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Geoengineering, marine microalgae, and climate stabilization in the 21st century

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Abstract Society has set ambitious targets for stabilizing mean global temperature. To attain these targets, it will have to reduce CO_2 emissions to near zero by mid-century and subsequently remove CO_2 from the atmosphere during the latter half of the century. There is a recognized need to develop technologies for CO_2 removal; however, attempts to develop direct air-capture systems have faced both energetic and financial constraints. Recently, BioEnergy with Carbon Capture and Storage (BECCS) has emerged as a leading candidate for removing CO_2 from the atmosphere. However, BECCS can have negative consequences on land, nutrient, and water use as well as biodiversity and food production. Here, we describe an alternative approach based on the large-scale industrial production of marine microalgae. When cultivated with proper attention to power, carbon, and nutrient sources, microalgae can be processed to produce a variety of *biopetroleum* products, including carbon-neutral biofuels for the transportation sector and long-lived, potentially carbon-negative construction materials for the built environment. In addition to these direct roles in mitigating and potentially reversing the effects of fossil CO_2 emissions, microalgae can also play an important indirect role. As microalgae exhibit much higher primary production rates than terrestrial plants, they require much less land area to produce an equivalent amount of bioenergy and/or food. On a global scale, the avoided emissions resulting from displacement of conventional agriculture may exceed the benefits of microalgae biofuels in achieving the climate stabilization goals.

Key Points:

- Industrial microalgae cultivation offers many advantages to help society achieve its climate stabilization targets.
- Microalgae-derived biopetroleum products can contribute to mitigating and reversing effects of CO_2 emissions.
- Microalgae cultivation can play important indirect role in reducing CO_2 emissions by displacing conventional agriculture.

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1. Introduction: The Challenge of Attaining the COP21 Climate Targets Set in Paris

Since its inception in 1988, the Intergovernmental Panel on Climate Change (IPCC) has made considerable progress in determining what actions must be taken to avoid dangerous anthropogenic interference with the climate system [*United Nations Framework Convention on Climate Change (UNFCCC)*, 1992]. Based on the findings of the IPCC's Fifth Assessment Report [*IPCC*, 2013], 195 nations agreed at the 21st Conference of the Parties to the UNFCCC (COP21) in Paris to limit the increase in mean global temperature to no more than 2°C relative to preindustrial levels and to pursue additional efforts to limit the increase to below 1.5°C [*United Nations Framework Convention on Climate Change (UNFCCC)*, 2015]. The COP21 climate agreement was a remarkable political accomplishment, setting targets that are ambitious, but both necessary and attainable in preventing dangerous climate disruptions [*Schellnhuber et al.*, 2016].

In terms of necessity, a 2°C upper limit was set with the intention of preventing society from leaving the relatively *safe operating space* that human civilization evolved in during the Holocene epoch [*Rockstrom et al.*, 2009]. Not far in excess of a 2°C increase, the Earth system becomes vulnerable to nonlinear and potentially irreversible disruptions to several of its important *tipping elements* [*Lenton et al.*, 2008], including complete loss of Arctic summer sea ice as well as deglaciations of the Greenland ice sheet, West Antarctic Ice Sheet, and a majority of the world's alpine glaciers [*Lenton*, 2012; *Schellnhuber et al.*, 2016]. The subsequent rise in sea level due to these deglaciations would threaten the survival of many coastal cities and island nations, while climate-induced droughts, floods, and extreme weather regimes would jeopardize global food security and biodiversity [*Hansen et al.*, 2016; *Schellnhuber et al.*, 2016]. Even at the lower-limit goal of a 1.5°C temperature increase, significant climate change impacts are projected, including a >1-m rise in peak sea level [*Hansen et al*., 2016; *Schellnhuber et al*., 2016].

In terms of attainability, some policy analysts view the climate goals agreed upon at COP21 as more aspirational than realistic, while others have claimed them to be completely unachievable [*Victor and Kennel*, 2014; *Geden*, 2015; *Boucher et al*., 2016]. We believe that these goals are attainable; however, achieving them will severely constrain the amount of CO_2 that can be emitted [*Allen et al*., 2009; *Meinshausen et al*., 2009] as well as the amount of fossil fuel reserves that can be burned [*McGlade and Ekins*, 2015; International Energy Agency (IEA), 2016] during the remainder of this century. In fact, it has become increasingly clear since the IPCC's Fourth Assessment Report [*IPCC*, 2007] that society will only be able to limit an increase in global mean temperature to 2°C or less by reducing CO_2 emissions to near zero by mid-century and subsequently achieving negative emissions during the latter half of the century [*Greene et al*., 2010a, 2010b; *IPCC*, 2013; *Edenhofer et al*., 2014; *Rogelj et al*., 2015].

In most discussions to date, geoengineering technologies have fallen into two general categories: solar radiation management (SRM) and carbon dioxide removal (CDR) [*Royal Society*, 2009; this issue]. SRM is the more controversial of the two, being a climate-intervention approach that alters the Earth's radiation budget to counterbalance the warming effect of greenhouse gases. In contrast, CDR is less controversial, being a remediation approach that directly reduces atmospheric CO_2 concentration to lower levels. While SRM technologies may prevent greenhouse warming from exceeding the temperature limits agreed upon in Paris, CDR technologies offer a more comprehensive solution to stabilize the Earth's climate system. It is for this reason that we focus only on CDR and related technologies in this article.

2. Carbon Dioxide Removal

Technologies associated with CDR are frequently discounted because of "*the technical challenges and large uncertainties surrounding [their large-scale] deployment*" [*Royal Society*, 2009]. This is an unfortunate perspective because, although CDR technologies may take longer to deploy globally, they offer a more comprehensive solution to the climate stabilization problem than SRM technologies. Many of the proposed CDR technologies can be viewed as extensions to the conventional mitigation technologies currently being explored for reducing CO_2 emissions into the atmosphere. Thus, the line between mitigation and remediation is becoming increasingly blurred.

The most commonly advocated CDR technology uses large-scale, direct air-capture (DAC) systems to remove CO_2 from the atmosphere for subsequent sequestration [*Keith et al*., 2006; *Jones*, 2009]. Such DAC systems share many similarities with the carbon capture and storage (CCS) technology being developed to remove CO_2 from the emission streams of coal- and gas-fired power plants. Both DAC and CCS technologies expose gas mixtures, either air or power plant emissions, to a sorbent material that selectively adsorbs CO_2. The material is subsequently treated, chemically and/or thermally, to regenerate fresh sorbent and produce a concentrated stream of CO_2, which can be stored or utilized industrially.

A common criticism of sorbent-based DAC systems is that they are prohibitively expensive due to the energetics involved in removing a very dilute gas (CO_2: ~400 ppm) from air [*American Physical Society (APS)*, 2011; *House et al*., 2011]. In principal, such systems require exposing large quantities of air to capture surfaces of sorbent material with large surface areas. Alternatively, capture surfaces with smaller surface areas can be used if the sorbent material is regenerated more frequently. Cost estimates for using DAC systems to remove CO_2 at ambient atmospheric concentrations range from <\$100/ton to >\$1000/ton [*American Physical Society (APS)*, 2011; *Holmes and Keith*, 2012].

3. BioEnergy With CCS

It is against this backdrop of recognizing the need for CDR while facing the energetic and financial constraints on DAC systems that the concept of BioEnergy with carbon capture and storage (BECCS) emerged as a leading candidate for climate stabilization [*Clarke et al*., 2014; *Edenhofer et al*., 2014; *Williamson*, 2016]. Although the concept can be traced as far back as 1998 [*Hickman*, 2016], BECCS really gained traction after the release of Working Group III's contributions to the IPCC's Fifth Assessment Report [*Clarke et al*., 2014]. Lying within that blurry gray area between mitigation and geoengineering, BECCS offers several benefits.

First, it uses photosynthesis to capture CO_2 directly from the atmosphere while generating stored energy in the form of biomass. Then, when that biomass is burned in a power plant to generate more useful forms of energy, the CO_2 emissions can be captured and stored, yielding negative emissions. Unfortunately, nearly all studies conducted on BECCS to date have focused on only terrestrial sources of bioenergy (but see *Lenton*, 2014), and many have concluded that this approach can have negative consequences on land, nutrient, and water use as well as on biodiversity and food production [*Searchinger et al*., 2015; *Smith et al*., 2016]. In our opinion, the magnitude and scale of environmental changes associated with BECCS implemented on a global scale appear to be comparable to or greater than those associated with many of the proposed geoengineering technologies.

4. The Marine Microalgae Option

In contrast to conventional BECCS based on terrestrial plant production, the large-scale production of marine microalgae from industrial facilities on land presents some interesting alternatives [*Huntley et al*., 2015; *Department of Energy (DOE)*, 2016a; *Efroymson et al*., 2016]. Bioenergy production from marine microalgae can have positive impacts on climate and food security, while avoiding many of the negative environmental consequences associated with terrestrial plant-based BECCS [*Lenton*, 2014; *Walsh et al*., 2015, 2016; *Greene et al*., 2016].

Since microalgae exhibit primary production rates that are typically more than an order of magnitude higher than those of the most productive terrestrial plants [*Huntley and Redalje*, 2007], they can produce an equivalent amount of bioenergy and/or food in less than one tenth of the land area. By scaling up production numbers from demonstration-scale cultivation facilities, *Greene et al*. [2016] have shown that the current U.S. liquid fuel demand can be met by growing microalgae in an area just over half of the size of Texas (~392,000 km^2), while the current global liquid fuel demand can be met by growing microalgae in an area slightly less than three times the size of Texas (~1.92 million km^2). The coproduction of protein in algal nutritional products for animal and aqua feeds as well as direct human consumption is also substantial. From the same ~1.92 million km^2 needed to meet the current global liquid fuel demand, 2.4 gigatons of protein can be coproduced [*Greene et al*., 2016]. This corresponds to about 10 times the total annual global production of soy protein [*United Nations Food and Agriculture Organization (UNFAO)*, 2016]. In addition to the potential significance of these nutritional coproducts to global food security, their high value will enable microalgae biofuels to become cost competitive with fossil fuels [*Beal et al*., 2015; *Gerber et al*., 2016]. Even using the current base-case, dry biomass productivity of 23 g/m^2/day, the coproduction of aqua feeds can bring the cost of biocrude down to below the U.S. Department of Energy's near-term research target of $5 per gallon gasoline equivalent (GGE) [*Gerber et al*., 2016]. Target scenarios that bring this cost down to below $3 per GGE are anticipated for mature technologies by 2022 [*Department of Energy (DOE)*, 2016c].

The large-scale production of bioenergy and/or food from 0 marine microalgae can also avoid many of the negative environmental consequences associated with an expansion of terrestrial agriculture [*Greene et al*., 2016]. First, by substantially reducing overall land requirements, the production of marine microalgae can be restricted to non-arable land, thus avoiding conflicts with agricultural food production. Second, because marine microalgae can be highly efficient in their use of nutrients, problems associated with fertilizer runoff and subsequent eutrophication of freshwater and marine ecosystems can be avoided. Finally, because the production of marine microalgae does not require freshwater, it does not have to compete with agriculture or other users for this valuable resource, which is often scarce in the arid subtropical environments most suitable for this industry.

In the context of climate change mitigation, the production of biofuels from marine microalgae can provide an important *stabilization wedge* [*Pacala and Socolow*, 2004] in reducing society's dependence on fossil fuels. Even assuming a transition to renewable sources of electricity and electrification of the light-vehicle fleet by mid-century [*Electrification Coalition*, 2010], energy-dense hydrocarbon fuels will still be needed to power heavy vehicles, shipping, and aviation in the transportation sector. The large-scale production of carbon-neutral biofuels from microalgae is possible; however, to do so will require that (1) the electricity used in upstream and downstream processes is provided from renewable sources [*Beal et al*., 2015], (2) new methods are developed to supply the necessary CO_2 directly from the atmosphere, and (3) the previous two requirements can be achieved at reasonable cost (see Section 5).

Once such methods are developed to produce carbon-neutral biofuels, they can subsequently be modified to achieve negative emissions through the production of long-lived *biopetroleum* products. By using 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], industry can achieve negative emissions while simultaneously generating revenue. In contrast to the geological storage of captured CO_2, use of these plastics and other *biopetroleum* products in construction projects on a global scale could provide a safer and more economically advantageous method for sequestering large amounts of carbon for extended periods of time [*Greene et al*., 2010b, 2016].

In addition to the direct role they can play in mitigating and potentially reversing the effects of fossil CO_2 emissions, marine microalgae can also play an equally important, but indirect role in climate mitigation. As previously mentioned, microalgae exhibit much higher primary production rates than terrestrial plants, thereby greatly reducing the land area required to produce an equivalent amount of bioenergy and/or food. By substituting the cultivation of marine microalgae for conventional agricultural practices, significant CO_2 emission and water savings can be achieved [*Walsh et al*., 2015, 2016]. In fact, on a global scale, the avoided emissions resulting from the displacement of conventional agriculture may exceed the benefits of microalgae biofuels in achieving climate stabilization goals [*Walsh et al*., 2015, 2016].

5. Challenges Ahead

The concept of cultivating marine microalgae on land for bioenergy, food security, and climate stabilization is attractive; however, for it to be successful, solar energy, electrical power, CO_2, and nutrients must be supplied in ways that can be demonstrated as favorable through life cycle assessment (LCA), technoeconomic analysis (TEA), and integrated assessment modeling (IAM) [e.g., *Sills et al*., 2013; *Beal et al*., 2015; *Gerber et al*., 2016; *Walsh et al*., 2016]. High levels of photosynthetically active radiation are necessary to achieve the rates of primary production required for profitable operations, and this sets geographical constraints on the siting of potential production facilities. In a global evaluation of microalgal biofuel production potential, *Moody et al*. [2014] demonstrated that the world's arid subtropical regions are especially attractive. For marine microalgae, coastal areas in Australia, Brazil, India, Mexico, the Middle East, Saharan North Africa, and southern Africa appear most promising [*Moody et al*., 2014, figure 1].

The electricity required to power upstream and downstream production processes accounts for a large fraction of the operational expenditures [*Beal et al*., 2015]. Given the solar radiation requirements for achieving high primary production rates from microalgae, concentrated and photovoltaic solar technologies provide attractive renewable energy options for generating the necessary electricity. Wind energy can also provide an efficient renewable source of electricity [*Beal et al*., 2015]. From an LCA perspective, the limited penetration of renewable energy sources in current utility-scale power generation makes electricity from the grid less attractive at many locations. However, the scalability of solar and wind energy may make them favorable for localized, onsite electricity generation, especially in the regions viewed as most attractive for large-scale marine microalgae production.

The production of marine microalgae also requires an enhanced supply of CO_2 to achieve high primary production rates even when grown in open systems exposed to atmospheric CO_2. This is because the flux of CO_2 gas across the air–water interface is typically rate limiting at the dilute, ambient concentrations of this gas in the atmosphere. Currently, projections of scaled-up microalgae cultivation rely on off-site industrial sources of CO_2 [*Department of Energy (DOE)*, 2016b]. This creates two major constraints on eventual commercialization. First, most industrial sources of CO_2 are powered by fossil fuels. Hence, the biofuels produced would release fossil-derived carbon when burned and thus are not truly carbon-neutral. Second, the cost of transporting CO_2 gas from off-site, industrial sources becomes prohibitively expensive at distances >10 km. In a detailed engineering design study conducted by Royal Dutch Shell (unpublished), it was determined that the combined costs of transporting CO_2 and seawater severely limited the number of potential sites worldwide that could accommodate the large-scale production of marine microalgae.

Both of the above constraints can be overcome if the required CO_2 can be directly captured from the atmosphere at the site of cultivation and done so at reasonable cost. One solution would be to deploy a sorbent-based DAC system, as previously described, and then bubble the captured CO_2 into the photobioreactors or open ponds used for cultivation [*Greene et al*., 2016]. To be attractive from an economic perspective, the CO_2 would have to be supplied at a cost near the lower end of the range estimated for DAC systems (<$100/ton). To be attractive from an LCA perspective, the electrical power driving CO_2 capture would preferably be provided onsite from a renewable energy source, most likely concentrated or photovoltaic solar.

Another potential solution would involve enhancing the gas transfer efficiency of CO_2 across the air–water interface of open ponds through the development of innovative hydro-mechanical approaches [*Greene et al*., 2016]. Currently, scientists and engineers at Cornell University are exploring the feasibility of increasing the driving gradient across this interface by reducing the concentration boundary layer thickness [*Citerone*, 2016]. The basic concept involves "tuning" the pond flow in a manner that induces flow instabilities and concentration boundary layer thinning. By taking advantage of the enhanced CO_2 transfer efficiency as well as the large surface area presented by the ponds for gas exchange, all of the CO_2 required for cultivation, at least in the open ponds, could theoretically be provided by hydro-mechanical means. Once again, the power requirements for hydro-mechanical enhancement would need to be cost effective and preferably provided onsite from a renewable energy source. Whether provided by a DAC system or hydro-mechanical enhancement, the onsite capture of CO_2 directly from the atmosphere would greatly expand the number of potential production sites worldwide.

An additional important challenge to the large-scale industrial production of marine microalgae is its relatively high demand for nutrients, especially phosphorus [*Lenton*, 2014; *Walsh et al*., 2016]. 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, microalgae can provide the basis for efficient wastewater treatment systems [*Mu et al*., 2014]. Therefore, we view the integration of microalgal-based wastewater treatment systems and efficient nutrient recycling as essential to finding a long-term solution to the phosphorus problem.

In conclusion, the large-scale industrial production of marine microalgae can play a multi-faceted role in helping society to achieve the climate stabilization targets agreed to at COP21 in Paris. Significant investments in research and development will be essential during the next decade to improve bioenergy and food production while simultaneously reducing land use and CO_2 emissions. Rigorous LCA, TEA, and IAM studies must guide future efforts to reduce the associated environmental impacts and financial costs [*Department of Energy (DOE)*, 2016c]. As this technology ramps up to globally relevant scales during the coming decades, society's prospects will improve for meeting the COP21 climate stabilization targets, while simultaneously achieving energy and food security.

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