Connecting Carbon Capture with Oceanic Biomass Production

Chen Wang

College of Chemistry and Molecular Engineerning, Peking University, Beijing 100871, China

Abstract

The climate change believed by anthropogenic emission is not isolated but tightly coupled with other issues including biodiversity loss and ocean acidification etc., and in order to prevent the potential serious impacts, both political and technological methods are being tried for greenhouse mitigation. Dimming the income sunlight by some "geoengineering" approaches currently seem ruinously expensive and technically difficult, and would not prevent the increase of greenhouse gases (GHGs) in atmosphere and ocean acidification, so capturing carbon to reduce the environmental concentration of carbon dioxide (CO_2) and promoting renewable energy development for the reduction of using fossil fuels are very necessary. Biofuels derived from natural and agricultural biomass could be deployed for power production and existing transportation needs. The current economics are more favorable for conversion of edible biomass into biofuels, which could spend plenty of freshwater and farmlands, compete with food supply, and create a "carbon debt" with local ecosystem destruction by deforestation to expand biofuel-crop production. So it is vital to develop processes for converting non-edible feedstock such as lignocellulose and microalgae into biofuels.

Compared with lignocellulose, microalgae have higher growth rates, don't need plenteous freshwater for irrigating, and can grow in the conditions that are not favorable for terrestrial biomass growth. The current limitation of microalgal biofuels is the microalgae cultivation cost, and to compensate the high cost of microalgal biofuels, three suggestions are propounded here. (*i*) Using ships as the platforms of cultivating microalgae, producing biofuels, and transporting feedstock and products on a large scale on subtropical oligotrophic oceans, where the ocean's least productive waters are formed with compared peaceful surface condition and poor marine communities. (*ii*) Operating different kinds of oceanic biomass productions for high-value products to compensate the cost of microalgal biofuels. Different kinds of microalgae and macroalgae (seaweeds) could be cultivated for biofuels, chemicals, healthy food, and feed for breeding economic marine species to satisfy the accelerating demands for seafood supply and simultaneously mitigate the fast decline of wild stocks. (*iii*) Constituting financial subsidies to make CO_2 as the feedstock of microalgae cultivation for

free, and exact quantifying the carbon captured in biomass products and the CO_2 reduction that these products would provide by displacing natural and nonrenewable carbon resources, to take part in the international carbon-credit trading markets and sell the offsets. In a word, this article mainly talks about trying to find a way that connect CO_2 capture with renewable energy development, and partially combat against deforestation, loss of biodiversity, shortage of food, and decline of marine lives etc., if possible.

Keywords climate change, biofuel, microalgae, oceanic production

The coming climate change likely caused by anthropogenic emission is just one of the issues of modern world, but it is tightly coupled with global biodiversity loss and ocean acidification etc., and "we do not have the luxury of concentrating our efforts on any one of them in isolation from the others"[1]. Studies in practice and models show that if heavily anthropogenic emission of greenhouse gases (GHGs), which consist mostly of carbon dioxide (CO_2), is resumed the pattern of recent decades, the atmospheric concentration of CO_2 would rise from 280 parts per million (p.p.m.) in pre-industrial period to 1,000 p.p.m. by 2100, and might lead to many unpredictable environmental changes that do harm to humanity and creatures[2].

To prevent the potential serious impacts, today's scientific and political consensus is to make efforts to prospect for climate change mitigation. The Kyoto Protocol is the first international entente to rein in GHGs emission with a binding agreement. Levy of a carbon tax is another approach for limiting nonrenewable carbon emission in developed countries[3], but it is unfair and unacceptable to most developing countries. So the attempts on technology for greenhouse mitigation are very necessary, and are being paid more attentions to the public.

Greenhouse Mitigation

The "geoengineering" approaches, which are schemed to combat against the climate change and global warming by human activities, are divided into short-wave and long-wave[4]. Defined as the short-wave approaches, reflecting incoming sunlight before it reaching the Earth by "sunshades" in space, aerosol particles, or brighter clouds could partially reduce the climate warming. But despite ruinously expensive and technically difficult, the increase of environmental CO_2 concentration, which would damage to coral and shellfish by dissolving their calcium carbonate skeletons in acidified oceans[2], will not be prevented.

Long-wave "geoengineering" approaches aim to capture carbon and reduce the GHGs concentrations in atmosphere, such as the "Carbon Capture and Storage" (CCS). The U.S. Department of Energy (DOE) intends to push industrial-scale attempts to capture CO_2 from coal-burning power plants or oil refineries, and lock it away deep underground[5]. Burying CO_2 underground (geologic sequestration) or the ocean floor (oceanic sequestration), as well as turning biomass into biochar[6] and forestation (terrestrial sequestration) are the major categories of carbon sequestration, which are believed to have the potential of storing CO_2 captured on a large scale, with the exception of current expensive cost in operation and a long-term watching for safety.

Another method for removing CO_2 from atmosphere is fertilizing plankton blooms by John Martin's "iron hypothesis"[7]. The marine phytoplankton dubbed "the ocean's invisible forest"[8] is responsible for nearly half of all the biological absorption of CO_2, and most of the carbon captured pass through the marine food web in the form of organisms and return to the atmosphere by respiration, but some will eventually sink to the ocean floor and remain there for many years[9]. In Martin's theory, fertilizing the "high-nitrate, low-chlorophyll" (HNLC) oceans such as north-east Pacific subarctic waters and the Southern Ocean around Antarctica with dissolved iron would facilitate phytoplankton blooming, and enhance the ocean's biological pump to offset the continuing increase of atmospheric CO_2[7,10]. Experiments in HNLC oceans have revealed that it works to bloom phytoplanktonic algae by iron fertilization in weeks[11-13], however, the fate of the carbon fixed by blooms, and how efficiently it is exported into the ocean's interior, still remain unknown[14]. Besides the unclear effect to tackle climate change[15,16], elevated phytoplankton blooms would also cause a large drawdown of macronutrients[11,12,17], and change the components of seawater in the experimented oceans[12]. The natural carbon fluxes could be altered by artificial iron-addition, and trigger a cascade of unwanted side effects, at last disrupt the pelagic food web and marine ecosystems[9]. All the limitations make the iron-fertilization plans remain to be discussed and evaluated before being operated on a large scale.

Scientists stressed that the effective and reliable strategy for tackling climate change is controlling of anthropogenic emission[15,18], but both short-wave and long-wave approaches face the fact that they cannot achieve this aim. Promoting energy efficiency and renewable energy productions are being actively developed to mitigate the net increase of CO_2 emission and reduce the use of fossil fuels as their price rise rapidly and lead to many conflicts of different regions. Electricity can be produced from solar, wind, nuclear, ocean waves, hydroelectric, and biomass[19]. Compared with the current technologies of fuel cell and electric vehicles, biofuels from renewable biomass resources are considered more available to power existing transportation vehicles.

Biofuels

Biomass, which can be used as the feedstock of biofuels, is the kind of organic products from using solar energy to combine CO_2 and water by natural and agricultural plants. Currently, the economics are more favorable for conversion of edible biomass into ethanol by fermentation of carbohydrates, and into biodiesel by transesterification of triglycerides, which are the two primary technologies for the generation of liquid biofuels today. Starch and sugars from corn grains and sugarcanes can be easily converted into ethanol with existing technology, due to their chemical structures. Biodiesel, which is an oxygenated hydrocarbon fuel derived from vegetable oils and animal fats, is also attractive because of its higher energy density compared with ethanol and compatibility with existing energy infrastructure. Although waste triglycerides, such as yellow grease and trap grease, are also available to produce biodiesel in some countries, they could only supply a few part of the annual diesel fuel consumption[20].

Because of the situation of spending plenty of farmlands and freshwater, and competing with food production, the sustainability of edible-based biofuel production has been brought into questions. Research shows that the “water footprints” (amounts of freshwater used for irrigating) of some biodiesel-feedstock crops such as soybean and rapeseed are even higher than those of bioethanol-feedstock crops[21]. Growing crops to produce biofuels from edible biomass instead of food supply for a higher income in the regions where malnutrition exists might increase the risk of suffering famines[20]. Biofuels from terrestrial feedstock were ever considered as a potential renewable low-carbon energy source, but “whether biofuels offer carbon saving depends on how they are produced”[22], they could create a “carbon debt” caused by deforestation if without meticulous programming. Clearing of carbon-rich habitats such as rainforests into farmlands for biofuel-crop production or food-crop production where existing agricultural land is used for biofuel-crop production, would release CO_2 as a result of burning or microbial decomposition of organic carbon stored in plant biomass and soil, that up to 420 times more than the annual reduction by using these biofuels produced to displace fossil fuels[22], and contribute to the local ecosystem destruction and biodiversity loss, instead of helping to mitigate the climate change.

Concerning the issues of terrestrial-feedstock biofuel production, following consensus are widely accepted: (*i*) avoid spending too much freshwater for irrigating biofuel-feedstock crops; (*ii*) avoid converting too many farmlands for biofuel production and creating food supply limitation, especially in the regions where famines still exist; (*iii*) avoid overly disturbing native ecosystems and causing wildlife habitats destruction. One solution is that waste biomass and native perennials grown on degraded and abandoned agricultural land could be used for biofuel production[22], so it is vital to develop processes for converting non-edible feedstock such as lignocellulose into biofuels. Lignocellulose, which consists mostly of cellulose, widely exists in agricultural wastes and logging residues. While the cost and technology of lignocellulose conversion have not been economically sustainable and demonstrated at a commercial scale, with the advantage of the lowest feedstock cost, lignocellulosic biomass has a large potential to be converted into ethanol by low-cost, high-efficient enzymatic hydrolysis and fermentation, or into hydrocarbons by acid hydrolysis and thermochemical reactions[20,23].

In another aspect, some researchers turn their interests back to the microalgae, which are also considered to have a tremendous potential as another source of carbohydrates and triglycerides, without necessity of plenteous freshwater supply. Microalgae are fast-growing marine and freshwater phytoplankton, and some kinds contain from 7 to 60 dry wt % triglycerides. The advantages of using microalgae as a biofuel feedstock are that they have very high growth rates, utilize a large fraction of the solar energy (up to 10%), absorb huge amounts of CO_2, and can grow in the conditions that are not favorable for terrestrial biomass growth[20]. The current limitation of microalgae is the high product cost. Since the feedstock represent over 70% of the biodiesel cost, the limiting factor of microalgal biofuel production is the microalgae cultivation cost[20].

Oceanic Production

Microalgae cultivation is primarily limited by the availability of water, nutrients, CO_2, flat "land", as well as temperature and sunlight for a high productivity. In order to compensate the high cost of microalgal biofuels, three suggestions are listed and discussed here.

Firstly, connect carbon capture with large scale production of microalgae in oceans. Although as the primary phytoplankton in natural marine ecosystems, microalgae absorb CO_2 nearly as much as the absorption of terrestrial plants, unlike forestation, the rapid turnover of them will not result in substantial carbon storage[24]. The carbon captured by microalgae is poorly quantified, and most carbon fixed will pass through the marine food webs and return to the atmosphere by decomposition and respiration[14]. It is one of the reasons that iron fertilization plans are doubted and against. Another reason is that a large number of CO_2 and macronutrients would be consumed by elevated phytoplankton blooms without further utilization, and natural carbon fluxes might alter and disrupt the marine ecosystems[25]. So what should be done are quantification of the carbon captured, and trying utilizing the CO_2

and nutrients consumed, instead of impacting the carbon fluxes of the ocean's interior.

Microalgae for biofuels can be cultivated in both freshwater and seawater in theory. Since serious eutrophication of many lakes and rivers on land would lead to shortage of clean freshwater, decrease of fish harvest, as well as loss of native aquatic biodiversity, and in order to obtain a large-scale "flat land" without hard working, oceans seem to be the right choice.

Nowadays, worldwide coastal eutrophication fueled by massive anthropogenic nutrient inputs has enhanced oceanic primary production, and exacerbated the formation of "dead zones"[26]. "Dead zones" are the hypoxic systems in oceans caused by the decrease of dissolved oxygen in bottom waters, created as planktonic algae die and add to the flow of organic matter to the seabed to fuel microbial respiration, they have been reported from more than 400 systems, and have developed in many major fishery areas[26]. Considering the serious impacts on marine harvests and ecosystems, coastal oceans are not fit for large-scale microalgae cultivation.

Not only less sunlight and lower temperature, but also luxuriant marine species diversities and turbulent wind surface condition, such as the strong southern westerlies on the Southern Ocean, make polar and subarctic oceans are unbefitting to be exploited, too. Some unique island ecosystems and coral-reef communities in equatorial oceans should also be paid attention to the impacts caused by human exploitations. So which kind of oceans is fittest on earth?

The ocean's least productive waters are formed in the centre of subtropical gyres with little nutrients left in surface, and become the ocean's most oligotrophic waters. With sunshiny, windless, compared peaceful surface condition and poor marine communities, these subtropical oligotrophic oceans are widely located in the Pacific and Atlantic, outside the equatorial zone, and seem to be expanding[27]. They are considered here to be the right places for large-scale microalgae cultivation, with the least impacts to natural marine ecosystems.

Secondly, connect microalgal biofuels with other oceanic biomass products. Using ships as the platforms of cultivating microalgae, producing biofuels, and transporting feedstock (CO_2 and nutrients, both of which could be collected from man-made wastes on land) and products on subtropical oligotrophic oceans would not obviously reduce the cost of microalgal biofuels. Being referred to the instances that co-products are sold when corn grains are used as the feedstock of ethanol production to reduce the overall cost, and the sale of glycerol, which is a byproduct of the transesterification process, improves the economics of biodiesel production[20], many other oceanic biomass productions could be operated for high-value products to compensate the high cost of microalgal biofuels.

Both microalgae and macroalgae (seaweeds) are fast-growing aquatic plants. Many kinds of seaweeds have been cultivated and collected for centuries for food and chemicals including agar, algin, and mannose. In the same way, not only the microalgae for biofuels but also the ones as healthy food and at the bottoms of marine food webs can be cultivated to feed the higher trophic levels such as jellyfish, shellfish, lobsters, prawns and crabs, and many kinds of fishes in warm waters. The chitin from carapaces of marine crustaceans is also a useful product with higher price than fuels.

Developing domestication of the ocean in oligotrophic waters could help to mitigate the fast decline of marine stocks, avoid frequent competitions and conflicts among rich and poor regions for fish harvests, and to some extent save rare wild species and island indigenous human cultures keeping away from collapse. Although environmental restorations and ecosystem-based fisheries managements are operated to prevent wild fish stocks declining, fishing in oceans is believed no longer sustainable because of over exploitation to satisfy the accelerating demands for seafood supply, and a large-scale mariculture in open oceans seems to be inevitable[28]. Compared with conventional marine farming, mariculture in open oligotrophic oceans could mitigate harming the marine ecosystems and wild species: (*i*) could prevent whole scale destruction of native coastal ecosystems, (*ii*) could mitigate enrichment of chemical pollutions caused by fish feed, and (*iii*) could mitigate serious genetic pollutions to native species, thanks to the ocean's least productivity and poor communities in oligotrophic waters.

Mariculture operated in open oceans could also afford large-enough room to mitigate crowding in enclosures or ponds, what is fit for breeding not only small pelagics but also some large carnivorous species such as tuna, rather than depleting their wild stocks. In recent decades, the accelerating demand for bluefin tuna drive their price sky high, ever up to about $1,000 per kilogram[29]. Heavy depredation and removing juveniles from the wild to fatten and consume them have led some stocks on the brink of collapse. As the salmon breeding in cold waters, with the spawning barriers broken through, bluefin tuna could be bred in bigger enclosures than used for other captive fishes in open oceans, or herded and aggregated by attracting of artificial device[28,29]. Developing mariculture in the subtropical oligotrophic oceans could help to maintain both economic and ecological sustainability of the ocean as a source of seafood, and find a solution for conservation of wild stocks to give them a reprieve.

The material used for constructing enclosures, ponds, or artificial reefs for mariculture in oceans needs to be light, stable to resist being degraded, and cheap enough to be used on a large scale, such as plastic. A large amount of plastic can be produced from fossil resources, with huge CO_2 emission into atmosphere; or paradoxically, can be collected by fishing nets from oceans. A report of Greenpeace revealed the serious issue on the plastic debris in the world's oceans, the plastic wastes mostly originated from the land are estimated as the type of marine debris floating in oceans all over the world, and are causing injuries and deaths of numerous marine animals and birds[30]. The centre of North Pacific Subtropical Gyre, which is not only a ocean's most oligotrophic water, but also a area of convergence that contain the maximum debris level, is dubbed the "Pacific Plastic Garbage Patch". Since in international waters the law against marine debris is inefficient or unenforceable, find some way to refloat and reuse them may be an available solution.

Thirdly, connect oceanic biomass production with policy concerns and financial subsidies. Since the cost for CO_2 is 20-30% of the total microalgae cultivation cost, it is believed that using free CO_2 would decrease the high cost of microalgal biofuels[20]. The CO_2 purchased for the merchant market can cost from $130 to $1,100 per tonne of carbon, but the price is only about $30 per tonne of carbon on the European carbon-credit trading market[31]. In another aspect, it is estimated that currently about $220 would be cost to capture and store per tonne of carbon in the U.S.[5], so it's unlikely that fossil fuel power companies will adopt the carbon-capture technology on a large scale, unless some financial subsidies will make CO_2 worth capturing and using as the feedstock of microalgae cultivation for free.

Compared with terrestrial feedstock productions, oceanic biomass production in the subtropical oligotrophic oceans would not cause obvious "carbon debts", competition for food and freshwater supply, or destruction of natural ecosystems. And compared with the iron fertilization plans, carbon captured would be converted into biofuels, chemicals and seafood, instead of impacting the carbon fluxes of the ocean's interior, what makes it much easier to be quantified. Using renewable biofuels and chemicals could partially decrease the consumption of fossil resources. The seafood cultivated and bred would satisfy the accelerating demands for food supply, and simultaneously maintain a large amount of natural biomass in marine ecosystems, rather than sending most of them into atmosphere. All the reasons would make the scheme of "capturing carbon for oceanic biomass production in subtropical oligotrophic oceans" available to take part in the international carbon-credit trading markets and sell the offsets quantified exactly, on condition that the coming climate change conference will discuss and recognize it.

Outlook

There is no free lunch. Even though the scheme is worth while to be carried out, some problems have to be solved in the first place.

The potential impacts to benthic ecosystems and the global ocean circulations. People perhaps know much more about the universe than deep oceans. The oceanic production activities without exactly programming might impact the benthic food webs and some unique habitats of surrounding deep waters in physical, chemical, or genetic ways, and will cause some species threatened, most of which have never been found. The effect of subtropical ocean gyres on the ocean circulations has not been understood enough yet, and whether large-scale production activities would result in some side effects to the global ocean circulations still need more investigations.

The net carbon absorption and energy produced. Including the CO_2 created in producing processes, and the emission of transporting feedstock and products, factual data should prove the carbon captured will be more than that released, and obtain a plus net-carbon-absorption result. In the same way, the energy produced by photosynthesis of microalgae should be proved much more than the energy required for production and transportation, to bear out the scheme is worth while being done.

The right places for large scale production. Even in the ocean's most oligotrophic waters, both ecological and safety factors should be adverted, so it is advised here that the chosen places had better keep away from the unique island ecosystems, the paths of cyclones, and the belts of earthquakes.

The daily supply to workers. Working on the open oceans far from land in a long time needs continuous supply to workers for their living and keeping them healthy. Fruits and vegetables could be transported by ships; and freshwater, which is one of the most important factors for living, could come from effective collection of rain water, or desalinization of seawater by developed solar-thermal technologies.

Someone who actively takes part in the project maybe just wants to obtain sudden huge profits, or depredate natural resources and extend the domain on public oceans. To avoid it farthest, international legislation and supervision by the U.N., with the helping of nongovernmental organizations from different countries, would be very necessary. Participant governments should obey the U.N. Convention on the law of the sea, and companies should also comply with the international laws, and share the gains of oceanic production by negotiating agreements.

The fact of modern world is paradoxical, people keep aspiring after cheaper fuels for consumption on the one hand, and they are preparing to expend uncountable money without stinting to solve the problems caused by burning cheaper fuels on the other hand. If there is a opportunity to find a way that connect CO_2 capture with renewable energy development, and partially combat against deforestation, loss of biodiversity, shortage of food, decline of marine lives, as well as plastic debris in oceans, why don't have a try?

References

1. Rockstrom, J. *et al*. *Nature* **461**, 472–475 (2009).
2. Schneider, S. *Nature* **458**, 1104–1105 (2009).
3. Patrinos, A. A. N. & Bradley, R. A. *Science* **325**, 949–950 (2009).
4. Morton, O. *Nature* **458**, 1097–1100 (2009).
5. Charles, D. *Science* **323**, 1158 (2009).
6. Lehmann, J. *Nature* **447**, 143–144 (2007).
7. Martin, J. H., Gordon, R.M. & Fitzwater, S. E. *Nature* **345**, 156–158 (1990).
8. Falkowski, P. *Sci. Am.* **287**(2), 54–61 (2002).
9. Schiermeier, Q. *Nature* **421**, 109–110 (2003).
10. Martin, J. H. & Fitzwater, S. E. *Nature* **331**, 341–343 (1988).
11. Coale, K. H. *et al*. *Nature* **383**, 495–501 (1996).
12. Boyd, P. W. *et al*. *Nature* **407**, 695–702 (2000).
13. Boyd, P. W. *et al*. *Science* **315**, 612–617 (2007).
14. Boyd, P. W. *et al*. *Nature* **428**, 549–553 (2004).
15. Joos, F., Sarmiento, J. L. & Siegenthaler, U. *Nature* **349**, 772–775 (1991).
16. Peng, T-H. & Broecker, W. S. *Nature* **349**, 227–229 (1991).
17. Watson, A. J. *et al*. *Nature* **371**, 143–145 (1994).
18. Crutzen, P. J. *Climatic Change* **77**, 211–219 (2006).
19. Ohlrogge, J. *et al*. *Science* **324**, 1019–1020 (2009).
20. Huber, G. W., Iborra, S. & Corma, A. *Chem. Rev.* **106**, 4044–4098 (2006).
21. Gerbens-Leenes, W., Hoekstra, A. Y. & van der Meer, T. H. *PNAS* **106**, 25, 10219–10223 (2009).
22. Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. *Science* **319**, 1235–1238 (2008).
23. Regalbuto, J. R. *Science* **325**, 822–824 (2009).
24. Field, C. B., Behrenfeld, M. J., Randerson, J. T. & Falkowski, P. *Science* **281**, 237–240 (1998).
25. Strong, A., Chisholm, S., Miller, C. & Cullen, J. *Nature* **461**, 347–348 (2009).
26. Diaz, R. J. & Rosenberg, R. *Science* **321**, 926–929 (2008).
27. Polovina, J. J., Howell, E. A. & Abecassis, M. *Geophys. Res. Lett.* **35**, L03618 (2008).
28. Marra, J. *Nature* **436**, 175–176 (2005).
29. Normile, D. *Science* **324**, 1260–1261 (2009).
30. Allsopp, M., Walters, A., Santillo, D. & Johnston, P. *Plastic Debris in the World's Oceans* (Greenpeace, Amsterdam, 02 November 2006), <http://oceans.greenpeace.org/en/documents-reports/plastic_ocean_report>.
31. Jones, N. *Nature* **458**, 1094–1097 (2009).