resulting dataset. First, 0 values where converted to No Data, greatly reducing the size of the dataset. At this point, pixel values are still stored as floats because of the calculation above. To further optimize the dataset, float values were reclassified to integers ranging from 1-10. These optimizations are important when rendering and analyzing the data locally but are even more so when making it accessible as a web service.

# Results

## Statistics

The final output data layer from the multicriteria site suitability analysis provides us with a great deal of information. Generating cell statistics on the dataset provides us with a breakdown of the total number of pixels for areas with each of the suitability scores. Furthermore, we can derive areal calculations for each of these suitability scores from the pixel resolution, detailed in Figure 12.

Although our original classification scheme was based on a scale of 1-10, when the weighted overlay was performed there were no pixels which were between 9.0 and 10.0, shortening the range.

In total, there are roughly 211,629ha of land in Florida that meet the minimum requirement of having a less than 2% slope and a land use classification of Fallow/idle cropland, Developed/open space, Barren, Shrubland, or Grassland/pasture.

Scores 1 (55.5ha) and 9 (101.9ha) represented the smallest areas while the area which had a value of 3 (90,666.9ha) more than doubled that of score 2 (42,520.5ha) which was the next nearest.

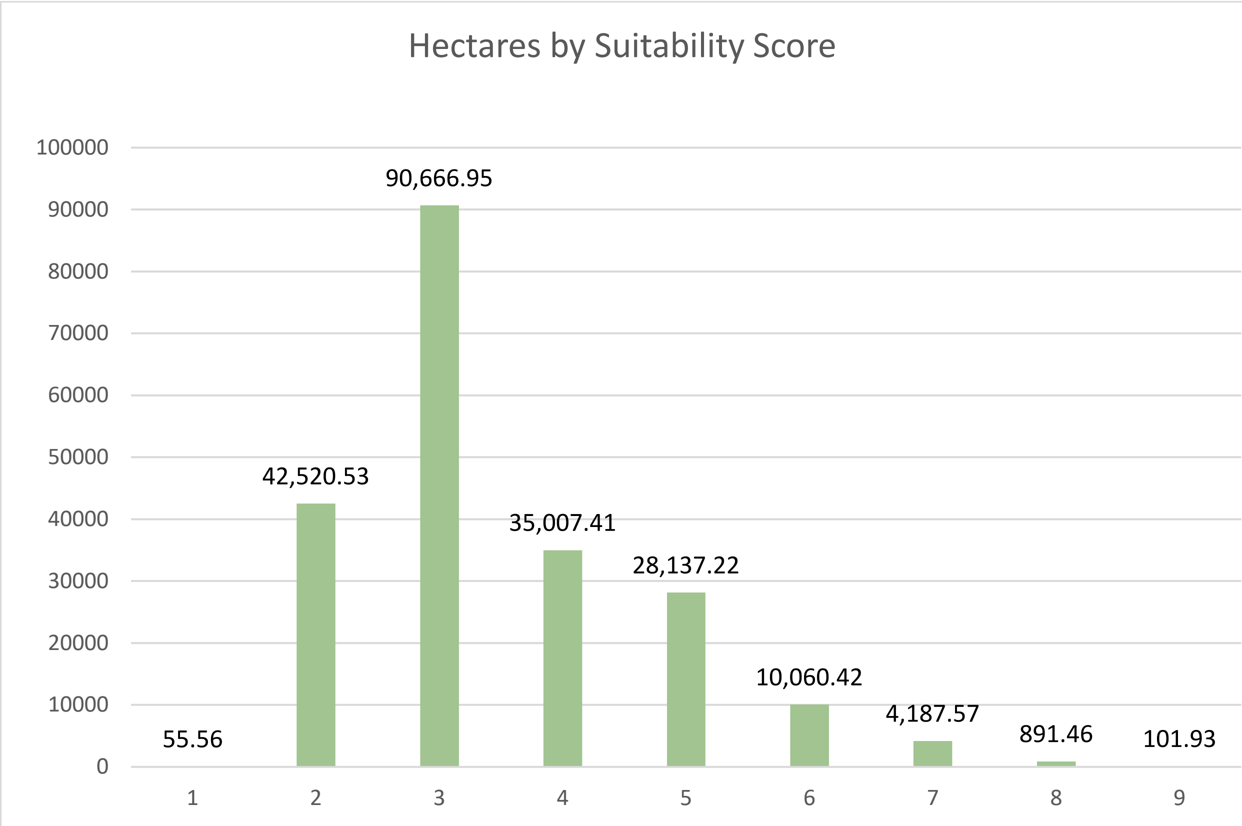


*Figure 12 – Breakdown of hectares by suitability score for the state of Florida.*

We can aggregate these scores further accrediting areas with values of 1-3 to be moderately suitable, 4-6 suitable, and 7-9 highly suitable. Areas which are moderately suitable (133,243ha) outrank those which are suitable (73,205ha), with highly suitable (5180ha) areas representing only 2% of the total area (Figure 13).

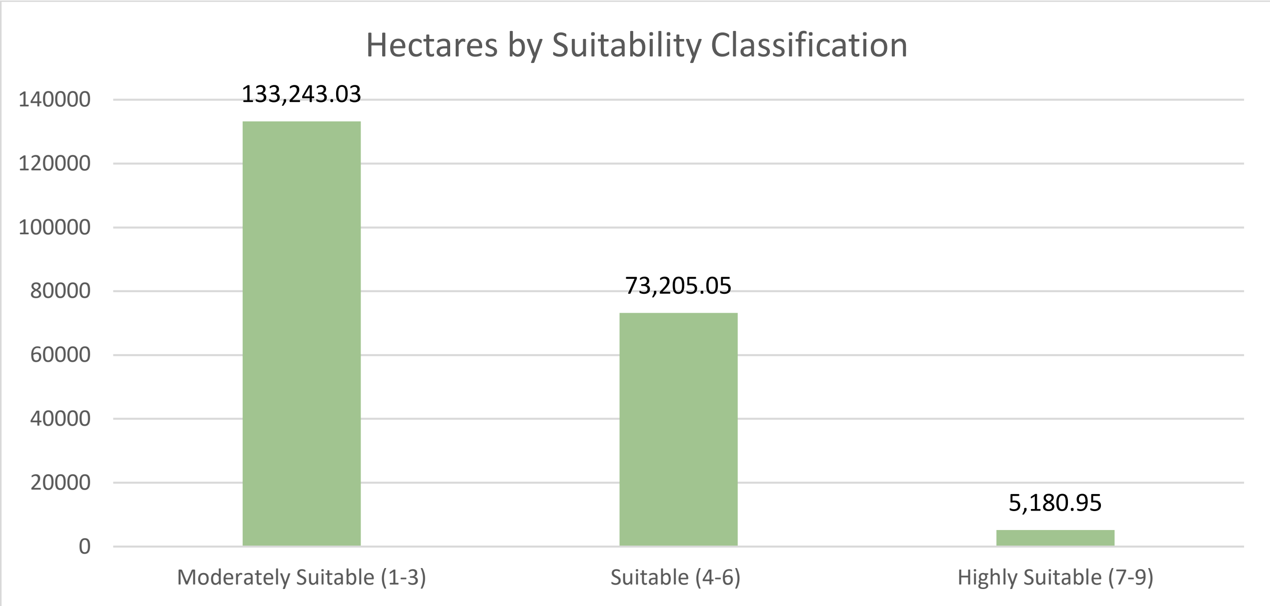


*Figure 13 – Breakdown of hectares by suitability classification for the state of Florida.*

## Multicriteria Suitability Map

Although these tables and charts give us an empirical breakdown of the output from the suitability model we must visualize the data layer to get a better understanding of where suitable locations are.

**Final Multicriteria Suitability Map**

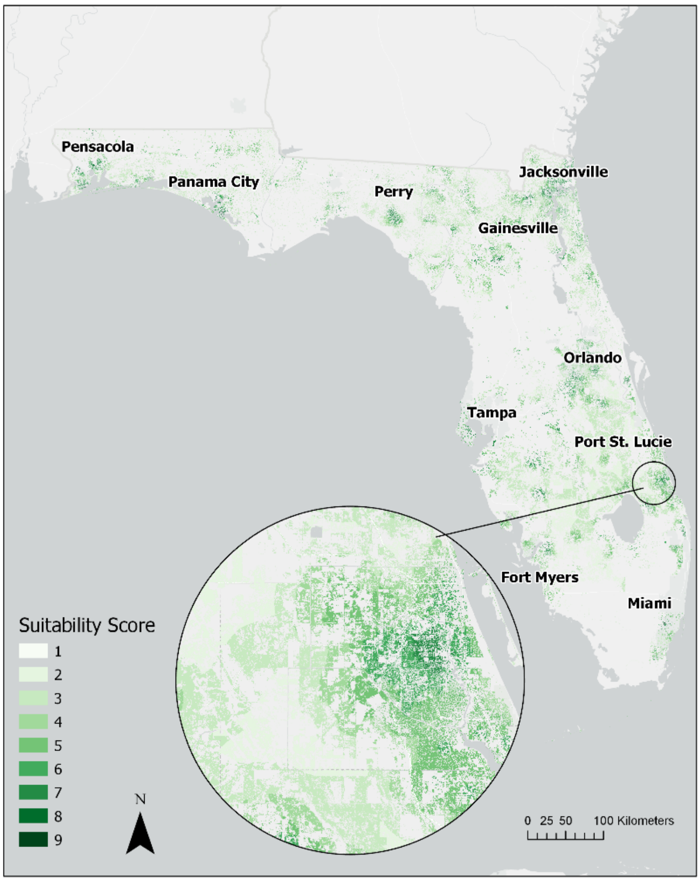


*Figure 14 – Final result of multicriteria suitability analysis with areas of more intense green indicating higher desirability.*

The areas considered to be highly suitable make up only a fraction of the total area that met the minimum criteria but there is still a significant amount of land that could serve as locations for algal biofuel production pilot facilities. These areas should of course be considered first when exploring options for building out these operations.

As can be seen in Figure 14, most of the suitable areas are clustered around urban or suburban centers. This is likely because these areas would have water treatment plants to service residents, as well as power plants or other industrial operations that are often found near economic centers. Furthermore, these areas would be well served by primary and secondary roads. For a more detailed look at the suitability distribution consult the web application in the following section.

## Web Application

Static maps showing the suitability scores for the individual data layers and the overall multicriteria assessment are helpful for visualizing landscape level distributions but fall short in letting viewers explore the results of the analysis in any detail. To address this shortcoming a web application was developed that allows a user to view the results of the analysis at different scales.

A lightweight and performant web layer was built out of the final suitability dataset by generating a tile cache down to 1:36,000 scale. This was then published to ArcGIS Online as a tile layer and brought into the Web AppBuilder, where the measurement and basemap gallery widgets were added to the web application (Esri 2018a).

The web application provides a number of capabilities to stakeholders assessing viability of locations for algal biofuel production. First, the user is able to pan and zoom around the area of interest down to a level of detail where individual 30m resolution pixels can be distinguished. The output of the suitability model can be compared to different basemaps through the gallery widget, allowing the users to switch between vector basemaps that provide contextual information like urban areas, roadways, and water bodies, and satellite imagery which can be used to compare the suitable areas to actual images for a given date. In addition to this overlay analysis between the suitability layer and the basemaps, users can also perform areal calculations with the measurement tool. If an area looks like a good candidate it can quickly be measured to determine if it meets the 100ha threshold value for pilot facilities proposed earlier. All of these capabilities are delivered to anyone with an internet connection by accessing the application visualized in Figure 15.

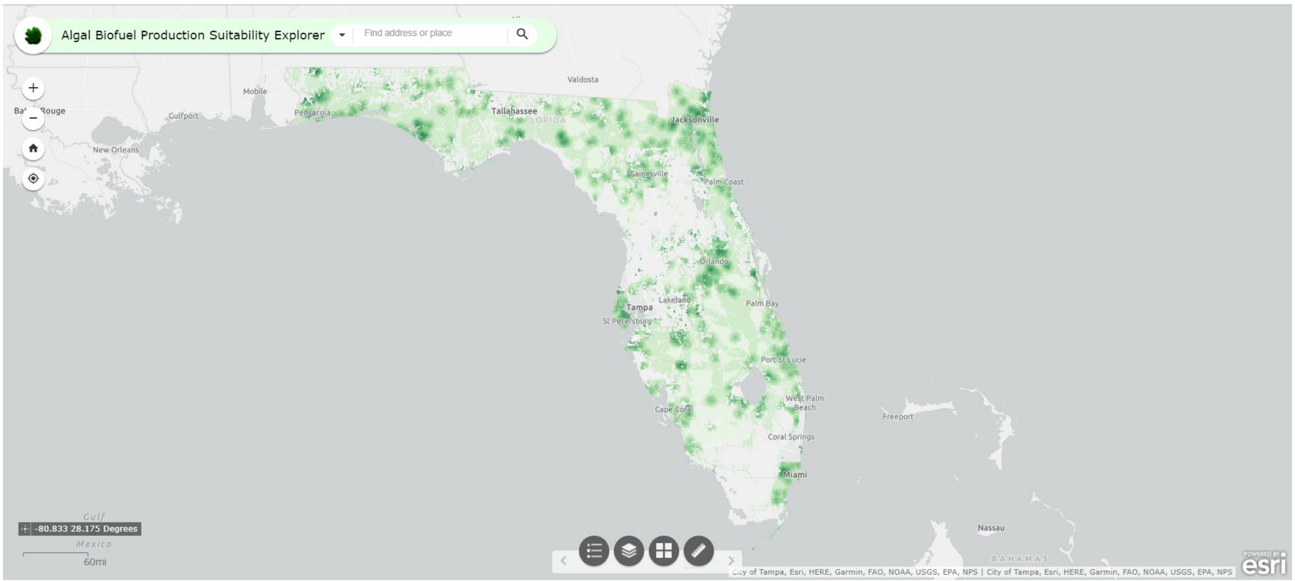


*Figure 15 – Screenshot of the Algal Biofuel Production Suitability Explorer. The app can be accessed at: http://bit.ly/2HrYUrE*

# Discussion

## Comparative Results

Quinn et al. 2013 and Wigmosta et al. 2011 are two widely cited studies which employed similar techniques to the analysis outlined in this paper but focused on the conterminous United States as its area of interest. Quinn et al.'s study combined models that assessed microalgae productivity, available land, and transport distance from $CO_2$ point sources to assess overall production potential. This is mostly aligned with the analysis performed in this study and it similarly looked at areas with a 2% slope and areas classified as marginal lands. However, differences include limiting potential locations to those with a minimum area of 400ha, focusing on growth methods utilizing photobioreactors, neglecting to consider proximity to waste water treatment plants, and having a component which predicted total lipid productivity based on land availability and thermal models. Based on the minimum parameters of appropriate land classification, slope, being within a 4.8km distance from $CO_2$ point sources, and the 400ha size requirement it determined that there were 0.28 million hectares of suitable land in the United States. This compares to the 0.21 million hectares identified as suitable in the present study for Florida alone. When one compares Figure 4 in their study to the final multicriteria suitability map in Figure 14 of this study the spatial distribution of potential locations is similar (p. 596). However, the requirement of continuous areas that meet the 400ha requirement is likely the cause of the difference in total area considered suitable.

Wigmosta et al. 2011 performed a similar national analysis with a focus on productivity potential. Their study limited locations to those with less than 1% slope, land areas with more than 490ha, were considered noncompetitive for development, and excluded areas adjacent to urban centers. Results from their model found roughly 43 million hectares of land in the United States that is suitable for algae cultivation, 5.5% of the entire country (p.4). This is a stark contrast to the results in Quinn et al. 2013 and are more aligned with the order of magnitude from this study. The reported numbers do not account for proximity to $CO_2$ point sources, differing from Quinn et al. 2013, and do not consider any of the other parameters outlined in the analysis above. However, they do require suitable locations to have contiguous areas of 490ha or larger which may explain why the numbers are comparable to those in this analysis instead of being much larger. The distribution of suitable land from Wigmosta et al.'s study is difficult to compare to that produced in this analysis as the map-based visualizations represent biofuel production potential and water requirements rather than land suitability scores.

Lundquist et al. 2011 provides a better point of comparison as it has a regional focus of California and less emphasis on biofuel production potential in favor of location suitability. Major differences lie in their use of a 5% slope threshold and temperature data from 1960-1990 and evaporation data amassed in 1982. Furthermore, although they included irrigated agricultural lands in their model, they did not remove waste water treatment plants that failed to meet estimated flow rate requirements and maintained a strict 1.5 mile buffer distance from roads for lands to be deemed suitable. They did acknowledge that this criterion could probably be relaxed in future studies as they were in the analysis above (p. 51). Lundquist et al. 2011 does not present quantitative results from their analysis so it is difficult to compare them to the present study.

The techniques from the studies above served as the inspiration for the analysis performed in this work. However, they focused on assessing the potential capacity for the United States to meet production figures outlined in Title II of the Energy Independence and Security Act of 2007. The research and analysis of this study attempted to build on these works in order to provide a methodology and practical tool for identifying test production facilities for Florida, which could also be applied to other areas of interest.

## Practical Applications

In the configuration of the suitability model applied to this analysis, 2% of areas which met the minimum slope and land use criteria were considered highly suitable. These locations, located mostly near urban areas, represent optimal locations to develop algal biofuel production facilities in the state of Florida as they relate to the variables and their weights in the model. Defining the different suitability layers and employing weighted overlay techniques allows decision makers to narrow the scope of their search for locations that would be economically viable for algae production. The web application especially provides the user with the ability to pan and zoom to separate locations on a map and overlay individual thematic layers like proximity to $CO_2$ point sources or waste water treatment plants as well as the multicriteria suitability assessment layer. They can then use the measure tool to get rough calculations of the size of a prospective area, which can inform whether they should investigate a location further. Field visits to the sites would be important to validate the suitability of the specific site, but would also be useful in validating the overall model.

## Model Considerations

As mentioned earlier, several biofuel production potential analyses have been performed at the national scale (Quinn et al. 2013; Venteris et al. 2012; Wigmosta et al. 2011) or at the regional scale in the American southwest (Lundquist et al. 2010, Lansford et al. 1990). The methods for this study largely depended on the catalogue of work in these different publications but incorporated new considerations into the model like hurricane and flood risk, which more accurately reflect environmental factors specific to Florida which may impact the decision process for implementing these facilities. The inclusion of these parameters is representative of the flexibility of the model to adapt to different geographies.

The output of this analysis is only one configuration of the multicriteria assessment model. The weights for this configuration were mostly determined from figures Lundquist et al. 2010 (p. 54). In this study, $CO_2$ and WWTP sources were given the highest weights similar to those in Lundquist et al. 2010. The values were balanced to account for the mitigation effects of removing N and P from watersheds that could have otherwise led to eutrophication in the Gulf of Mexico and other waterways (Mitsch et al. 2001). Saline aquifers were not considered in this model so extra weight was applied to precipitation and evapotranspiration desirability. In future studies, these figures could be combined by assessing net precipitation. Land use and slope were used as filters rather than weighted data layers, explaining their absence from the overlay analysis. The weight for proximity to roads was increased for reasons stated above and temperature, hurricane and flood risk were all given values of 5% so that these parameters would have some influence in the output of the multicriteria assessment layer. However, there are virtually endless combinations of configurations depending on which parameters you want to consider, and how those parameters are weighted. Different stakeholders will have different interests which will influence how one should configure the model. This investigation provided one such option according to the explanation provided in the above but the model could easily be configured and run to account for any number of stakeholder perspectives.

## Uncertainties

There are a number of uncertainties in this multicriteria assessment. First, both the slope and land use data layers are secondary information products, having been derived from remotely sensed satellite imagery. The Cropland Data Layer is at best 80 to 90% accurate (National Agricultural Statistics Service 2018) while the DEM's accuracy has a 95% confidence level within 3 meters (USGS 2018).

The precipitation and evapotranspiration layers also have a degree of uncertainty in them since they were generated by interpolating annual daily averages from weather stations. Although the stations are pretty well distributed and Florida is relatively devoid of elevation changes that might impact estimates, changes in microclimates might result in differences between interpolated values and actual conditions. When comparing the interpolated surface for the precipitation layer to other maps there is pretty good correlation. For example, a map of average annual precipitation from 2002-2014 produced by the Southeast Regional Climate Center (Figure 16) is consistent with that produced in Figure 5 (SERCC 2018).

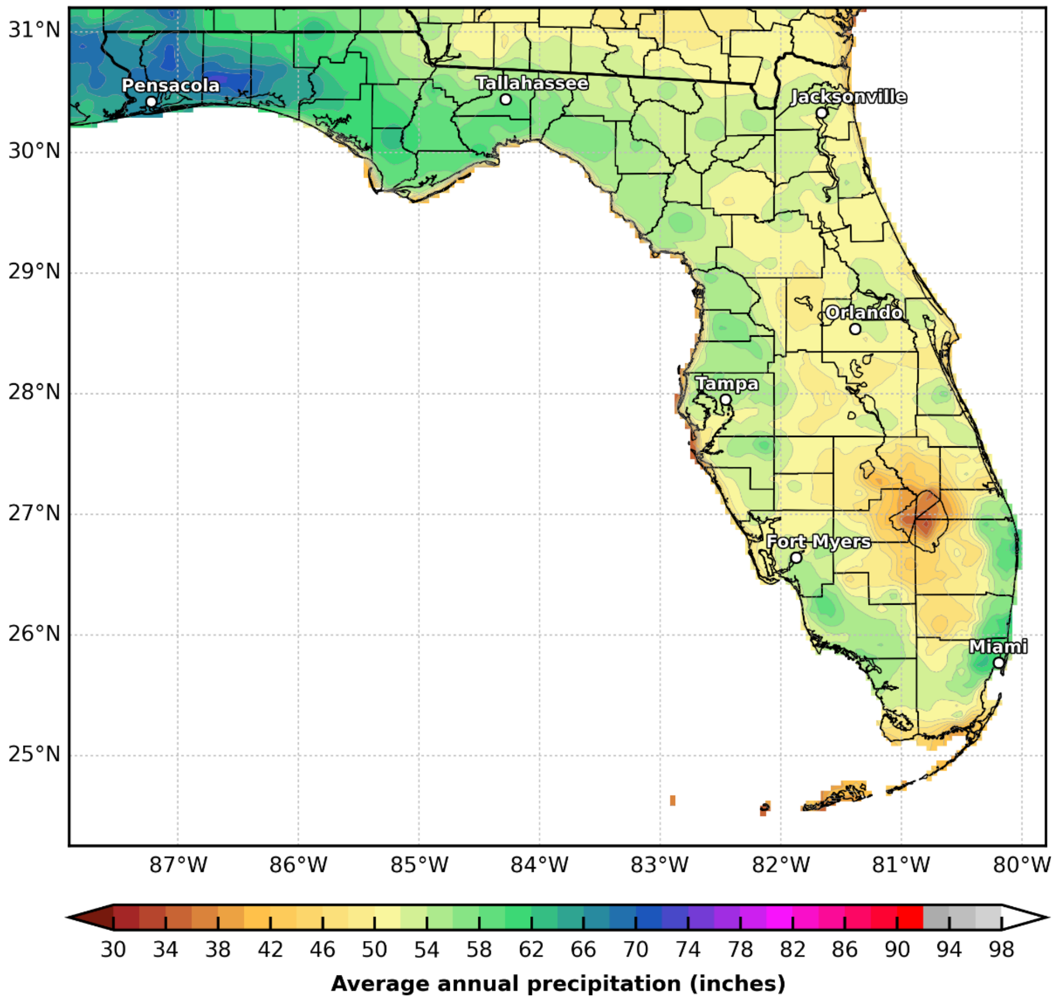


*Figure 16 – Florida Average Annual Precipitation, 2002-2014*

Areas in the northwest and southeast exhibit higher values for precipitation while the only major discrepancy occurs around Lake Okeechobee which has significantly lower precipitation values than the rest of the state. Future studies may want to explore other precipitation datasets.

The interpolated surface expressing desirability when considering evaporation is a bit more complicated. Recent studies have employed Bowen ratio energy-budget (BREB) micrometeorological methods to estimate evaporation from major open water lakes as well as Geostationary Operational Environmental Satellite (GOES)-based estimates for regional evapotranspiration for the state of Florida. Figure 17 illustrates annual potential evapotranspiration from 1996 to 2011 for Florida using this mixed method (Lee et al. 2014, p.3054-3063).

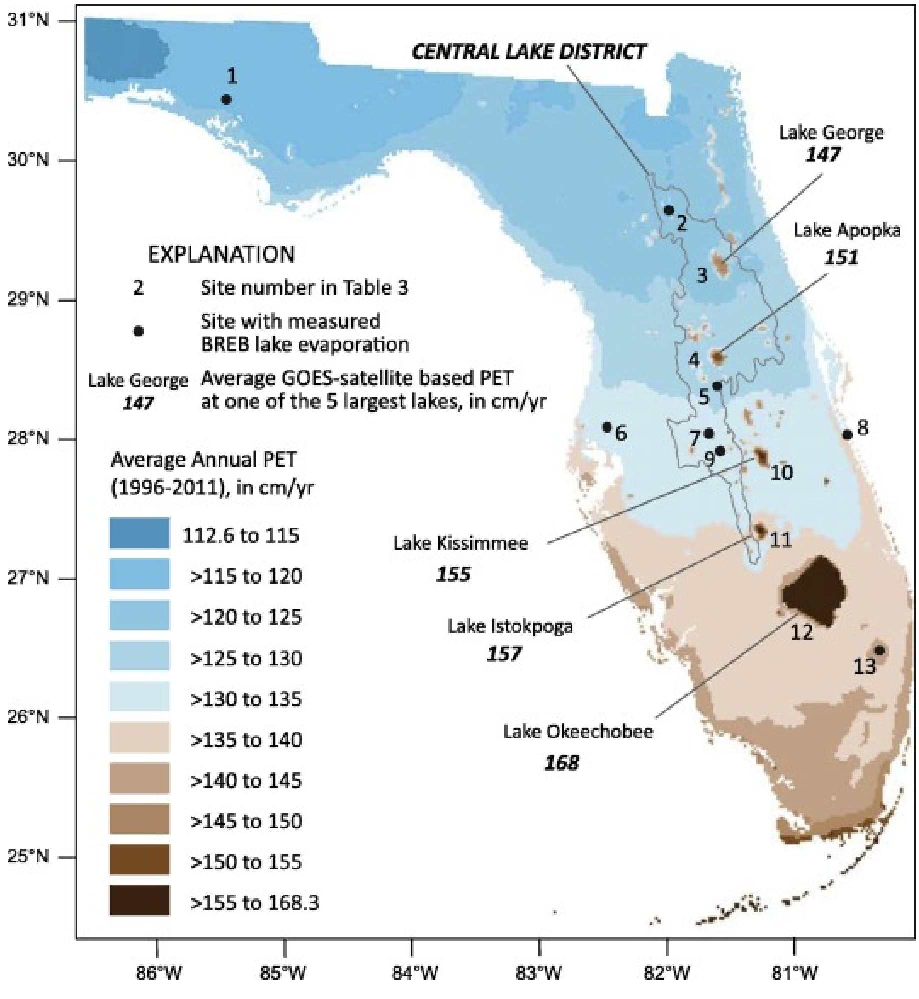


*Figure 17 - Annual average potential evapotranspiration during 1996–2011.*

Regional trends are similar to those found in Figure 6, however major differences are visible in areas where there are large lakes likely from the inclusion on BREB values in Lee et al.'s study. In the future, evaporation data layers incorporated into the multicriteria site suitability analytical model may want to rely on datasets derived from continuous GOES observations as well as methods that account for regional variations like large open water lakes as seen above.

Assessing the accuracy of the hurricane and flood models is also difficult. Hurricane risk was assessed using historic hurricane track data over a 94 year period but the effects of climate may impact the distribution and level of risk. For instance, the likelihood of the occurrence of hurricanes and the strength at which they make landfill may be increasing (Elsner 2006).

## Future Studies

At this point it is difficult to measure the effectiveness of the suitability model. One could compare areas of predicted high desirability with satellite imagery to visually inspect if areas appear to be undeveloped or marginal, but this only confirms or denies the reliability of the land use model. To effectively, validate or refute the model on-site inspections and/or forensic investigations would first need to be done to verify land suitability from both an economic and legal perspective. Furthermore, to test the impact of environmental conditions have on production, several sites would need to be operational in order to be able to compare productivity at locations with different growing conditions. Both of these activities would be either too costly or untimely to be addressed in the scope of this investigation but should be considered for future studies. To date, the author is unaware of any publications that have compared output figures from different facilities at production scale.

One opportunity for improvement would be to host the different data layers and plug them into a weighted overlay tool that would allow stakeholders to change the scoring schema for individual layers, as well as modify the weights of the different layers so that users could interactively generate different scenarios that reflect different stakeholder perspectives. In this study one perspective was presented while a web tool as just mentioned would allow a user to generate any number of configurations of the weighted model in a matter of minutes. Again, this was outside of the scope of this study but could be a focus on any further work with these datasets.

## Conclusion

The objective of this study was to define a GIS methodology and toolset that can help stakeholders identify the ideal areas for biofuel feedstock cultivation in Florida. To achieve this objective, a framework was produced to generate multiple science-based location scenarios from a diverse set of inputs. Furthermore, a single configuration of the analytic model with relative weights applied to these inputs was created resulting in a land suitability data layer representing locations which are moderately suitable, suitable, or highly suitable. Validating the accuracy of the model is a challenge in the absence of ground truthing, which falls outside of the scope of the study, and data regarding the impact of the suitability criteria on production scale facilities. However, the creation of a web tool which leverages the output dataset from the multicriteria assessment, satellite imagery, and the measurement widget provides functionality to decision-makers to interactively search for and measure potential sites for production facilities based on the inputs of the configuration of the model. This builds on previous national and regional scale analyses which offer a more prescriptive view of potential locations based on a narrower set of inputs. Moving forward, there is an opportunity to expand on this work and build a toolset that would allow decision-makers to dynamically configure the multicriteria assessment model and generate suitability scenarios which represent the perspectives of different stakeholders.

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