Marine Microalgae: Climate, Energy, and Food Security for the 21st Century

Food, Fuel, and Land-sparing Strategies Using Algal Biomass

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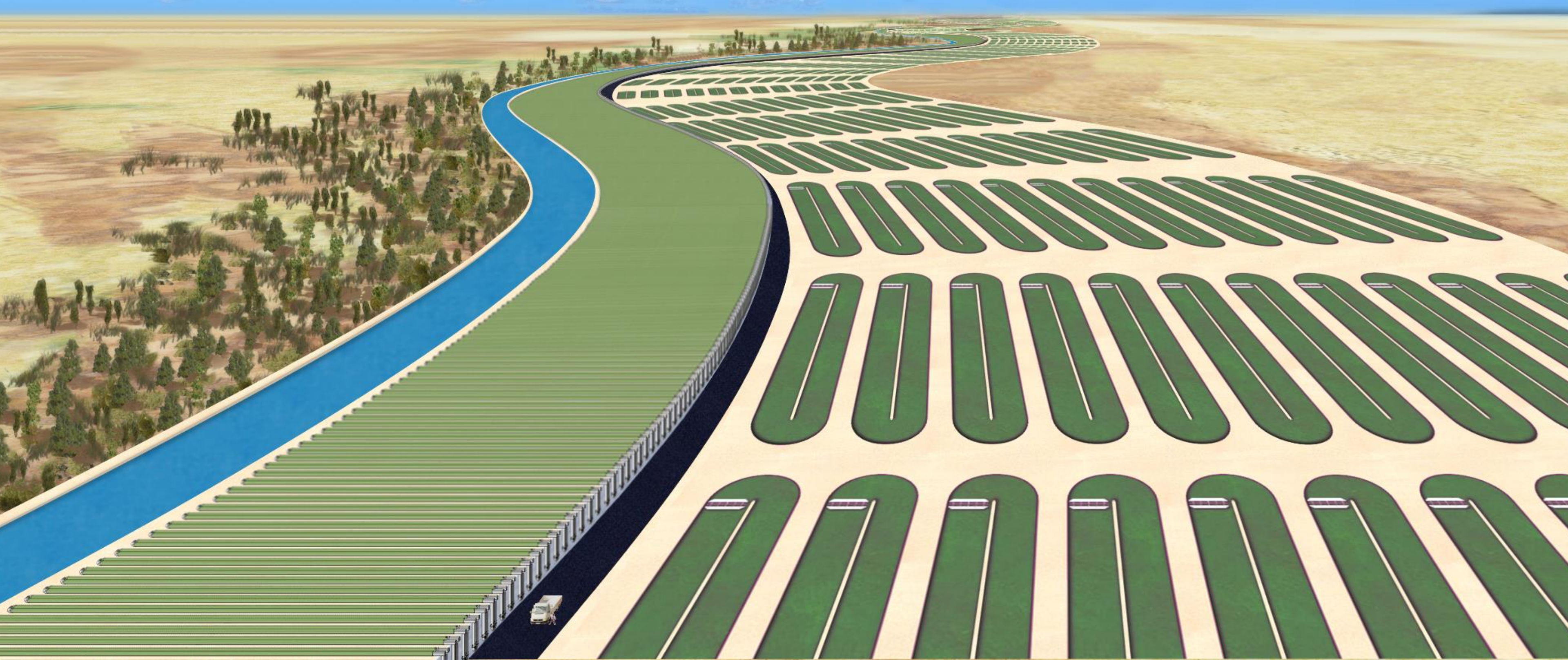


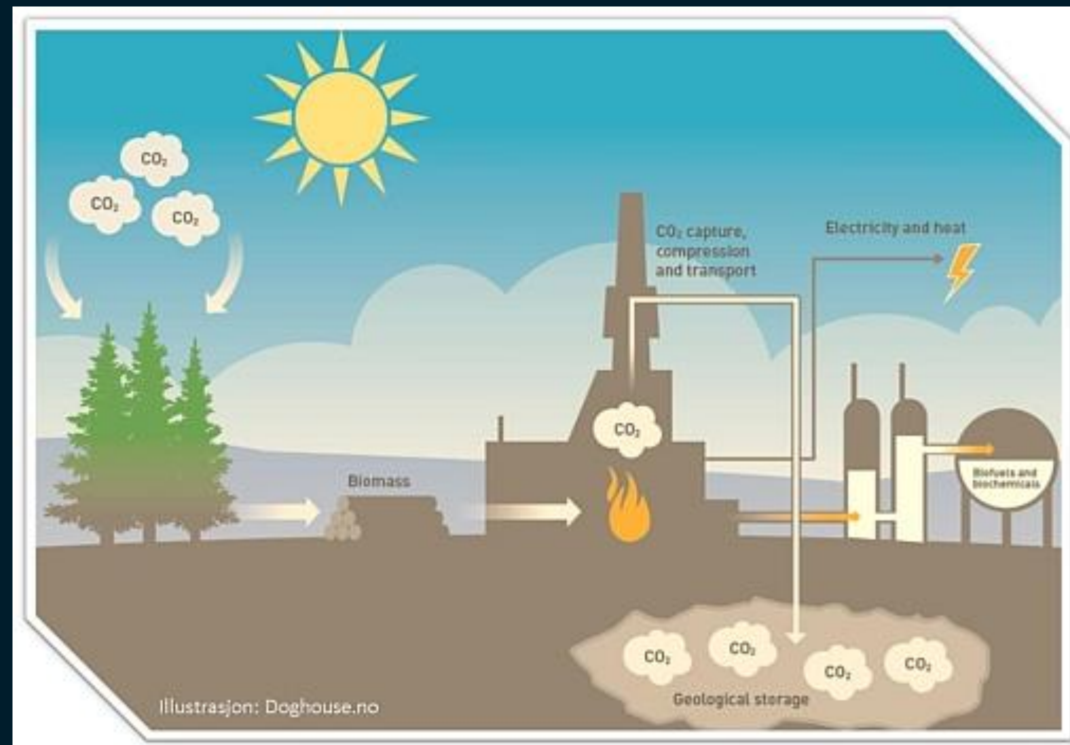
To achieve the goals of the 2015 Paris Climate Agreement, society will not only need to reduce CO_2 emissions, it will need to remove CO_2 from the atmosphere (negative emissions).

Carbon Dioxide Removal

Carbon dioxide removal (CDR) refers to the extraction of carbon dioxide from the atmosphere and its long-term storage underground, in the ocean, in the terrestrial biosphere, or in the built environment.

Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is the negative emissions darling of the climate modelers associated with the IPCC.



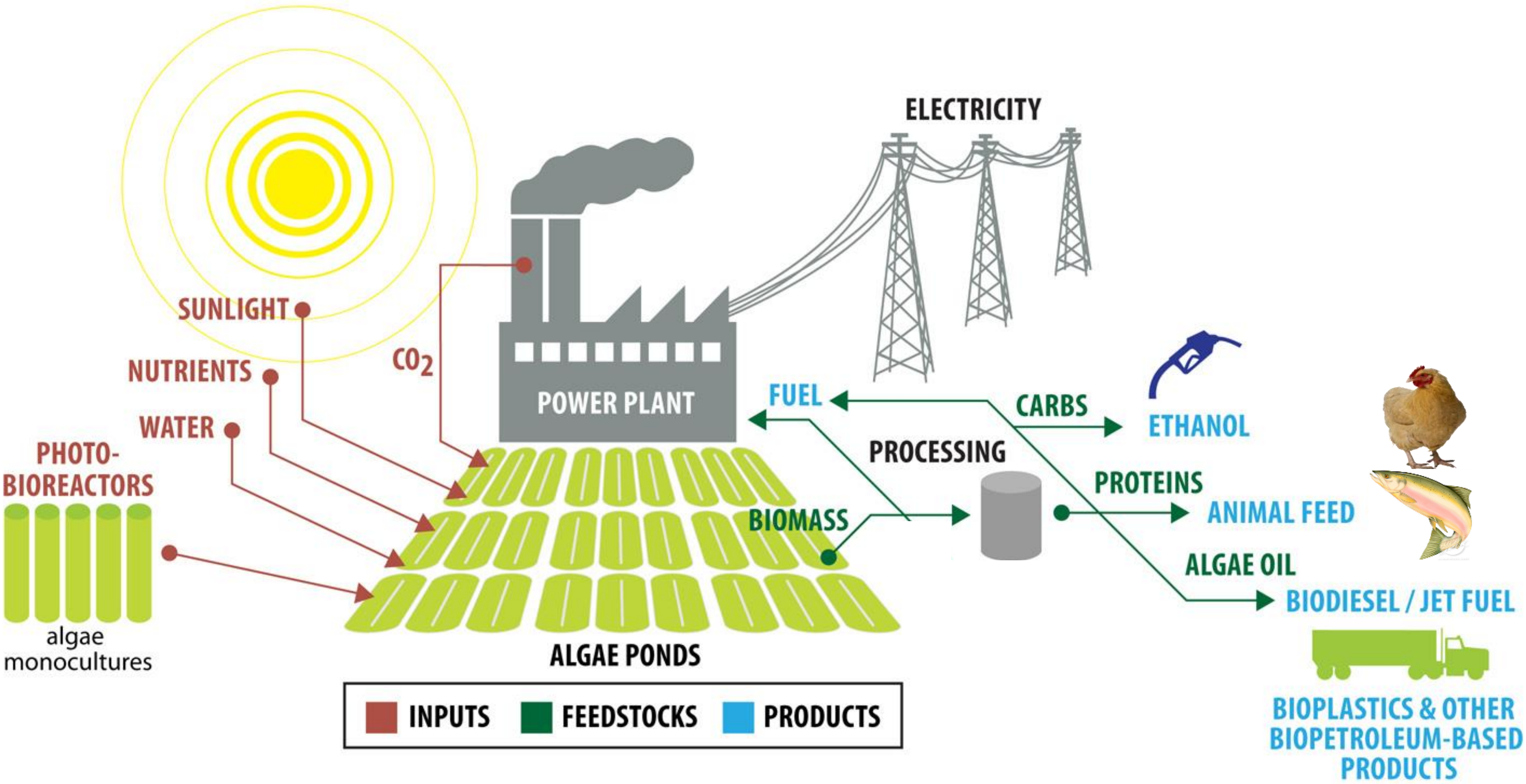
Problems:

1. Will require huge amounts of land,
2. Will compete with agriculture for land and freshwater,
3. Will encourage deforestation and biodiversity loss.

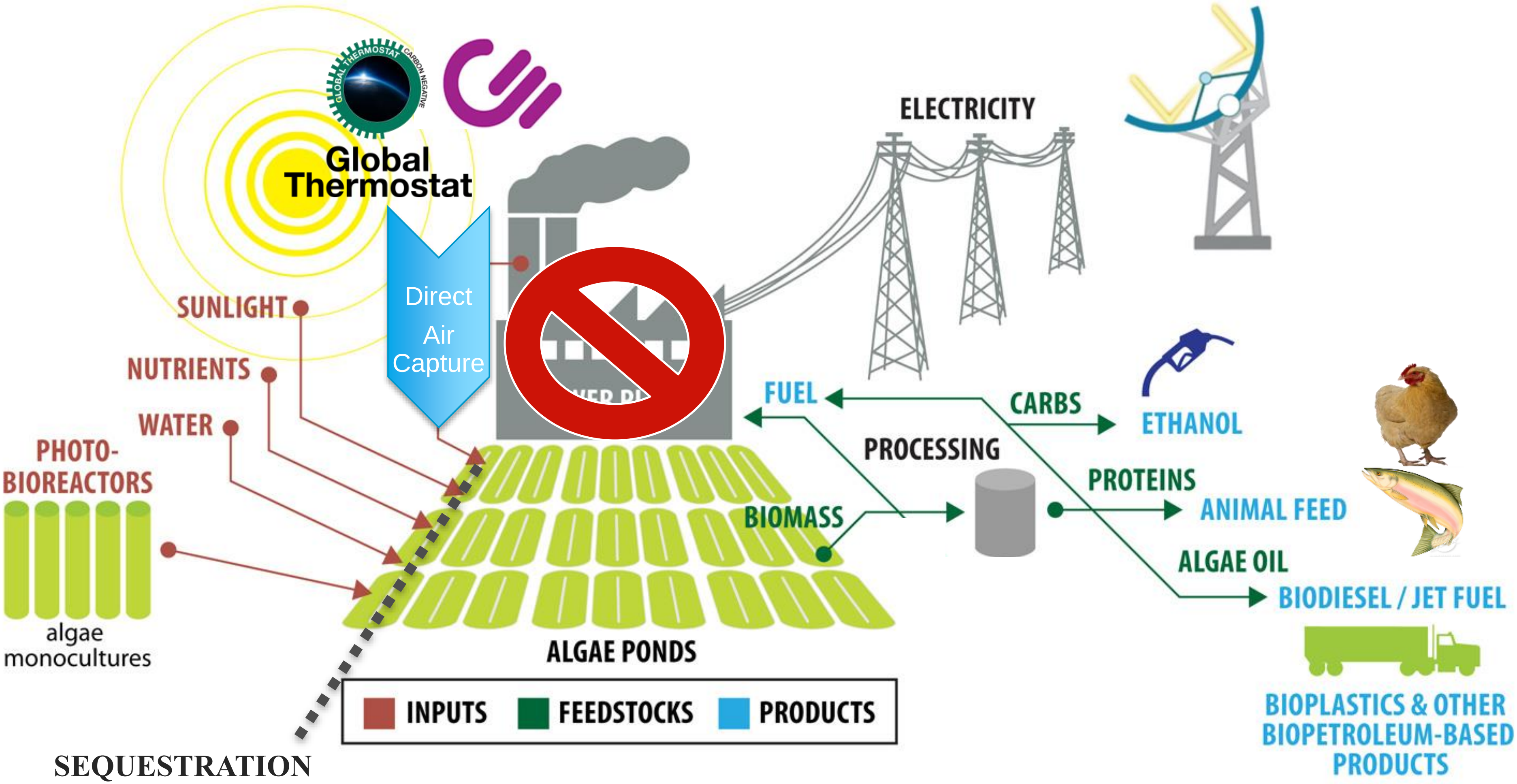
Is there anything else we can do globally?

Better Living Through Algae

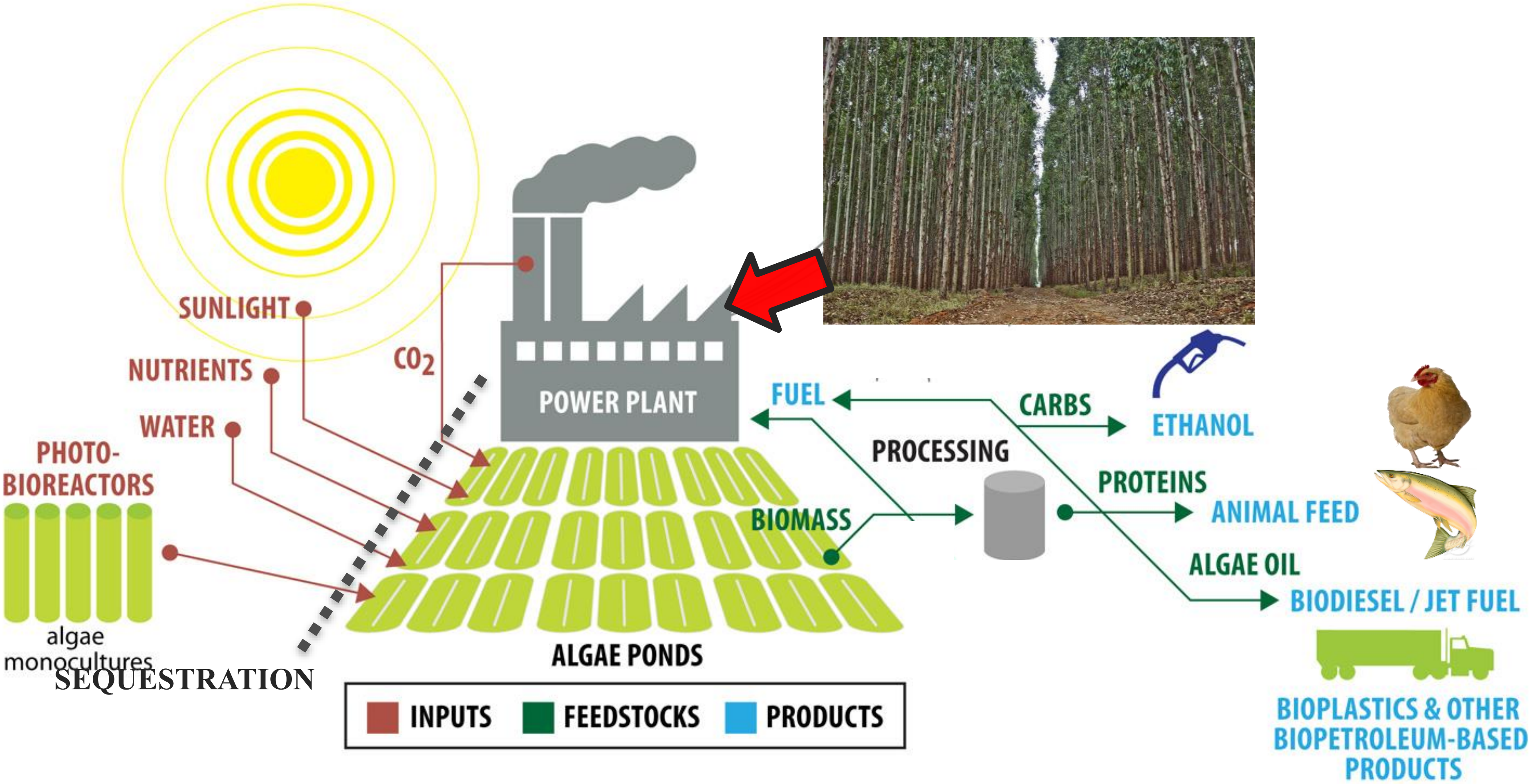
Algal Biomass for Biofuels and Other Products



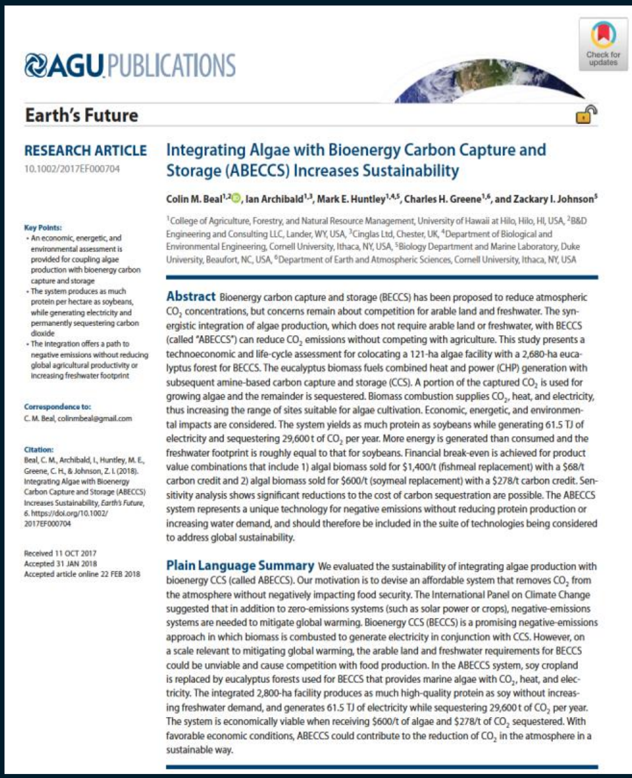
Algal Biomass Production with Direct Air Capture



Algal Biomass Production and Bioenergy with Carbon Capture and Storage (ABECCS)



Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS)



AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2017EF000704

Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability

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Key Points:
- An economic, energetic, and environmental assessment is provided for coupling algae production with bioenergy carbon capture and storage
- The system produces as much protein per hectare as soybeans, while generating electricity and permanently sequestering carbon dioxide
- The integration offers a path to negative emissions without reducing global agricultural productivity or increasing freshwater footprint

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Abstract Bioenergy carbon capture and storage (BECCS) has been proposed to reduce atmospheric CO_2 concentrations, but concerns remain about competition for arable land and freshwater. The synergistic integration of algae production, which does not require arable land or freshwater, with BECCS (called "ABECCS") can reduce CO_2 emissions without competing with agriculture. This study presents a technoeconomic and life-cycle assessment for colocating a 121-ha algae facility with a 2,680-ha eucalyptus forest for BECCS. The eucalyptus biomass fuels combined heat and power (CHP) generation with subsequent amine-based carbon capture and storage (CCS). A portion of the captured CO_2 is used for growing algae and the remainder is sequestered. Biomass combustion supplies CO_2, heat, and electricity, thus increasing the range of sites suitable for algae cultivation. Economic, energetic, and environmental impacts are considered. The system yields as much protein as soybeans while generating 61.5 TJ of electricity and sequestering 29,600 t of CO_2 per year. More energy is generated than consumed and the freshwater footprint is roughly equal to that for soybeans. Financial break-even is achieved for product value combinations that include 1) algal biomass sold for $1,400/t (fishmeal replacement) with a $68/t carbon credit and 2) algal biomass sold for $600/t (soymeal replacement) with a $278/t carbon credit. Sensitivity analysis shows significant reductions to the cost of carbon sequestration are possible. The ABECCS system represents a unique technology for negative emissions without reducing protein production or increasing water demand, and should therefore be included in the suite of technologies being considered to address global sustainability.

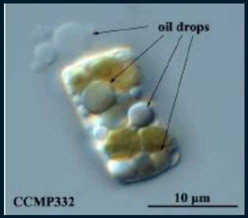
Plain Language Summary We evaluated the sustainability of integrating algae production with bioenergy CCS (called ABECCS). Our motivation is to devise an affordable system that removes CO_2 from the atmosphere without negatively impacting food security. The International Panel on Climate Change suggested that in addition to zero-emissions systems (such as solar power or crops), negative-emissions systems are needed to mitigate global warming. Bioenergy CCS (BECCS) is a promising negative-emissions approach in which biomass is combusted to generate electricity in conjunction with CCS. However, on a scale relevant to mitigating global warming, the arable land and freshwater requirements for BECCS could be unviable and cause competition with food production. In the ABECCS system, soy cropland is replaced by eucalyptus forests used for BECCS that provides marine algae with CO_2, heat, and electricity. The integrated 2,800-ha facility produces as much high-quality protein as soy without increasing freshwater demand, and generates 61.5 TJ of electricity while sequestering 29,600 t of CO_2 per year. The system is economically viable when receiving $600/t of algae and $278/t of CO_2 sequestered. With favorable economic conditions, ABECCS could contribute to the reduction of CO_2 in the atmosphere in a sustainable way.

Beal, C. M., Archibald, I., Huntley, M. E.,
Greene, C. H., & Johnson, Z. I. 2018. Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) increases sustainability, Earth's Future 6:

- For example, 2,800 ha of soy cropland is replaced by an integrated ABECCS system with a 2,680-ha eucalyptus forest and a 120-ha marine algae production facility.
- The eucalyptus-fired power plant provides the marine algae production facility with CO_2 and electricity.
- The integrated 2,800-ha ABECCS system produces as much protein (and it is higher quality) as the soy cropland without increasing land or freshwater demand, and generates 61.5 TJ of electricity while sequestering 29,600 t of CO_2 per year.
- The system is economically viable when receiving $1400/t of algae as a fish meal replacement and a $68/t of CO_2 carbon credit.

Prototype Facility for Algal Biomass Production

Advantages of Marine Microalgae

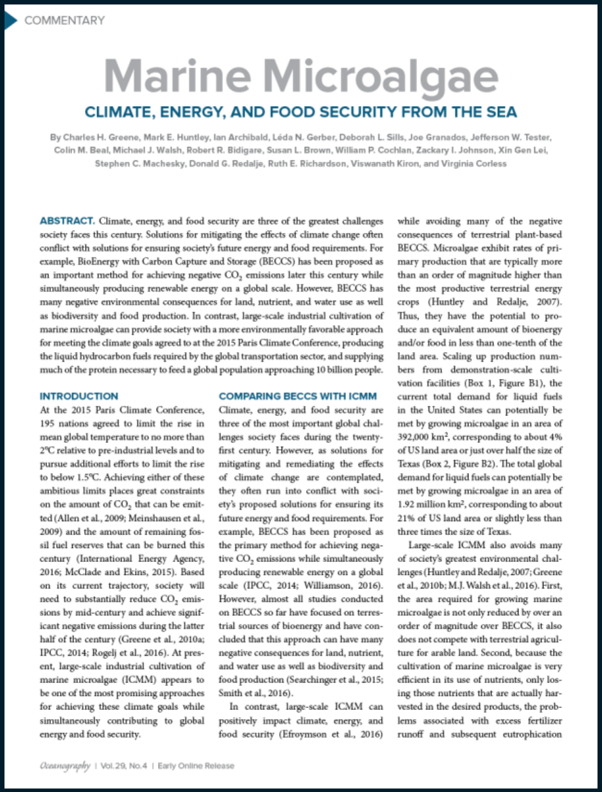


1. High productivity,
2. Can use otherwise non-productive, non-arable land,
3. Does not compete with agriculture for land,
4. Does not compete with agriculture for freshwater,
5. No fertilizer runoff and downstream eutrophication,
6. Production of food, fuels, and other valuable co-products.

Oil Source	Biomass (Mt/ha/yr)	Oil Content (% drymass)	Biodiesel (Mt/ha/yr)	Energy Content (boe/1000ha/day)
Soya	1-2.5	20%	0.2-0.5	3-8
Rapeseed	3	40%	1.2	22
Palmoil	19	20%	3.7	63
Jatropha	7.5-10	30-50%	2.2-5.3	40-100
Microalgae	**140-255**	**35-65%**	**50-100**	**1,150-2,000**

mt = metric tons, ha = hectare, boe = barrel of oil equivalents

Climate, Energy, and Food Security from the Sea


COMMENTARY

Marine Microalgae

CLIMATE, ENERGY, AND FOOD SECURITY FROM THE SEA

By Charles H. Greene, Mark E. Huntley, Ian Archibald, Léda N. Gerber, Deborah L. Sills, Joe Granados, Jefferson W. Tester, Colin M. Beal, Michael J. Walsh, Robert R. Bidigare, Susan L. Brown, William P. Cochlan, Zackary I. Johnson, Xin Gen Lei, Stephen C. Machesky, Donald G. Redalje, Ruth E. Richardson, Viswanath Kiron, and Virginia Corless

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

Scaling things up globally…

Greene, C.H., et al. 2016. Marine microalgae: climate, energy, and food security from the sea. *Oceanography* 29(4), https://doi.org/10.5670/oceanog.2016.91.

Algal Liquid Fuel Production

1. Meeting 2016 US Total Liquid Fuel Demand: ~19.6 million bbl/d*

    Assumed productivity from our data: = 0.5 bbl/ha d

    Land Requirement to meet US Transportation Fuel Demand:

        19,600,000 bbl/d x (1/0.5 bbl/ha d) = 39,200,000 ha

        39,200,000 ha => 392,000 km^2

    Corresponds to ~4% of US land area, about half the size of Texas

2. Meeting 2016 Global Total Liquid Fuel Demand: ~96 million bbl/d*

    US Total Liquid Fuel Demand is ~20% of Global Demand

    Land Requirement to meet Global Fuel Demand: ~192 million ha => 1.92 million km^2

    Corresponds to ~21% of US land area, slightly less than 3x the size of Texas

* US Energy Information Agency

Algal Protein Co-Production

1. Protein produced in comparison to US Transportation Fuel Demand:

125 million kg/km^2 yr/ ha yr x 392,000 km^2 = 490 billion kg/yr

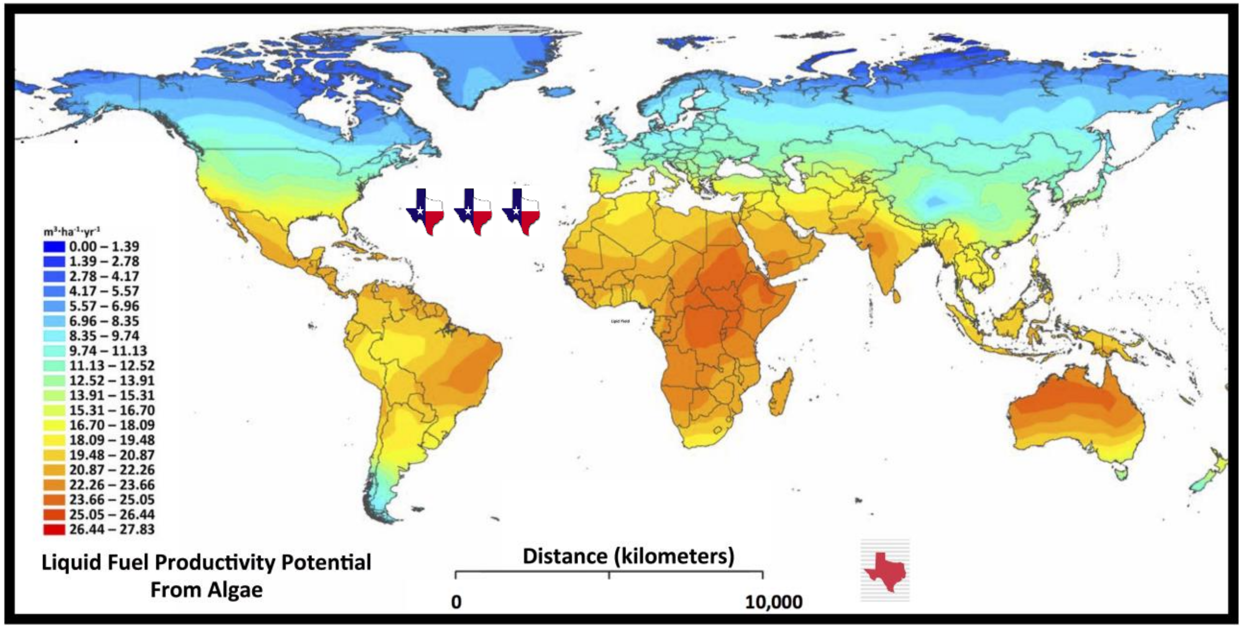
Corresponds to slightly less than 2x global soybean protein production
(and it is higher quality protein)

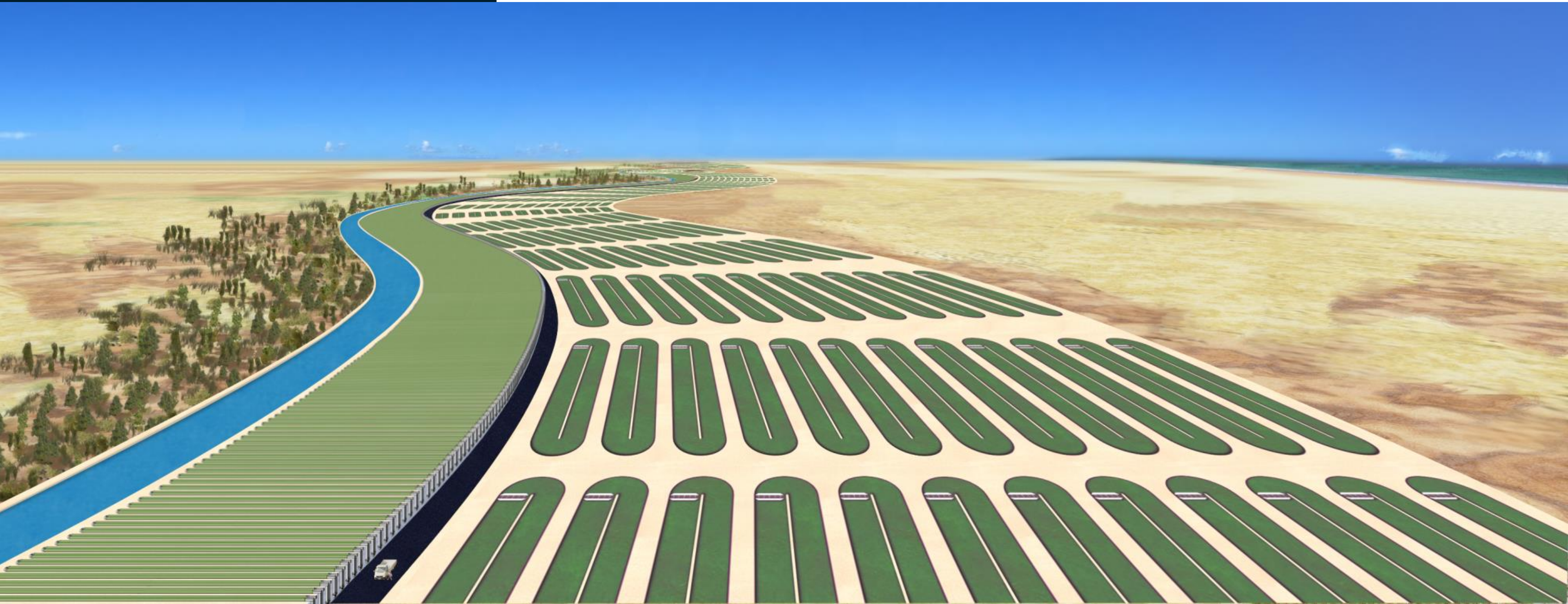
2. Protein produced in comparison to Global Liquid Fuel Demand:

125 million kg/km^2 yr/ ha yr x 1,920,000 km^2 = 2.4 trillion kg/yr

Corresponds to ~10 x global soy protein production

The Global Vision…

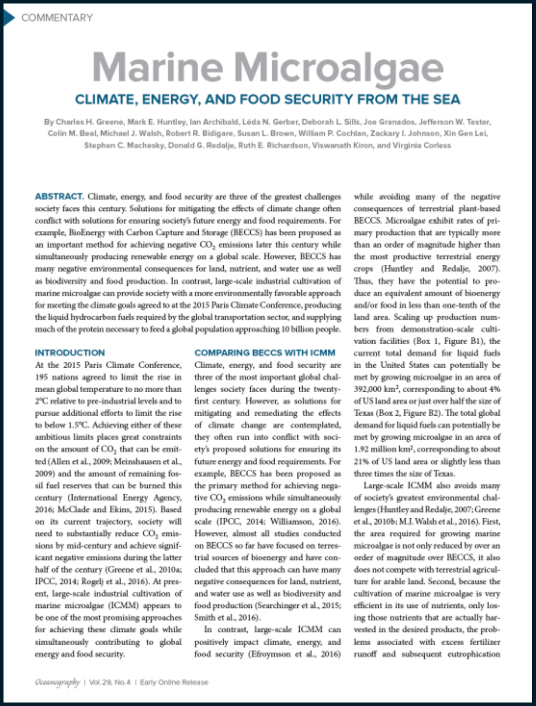




Key Points

The large-scale industrial cultivation of marine microalgae on land can provide society with:

- an environmentally favorable approach to meet the Paris climate goals,
- the liquid hydrocarbon fuels required for jet aviation, shipping and heavy vehicles,
- the carbon-negative, long-lived bio-petroleum products required to reduce atmospheric CO_2 concentration,
- the protein necessary to feed a global population approaching 10 billion people,
- a means to reduce the land demand for food and fuel production, thus avoiding the CO_2 emissions associated with land-use change.



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AGU PUBLICATIONS

Earth's Future

COMMENTARY

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

Charles H. Greene[1,2], Mark E. Huntley[2,3], Ian Archibald[2,4], Léda N. Gerber[1,2], Deborah L. Sills[1,5], Joe Granados[2], Colin M. Beal[2,6], and Michael J. Walsh[7]

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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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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.

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