Large Scale Ocean-Based Algae Production and the Arithmetic of Climate Stability

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1 Abstract

Large scale ocean-based algae production could be a key technology for removing carbon from the atmosphere at the scale needed to stabilise the planetary climate. The arithmetic of climate change shows that carbon removal must be the main focus to prevent and reverse global warming. Cutting emissions alone is too small a response against the scale of the climate problem, able only to slow the rate of CO_2 increase. Carbon removal using ocean-based biomass production has potential to convert tens of gigatonnes (Gt) of CO_2 into useful commodities per year. Converting CO_2 from waste to assets with ocean-based technologies could offer a practical path to climate repair and restoration, with orders of magnitude larger climate impact than emission reduction, using the area, energy and resources of the world ocean to achieve the required scale of carbon conversion. A possible starting point for this work comes from the Offshore Membrane Enclosures for Growing Algae industrial technology developed by NASA, which could be combined with other advances in marine algae research to eventually remove enough carbon to reverse climate change. Intensive algae farms on ten percent of the world ocean would be the eventual estimated order of magnitude required to safely convert all the excess carbon from dangerous CO_2 into valuable products, stabilizing the climate, protecting biodiversity and supporting economic, political and ecological security.

2 Introduction

After surveying the catastrophic destruction caused by the 2020 fires, California Governor Gavin Newsom said the debate is over about climate change.[1] Such events indicate the real debate about climate change is actually only starting, over the need to shift policy focus from emission reduction to CO_2 removal. Against the real scale of the climate problem, driven mainly by past emissions, decarbonising the world economy is by itself too slow, small, risky, divisive, disruptive, unfeasible and costly to stop global warming. The urgency and danger of climate change require new thinking to remove greenhouse gases at planetary scale to prevent catastrophic disruption of global economic and ecological systems.

Climate stability is at the foundation of economic and political stability. A stable and reasonably predictable climate is a fundamental existential requirement for planetary security, but the current public policy focus on emission reduction offers no prospect of stopping dangerous warming. The need is to remove more CO_2 from the atmosphere than total global emissions. Intensive industrial algae production in the oceans is one possible method that could contribute to this goal, creating a new commercial industry in carbon utilization with a trajectory to stabilize the climate, operating on far larger scale than land-based alternatives. The 'thought experiment' conducted in this paper is to 'backcast'[2] from such an imagined stable future to consider a feasible path to achieve that necessary result, with carbon removal becoming a far larger factor than emission reduction in climate restoration.

Global warming is caused by the roughly trillion tonnes of carbon that humanity will have transferred from the planetary crust to the biosphere by 2050. Using algae biomass to build a trillion tonnes of carbon-based infrastructure could convert this CO_2 waste into assets, but that idea faces immense challenges of economic, ecological and technological feasibility. The premise of this paper is that a trajectory to create a stable climate requires planetary transformation, cutting the CO_2 level below 300 parts per million (ppm), toward the 280 ppm of the Holocene geological epoch. Restoring a healthy climate with a resilient, productive and diverse ocean[3] by converting CO_2 into biomass through algae production would protect and enhance the role of the ocean as an enabler of planetary biodiversity. This large goal would also have major economic and political benefits, supporting planetary prosperity and peace and enabling a gradual shift toward a human security framework grounded in integral ecology.[4]

Leaving aside the contributions from other carbon removal methods, algae production on 5-10% of the total ocean surface area is the scale needed to stabilize the climate. Such a scale of operation would need to develop new markets for carbon utilization in locations such as roads, buildings and soil, aiming to store the quantity of carbon needed to cool ocean water and the atmosphere, reverse acidification and prevent climate tipping points.

Oceans cover 71% of the globe, more than double the planetary land area. Total ocean water volume is more than 1.3 billion km^3, with average depth 3.7 km. Ocean energy sources include sun, wind, tide, current, wave, water pressure at depth, chemistry, ocean thermal and geothermal, while deep water has abundant elements required for plant growth. The vast area, energy and nutrients available in the world ocean have potential to far outstrip the resources available for carbon removal on land, especially in view of competing land uses and costs. However, ocean operations face major difficulties of permissions and feasibility, involving work in harsh, fragile and remote environments.

Cultivation of marine algae species for biofuel is a vigorous field of research.[5] [6] [7] Ocean algae production as a global climate solution would require expanding from discipline-based analysis to develop wider strategic perspectives on biomass utilization. The futuristic idea examined in this paper is that efficient algae production at sea in enclosed fabric containers using renewable ocean energy and nutrients could convert enough CO_2 into useful products to stabilize the climate.

3 Materials and Methods

3.1 Overview

The method for this paper presents a personal research journey, developed partly while working as an Australian government official for the Australian Agency for International Development. My work on the Global Initiative on Forests and Climate[8] in 2007 compared trees and algae as carbon sinks, suggesting that algae-based climate solutions have much higher potential than forestry-based methods, given that marine algae are among the most productive plants on earth. This interest led to analysis of the concept of floating algae photobioreactors as potentially the most efficient carbon removal technology. These ideas gradually developed into ideas for large scale ocean-based algae production as a method with possibly unique scalability.[9] This article builds on that research, drawing on interdisciplinary scientific information to provide a conceptual description of a possible new technology, against the underlying agenda of defining the scale of intervention needed for climate stability.

In making comments as an expert reviewer on the 2020 draft Sixth Assessment Report on Climate Change Mitigation from IPCC Working Group Three, I found many themes in the document that deserve broader public debate. An underlying concern of my comments to IPCC was that the stable climate needed for sustained human flourishing can only be achieved by large scale rapid removal of carbon and heat from the air and sea. The IPCC draft report does not have enough to say about how to achieve that high goal, so this article attempts to set out some strategic and practical considerations for how ocean biomass production could build a future with a well-regulated atmosphere. IPCC and broader public discussion of carbon removal is constrained by the strong political focus on emission reduction as the main climate policy and by broad public concerns about the moral hazard of geoengineering. A strategic governance and permission framework for new ideas in technology needs to model the possible contributions of carbon removal and emission reduction to a stable climate.Ocean biomass production at climate-relevant scale is presented here as a method with potential to restore and regulate the historically stable composition of the atmosphere and the planetary temperature . The specific technologies presented in this paper are intended to illustrate how the scale of operation needed to stabilize the climate is far bigger than what emission reduction alone could deliver. These ideas are only at a preliminary concept stage in terms of scientific validation and testing, involving a range of new and original suggestions. The hypothesis is that algae grown in floating bags at sea could become the most efficient carbon removal system possible, with economies of scale applying new technologies across the enormous frontier of the world ocean.

3.2 Climate Stabilisation

In conventional climate policy, such as the Objective of the UNFCCC[10], a false assumption prevails that stabilising the level of CO_2 at an amount well above pre-industrial figures could stabilise the climate. That wrongly assumes that carbon removal at scale is impossible, and that we can discount the risk of system tipping points at high levels of CO_2. Those assumptions are profoundly dangerous and complacent. Slowing global warming requires rapid drawdown of atmospheric CO2 by negative emissions.[11] The risk of system tipping points[12] means ongoing elevated CO_2 brings extreme risks of climate disruption. Climate stability requires a return toward the Holocene atmospheric composition[13] illustrated in Figure 1. The extreme risks of destabilising climate effects from an ongoing high CO_2 level justify this definition of climate stability as the restoration of the Holocene CO_2 norms shown in Figure 1 that enabled human development over the last ten millennia.[14] The IPCC Representative Concentration Pathways (RCPs) shown in Fig 1 panel b[15] do not achieve this stabilization goal, which needs to bring CO_2 level down below 300 ppm and then ensure it stays at that level. Fig 1 illustrates that the goal of climate stability defined as a return to historic atmospheric norms requires far more carbon removal than is envisaged in the RCPs, showing why the political importance of negative emissions goes beyond scientific analysis to include strategic policy problems of planetary stability and security.

Figure 1: Modelling Climate Stability

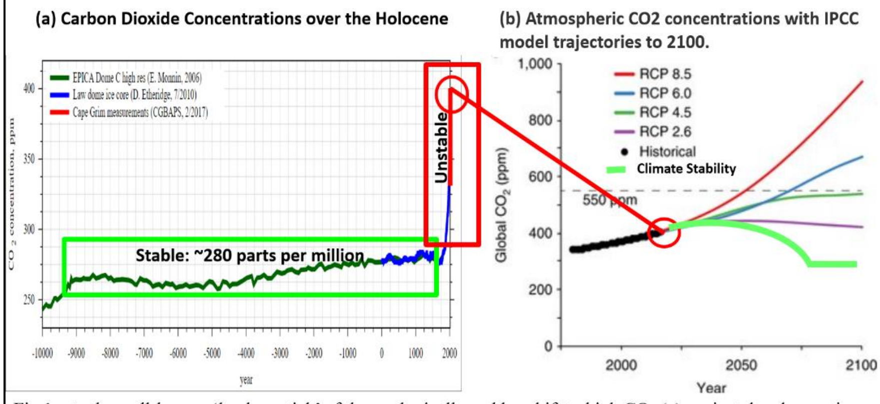


Fig 1 sets the well-known ‘hockey-stick’ of the geologically sudden shift to high CO_2 (a) against the observation (b) that a return to Holocene stability would need to remove far more carbon than envisaged in IPCC scenarios
Sources: (a) https://upload.wikimedia.org/wikipedia/commons/1/1d/Ghgs-epcia-holocene-CO2-en.svg, (b) Myers and Smith, 2018. Stable and Unstable bars in (a) and Climate Stability line in (b) added by Robert Tulip.

Decarbonisation alone, shifting the world economy to renewable energy, can only slow the rate of warming increase and therefore cannot reverse climate change or deliver the required momentum toward climate stability. As well, rapid emission cuts are very difficult in view of the strong political and economic drivers of the fossil fuel economy, and by themselves would not be enough to stop dangerous climate change even if achieved. Reliance mainly on cutting emissions does not reduce the high risk of a looming hothouse collapse at planetary scale. Decarbonisation is therefore only a placeholder strategy while the world wakes up to the need to remove CO_2 at scale.

3.3 Climate Arithmetic

The postulate of this paper is that climate stability requires annual net removal of 15 Gt C (>30 Gt gross) from the atmosphere, aiming to restore a stable climate over the next fifty years. Annual emissions of CO_2 are about 10 Gt C = 37 Gt CO_2, or about 15 Gt C = 55 Gt CO_2e including equivalents such as methane. For emission reduction to deliver 20% of this postulated total carbon reduction would require economic restructuring on a far bigger scale than now envisaged, cutting emissions by more than 6 GT C/y. For reference, Germany, one of the most ambitious nations on climate action,[16] plans to cut emissions by less than 0.1 Gt C/y from 2014 to 2030,[17] a rate that would cut 3 Gt C/y if matched by the whole world economy. That world total is just 10% of the suggested stability goal.

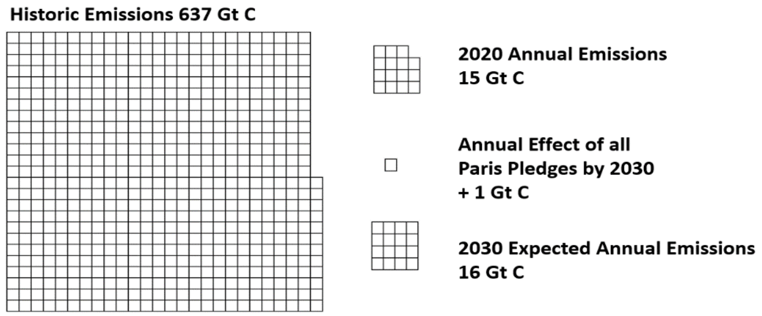
Global warming from the impact of emissions has increased radiative forcing (RF)[18] to more than 70% higher than in the Holocene. CO_2 causes two thirds of anthropogenic RF effect from GHGs,[19] with methane and other GHGs providing the remaining third. The RF imbalance against the Holocene GHG baseline is increasing by about 2% per year, including 2.5 ppm CO_2[20], while decreasing albedo may add a further significant component to RF.[21]

The broad goal of climate policy should be to remove all the carbon that humans have added to the air and sea, and then manage the global atmosphere to maintain its historically stable composition to prevent dangerous warming or cooling. The arithmetic of this goal indicates that removing carbon at double the rate of emission, ie at 30 Gt C/y gross or 15 Gt net, assuming emissions will continue near their present rate, would stabilize the climate in about 50 years, removing 750 Gt C.

Climate policy should see achieving this 750 Gt removal as fast as possible as the main goal. That means net zero emissions is not an end in itself, but only one milestone on the path to the real goal of large net negative emissions. ‘Net zero emissions’ simply means that GHG removals equal emissions. Net zero could theoretically be achieved by any equal combination of additions and removals. The approach here is that a main focus on removals is likely to prove a better, simpler and more feasible approach than scaling up emission reduction.

The popular climate movement does not generally understand or support this analysis. An example of the confusion about potential factor contributions is seen in the January 2020 speech by Greta Thunberg at Davos,[22] where she said “forget about net zero. We need real zero.” The difficult reality ignored by this comment is that we do not in fact need ‘real zero’, understood as a complete end to emissions. Considered from the scale of change needed for climate stability, emission reduction is marginal to cooling the planet compared to the primary role of carbon removal. Fully decarbonising the world economy would remove about 2.5% of anthropogenic radiative forcing per year if all combustion stopped, as shown in Figure 2. Realistic levels of decarbonisation could deliver maybe one tenth of that each year, more like 0.2% of the total required carbon removal. But even that is highly unlikely, as current projections are that by 2030 emissions will increase, not decrease. A goal of “real zero” would invest scarce resources and time in expensive and inadequate methods while rejecting methods that could actually stabilize the climate.

Figure 2:
Historic Emissions, Annual Emissions and Paris Pledges



Emission reduction addresses the relatively small warming effect of new emissions (right), not the main warming effect of past emissions (left).

Figure 2 shows the overall radiative forcing of historic emissions is more than forty times the annual increase. It compares historic CO_2e emissions, estimated[23] at 637 Gt C, with the annual increase of 15 Gt C added in 2020, the additional 1 Gt C/y by which the current emission rate will increase if all Paris Accord pledges are met by 2030, and the expected 2030 annual emissions of 16 Gt C, or 55 Gt CO_2e.

The inadequacy of the emission reduction strategy is reflected in the current projections that by 2030 emissions will increase, not decrease. Climate Action Tracker (CAT)[24] compiled the "Optimistic Policy Projections" shown in Figure 3. This scenario has annual emissions growing to 5% higher than now by 2030, and then remaining above 55 Gt CO_2e to 2050 and above 40 Gt for the rest of the century, doing nothing to address the scale of RF that must be removed to prevent dangerous tipping points. The BP Energy Outlook 2019 similarly predicts a 20% increase in annual CO_2 emissions by 2040, or at best a 40% cut.[25] Such projections show the planetary security risks of worsening RF, highlighting the need for concerted measures to remove the excess carbon.

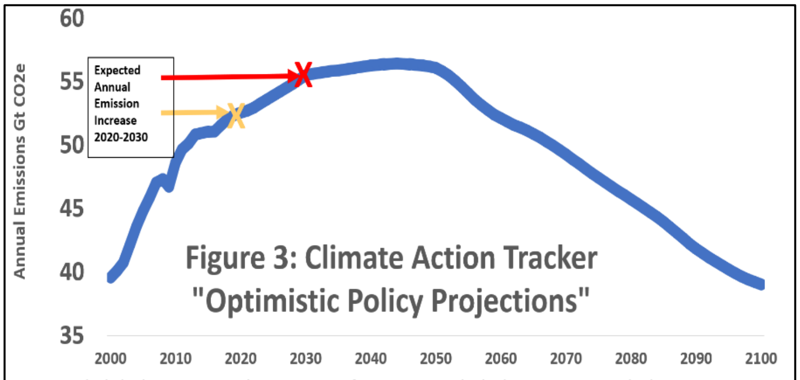


Figure 3: Climate Action Tracker "Optimistic Policy Projections"

Projected global emissions this century if Paris Accord pledges are exceeded.
Chart by Robert Tulip, data used with permission from https://climateactiontracker.org/data-portal/

CAT projections show that current measures will not begin to remove past emissions. Even if all Paris pledges were met, annual world emissions would still be more in 2030 than now. Contributions under the Paris Accord would need to increase well above current pledges just to remove a small fraction of new emissions in net terms. Achieving this is unlikely given the economic and political constraints and drivers. Speeding up reduction of new emissions can therefore only provide a small part of a realistic overall strategy for climate stability.

The excess CO_2 in the air and sea will continue to cause dangerous warming until it is removed. Climate arithmetic shows there is no remaining 'carbon budget', contrary to widely held assumptions.[26] ANU Oceans Professor Dr Eelco Rohling explained in *The Climate Question*[27] that committed warming from past emissions means carbon removal is essential to stop the planet from warming by more than 2°C. Temperature would keep rising even if all emissions stopped.[28] Without carbon removal at larger scale than emissions, a new hotter climate equilibrium is inevitable: Rohling says "the slow components in the climate system mean we are already committed to further warming of 1°C or so…. avoidance of 2°C warming requires stabilisation of CO_2 levels below 400 ppm… the onus is on us to find engineering and/or Earth System based solutions."

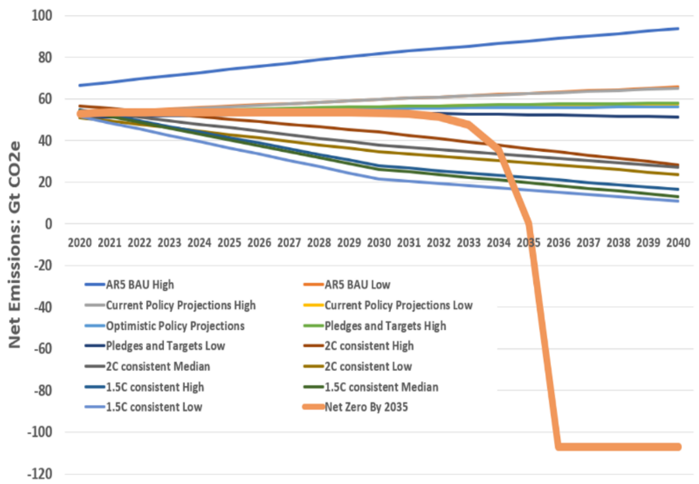
Rohling's call to cut CO_2 below 400 ppm should be a start on a path to return the planet toward the Holocene climate stability of 280 ppm. The concept of a remaining carbon budget ignores this need for carbon removal and assumes the earth system is less fragile and sensitive than the growing momentum of emerging tipping points indicates.[29] [30] Stopping dangerous warming requires a primary focus on methods to reverse the interconnected accelerating feedback mechanisms recorded across the planet.[31] The CO_2-temperature alignment of the Holocene[32] delivered stable sea level for all recorded history.[33] Large-scale intervention is needed to minimise sea level rise and its impact on coastal communities, to prevent the range of expected tipping points into a hothouse earth.

Simple arithmetic shows that decarbonisation cannot get close to solving the climate problem. To stabilise the climate, whether or not emissions continue much as expected, durable carbon removal would have to grow rapidly to a scale more than double total current emissions. The scenario for this paper is to ask how this goal might be achievable through ocean biomass production, aiming for exponential increase of carbon removal to deliver the needed level of net negative emissions. That would change the world trajectory from the current emission increase of 5% per year to carbon removal targets above 200% of annual emissions. Growing algae intensively on up to 10% of the total ocean surface is the scale of action needed to deliver that result.

Figure 4 shows the range of emission scenarios to 2040 calculated by Climate Action Tracker, together with a hypothetical ‘Net Zero By 2035’ scenario based on exponential increase of ocean biomass, annually tripling coverage with all produced carbon stored in forms that do not return to GHGs. The Net Zero by 2035 scenario is obviously extremely compressed, but is included to illustrate an ideal case to secure climate stability, showing how much larger this objective is than currently discussed scenarios. On this model, net zero global CO_2 emissions would be achieved by 2035 through industrial algae production on about 1% of the world ocean, ramping up removals to equal continued emissions of about 15 Gt C/y. The rationale is that achieving net zero emissions as soon as possible, with a trajectory to then move rapidly to achieve large ongoing net negative emissions, might best be achieved in this way, and is essential to minimise the risk and effect of potential catastrophic tipping points in the earth climate system.

Figure 4

Emission Scenarios to 2040, with Net Zero By 2035



Exponential path to Net Zero By 2035, based on annual tripling of algae production and storage of produced carbon. Author calculation by Robert Tulip. All other data from https://climateactiontracker.org/data-portal/ Copyright © 2019 by Climate Analytics and NewClimate Institute. All rights reserved. Used with permission.

Achieving such a rapid result would require immediate large resourcing of research and development of ocean algae production, then tripling of production each year, with development and construction of stable methods for carbon storage and utilization such as conversion of produced biomass to hydrocarbon products. This hypothetical calculation assumes an algae farming area of 2.5 km^2 in 2022 could grow exponentially to 3.5 million km^2 in 2035 in available ocean locations, illustrating just how immense the climate stability problem really is. To achieve net zero would require all processed carbon to be stored rather than returned to the climate. To achieve climate stability, cutting CO_2 to 300 ppm by 2050, coverage would then need to continue growth to cover up to 10% of the ocean surface area, about 36 million km^2, not considering other technology contributions. The diagram shows such growth continuing at exponential rate and stabilising at annual removal rate of 110 Gt CO_2e, double total expected emissions.

Emission reduction of 6 Gt C/y would contribute 20%, to the proposed gross RF removal of 30 Gt/y. That would require cutting emissions by 40% to 9 GtC/y. Such a result is far more ambitious than Paris pledges and targets, which propose annual emission increase of 4-8% by 2030, while CAT projections of current policy indicate an even bigger increase of 8-13%. Given these far higher expected emissions levels, and the scale of required carbon removal, decarbonization cannot make much difference to the time frame for climate stability. Even if ramped up well above Paris pledges, achieving CAT’s projection of a 20-30% cut in global 2030 emissions needed to hold warming below 2°, the annual cut in forcing would be less than 2%. Even such a big emission cut would only make a relatively small contribution to the overall goal of stabilizing the climate over the next fifty years.

This analysis illustrates that carbon removal involves a different way of thinking about climate solutions. To achieve the 2035 net zero goal is obviously unlikely, and would involve a major international cooperative endeavour of public private partnership finding solutions to a range of formidable engineering, environmental, political, economic and institutional problems. But without consideration of such an ideal transformative best case, the planet is condemned to extreme risks. Unlike the current decarbonization proposals, this focus on carbon removal would create infrastructure momentum with a trajectory to power through net zero to achieve the large net negative removal shown in Figure 4 that is needed for climate stability.

3.4 Precursor Methods for Marine Microalgae Production

Two major research projects studied marine microalgae production in ways that can inform the feasibility of such rapid scale up. The Offshore Membrane Enclosures for Growing Algae (OMEGA) study[34] by the US National Aeronautical and Space Administration (NASA) ran from 2010 to 2012, examining the feasibility of using algae to convert wastewater to biofuels, and the Large-Scale Production of Fuel and Feed from Marine Microalgae Project was completed in 2015 by the Cornell Marine Algae Biofuels Consortium.[35]

Results of the NASA study are documented in its OMEGA Final Report.[36] OMEGA is a method to grow freshwater algae in flexible clear plastic floating photobioreactors anchored in sheltered ocean waters. The pilot project demonstrated prototype systems up to 1,600 liters. Ocean deployment would use treated wastewater from coastal sewerage works and CO_2 from power plants as feedstock, producing algae biomass, clean water and associated aquaculture and biodiversity benefits.

Key barriers for algae production include the cost and availability of land, feedstock and energy. OMEGA's use of marine locations addressed these problems, while using ocean water for buoyancy, to stabilize temperature and to help mix the algae with wave action. Recognising that biofuels cannot now compete on price against fossil fuels, the OMEGA system treats fuel as one of several products, integrating algae biofuel production with wastewater treatment, multitrophic aquaculture and energy from solar, wind and wave. As shown in Figure 39 in the OMEGA report, algae grown in plastic tubes between solid platforms aims to provide a method able to withstand ocean stresses such as weather, currents and corrosion, working only in sheltered coastal locations.

The direct cooling effect of OMEGA operation is from concentrated photosynthesis, using solar energy that would otherwise heat the surrounding water. Indirect cooling comes from efficient removal of CO_2 from air and sea, as long as the carbon is stored in durable form. Carbon removal on this OMEGA model has potential to support a clean circular economy,[37] converting emissions from waste to asset to extract value on the principles of industrial ecology.[38]

Subsequent scientific research[39] [40] is investigating ocean algae membrane methods. However, OMEGA has not yet been commercialized. The OMEGA report explores the combination of biofuel, energy and aquaculture as a feasible and viable investment, but life cycle and technoeconomic analysis did not adequately prove commercial viability. There has been little follow up on the OMEGA system because the initial pilot studies were not sufficiently promising. To take this technology forward would require new efficient technologies able to cut its costs.

I explore here the idea that ocean nutrients mined by tidal pumping and hydrothermal liquefaction (HTL) in fabric systems, together with intensive work to lift productivity and build on the OMEGA model, could cut algae production costs well below current assumptions, creating a major new profitable industry. Tidal pumping and HTL could increase the OMEGA energy return on investment, justifying renewed attention to its approach.

Generating strategic political focus on biomass production as a primary climate solution is essential to mobilize investment, illustrating the importance of the critique of current climate policy frameworks. OMEGA methods have high potential to increase the size and efficiency of photobioreactors at global scale as a CO_2 removal method. Methods building upon the OMEGA concept are needed to show if the described goal of large-scale ocean operation would be feasible. A recent study[41] on design of plastic photobioreactors found technical challenges include photo-limitation, mixing, cell growth inhibition, fragility, leakage, lifespan, cleaning and disposal. This study noted that immersion of bags in water can reduce cost and control temperature and that ocean-based operation can improve mixing and mass transfer by using wave energy. Other studies[42] have found that zooplankton or viruses can destroy contained algae, showing the difficulties involved to sustain a balanced ecology inside the bags. The OMEGA project sought to address these problems at theoretical and pilot study level.

The algae yields achieved in the pilot OMEGA project averaged about 15 grams dry weight per square metre per day ($g\ m^{-2}\ d^{-1}$). Scaled up to about 1% of the world ocean, this output rate would utilise 50 Gt of CO_2 per year (15 Gt C), the basis for the calculation in this paper of the area needed for net zero emissions. Processes of ocean outgassing and impermanence of carbon removal described by Keller et al (2018)[43] mean most of this removed carbon would rapidly return to the climate system if left in biological (labile) forms. Achieving climate impact depends on how much carbon is locked up in long term sinks. Carbon removal at ten times bigger scale, 36 million km^2, could cause a rapid decline in the atmospheric CO_2 level, while providing carbon for a range of environmental and economic uses. Such scaling could not be achieved using freshwater as algae feedstock, but might be possible using saltwater algae photobioreactors.

Higher algae yields would reduce the area required, indicating the importance of maximizing productivity. One company asserts that algae can use artificial intelligence-enhanced CO_2 diffusion to grow four hundred times faster than trees,[44] illustrating its productive potential.

Park and Lee[45] found 36 $g\ m^{-2}\ d^{-1}$ yield in their analysis of ocean algae production methods, more than double the OMEGA yield. They state that farms on 0.06% of the world ocean could replace 30% of global transportation fuel consumption by volume, although costs of the methods they study are not yet competitive.

The Cornell Marine Algae Biofuels Consortium Project conducted intensive research using saltwater algae species at the Kona Demonstration Facility in Hawaii. The project demonstrated hybrid systems combining photobioreactors and raceway ponds with biomass yields of 78 tonnes per hectare per year, (21 $g\ m^{-1}\ d^{-1}$), and calculated that system improvements could increase this yield by >25% up to 100 tonnes.[46] Its research has focused on conducting large-scale, marine microalgae cultivation onshore, primarily on non-arable land where it does not compete for land with terrestrial agriculture. My suggestion is that the excellent results from the Cornell work could be augmented by the efficiencies of floating PBRs described in the OMEGA system.

Another technology with important lessons is the offshore cultivation of seaweed on floating arrays known as Marine Permaculture[47], which provides a simpler way to operate in the deep ocean than fabric bags, potentially helping show how robust bag technology could cope with ocean conditions.

3.5 Potential Ocean Algae Production Methods: River Deployment

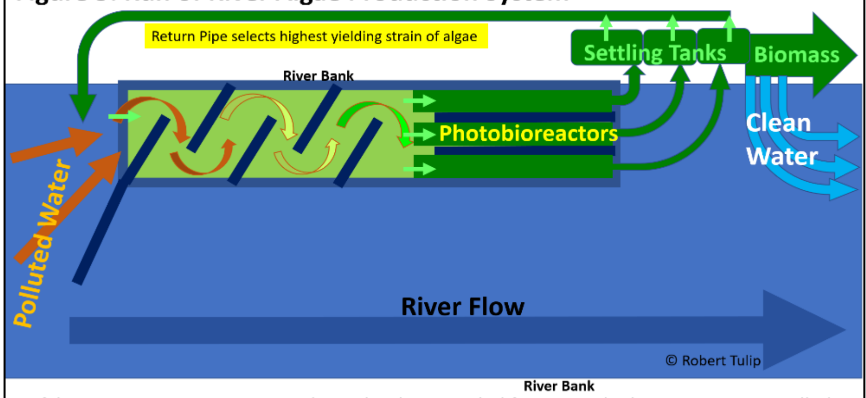
The problem is how these highly innovative and productive methods that have been developed at small scale could be scaled up to the Gt carbon removal magnitude needed to stabilize the climate. The harsh conditions of the world ocean make implementing marine microalgae photobioreactors very challenging. The projects mentioned are examples of many that have sought to commercialise algae, illustrating some key ideas about how deployment could be possible in the ocean, using the available locations, energy and nutrients to take advantage of economies of scale.

A path toward possible eventual ocean deployment could begin on small scale in rivers and lakes as partial proof of concept for ocean-based photobioreactors, a new technology that has not yet been commercialised despite extensive research. As suggested in the OMEGA report, removing river nutrients to prevent hypoxia could be the most immediate way to commercialise the floating PBR concept, as a first step on the critical path toward ocean deployment. The NASA report explains how the OMEGA concept originated in 2008 from discussion of how to manage algal blooms in rivers, caused by nutrient-rich agricultural runoff and wastewater. Forward osmosis can draw nutrients from polluted water into a membrane enclosure, a method that would clean the water while also preparing materials and design for subsequent ocean deployment in much more challenging conditions.

Initial riverine use could justify OMEGA technology for its direct environmental benefits as well as commercial products. Hypoxia, the loss of dissolved oxygen in water due to excessive nutrients, is a major environmental problem causing dead zones in river outflows such as from the Mississippi River.[48] OMEGA technology could reduce hypoxia in river and lake systems on the sanitation model of treating waste. Similarly, membrane enclosures could remove nutrient pollution from city lakes and from rivers flowing to endangered ecosystems such as coral reefs.[49] This method could be sustained commercially by sale of produced algae biomass. System engineering risks such as eutrophication and invasion by toxic species can be addressed as discussed in papers on photobioreactors such as Huang et al.[50]

Figure 5 is my concept sketch of a run of river algae production system for nutrient removal. This diagram shows polluted river water flowing into a floating photobioreactor, separated into three channels, with produced algae pumped into shoreline settling tanks. Clean water is returned to the river, algae biomass is sold, and continuous measurement of yield from each channel enables selection and return of a fraction of the best yielding variety as inoculant to seed the photobioreactor. Controlled adaptive pressure for constant increase in productivity enables the system to utilize higher quantities of CO_2 from coal fired power stations.

Figure 5: Run of River Algae Production System



A fabric PBR in a river can prove the technology needed for ocean deployment in a controlled environment, funded by sale of produced biomass and public investment in cleaner water.

3.6 Eventual Oceanic Scale

There are immense differences between growing tonnes of algae for niche markets and growing billions of tonnes for carbon storage. As a first step in the scale up, ocean deployment in sheltered bays could expand the river algae bag model, addressing the major challenges and risks for use of plastic fabric materials in ocean conditions.[51] The gradual scaling up would respond to the need to establish new commodity markets for biomass products, ideally with funding incentives from taxation of emissions.

An essential condition for development of ocean algae systems is that the whole system should protect and enhance biodiversity, with cultivated algae developed safely to present no risk to natural ecosystems. The proposed stepwise deployment enables development of governance, monitoring and permissions at a range of levels. If proven feasible and acceptable, this method for algae processing could point toward a rapid solution to global warming with economic advantages in scaling up production, reducing costs, converting CO_2 into useful products and obtaining new sources of nutrient.

As proposed in the NASA report, protected coastal locations with treated sewage and river water outflows could be suitable initial sites. However, the challenges to develop industrial scale algae production are considerable, as indicated by Huntley et al (2015) and Kiesenhofer and Fluch (2018).[52] Harnessing methods for algae biomass production and storage will require development and integration of a series of major technological innovations to optimize production at oceanic scale.

The ideas proposed in this paper augment the OMEGA freshwater concept and the Cornell saltwater results with potential efficiencies from tidal pumping and hydrothermal liquefaction (HTL). Scaling up algae technology to the multi Gt level needed for climate stability would require such new methods to maximise the efficiency of conversion of biomass into stable valuable forms. These new technologies would need to be established in sheltered coastal locations to assess their potential for deep sea operation. An eventual goal is to use salt water as feedstock, as used in the Cornell Project, with tidal pumping enabling larger scale of operation by tapping the abundant nutrients of the deep ocean at low energy cost. Deep ocean HTL and tidal pumping, if proven feasible, could utilise ocean nutrients and geothermal energy for large scale algae production. The eventual goal is that available ocean area for this technology could convert atmospheric CO_2 into biofuel and permanent forms of carbon storage at larger scale than total emissions, driving down radiative forcing. At the scales described this might be done most efficiently using natural sources of heat and pressure, with these novel methods only coming into play once such scale became viable. OMEGA appears to have failed because of the lack of such scaling methods that might make it economic.

A key problem in scaling up algae production is the availability of nutrients. The proposed exponential growth of carbon removal using algae would require large new sources of phosphate and nitrate. The world ocean contains abundant amounts of these nutrients at low concentration, mostly in deep water. Depths below 1km contain P at 0.1 ppm and N at 0.7 ppm.[53] These figures indicate total world ocean quantities of about 135 Gt P and 950 Gt N. These nutrients could be extracted using the method described below to concentrate and utilize algae biomass with seafloor processing. Development of OMEGA from an initial freshwater system to a method using deep ocean water as feedstock could mine ocean nutrients at Gt scale.

Figure 6 presents an original schematic hypothesis of how deep ocean nutrients could be used to fertilize ocean algae enclosures. This system would mine and recycle abundant nutrients to transform algae into profitable commodities. The concept begins with nutrient-rich deep ocean water pumped by tide into an OMEGA system, where it mixes with seeded algae species as inoculant and with CO_2 from point sources and ambient air. Wave energy is used to pump gases and liquids at the ocean surface. CO_2 from point sources such as coal fired power station emissions[54] or offshore gas projects, together with nutrients as algae feedstock, optimises yield, cultivating algae varieties that flourish in high CO_2 environments.[55]

Figure 6: Ocean Biofuel Production Method

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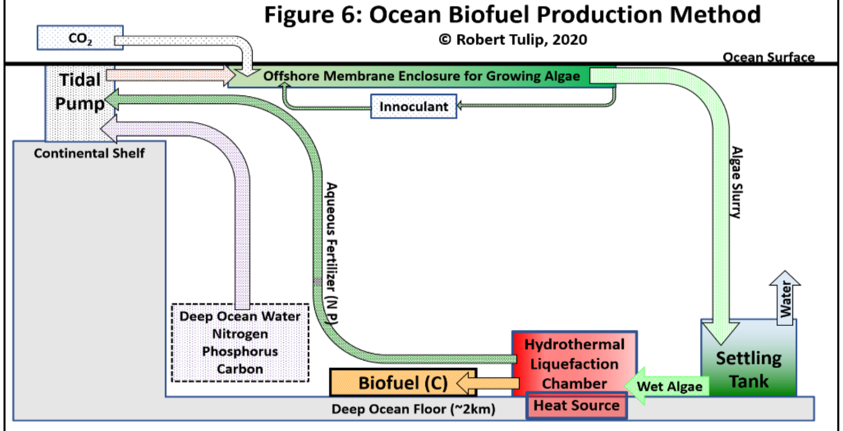


Schematic Process Flow Diagram: nutrients from deep ocean water pumped into algae production system on surface then to ocean floor for conversion into biofuel and fertilizer.

The OMEGA chamber produces algae slurry, which is pumped down a vertical pipe to a settling tank on the ocean floor. Ocean conditions mean such a vertical pipe system would require immense scale and thickness, essentially functioning as an ocean dam into which algae-rich water is poured. In the settling tank at the base of the pipe, methods such as electroflocculation[56] can create a ~20% wet algae sediment, while water is drawn off. The wet algae sediment flows into the HTL chamber, where heat and pressure convert this biomass into biocrude oil and an aqueous solution containing N and P as liquid fertilizer. Smaller amounts of gas and solid are also produced. Different methods will produce a range of outputs, for example with high N content in oil.[57]

Liquid fertilizer produced in the HTL chamber is returned to the OMEGA chamber via the tidal pump, where it combines with deep ocean water as algae feedstock. Each cycle through the HTL chamber increases the amount of fertilizer in the system. Once N and P are optimized in the algae culture any excess can be drawn off or released to the surface ocean, where it will increase natural biomass at the base of the food chain, mimicking the natural creation of algal blooms from deep ocean water upwelling.[58]

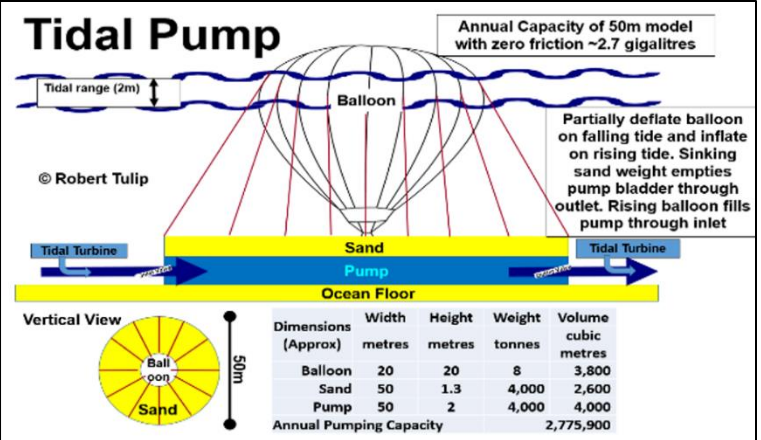
HTL converts wet biomass into biocrude oil and chemicals at temperature of 200–400°C and pressure of 10–25 MPa.[59] It offers a biorefining method to recycle mixed waste such as plastic and food as the key technology for a circular economy of the chemical industry.[60] The principle is that sufficient pressure and heat will break down organic structures and enable circular reuse of nutrients to catalyse the creation of biomass products,[61] [62] providing a responsible method to recycle all OMEGA materials at the end of their life. Applying HTL for ocean algae in the way described is speculative, but if achieved would provide a large scale rapid solution to climate change. The HTL method aims to convert most of the carbon in the biomass into fuel, which can then either be stored, used for energy or converted into useful stable products such as plastic and bitumen, while also producing natural fertilizer.[63] Recent HTL research[64] showed nutrient recycling for algal cultivation can produce value-added chemicals.

At sea level, HTL needs high pressure metal containers. The ocean provides the required HTL pressure at depth of 2km, where pressure is 20 MPa, 200 times air pressure of 0.1 MPa. Construction for such depth is possible, although difficult, given that work at even greater depth has been developed in extractive industries.[65] The offshore oil and gas industry is developing remotely operated vehicles[66] that could offer suitable robotic and materials technology for deep ocean HTL, such as for construction, maintenance and cleaning.

The required temperature for oceanic HTL can be generated using solar energy adjacent to continental shelves. This heat also occurs naturally at sites at 2km depth along the extensive mid ocean ridges, where magma rises from the mantle. The remoteness and depth of the mid ocean ridges means the HTL technologies would have to be fully proven in coastal locations before venturing to the deep sea, which could only be justified if the overall concept of scaling up to gigatonne production levels were proved.

Materials for the pipes, settling tank and HTL chamber would aim to only use carbon polymers rather than metals, involving few moving parts and always with internal pressure equal to the surrounding water pressure. High performance polymers are rated for these temperatures.[67] Ocean conditions of corrosion and water movement make the idea of operating large new technology in deep waters far from shore extremely difficult. Materials might only have short life. The use of carbon fabrics would mean all materials would themselves be a recycled location of carbon storage, justifying the required material size and thickness to cope with the harsh ocean environment.

The Biofuel Production system in Fig 6 uses a tidal pump on the edge of the continental shelf to pump deep ocean water containing high levels of N, P and C to the surface. Tidal pumping could be a low-cost way to pump deep ocean water to the surface to obtain and recycle nutrients. Figure 7 shows my original tidal pump design that won the MIT CoLab Energy-Water Nexus Competition in 2015.[68] A submerged air chamber, shown as a balloon, is filled with air and tethered to a circular weight on the ocean floor filled with sand. The balloon rises and falls with the tide, causing a pump bladder between the weight disc and the ocean floor to fill with water on a rising tide and empty on a falling tide. Deep ocean water is sucked into the bladder on the rising tide and pumped out to the algae bag on the surface as the tide falls. A 50 metre diameter tidal pump on a two metre tide would pump about 7 megalitres per day, less friction. This tidal pump method can have other applications such as pumping water onto Arctic sea ice to increase its thickness, or pumping fresh water towed in fabric waterbags[69] from rivers.



Dimensions (Approx)	Width metres	Height metres	Weight tonnes	Volume cubic metres
Balloon	20	20	8	3,800
Sand	50	1.3	4,000	2,600
Pump	50	2	4,000	4,000
Annual Pumping Capacity				2,775,900

Figure 7: Original invention of method to pump large volumes of ocean water at low cost. System rises and falls with the tide to pump deep ocean water to the surface.

A key to the biofuel production model is the large scale production of nutrients through separation of biomass in HTL into oil and fertilizer. Alba et al (2013),[70] described aqueous phase HTL recycling with supplied micronutrients, enabling 50% recycling of input nitrogen with prospect for further improvement. This finding suggests that the proposed method could constantly reuse nitrogen and phosphorus obtained from deep ocean water, as an efficient catalytic method to grow algae biomass on large scale.

This deep ocean method copies the natural pressure and heat that produced petroleum from algae. It aims to develop high yielding varieties of algae that will utilize C, N and P concentrations well in excess of ambient levels, forcing selective evolutionary adaptation to generate varieties that can only survive in the enclosed high CO_2 environment. Seeding of production with the best performing algae varieties as inoculant would rapidly drive up productivity. The Cornell hybrid model shows the potential to rapidly increase yields, applying natural plant husbandry methods used in the Cornell trials as developed further in Hawaii by Cellana.[71]

A further speculative theme is that the ocean floor could provide the required temperatures for HTL at geothermal locations.[72] The Mid Ocean Ridge mountain range shown in Figure 8 extends over 65,000 km of the sea floor, by far the longest range in the world, at typical depth of 2.6 km.[73] Mid Ocean Ridges are tectonic sites of continental plate formation. This large planetary system provides extensive sources of the heat and pressure needed for large scale biomass fuel conversion.[74] Figure 8 also sketches the rough scale of OMEGA-type systems – over 3 million km^2 - that would be needed to achieve net zero emissions (15 Gt C) on algae yield of 15 g m^{-2} d^{-1}. The map places circles on mid ocean ridge heat sources to represent the total needed size of algae production locations, although a much larger number of smaller sites with the same total area would be more likely. Tidal pumps and OMEGA farms would be sited at continental shelf or island locations upstream from ocean ridge geothermal sources. When the algae container is full of feedstock, it can float down the ocean current to release fully grown algae into the pipe head above the HTL system on the mid ocean ridge. For example, floating algae farms of size 100 km^2 created in the Gulf of Mexico could float along the Gulf Stream to a processing location in the mid-Atlantic Ocean, a process that could significantly cool ocean waters flowing under the North Pole and reduce the speed of Arctic ice melt.

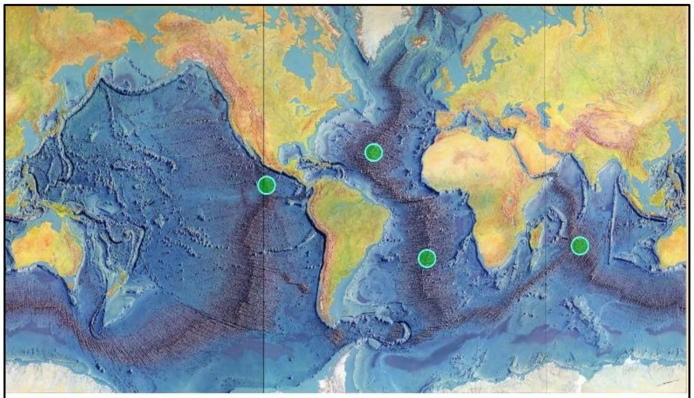


Figure 8: Mid Ocean Ridge Mountain Range, with indicative scale of algae systems required to achieve net zero emissions. Each circle is about 800,000 km^2.

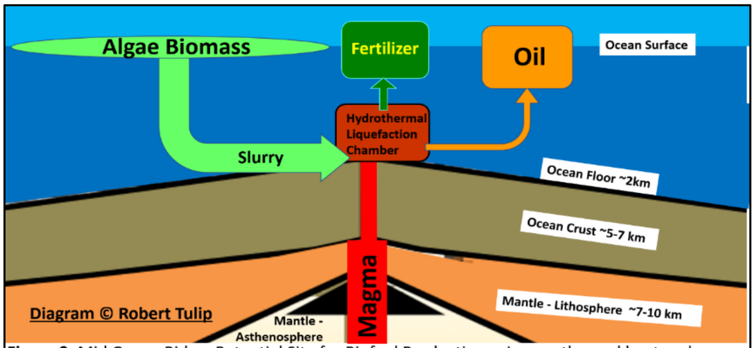


Figure 9: Mid Ocean Ridge: Potential Site for Biofuel Production using geothermal heat and ocean depth to power hydrothermal liquefaction of algae slurry. Background picture detail from https://upload.wikimedia.org/wikipedia/commons/1/15/Mid-ocean_ridge_cut_away_view.png

A Mid Ocean Ridge Cut Away view[75] shows how hot magma rises from the mantle at these locations. Figure 9 sketches the process of converting biomass to oil and fertilizer with deep ocean HTL at an ocean ridge. The biocrude produced by this geothermal HTL method would be refined into fuel and petrochemical products[76] such as fabrics and plastics, including to replicate the algae bag infrastructure.

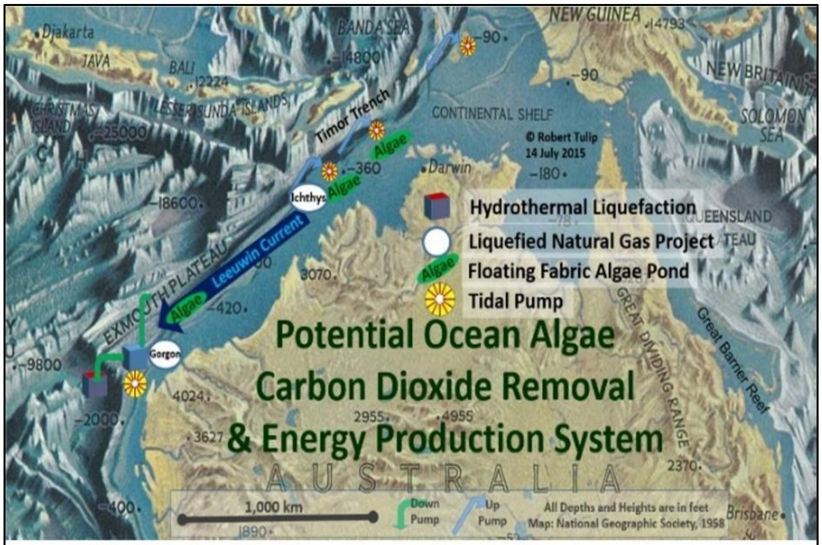


Figure 10: Map of possible ocean algae production system on Australia's Northwest Shelf, using deep ocean water from Timor Trench, CO2 from offshore gas projects and HTL in Indian Ocean.

Figure 10 is a sketch of how industrial algae production might be done in Australian waters, using tidal pumping to combine nutrients from deep ocean water in the Timor Trench with CO_2 from the Gorgon and Ichthys natural gas projects in floating fabric photobioreactors. Massive tides in nearby locations such as King Sound could provide pumping energy for algae production sites. The Gorgon gas project[77] expects to geosequester 0.1 Gt of co-produced CO_2, which could provide algae feedstock. Australia's North West Shelf may be the single best location in the world for development of ocean algae production. The shelf is one of the largest shallow regions of maximum microalgal productivity,[78] and can take advantage of the proximity of suitable nutrients and a major offshore oil and gas industry for technical and material inputs.

4 Results and Discussion

4.1 Overview

The eventual goal of tapping geothermal energy at the mid ocean ridges to convert algae into fuel and fertilizer presents formidable scientific, engineering, economic, ecological and political challenges. It is presented here to illustrate the vast scale of the new technologies needed to address the climate emergency, as one method potentially able to remove carbon on the needed scale of 30 Gt/y as explained above in the discussion of climate arithmetic. The above analysis is purely conceptual, and has not been subject to any of the life cycle assessment needed to assess economic viability and environmental impact. Ocean algae systems would need proof of safety and effectiveness at small scale, following the incremental evolutionary path from rivers to bays and estuaries before any move to the pelagic deep ocean. Coastal operations can demonstrate whether open ocean operations would be possible, desirable and economic.

4.2 Carbon Removal as a New Climate Paradigm

The suggestion to use ocean biomass to stabilize the climate requires a new climate paradigm in which carbon removal has far greater importance than emission reduction, shifting the immediate priority from decarbonization of the world economy to biomass production and storage. High yielding algae biomass has potential to protect and repair ecosystems and feed the world, and should be a priority for mitigating climate change. This agenda illustrates the large challenges to define, test and implement the changes in earth systems that are needed to sustain human flourishing in a rapidly warming climate, through focus on large scale rapid removal of carbon from the air and sea and restoring planetary albedo. The world needs to remove carbon at this multi-million-square kilometre scale to address the security and stability threats posed by unchecked climate change.

Ocean biomass is presented as potentially the best way to achieve the goal of CDR at scale, but only as one possible method, as part of the critical shift in thinking from abatement of future emissions to transformation of past emissions as the core climate priority. The paradigm shift operates at the level of policy goals. With CDR as the main climate paradigm, there is even room for the provocative argument that CDR could substitute for abatement. Working out how to do CDR on sufficient scale is essential if continued emissions are to be compatible with climate stability.

The critique of the inadequate potential of emission reduction is a core justification for this ocean proposal. Emission reduction is now the main climate strategy for governments, focused on cutting new CO_2 sources through a shift to renewable energy to decarbonize the world economy. Cutting emissions has immense benefits for economic efficiency and pollution control, but these important positive contributions can deliver only a tiny fraction of the earth system changes needed for climate stability. Scaling up carbon conversion with ocean biomass offers the prospect of a safe and realistic path to climate stability. The carbon removal trajectory of ocean biomass production creates a renewable energy source and a carbon sink, with eventual potential larger than total emissions. The balance of climate policy needs to shift from cutting carbon sources toward building sinks, primarily in the ocean, aiming to build new safe and productive carbon stores that are bigger than total emissions.

4.3 Atmospheric Regulation

Rapid expansion of ocean biomass as a carbon sink would require global political cooperation to target, achieve and maintain a well-regulated atmosphere, working to restore the CO_2 level needed to optimize climate conditions. This hopeful scenario can mobilise resources and systems needed to support world peace and prosperity. The key task is to get radiative forcing progressively into balance so that global warming is halted, and then into the negative so the global temperature falls from its current dangerous level.[79]

Climate stability requires restoration of the Holocene homeostatic equilibrium between interdependent elements of the planetary system. The metaphor of Gaia proposed by James Lovelock[80] to describe such planetary homeostasis reflects the need for physiological systems to stay within narrow limits. On that basis, the current 1°C of global warming is already like a fever. Humanity now has the central task of using science to return society to a recognition that an economy can only exist inside an ecology. Ocean algae farms could function like an emergency medical response, a defense system deployed to restore planetary balance and health, like white blood cells, or bandages for Gaia. The ongoing need for planetary climate stability requires permanent systems to stabilize and regulate atmospheric composition. Speed is of the essence, treating the excess CO_2 in the air like a planetary tumour. Every delay in ramping up removal poses grave risks.

The potential to achieve net zero global emissions by 2035 requires political vision akin to US President Kennedy's 25 May 1961 announcement of the Apollo Project.[81] The new climate ‘moonshot’ can be achieved through a primary focus on carbon removal as a strategy for ongoing atmospheric regulation. The need for climate action is like the security agenda that prompted the USA to launch the Manhattan Project to build the atomic bomb in World War Two, or the clarity that inspired the Apollo Program. Scientific evidence, leadership decisions, resource deployment, cooperative partnerships and strategic vision can drive a pragmatic recognition that ocean-based technology offers major potential to stabilise the climate.

4.4 A 7F commodity strategy

Development of new commodity markets is essential to fund the scale up of biomass for carbon removal and creation of a sustainable new commercial industry. Large-scale ocean-based algae production can aim to store 100 Gt of CO_2 each year in a range of productive biomass locations, creating a trajectory toward climate repair and restoration. Biofuel is key to the CDR agenda, especially the varied potential for hydrocarbons to be converted into stable products such as for buildings and roads. The proposed ocean system also has a strong justification as a method to protect and enhance biodiversity, through creation of biomass for a range of biological carbon purposes, many of which could be commercially viable supports for the development of storage methods.

Most biological carbon is labile, meaning it is subject to geologically rapid turnover and does not serve as long term storage. Even so, use of algae to increase the labile carbon stock has climate benefits through increasing the total planetary biomass. Use of algae to convert CO_2 from waste to assets such as food, feed, fish, forests, fuel, fertilizer and fabric suggests a '7F strategy' involving an industrial approach to maximise controlled photosynthesis from algae. 7F methods could convert 100 Gt or more of CO_2 per year into biomass while also cooling the ocean and producing abundant life at the base of the marine food web to enhance biodiversity. Even though much of this 7F carbon will only deliver temporary removal, it is possible and desirable that most of it could be used to build carbon-based infrastructure and soil as long-term carbon sinks. For example, Australia's agricultural soil carbon content has fallen by an estimated 75%.[82] Restoring this soil carbon through algae biochar would provide long term carbon storage. The ocean-based algae production systems described would themselves have large ongoing carbon storage in their fabric infrastructure. Converting CO_2 into stable commodities and systems would help remove excess radiative forcing if continued on sufficient scale alongside other cooling methods, while also delivering a range of important economic and ecological benefits.

Algae can make a major contribution to strengthen global food security through ecologically sound, low cost nutrient-rich food sources that can compete effectively against land-based food sources.[83] [84] [85] Ocean-based production does not compete for arable land the way bioenergy crops or reforestation might. Algae for animal fodder can replace ecologically harmful crops.[86] In the ocean, algae production can replace fishmeal in aquaculture,[87] increase biomass at the base of and throughout the marine food chain, improve water quality by reversing acidification,[88] and protect against population stress and poleward migration[89] by cooling ocean water, protecting ocean biodiversity by creating havens and cooling the surrounding water, reducing heat stress on endangered ecosystems. Algae farms provide a local environment for integrated multitrophic aquaculture.[90] Microalgae can support blue carbon[91] in combination with marine permaculture methods to grow kelp and other seaweeds,[92] with atmospheric cooling effects such as from dimethyl sulphide produced by plankton.[93] On the potential scale described, algae systems would occupy areas now used for unsustainable deep-sea fishing, but would more than compensate for loss of these fishing grounds by increasing overall ocean productivity and stability. For land forests, ocean algae can reduce pressures for land clearing by replacing a range of agricultural and forest products,[94] and enabling rewilding of current agricultural locations.[95] Algae biofuels[96] [97] require the economies of scale and sources of energy and nutrient that can come from ocean production. The described ocean HTL method has potential to help cut biofuel and other algae production costs to create a genuine circular economy where carbon collected for algae feedstock exceeds total emissions.

The described system to extract nutrients from deep ocean water could enable sustained increase in fertilizer production and soil quality. Algae can serve as feedstock for biochar, [98] pyrolising biomass to make stable soil carbon, linking industrial algae production to restorative agriculture to use soil as a productive carbon store.

Production of fabrics, as a generic term for all stable polymers made from algae, offers a main strategy for carbon removal. Construction with carbon-based infrastructure in locations such as algae farms, buildings and roads offers a far better long-term carbon store than burying CO_2 in the ground, if new markets can be constructed at the scale needed. Biocrude produced by algae HTL could provide the materials required for all petrochemical products. Bioplastics[99] have immense potential for long term carbon storage. Rapid replication and recycling of biomass algae infrastructure would store a high volume of carbon.

4.5 Other Ocean Cooling Methods

The industrial microalgae method described here is just one of many potential ocean cooling methods involving a range of carbon removal and solar radiation management methods. Others include iron fertilization[100], iron salt aerosol[101], alkalinity addition[102], macroalgae[103] [104], artificial upwelling[105], foam[106], marine cloud brightening[107], ocean thermal energy conversion[108], buoyant flakes[109], ice thickening[110] and CO_2 air capture.[111] All such methods would need to follow UN protocols on marine geoengineering in developing field testing and deployment.[112]

5 Conclusion

The goal of this article is to show that technological utilization of the ocean should become the pioneering frontier for climate repair and restoration. Large scale algae systems can become a globally significant carbon sink and source of materials in this century through the creation of new markets and economies of scale. The power of the ocean can be harnessed to convert CO_2 into valuable commodities as a profitable investment opportunity, instead of burying CO_2 or leaving it to accumulate in the atmosphere. The key goals of net zero and net negative emissions would be supported by building a new circular '7F' economy through a major research program into uses of the world ocean, utilizing its area, energy and nutrients for carbon conversion.

The overriding goal should be to implement practical methods that can slow and reverse climate change at the required scale and speed. The ocean technology strategy described could work to effectively address the global climate crisis. Public policy should support measures to mobilise investment in ocean biomass, aiming to address climate change in the most effective ways possible.

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Endnotes

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[1] https://globalnews.ca/news/7330812/california-wildfires-governor-climate-change/
[2] Robinson, John B. 1990. Futures under glass: a recipe for people who hate to predict Futures, vol. 22, issue 8, pp. 820–842 https://doi.org/10.1016/0016-3287(90)90018-D
[3] Franke et al;, Operationalizing Ocean Health: Toward Integrated Research on Ocean Health and Recovery to Achieve Ocean Sustainability, One Earth (2020), https://doi.org/10.1016/j.oneear.2020.05.013
[4] Thomas Reese, Integral ecology: everything is connected, Aug 27, 2015, National Catholic Reporter, https://www.ncronline.org/blogs/faith-and-justice/integral-ecology-everything-connected
[5] Anto, S et al, Algae as green energy reserve: Technological outlook on biofuel production. Chemosphere, Volume 242: Feb 2020 DOI: 10.1016/j.chemosphere.2019.125079
[6] Greene, C. H., M. E. Huntley, I. Archibald, L. N. Gerber, D. L. Sills, J. Granados, C. M. Beal, and M. J.Walsh (2017), Geoengineering, marine microalgae, and climate stabilization in the 21st century, Earth's Future, 5, 278–284, doi:10.1002/2016EF000486.
[7] Kristian Spilling (ed), Biofuels from Algae Methods and Protocols, Springer 2020, https://doi.org/10.1007/978-1-4939-9416-8
[8] http://www.cifor.org/publications/pdf_files/media/Howard%20Downer%20Turnbull%20Release.pdf
[9] http://rtulip.net/ocean_based_algae_production_system
[10] Objective of the UNFCCC: https://unfccc.int/resource/docs/convkp/conveng.pdf
[11] Greg H. Rau, Charles H. Greene, Emissions reduction is not enough, *Science*, 25 Sep 2015: Vol. 349, Issue 6255, pp. 1459 DOI: 10.1126/science.349.6255.1459-b 2
[12] Will Steffen, Johan Rockström, Katherine Richardson, Hans Joachim Schellnhuber, Trajectories of the Earth System in the Anthropocene, 2018, Proceedings of the National Academy of Sciences et al DOI: 10.1073/pnas.1810141115
[13] https://upload.wikimedia.org/wikipedia/commons/1/1d/Ghgs-epcia-holocene-CO2-en.svg
[14]
[15] Smith, M.R., Myers, S.S. Impact of anthropogenic CO2 emissions on global human nutrition. Nature Clim Change 8, 834–839 (2018). https://doi.org/10.1038/s41558-018-0253-3
[16] https://www.auswaertiges-amt.de/en/aussenpolitik/themen/klima/climate-environment/2249226
[17] https://www.bmu.de/en/topics/climate-energy/climate/national-climate-policy/greenhouse-gas-neutral-germany-2050/#c12744
[18] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[19] US National Oceanographic and Atmospheric Administration: Annual Greenhouse Gas Index Chart https://www.esrl.noaa.gov/gmd/aggi/aggi.fig4.png
[20] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
[21] Wadhams, Peter, The Polar Regions, 2014, http://www.casinapioiv.va/content/dam/accademia/pdf/es41/es41-wadhams.pdf
[22] https://www.nytimes.com/2020/01/21/climate/greta-thunberg-davos-transcript.html
[23] Friedlingstein, Pierre et al; Global Carbon Budget 2019 Earth Syst. Sci. Data, 11, 1783–1838, 2019 https://doi.org/10.5194/essd-11-1783-2019 with June 2020 calculation from https://trillionthtonne.org/.
[24] https://climateactiontracker.org/data-portal/
[25] https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/carbon-emissions.html
[26] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf
[27] Rohling, Eelco, *The Climate Question*, Oxford University Press, 2019
[28] Frölicher, Thomas Lukas; Winton, Michael; Sarmiento, Jorge Louis;
Continued global warming after CO2 emissions stoppage; 2013 Nature Climate Change; doi:10.1038/nclimate2060
29 Lenton, TM; Rockström, J; Gaffney, O; Rahmstorf, S; Richardson, K; Steffen, W; & Schellnhuber HJ, Climate tipping points — too risky to bet against, Nature Comment article, 2019 https://www.nature.com/articles/d41586-019-03595-0
[30] Goreau, T, Book Review of *The Climate Question* https://remineralize.org/2019/08/review-of-eelco-rohlings-the-climate-question/
[31] Climate Institute, Expert Input to the Talanoa Dialogue, UN Climate Change, 2018 https://unfccc.int/sites/default/files/resource/97_Talanoa%20Submission_climate%20institute.pdf
[32] Englander, J https://johnenglander.net/chart-of-420000-year-history-temperature-co2-sea-level/
[33] https://upload.wikimedia.org/wikipedia/commons/thumb/1/1d/Post-Glacial_Sea_Level.png/800px-Post-Glacial_Sea_Level.png
[34] NASA OMEGA Fact Sheet: https://www.nasa.gov/centers/ames/pdf/638200main_OMEGA_FactSheet_final.pdf
[35] Huntley, M.E., Z.I. Johnson, S.L. Brown, D.L. Sills, L. Gerber, I. Archibald, S.C. Machesky, J. Granados, C. Beal, and C.H. Greene. 2015. Demonstrated large-scale production of marine microalgae for fuels and feed. *Algal Research* 10:249–265, https://doi.org/10.1016/j.algal.2015.04.016.

---

[36] Trent, Jonathan. (NASA Ames Research Center). 2012. *OMEGA (Offshore Membrane Enclosures for Growing Algae) - A Feasibility Study for Wastewater to Biofuels.* California Energy Commission. https://ww2.energy.ca.gov/2013publications/CEC-500-2013-143/CEC-500-2013-143.pdf

[37] Schroeder, Patrick; Anggraeni, Kartika; Weber, Uwe, The Relevance of Circular Economy Practices to the Sustainable Development Goals, 2019 Journal of Industrial Ecology, doi:10.1111/jiec.12732

[38] Chester, Mikhail V. Industrial ecology in support of climate change adaptation, 2020 Journal of Industrial Ecology doi:10.1111/jiec.13006

[39] Kim, Kwangmin; Kim, Z-Hun; Park, Hanwool; Lee, Yunwoo; Kim, Kihyun; ... [+] Enhancing Microalgal Biomass Productivity in Floating Photobioreactors with Semi-Permeable Membranes Grafted with 4-Hydroxyphenethyl Bromide, 2020 "Macromolecular Research" doi:10.1007/s13233-020-8023-2

[40] Kim, Z-Hun; Park, Hanwool; Hong, Seong-Joo; Lim, Sang-Min; Lee, Choul-Gyun Development of a floating photobioreactor with internal partitions for efficient utilization of ocean wave into improved mass transfer and algal culture mixing, 2016 Bioprocess and Biosystems Engineering doi:10.1007/s00449-016-1552-6 pmid:26857371

[41] Huang Q., Jiang F., Wang L., Yang C. Design of Photobioreactors for Mass Cultivation of Photosynthetic Organisms, (2017), Engineering 3 (3), pp. 318-329.

[42] Flynn, K.J., Kenny, P. & Mitra, A. Minimising losses to predation during microalgae cultivation. *J Appl Phycol* **29,** 1829–1840 (2017). https://doi.org/10.1007/s10811-017-1112-8

[43] Keller, D.P., Lenton, A., Littleton, E.W. et al. The Effects of Carbon Dioxide Removal on the Carbon Cycle. Curr Clim Change Rep 4, 250–265 (2018). https://doi.org/10.1007/s40641-018-0104-3

[44] https://www.hypergiant.com/green/ https://qz.com/1718988/algae-might-be-a-secret-weapon-to-combatting-climate-change/

[45] Hanwool Park, Choul-Gyun Lee, Theoretical calculations on the feasibility of microalgal biofuels: Utilization of marine resources could help realizing the potential of microalgae Biotechnol. J. 2016, 11, 1461–1470 DOI 10.1002/biot.201600041

[46] Huntley, Mark. Large-Scale Production of Fuel and Feed from Marine Microalgae. United States Department of Energy, 2015. doi:10.2172/1351099

[47] https://www.climatefoundation.org/marine-permaculture.html

[48] Tian, Hanqin et al, Long-Term Trajectory of Nitrogen Loading and Delivery From Mississippi River Basin to the Gulf of Mexico, 2020 Global Biogeochemical Cycles, doi:10.1029/2019GB006475

[49] Andrew H. Altieri, Seamus B. Harrison, Janina Seemann, Rachel Collin, Robert J. Diaz, and Nancy Knowlton, Tropical dead zones and mass mortalities on coral reefs, PNAS April 4, 2017 114 (14) 3660-3665; first published March 20, 2017 https://doi.org/10.1073/pnas.1621517114

[50] Huang Q., Jiang F., Wang L., Yang C. Design of Photobioreactors for Mass Cultivation of Photosynthetic Organisms (2017), Engineering 3 (3), pp. 318-329. DOI: 10.1016/J.ENG.2017.03.020

[51] Seymour, R Engineering Considerations in Open Ocean Farming of Algae, Scripps Institutions of Oceanography, USA, Proceedings of the Wind, Sea, Algae Workshop, Maribo, Denmark, April 2009

[52] Kiesenhofer, Daniel P; Fluch, Silvia The promises of microalgae—still a long way to go 2018 FEMS Microbiology Letters doi:10.1093/femsle/fnx257 pmid:29228181

[53] Sverdrup, Johnson and Fleming, *The Oceans, Their Physics, Chemistry, and General Biology.* New York: Prentice-Hall, 1942. http://ark.cdlib.org/ark:/13030/kt167nb66r/

[54] Wilson, Michael; Mohler, Daniel; Groppo, John; Grubbs, Thomas; Kesner, Stephanie; ... [+] Capture and recycle of industrial CO2 emissions using microalgae 2016 Applied Petrochemical Research doi:10.1007/s13203-016-0162-1

[55] Chiu SY, Kao CY, Chen CH, Kuan TC, Ong SC, Lin CS. Reduction of CO2 by a high-density culture of Chlorella sp. in a semicontinuous photobioreactor. Bioresour Technol 2008;99(9):3389–96.

[56] Valero, Enrique; Álvarez, Xana; Cancela, Ángeles; Sánchez, Ángel, Harvesting green algae from eutrophic reservoir by electroflocculation and post-use for biodiesel production. 2016 Bioresource technology, doi:10.1016/j.biortech.2015.03.138

[57] Frank, Edward; Elgowainy, Amgad; Han, Jeongwoo; Wang, Zhichao, Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae, 2012 Mitigation and Adaptation Strategies for Global Change doi:10.1007/s11027-012-9395-1

[58] Williamson, Nicholas; Komiya, Atsuki; Maruyama, Shigenao; Behnia, Masud; Armfield, Steve Nutrient transport from an artificial upwelling of deep sea water 2009 Journal of Oceanography doi:10.1007/s10872-009-0032-x

[59] Y. Zhang, W.T. Chen, *Hydrothermal liquefaction of protein-containing feedstocks* in Direct Thermochemical Liquefaction for Energy Applications, 2018

[60] Biller and dos Passos, Hydrothermal liquefaction of waste materials as the key technology for a circular economy of the chemical industry, Aarhus University, https://conferences.au.dk/fileadmin/conferences/2019/bioeconomy/Posters/Juliano_Souza_dos_Passos_CBIO_poster_JSP_V2.pdf

[61] Edward S Jones et al, Saltwater based fractionation and valorisation of macroalgae, Journal of Chemical Technology & Biotechnology (2020). DOI: 10.1002/jctb.6443

[62] Garcia Alba, Laura; Vos, Mathijs P.; Torri, Cristian; Fabbri, Daniele; Kersten, Sascha R. A.; ... [+] Recycling Nutrients in Algae Biorefinery, 2013 ChemSusChem - Chemistry and Sustainability, Energy & Materials, doi:10.1002/cssc.201200988 pmid:23828814

---

[63] Audo, Mariane; Paraschiv, Maria; Queffelec, Clemence; Louvet, Isabelle; et al. Subcritical Hydrothermal Liquefaction of Microalgae Residues as a Green Route to Alternative Road Binders [2015], ACS Sustainable Chemistry & Engineering 3(4):583-590 DOI: 10.1021/acssuschemeng.5b00088

[64] Song, Wenhan; Wang, Shuzhong; Xu, Donghai; Guo, Yang; Yang, Chuang; ... [+], Comprehensive potential evaluation of the bio oil production and nutrient recycling from seven algae through hydrothermal liquefaction, 2019 Korean Journal of Chemical Engineering, doi:10.1007/s11814-019-0345-49

[65] Yungmeister, D A; Ivanov, S E; Isaev, A I Calculation of parameters of technological equipment for deep-sea mining 2018 IOP Conference Series: Materials Science and Engineering doi:10.1088/1757-899X/327/2/022050

[66] Bogue, Robert, Robots in the offshore oil and gas industries: a review of recent developments, 2019 Industrial Robot: The International Journal of Robotics Research and Application, doi:10.1108/IR-10-2019-0207

[67] David Parker; Jan Bussink; Hendrik T. van de Grampel; Gary W. Wheatley; Ernst-Ulrich Dorf; Edgar Ostlinning; Klaus Reinking; Frank Schubert; Oliver Jünger; Reinhard Wagener; Polymers, High-Temperature; Published online: 15 October 2012; DOI: 10.1002/14356007.a21_449.pub4

[68] Tulip, Robert. Tidal Pump, Energy-Water Nexus Climate Colab Competition Winner, Massachusetts Institute of Technology, 2015 https://www.climatecolab.org/contests/2015/energy-water-nexus/c/proposal/1320162

[69] https://en.wikipedia.org/wiki/Flexible_barge

[70] Laura Garcia Alba, Cristian Torri Daniele Fabbri Sascha R.A.Kersten Derk W.F.(Wim) Brilman, Microalgae growth on the aqueous phase from Hydrothermal Liquefaction of the same microalgae, https://doi.org/10.1016/j.cej.2013.04.097

[71] http://cellana.com/

[72] Beaulieu, Stace E.; Baker, Edward T.; German, Christopher R.; Maffei, Andrew (November 2013). "An authoritative global database for active submarine hydrothermal vent fields". Geochemistry, Geophysics, Geosystems. 14 (11): 4892-4905. doi:10.1002/2013GC004998.

[73] Berann, Heinrich C., Heezen, Bruce C., Tharp, Marie. - https://picryl.com/media/manuscript-painting-of-heezen-tharp-world-ocean-floor-map-by-berann Painting of the Mid-Ocean Ridge with rift axis by Heinrich Berann based on the scientific profiles of Marie Tharp and Bruce Heezen (1977). (High-resolution versions are available at https://www.loc.gov/item/2010586277/).

[74] Jim Shnell, Gerardo Hiriart, Ken Nichols, John Orcutt, Energy from Ocean Floor Geothermal Resources, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015

[75] https://upload.wikimedia.org/wikipedia/commons/1/15/Mid-ocean_ridge_cut_away_view.png

[76] Abdul Latif et al, Hydrothermal liquefaction of Malaysia's algal biomass for high-quality bio-oil production, 2019 Engineering in Life Sciences doi:10.1002/elsc.201800144

[77] https://australia.chevron.com/-/media/australia/publications/documents/gorgon-co2-injection-project.pdf https://www.inpex.com.au/media/xumm5bu0/draft-eis-fact-sheet-greenhouse-gas.pdf

[78] Hanwool Park, Choul-Gyun Lee, Theoretical calculations on the feasibility of microalgal biofuels: Utilization of marine resources could help realizing the potential of microalgae Biotechnol. J. 2016, 11, 1461–1470 DOI 10.1002/biot.201600041

[79] John Nissen, personal communication.

[80] Lovelock, J.E.; Margulis, L. (1974). "Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis". *Tellus*. Series A. Stockholm: International Meteorological Institute. **26** (1–2): 2–10. https://doi.org/10.3402/tellusa.v26i1-2.9731

[81] Kennedy, JF, speech https://www.space.com/11772-president-kennedy-historic-speech-moon-space.html

[82] https://soilsforlife.org.au/wp-content/uploads/2019/12/Soils20For20Life20Workshop_201812071.pdf

[83] Jung, F.; Krüger-Genge, A.; Waldeck, P.; Küpper, J.-H. Spirulina platensis, a super food? 2019 Journal of Cellular Biotechnology doi:10.3233/JCB-189012

[84] Ścieszka, Sylwia; Klewicka, Elżbieta Algae in food: a general review. 2020 Critical reviews in food science and nutrition doi:10.1080/10408398.2018.1496319

[85] Mark L. Wells, Philippe Potin, James S. Craigie, John A. Raven, Sabeeha S. Merchant, Katherine E. Helliwell, Alison G. Smith, Mary Ellen Camire, and Susan H. Brawley J Appl Phycol. 2017; 29(2): 949–982. Published online 2016 Nov 21. doi: 10.1007/s10811-016-0974-5 PMCID: PMC5387034 PMID: 28458464 Algae as nutritional and functional food sources: revisiting our understanding

[86] Pikaar et al; Decoupling Livestock from Land Use through Industrial Feed Production Pathways**.** *Environmental Science & Technology*, 2018; DOI: 10.1021/acs.est.8b00216

[87] Sarker PK, Kapuscinski AR, Bae AY, Donaldson E, Sitek AJ, Fitzgerald DS, et al; https://thefishsite.com/articles/the-use-of-algae-in-fish-feeds-as-alternatives-to-fishmeal (2018) Towards sustainable aquafeeds: Evaluating substitution of fishmeal with lipid-extracted microalgal co-product (*Nannochloropsis oculata*) in diets of juvenile Nile tilapia (*Oreochromis niloticus*). PLoS ONE 13(7): e0201315. https://doi.org/10.1371/journal.pone.0201315

[88] https://e360.yale.edu/features/kelp_seagrass_slow_ocean_acidification_netarts

[89] Habary, Adam; Johansen, Jacob L.; Nay, Tiffany J.; Steffensen, John F.; Rummer, Jodie L. Adapt, move or die – how will tropical coral reef fishes cope with ocean warming? 2017 Global Change Biology doi:10.1111/gcb.13488 pmid:27593976

[90] Granada, Luana; Sousa, Nádia; Lopes, Sofia; Lemos, Marco F. L. Is integrated multitrophic aquaculture the solution to the sectors' major challenges? – a review 2016 Reviews in Aquaculture doi:10.1111/raq.12093

[91] Nellemann, Christian et al; (2009): Blue Carbon. The Role of Healthy Oceans in Binding Carbon. A Rapid Response Assessment. Arendal, Norway: UNEP/GRID-Arendal https://www.grida.no/publications/145

[92] Von Herzen, B, https://www.climatefoundation.org/marine-permaculture.html

---

[93] Ah-Hyun Kim, Seong Soo Yum, Hannah Lee, Dong Yeong Chang and Sungbo Shim, Polar Cooling Effect Due to Increase of Phytoplankton and Dimethyl-Sulfide Emission, Atmosphere 2018, 9, 384; doi:10.3390/atmos9100384

[94] Paniz, Oscar G.; Pereira, Claudio M. P.; Pacheco, Bruna S.; Wolke, Silvana I.; Maron, Guilherme K.; ... [+] Cellulosic material obtained from Antarctic algae biomass 2020 Cellulose doi:10.1007/s10570-019-02794-2

[95] Lorimer, Jamie; Sandom, Chris; Jepson, Paul; Doughty, Chris; Barua, Maan; ... [+] Rewilding: Science, Practice, and Politics 2015 Annual Review of Environment and Resources doi:10.1146/annurev-environ-102014-021406

[96] Dixon, Robert K. Algae based biofuels August 2013 Mitigation and Adaptation Strategies for Global Change 18(1) DOI: 10.1007/s11027-012-9412-4

[97] https://www.exxonmobil.com.au/Research-and-innovation/Advanced-biofuels/Advanced-biofuels-and-algae-research

[98] Wu, Ping; Wang, Zeyu; Wang, Hailong; Bolan, Nanthi S.; Wang, Yujun; ... [+] Visualizing the emerging trends of biochar research and applications in 2019: a scientometric analysis and review 2020 Biochar doi:10.1007/s42773-020-00055-1

[99] Zeller, Mark Ashton; Hunt, Ryan; Jones, Alexander; Sharma, Suraj Bioplastics and their thermoplastic blends from Spirulina and Chlorella microalgae, 2013 Journal of Applied Polymer Science doi:10.1002/app.39559

[100] Martin, John H. Glacial-interglacial CO2 change: The Iron Hypothesis 1990 Paleoceanography and Paleoclimatology doi:10.1029/PA005i001p00001

[101] Oeste, Franz Dietrich; de Richter, Renaud; Ming, Tingzhen; Caillol, Sylvain. Climate engineering by mimicking natural dust climate control: the iron salt aerosol method, Earth Syst. Dynam., 8, 1–54, https://doi.org/10.5194/esd-8-1-2017, 2017

[102] Rau, Greg H, Electrochemical splitting of calcium carbonate to increase solution alkalinity: implications for mitigation of carbon dioxide and ocean acidity.2009 Environmental science & technology, doi:10.1021/es800366q

[103] N'Yeurt, Antoine De Ramon, David P. Chynoweth, Mark E. Capron, Jim Stewart, Mohammed A. Hasan, Negative Carbon Via Ocean Afforestation, 2012, Process Safety and Environmental Protection 90:467-474 DOI: 10.1016/j.psep.2012.10.008

[104] https://arpa-e.energy.gov/?q=arpa-e-programs/mariner Advanced Research Projects Agency within the U.S. Department of Energy (DOE) MARINER Program - Macroalgae Research Inspiring Novel Energy Resources

[105] Lovelock, J., Rapley, C. Ocean pipes could help the Earth to cure itself. *Nature* **449,** 403 (2007). https://doi.org/10.1038/449403a

[106] Garciadiego Ortega, Eduardo; Evans, Julian RG On the energy required to maintain an ocean mirror using the reflectance of foam, 2019 Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment doi:10.1177/1475090217750442

[107] Salter, Stephen; Sortino, Graham; Latham, John, 2008, "Sea-going hardware for the cloud albedo method of reversing global warming, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. **366**. doi:10.1098/rsta.2008.0136.

[108] Greg H.Rau Jim R.Baird, Negative-CO2-emissions ocean thermal energy conversion, Renewable and Sustainable Energy Reviews Volume 95, November 2018, Pages 265-272 https://doi.org/10.1016/j.rser.2018.07.027

[109] https://www.climate-restoration-foundation.com/winwick-business-solutions

[110] Desch, SJ et al, (2017), Arctic Ice Management, Earth’s Future, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016EF000410

[111] Armstrong, Mitchell; Shi, Xiaoyang; Shan, Bohan; Lackner, Klaus; Mu, Bin Rapid CO2 capture from ambient air by sorbent-containing porous electrospun fibers made with the solvothermal polymer additive removal technique, 2019 Aiche Journal doi:10.1002/aic.16418

[112] Boyd, P.W. and Vivian, C.M.G., eds. GESAMP (2019). “High level review of a wide range of proposed marine geoengineering techniques”. (). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p. http://www.gesamp.org/work/groups/41