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Marine Microalgae

CLIMATE, ENERGY, AND FOOD SECURITY FROM THE SEA

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ABSTRACT. Climate, energy, and food security are three of the greatest challenges society faces this century. Solutions for mitigating the effects of climate change often conflict with solutions for ensuring society's future energy and food requirements. For example, BioEnergy with Carbon Capture and Storage (BECCS) has been proposed as an important method for achieving negative CO_2 emissions later this century while simultaneously producing renewable energy on a global scale. However, BECCS has many negative environmental consequences for land, nutrient, and water use as well as biodiversity and food production. In contrast, large-scale industrial cultivation of marine microalgae can provide society with a more environmentally favorable approach for meeting the climate goals agreed to at the 2015 Paris Climate Conference, producing the liquid hydrocarbon fuels required by the global transportation sector, and supplying much of the protein necessary to feed a global population approaching 10 billion people.

INTRODUCTION

At the 2015 Paris Climate Conference, 195 nations agreed to limit the rise in mean global temperature to no more than 2°C relative to pre-industrial levels and to pursue additional efforts to limit the rise to below 1.5°C. Achieving either of these ambitious limits places great constraints on the amount of CO_2 that can be emitted (Allen et al., 2009; Meinshausen et al., 2009) and the amount of remaining fossil fuel reserves that can be burned this century (International Energy Agency, 2016; McClade and Ekins, 2015). Based on its current trajectory, society will need to substantially reduce CO_2 emissions by mid-century and achieve significant negative emissions during the latter half of the century (Greene et al., 2010a; IPCC, 2014; Rogelj et al., 2016). At present, large-scale industrial cultivation of marine microalgae (ICMM) appears to be one of the most promising approaches for achieving these climate goals while simultaneously contributing to global energy and food security.

COMPARING BECCS WITH ICMM

Climate, energy, and food security are three of the most important global challenges society faces during the twenty-first century. However, as solutions for mitigating and remediating the effects of climate change are contemplated, they often run into conflict with society's proposed solutions for ensuring its future energy and food requirements. For example, BECCS has been proposed as the primary method for achieving negative CO_2 emissions while simultaneously producing renewable energy on a global scale (IPCC, 2014; Williamson, 2016). However, almost all studies conducted on BECCS so far have focused on terrestrial sources of bioenergy and have concluded that this approach can have many negative consequences for land, nutrient, and water use as well as biodiversity and food production (Searchinger et al., 2015; Smith et al., 2016).

In contrast, large-scale ICMM can positively impact climate, energy, and food security (Efroymson et al., 2016) while avoiding many of the negative consequences of terrestrial plant-based BECCS. Microalgae exhibit rates of primary production that are typically more than an order of magnitude higher than the most productive terrestrial energy crops (Huntley and Redalje, 2007). Thus, they have the potential to produce an equivalent amount of bioenergy and/or food in less than one-tenth of the land area. Scaling up production numbers from demonstration-scale cultivation facilities (Box 1, Figure B1), the current total demand for liquid fuels in the United States can potentially be met by growing microalgae in an area of 392,000 km^2, corresponding to about 4% of US land area or just over half the size of Texas (Box 2, Figure B2). The total global demand for liquid fuels can potentially be met by growing microalgae in an area of 1.92 million km^2, corresponding to about 21% of US land area or slightly less than three times the size of Texas.

Large-scale ICMM also avoids many of society's greatest environmental challenges (Huntley and Redalje, 2007; Greene et al., 2010b; M.J. Walsh et al., 2016). First, the area required for growing marine microalgae is not only reduced by over an order of magnitude over BECCS, it also does not compete with terrestrial agriculture for arable land. Second, because the cultivation of marine microalgae is very efficient in its use of nutrients, only losing those nutrients that are actually harvested in the desired products, the problems associated with excess fertilizer runoff and subsequent eutrophication of aquatic and marine ecosystems can be avoided. Finally, because freshwater is not required, ICMM does not have to compete with agriculture or other users for this valuable resource, which is often scarce in many of the arid, subtropical regions most suitable for this industry (Box B2, Figure B2).

The advantages of producing bioenergy from marine microalgae instead of terrestrial energy crops go far beyond avoiding the environmental problems associated with land-use change, inefficient uptake of nutrients, and competing demands for freshwater. For microalgal bioenergy to be cost competitive with fossil fuels, it must be produced with sufficiently valuable co-products (Beal et al., 2015; Gerber et al., 2016). Animal feeds are one type of co-product that has a global market of appropriate scale and value, 1 gigaton per year and $460 billion per year, respectively (Alltech Global Feed Survey, 2015). However, by mid-century, the protein demands for a global population of 9.6 billion people will be unsustainable with today's conventional industrial agricultural practices, especially with anticipated future constraints on the use of fossil fuels (Tilman et al., 2011). In contrast, ICMM can provide the basis for a new "green revolution." To gain a sense of its potential, we can once again scale up the production numbers from demonstration-scale cultivation facilities (Box 2). From the same 392,000 km^2 needed to meet the current total liquid fuel demand of the United States, 0.490 gigatons of protein could be produced. This corresponds to about twice the total annual global production of soy protein. From the same 1.92 million km^2 needed to meet the current total global liquid fuel demand, 2.40 gigatons of protein could be produced. This corresponds to about 10 times the total annual global production of soy protein (United Nations Food and Agriculture Organization, 2016). In addition to these staggering quantitative advantages, microalgal biomass is also of higher nutritional quality than soy biomass in terms of its well-balanced

BOX 1. ADVANCES IN MICROALGAE PRODUCTION

Early efforts to develop liquid transportation fuels from microalgae can be traced back to the beginning of the US Department of Energy (DOE) Aquatic Species Program in 1978 (Sheehan et al., 1998). Two approaches were being used for algal cultivation during this program, closed photobioreactor systems and open raceway ponds (Figure B1a,b). Both approaches had their advantages and limitations. While closed photobioreactor systems could be designed to avoid most contamination problems, such systems were determined to be too expensive to construct for large-scale cultivation. In contrast, open raceway ponds could be constructed at relatively low cost, but contamination problems made them unsuitable for long-term cultivation of monocultures. The Aquatic Species Program was terminated in 1996 when it was concluded that the large-scale cultivation of microalgae for fuels was not economically viable with the existing technologies.

A decade later, Huntley and Redalje (2007) described a hybrid approach for large-scale cultivation of microalgae. In this hybrid approach, subsequently called ALDUO™ technology, microalgae are grown initially in closed photobioreactors and then moved to open raceway ponds for short-term cultivation once the concentrations are sufficiently high to avoid contamination problems. In a joint venture between Royal Dutch Shell and HR Biopetroleum, the first hybrid, demonstration-scale facility specifically designed for the cultivation of marine microalgae was built in Kona, Hawaii.

Owned and operated by Cellana LLC, the Kona Demonstration Facility (KDF) has been the site of numerous experimental studies from 2009 to 2015 on strain selection and cultivation methods (Cornell Algal Biofuel Consortium, 2015). These experimental studies were supported initially by Royal Dutch Shell, and subsequently by DOE and USDA (US Department of Agriculture). DOE and USDA also funded animal feeding trials on the microalgal biomass produced at the KDF (Kiron et al., 2012; Gatrell et al., 2014) as well as techno-economic analysis (TEA) and life-cycle assessment (LCA) studies (Sills et al., 2013; Beal et al., 2015; Huntley et al., 2015; Gerber et al., 2016). Based on experimental cultivation data collected at large scale, the TEA and LCA studies compared 20 different process pathways for the production of fuels and high-value nutritional products. The results from these studies demonstrate that algal biofuels produced for the transportation sector can be cost competitive with fossil fuels when valuable nutritional products are co-produced.

FIGURE B1. The Cellana Kona Demonstration Facility (KDF) where demonstration-scale cultivation experiments using ALDUO™ technology were conducted. (a) Closed-loop photobioreactors. (b) Open raceway ponds.

BOX 2. LARGE-SCALE IMPACTS ON LAND USE, CO_2 UPTAKE, AND PROTEIN CO-PRODUCTION

Extrapolating from the techno-economic analysis (TEA) and life-cycle assessment (LCA) results reported by Beal et al. (2015), Huntley et al. (2015), and Gerber et al. (2016), we estimate the land use, CO_2 uptake, and protein co-production associated with meeting projected 2016 total US and global liquid fuel demands. It is anticipated that most large-scale cultivation of marine microalgae will occur along the coastlines of the arid subtropical regions of the world (Figure B2a,b), where incoming solar radiation is abundant and land is not in high demand.

Land Use

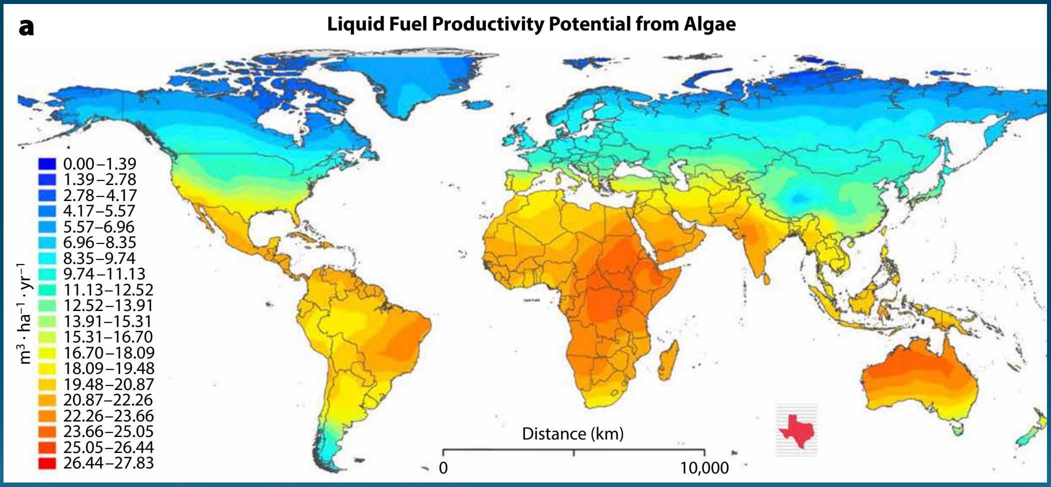
1. Land required for microalgal cultivation to meet projected 2016 total US liquid fuel demand of ~19.6 million barrels per day (bbl/d; US Energy Information Administration, 2016), assuming a fuel productivity of 0.50 bbl/ha · d, would be 19.6 million bbl/d × (1/0.50 bbl/ha · d) = 39.2 million ha = 392,000 km^2. This corresponds to ~4% of US land area (9,148,593 km^2), just over half the size of Texas (676,587 km^2). This fuel productivity of 0.50 bbl/ha · d is the average between a microalgal cultivation process pathway optimizing fuel production (0.64 bbl/ha · d) and one optimizing food production (0.35 bbl/ha · d).
2. Land required for microalgal cultivation to meet projected 2016 total global liquid fuel demand of ~96 million bbl/d (International Energy Agency, 2016), assuming the same fuel productivity of 0.50 bbl/ha · d would be 96 million bbl/d × (1/0.50 bbl/ha · d) = 192 million ha = 1.92 million km^2. This corresponds to ~21% of US land area, slightly less than three times the size of Texas.

CO_2 Uptake

1. The net uptake of CO_2 during microalgal cultivation to meet the projected 2016 total US liquid fuel demand, assuming microalgal uptake of 15.4 million kg/km^2 · yr, would be 392,000 km^2 × 15.4 million kg/km^2 · yr = 6.04 trillion kg/yr = 6.04 gigatons/yr.
2. The uptake of CO_2 during microalgal cultivation to meet the projected 2016 total global liquid fuel demand, assuming microalgal uptake of 15.4 million kg/km^2 · yr, would be 1.92 million km^2 × 15.4 million kg/km^2 · yr = 27.7 trillion kg/yr = 27.7 gigatons/yr. These uptakes of CO_2 during microalgal cultivation are of comparable magnitude to the 2014 global anthropogenic CO_2 emissions of 40 gigatons/yr associated with the burning of fossil fuels, cement production, and land-use change (Le Quéré et al., 2015).

Protein Co-Production

1. Protein co-produced annually from the 392,000 km^2 of land required to meet the projected 2016 total US liquid fuel demand, assuming a protein productivity of 1.25 million kg/km^2 · yr, would be 1.25 million kg/km^2 · yr × 392,000 km^2 = 490 billion kg/yr = 0.490 gigatons/yr. This corresponds to slightly less than twice the annual global soy protein production of 0.25 gigatons/yr (United Nations Food and Agriculture Organization, 2016). This protein productivity assumes that microalgal cultivation is averaged between a process pathway optimizing biopetroleum production (0 million kg/km^2 · yr) and one optimizing food production (2.5 million kg/km^2 · yr).
2. Protein co-produced annually from the 1.92 million km^2 of land required to meet the projected 2016 total global liquid fuel demand, assuming a protein productivity of 1.25 million kg/km^2 · yr, would be 1.25 million kg/km^2 · yr × 1.92 million km^2 = 2.40 trillion kg/yr = 2.40 gigatons/yr. This corresponds to ~10 times the annual global soy protein production of 0.25 gigatons/yr.



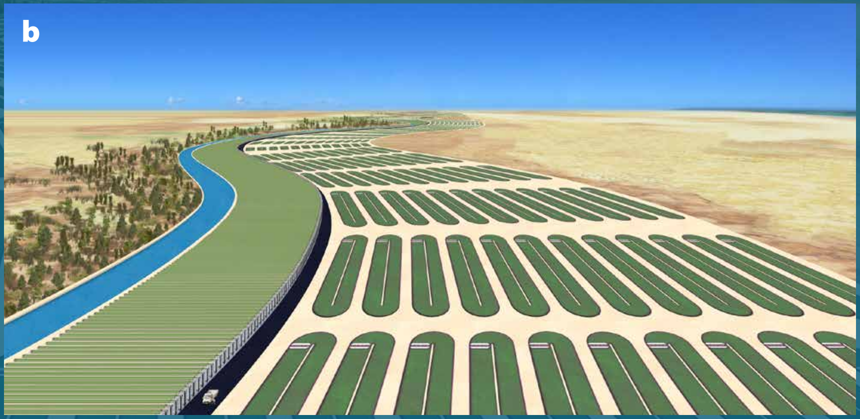


FIGURE B2. (a) World map of relative liquid fuel production potential from microalgae, with production potential increasing from blue to orange (modified from Moody et al., 2014). Many arid environments in the world's subtropical coastal regions provide an ideal setting for large-scale cultivation of marine microalgae. The total US liquid-fuel demand can be met by cultivating marine microalgae in an area slightly more than half the size of Texas, while the total global liquid-fuel demand can be met in an area slightly less than three times the size of Texas. Texas is shown to scale on the map. (b) An artistic rendering of a commercial-scale microalgal production facility.

amino acid profile and its rich content of omega-3 fatty acids, minerals, vitamins, and other unique bioactive compounds (Lum et al., 2013).

CLIMATE SOLUTIONS

From a climate perspective, large-scale ICMM can provide an effective tool for mitigating and remediating the effects of society's fossil fuel-based industrial revolution (Greene et al., 2010b; Moody et al., 2014). Even with the transition to renewable sources of electricity and electrification of the light-vehicle fleet (Miotti et al., 2016), energy-dense, liquid hydrocarbon fuels will still be needed to power the heavy-vehicle, shipping, and aviation components of the transportation sector into the foreseeable future. To cost effectively produce fossil-free, carbon-neutral fuels from microalgae on a large scale, methods still must be developed to utilize electricity from renewable sources, recycle nutrients more efficiently from wastewater, and directly utilize CO_2 captured from the atmosphere (see next section). Once such methods are developed, they can subsequently be used to achieve negative emissions through the production of long-lived chemical products. The chemical industry can achieve significant negative emissions by using captured CO_2 or microalgae-based biopetroleum as a feedstock in the synthesis of many widely used chemical products, such as plastics (Zeller et al., 2013; Otto et al., 2015). Used in construction projects on a global scale, these plastics and other chemical products could provide an economically advantageous method for sequestering a large amount of carbon for an extended period of time (Greene et al., 2010b).

To get a sense of the biogeochemical scale being envisioned, the annual net uptake of CO_2 during the cultivation of microalgae required to meet the total global liquid fuel demand would be ~28 gigatons per year (Box 2). This is on the same order of magnitude as current annual global anthropogenic CO_2 emissions of 40 gigatons per year associated with the burning of fossil fuels and land-use change (Le Quéré et al., 2015). Because all of the CO_2 being taken up by microalgae for fuel and feed production will eventually be re-emitted to the atmosphere when the fuel is burned and the feed is metabolized, this introduces no net sink for CO_2 emissions. However, the microalgae-based chemical production scenario does provide a closely related pathway to negative emissions. In addition, afforestation and other favorable land-use practices applied to the land freed up from agricultural food and fuel production can have significant positive mitigation effects on CO_2 emissions (B.J. Walsh et al., 2015; M.J. Walsh et al., 2016). While not trivial, the problems associated with ramping up ICMM to globally relevant scales are tractable, economically viable, and less daunting than the environmental and food-security problems associated with the production of terrestrial plant biomass for BECCS (Fuss et al., 2014; Searchinger et al., 2015; Smith et al., 2016).

SEEKING ALGAL SOLUTIONS: PAST, PRESENT, AND FUTURE CHALLENGES

During the 1990s and 2000s, a series of in situ iron fertilization experiments were conducted in high-nutrient, low-chlorophyll (HNLC) regions of the global ocean to determine if the primary production of marine microalgae and subsequent carbon export to the deep sea are iron limited in HNLC waters (see review by de Baar et al., 2005; Strong et al., 2009b). The geoengineering implications of this research were recognized from its outset, as demonstrated by John Martin's memorable quip, "Give me half a tanker of iron, and I'll give you an ice age" (Martin, 1990). From this geoengineering perspective, the experiments enabled ocean scientists to quantify the potential of marine microalgae for drawing down CO_2 concentrations in the atmosphere and sequestering it as organic carbon in the deep sea. After two decades of experimental and modeling studies, most scientists have concluded that the sequestration potential from in situ iron fertilization is insufficient to justify the amount of effort required and potential negative environmental impacts (Strong et al., 2009a,b; Lenton, 2014). Ironically, it may turn out that scaling up the cultivation of marine microalgae on land rather than in the sea may be more effective in enabling society to achieve its desired climate mitigation and remediation goals.

To be effective in addressing society's climate, energy, and food security needs, the scaled-up ICMM on land still faces a number of challenges. The electricity required to power upstream and downstream production processes will be most favorable from a life-cycle assessment (LCA) perspective if it is derived from renewable energy sources. Concentrated and photovoltaic solar technologies are cost-effective options given the high solar radiation levels required to achieve optimal primary production rates. Wind energy also has great potential as a cost-effective renewable electricity source (Beal et al., 2015). From an LCA perspective, the limited penetration of renewable energy sources in current utility-scale power generation makes grid electricity less attractive at many locations. However, solar and wind energy are both scalable, making them favorable for localized, on-site electricity generation, at least until most of the fossil-generated power for the electrical grid is displaced by renewables.

Large-scale ICMM also requires a major source of CO_2 to support primary production in both photobioreactors and open ponds. Because photobioreactors are closed systems, the required addition of CO_2 is not surprising. However, this requirement is also the case for open ponds because the flux of CO_2 gas across the air-water interface is typically rate limited at the relatively dilute, ambient CO_2 concentrations in the atmosphere. This constraint can be overcome if the required CO_2 can be captured directly from the atmosphere at the site of cultivation at reasonable cost (McGlashan et al., 2012). One solution would be to deploy a sorbent-based, direct air-capture (DAC) system (Keith et al., 2006; Jones, 2009) and then add the captured CO_2 into the photobioreactors or open ponds used for cultivation. To be cost effective, the CO_2 would have to be supplied near the lower end of the cost-estimate range for DAC systems (~$100 per ton). To be attractive from an LCA perspective, the power driving DAC would preferably be provided on site from a renewable energy source, most likely concentrated or photovoltaic solar.

An alternative approach could involve hydromechanically enhancing the gas transfer efficiency of CO_2 across the air-water interface of open ponds. Currently, scientists at Cornell University are exploring the feasibility of "tuning" pond flow in a manner that induces flow instabilities and concentration boundary layer thinning (Citerone, 2016). By taking advantage of the enhanced CO_2 transfer efficiency as well as the large surface area presented by the ponds for gas exchange, it is possible that the CO_2 required for open-pond cultivation could be provided primarily by hydromechanical means. The power requirements for this hydromechanical enhancement would need to be cost effective and preferably provided on site from a renewable energy source. Whether provided by a DAC system or hydromechanical enhancement, on-site capture of CO_2 directly from the atmosphere would greatly expand the number of potential sites available globally for cultivating microalgae.

Perhaps the greatest challenge to large-scale ICMM is its large demand for nutrients, especially phosphorus (Lenton, 2014). The Redfield Ratio of carbon to nitrogen to phosphorus for marine microalgae is much lower than for macroalgae or land plants (Lenton, 2014). Current agricultural demands for phosphorus are unsustainable, and global food security is already at risk this century unless society can become much more efficient in its use of fertilizers and recycling of nutrients from wastewater (Canter et al., 2015). Fortunately, the cultivation of marine microalgae can be highly efficient in its use of nutrients, only losing those that are actually harvested in the desired products. In addition, because microalgae can deplete nutrients in the water to undetectable levels prior to harvest, they can provide the basis for efficient wastewater treatment systems (Mu et al., 2014). Therefore, even though the nutrient challenge is a critically important one and should not be underestimated, we view the combination of microalgal-based wastewater treatment systems and efficient nutrient recycling as valuable parts of an integrated solution.

Despite the many concerns that have been raised about scaling up terrestrial plant-based BECCS to achieve globally significant negative emissions, it is worth noting that marine macroalgae may present a more attractive option for BECCS (Lenton, 2014). While primary production rates are generally lower for macroalgae relative to microalgae, they are still considerably higher than those of the most rapidly growing terrestrial energy crops. The cultivation costs for producing macroalgal biomass are also considerably lower than those for producing microalgal biomass, making combustion of the former for power generation more cost effective. While marine macroalgae-based BECCS appears to be a viable option for achieving negative emissions, its scalability needs to be explored in much greater detail before its climate remediation potential can be evaluated properly.

Research and development investments during the next decade will be necessary to further improve the performance and reduce the costs and resource requirements associated with large-scale production of fuels, animal feeds, and human nutritional products from marine microalgae (Beal et al., 2015; Huntley et al., 2015; Gerber et al., 2016). Ramping up this production to a globally relevant scale will take additional decades to accomplish. By the second half of the century, large-scale ICMM can help society achieve net-negative fossil-carbon emissions; produce the liquid, energy-dense hydrocarbon fuels needed to power the heavy-vehicle, shipping, and aviation components of the transportation sector; and supply the necessary protein to feed an increasingly crowded world.

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