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A national-scale comparison of resource and nutrient demands for algae-based biofuel production by lipid extraction and hydrothermal liquefaction

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Algae's high productivity provides potential resource advantages over other fuel crops. However, demand for land, water, and nutrients must be minimized to avoid impacts on food production. We apply our national-scale open-pond, growth, and resource models to assess several biomass to fuel technological pathways based on *Chlorella* sp. We compare resource demands between hydrothermal liquefaction (HTL) and lipid extraction (LE) to meet 1.89E+10 and 7.95E+10 L yr^{-1} renewable diesel targets. We estimate nutrient demands where post-fuel biomass is consumed as co-products and recycling by anaerobic digestion (AD) or catalytic hydrothermal gasification (CHG). Sites are prioritized based on fuel value relative to a set of site-specific resource costs. The highest priority sites are located along the Gulf of Mexico coast, but potential sites exist nationwide. Compared to LE, HTL reduces land requirements at least 50%, freshwater consumption at least 33%, and saline groundwater by 85%. Without recycling, nitrogen (N) and phosphorous (P) demand is reduced 44%, but remains significant relative to current U.S. agricultural consumption. The most nutrient-efficient pathways are LE + CHG for N and HTL + CHG for P (by 52%). Resource gains for HTL + CHG are offset by a 284% increase in N consumption relative to LE + CHG (with potential for further recycling). Nutrient recycling is essential to effective use of alternative nutrient sources. While modeling of availability and costs remains, for HTL + CHG at the 7.95E+10 L yr^{-1} production target, municipal sources can offset up to 20% of N and 49% of P demand and animal manure could potentially satisfy demands.

1. Introduction

There is a persistent concern expressed in the literature and in a recent report by the National Research Council (NRC [1]) that nutrient supply and availability is a significant impediment to sustainable, large-scale algae biofuel production. Whereas algae-based biodiesel is a promising renewable transportation fuel, production may require significant amounts of nutrients including carbon dioxide (CO_2), nitrogen

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Abbreviations

AD	anaerobic digestion
BAT	biomass assessment tool
BGY	billion gallon year^{-1}
CHG	catalytic hydrothermal gasification
CO_2	carbon dioxide
CONUS	contiguous United States
EOR	enhanced oil recovery
GHG	greenhouse gas
GIS	geographic information systems
HTL	hydrothermal liquefaction
L	liter
LE	lipid extraction
MPa	mega Pascal
N	nitrogen
NATCARB	National Carbon Sequestration Database and Geographic Information System
NRC	National Research Council
P	phosphorous
T	tonne (metric tonnes).

(N), and phosphorous (P). The amount of these nutrients consumed and the potential for offsetting demand with recycled sources are highly dependent on the technology pathway chosen to convert biomass to biofuel such as "traditional" lipid extraction (LE) and newer approaches including hydrothermal liquefaction (HTL [2–4]). We investigate nutrient supply and sustainability concerns using the high-resolution resource assessment capabilities of the Biomass Assessment Tool (BAT [5,6]) to characterize in detail the geospatial and temporal distribution of potential biomass production and associated nutrient demand for the organism *Chlorella*. Specifically, we compare and contrast selected processing technology pathways for overall biofuel production, land and water requirements, and nutrient supply and demand. The analyses elucidate the impact of chosen technology on the optimization of algal biofuel enterprise siting and assess contrasts in resource demands, especially for nutrients. We consider these demands relative to both conventional (fertilizer) and alternative (recycled) nutrient resources such as municipal sewerage and animal manures.

The resource demands required to satisfy a commercial-scale algae biofuel industry have long been a concern. Several studies were conducted during the time of the Aquatic Species Program (1978–1996 [7]) in the form of techno-economic analyses [8] and spatial models based on early geographic information systems (GIS [9,10]). These previous works focused on the identification of promising algae strains, cultivation methods, and inventory of key resources including land, water and nutrients, with an assessment of potential limitations. The geographic focus of this work was on the southwestern US, largely due to the availability of unoccupied land and warm sunny climate. Recent regional-scale resource analyses for open pond [11] and site-specific analyses for photobioreactors [12] have confirmed that resource sustainability is a potentially serious limitation.

The work presented here builds off our previous BAT-based resource analyses. Those studies focused on water and land demands required for traditional lipid extraction technology and were based on modeling the growth of a generic algal organism with growth rate factors and nutrient profile chosen to represent the middle of ranges from the literature. Site selection and prioritization were based on biofuel production relative to water availability and costs. Here we present an incremental advance in specificity, where biomass production is based on species-specific growth model results (*Chlorella*, M. Huesemann, unpublished data) that are modified to account for the operating salinity of the pond. However, we continue to use a generalized nutrient profile until statistically representative data become available. *Chlorella* was selected for its relatively high growth potential [13] and demonstrated ability to grow in a range of fresh to brackish salinities. Accordingly, two water sources are considered, freshwater limited by competitive demand and a saline groundwater resource where supply is specified as unlimited. In addition to fuel production through LE [5,6,14], we explore the resource impacts of hydrothermal liquefaction, an alternative fuel production technology. In HTL, the wet biomass (roughly 10–30% water content) is introduced to a pressure chamber and subjected to temperatures around 300 °C with pressure in the range 10–25 MPa, with or without catalysts. The process produces waste gas and water fractions as well as the product, a petroleum-like liquid requiring upgrading to produce renewable diesel. A potential advantage of the process is utilization of the whole biomass to produce fuel, rather than just the lipid fraction. While not the emphasis of this work, we have also added further refinement and realism to our site prioritization and selection algorithms relative to previous efforts [5,6,15], adding additional criteria based on CO_2 supply by flue gas, constructability, and infrastructure access.

Our focus in this paper is on the comparison of sources and sinks for CO_2, N, and P based on autotrophic cultivation of microalgae in open-ponds. Specifically, we compare the nutrient demands between LE and HTL fuel production technology pathways (Fig. 1), consumption magnitudes relative to agricultural fertilizer markets, and assess the potential for offsets with alternative nutrient resources through estimates of total N and P contained in municipal and animal sewage for the CONUS. A thorough review of HTL and LE technologies, detailed process descriptions, and lifecycle analyses is provided in Ref. [16]. For this resource analysis, we estimate the N and P demands for five scenarios (Fig. 1). We consider biomass demands with no recycling for both LE and HTL. These scenarios explore nutrient impacts where all biomass is converted to fuel and co-products (pharmaceuticals, nutraceuticals, animal feed, etc.) [17], or where post-fuel biomass is buried for carbon sequestration [18]. The third and fourth scenarios are the "traditional" biodiesel production pathway where algae are grown, lipids extracted, and then sent to a refinery for upgrading. The difference between these two scenarios is the recycling technology applied to post-extraction biomass. We consider both anaerobic digestion (AD) as analyzed in Refs. [14,19] and catalytic hydrothermal gasification (CHG) as presented in Refs. [16,19]. The final scenario is based on HTL and CHG recycling of remaining biomass, as the C:N ratio of post-HTL byproducts is not suitable for anaerobic digestion [16]. For all scenarios, we calculate the total amount of nutrients required to satisfy portions of