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Regional algal biofuel production potential in the coterminous United States as affected by resource availability trade-offs

Erik R. Venteris *, Richard L. Skaggs, Mark S. Wigmosta, Andre M. Coleman

Pacific Northwest National Laboratory, P.O. Box 999, 902 Battelle Boulevard, Richland, WA 99352, USA

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ABSTRACT

A warm sunny climate and unoccupied arid land as in the American Southwest are favorable for algal cultivation. However, additional resource constraints affect the overall viability of specific sites and regions. We investigated tradeoffs between growth rate, water, and CO_2 availability and costs for two strains: *Nannochloropsis salina* and *Chlorella* sp. We conducted site selection exercises to produce 7.95E + 10 L yr^{-1} (21 billion gal yr^{-1} (BGY)) of renewable diesel (RD). Experimental trials from the National Alliance for Advanced Biofuels and Bio-Products (NAABB) team informed the growth model of our Biomass Assessment Tool. We simulated RD production by both lipid extraction (LE) and hydrothermal liquefaction (HTL). Sites were screened for the availability of freshwater and flue gas, and prioritized by the net value of biofuel minus water (the least-expensive and available source) and flue gas delivery costs. Water sources considered were ground waters ranging in salinity from fresh to brines and seawater. We found that HTL produced more RD per unit biomass than LE, resulting in an improvement in economic efficiency of 76%. Selections constrained by production and water were concentrated along the Gulf of Mexico and southeastern Atlantic coasts. Adding flue gas constraints increased the spatial distribution to include sites nationwide. The 21 BGY target required ~3.8 million ha of mainly forest (41.3%) and pasture (35.7%). Exclusion in favor of barren and scrub lands forced most production to the southwestern US, but with increased water consumption (5.7 times) and decreased economic efficiency (−38%).

1. Introduction

This paper investigates the question of how resource requirements impact the location of the most promising sites for algal cultivation facilities. Legacy algal siting studies [1,2] and the location of early [1,2] and current [3,4] pilot cultivation facilities emphasized areas where growth rates were expected to be large due to climate. These previous works focused on the southwestern US as the most promising region for algal biofuel development due to climate (warm, sunny, and relatively cloud-free) and unoccupied, inexpensive land [42]. Our work based on the Biomass Assessment Tool (BAT) [5,6] has shown that there are indeed promising locations in the Southwest, but overall, coastal areas of the Gulf of Mexico have the best combination of productivity and water consumption. Here, we explore the interaction between species-specific algal production, biomass to biofuel technological pathways, and resource requirements (freshwater, brackish water, high salinity groundwater, or seawater, and CO_2 delivered as flue gas) and how these affect the geographic distribution of sites required to produce 7.95E + 10 L yr^{-1} (21 BGY) of renewable diesel (RD). The RD production target represents the entire advanced biofuel target [7] to be met by the year 2022 as prescribed by the Energy Independence and Security Act of 2007. We explore the factors that contribute to our geographic conclusions compared to historical and more recent studies [8,9]. We also discuss in detail the land use categories that are most favorable for conversion to algal cultivation and the geographic and resource implications if their conversion proves undesirable.

The overall goal of the study is to explore the impacts of algal biology (growth rates), cultivation resources (land, water, and carbon dioxide) and biomass to biofuel technology on the sustainability of algal biofuels. The analysis is based on an enhanced version of the BAT model, which predicts algal productivity and resource requirements for the coterminous United States (CONUS) [5]. The previously presented growth model [5] is used, but with species-specific parameters (Table 1). As part of the National Alliance for Advanced Biofuels and Bio-products (NAABB) project, growth model parameters were determined for a strain of *Chlorella* (M. Heusemann, personal communication) and for *Nannochloropsis salina* [10,11]. In addition, we are exploring contrasts between two technological pathways for biomass to biofuel conversion, "traditional" lipid extraction (LE) where cells are disrupted to separate

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Abbreviations: BAT, Biomass Assessment Tool; BGY, billion gallon $year^{-1}$; CO_2, carbon dioxide; CONUS, coterminous United States; GIS, geographic information systems; HTL, hydrothermal liquefaction; L, liter; LE, lipid extraction; NATCARB, National Carbon Sequestration Database and Geographic Information System; NP, naphtha; RD, renewable diesel; T, tonne (metric tonnes).

* Corresponding author at: Pacific Northwest National Laboratory, P.O. Box 999, MSIN K9-33, 902 Battelle Boulevard, Richland, WA 99352, USA. Tel.: +1 509 372 6147.
E-mail address: erik.venteris@pnnl.gov (E.R. Venteris).

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Table 1
List of parameter values used in the growth and biofuel production models.

Parameter	Value	Source
Growth model light saturation constant (S_o) *N. salina*/*Chlorella*	250/250	M. Huesemann
Growth model biomass accumulation efficiency ε_b *N. salina*/*Chlorella*	0.21/0.61	M. Huesemann
Growth model minimum water temperature for zero productivity T_{min} *N. salina*/*Chlorella*	11.0/12.8	M. Huesemann
Growth model lower water temperatures for optimal productivity T_{opt_low} *N.salina*/*Chlorella*	26.3/36.0	M. Huesemann
Growth model upper water temperatures for optimal productivity T_{opt_high} *N.salina*/*Chlorella*	28.0/36.2	M. Huesemann
Growth model maximum water temperature for zero productivity T_{max} *N salina*/*Chlorella*	36.0/45.0	M. Huesemann
Carbon Utilization Efficiency (E_{co2})	0.82	[12]
Harvest Efficiency (H)	0.95	[12]
Lipid Content (l) for *Chlorella*	0.25	[12]
Lipid Content (l) for *N. salina*	0.354	M. Huesemann
Lipid Extraction Efficiency (E_e)	0.855	[12]
RD Fuel Recovery, LE (E_{LERD})	0.928	[12]
Naptha Fuel Recovery, LE (E_{LEN})	0.036	[12]
Biomass to HTL Oil Efficiency ($E_{HTL.}$)	0.606	S. Jones
HTL Renewable Diesel Upgrading Efficiency (E_{RD})	0.685	S. Jones
HTL Naphtha Upgrading Efficiency ($E_{N.}$)	0.0996	S. Jones
Lipid Density (ρ_l) (kg L^{-1})	0.909	[12]
HTL Renewable Diesel Density (ρ_{RD}) (kg L^{-1})	0.793	S. Jones
HTL Naphtha Density (ρ_{NP}) (kg L^{-1})	0.780	S. Jones

lipids (for example by solvents such as hexane) [12], and hydrothermal liquefaction (HTL) [13–16], where the full biomass is converted to a petroleum-like fuel precursor through the application of heat (~300 °C) and pressure (10 to 25 Mpa). Regardless of strain or technological pathway, water is a key resource for algal cultivation especially for open ponds. Accordingly, we have made significant improvements to our previously-presented water cost and availability models [6]. We now classify waters as competitive surface and shallow groundwater, brackish groundwater, saline groundwater, and seawater. The modeling of groundwater resources is enhanced through the analysis of data for over 200,000 wells from the USGS National Water Information System (NWIS) [17]. In addition, we apply a model of flue gas availability and costs based on previously presented GIS cost–distance techniques [18].

2. Methodology

The site prioritization and selection models are based on a national set of locations deemed suitable for large, open, cultivation ponds [5] for which algal growth rate, water, and carbon dioxide demands were calculated. Land areas with slopes >1%, protected parklands and preserves, urban areas, and croplands are excluded from consideration. Potential sites are modeled as points, each representing a 485 ha unit farm with 405 ha being used for production ponds and the remainder for support facilities. Algal growth in open ponds is simulated based on a series of coupled model components developed at high spatiotemporal resolution (hourly, 10^1 m). The model uses incoming solar radiation, air temperature, dew point temperature, wind speed, and precipitation (disaggregated from daily Cligen values [19]), in a full mass and energy balance hydrodynamic model to simulate the pond state [20], including water temperature and net evaporative water loss. This is coupled to a microalgal growth model that simulates the conversion of incident solar radiation to biomass, accounting for light saturation and water temperature impacts on conversion efficiencies using growth parameters taken from laboratory experiments. In this contribution we do not explicitly account for the effects of operating salinity on growth rate [21], however the operating salinities selected would have growth rates within 25% of optimal salinity levels (*N. salina* [22], *Chlorella* [23] and Huesemann, unpublished data), a deficit potentially overcome by strain selection and other cultivation improvements.

Water salinity is central to estimating water demands and costs. Both the salinity of the water source and the operating salinity of the pond must be considered. The source salinity depends on the nature of the water source, being either seawater or groundwater, with groundwater salinity determined by local geologic conditions and seawater salinity determined largely by local freshwater influx [6]. The pond operating salinity is dictated by both the water source salinity and the salinity tolerance of the algal strain. Due to blowdown [6], the operating salinity must both exceed that of the source to keep replacement water amounts reasonable and be within the range of high growth for the selected organism. Accordingly, we split the spectrum of potential water resources into four main categories based on both the salinity of the water resource and that needed for the organisms in question (as opposed to traditional categorization schemes used in agriculture and hydrology). We define freshwater (f) as near surface ground waters expected to have a wide range of competing interests from municipal and agricultural consumers. This "competitive waters" resource is defined as surface waters and wells with salinity (generally measured by electrical conductivity) ranging from 0 to 2000 mg L^{-1} and depths up to 300 m. Brackish water (b) is defined as groundwater with salinity ranging from 2000 mg L^{-1} to 10,000 mg L^{-1} and a depth up to 1000 m. These defined ranges are partially based on the salinity needs of *Chlorella*. Sensitivity analyses [23] show that the most economical operating salinity is 4000 mg L^{-1} when using freshwater and 10,000 mg L^{-1} when using brackish water. *N. salina* could also utilize these two resources, but is not considered as *Chlorella* productivity is far greater. Saline groundwater (s) is defined with salinity ranging from 2000 mg L^{-1} to 50,000 mg L^{-1} and a depth less than 1000 m. The upper bound is tolerable for *N. salina* [22], and was selected as the operating salinity to minimize water consumption and costs for both saline groundwater and seawater (m).

The following define the algorithm used to determine the subset of sites and their priority in meeting the specified production target (21 BGY). Given a set of possible water sources (S_p), with each matched to its best performing strain as defined above:

$$S_p = \{f, b, s, m\} \tag{1}$$

where f is fresh (competitive) water, b is brackish water, s is highly saline groundwater, m is seawater. The elements of S_p are members of the set of possible water sources to test for membership in (S) for a given location ($\mathbf{u}$)

$$\left\{\begin{array}{c} I_f(\mathbf{u}) = 1 \wedge V_f(\mathbf{u}) > 0 \rightarrow f \in S(\mathbf{u}) \\ V_b(\mathbf{u}) > 0 \rightarrow b \in S(\mathbf{u}) \\ V_s(\mathbf{u}) > 0 \rightarrow s \in S(\mathbf{u}) \\ V_m(\mathbf{u}) > 0 \rightarrow m \in S(\mathbf{u}) \end{array}\right\} \tag{2}$$

where I_f is an indicator variable for the availability of freshwater [6], and V_x is the annual cost of water for each element (x) in S_p. The cost of