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The Production of Additional Marine Protein by Nitrogen Nourishment

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Abstract

Ocean nutrient enrichment to decrease carbon dioxide concentration in the atmosphere and to increase the sustainable fish stocks is being actively considered. The positive benefits of lowered carbon dioxide concentration in the atmosphere and of increased fish stocks are clear. The risks of such enrichment are readily divided into two categories, effectiveness risk and ecological risk. Effectiveness risks are the concern of the project participants while ecological risks are the concern of society. Ecological risks could include the possibility of eutrophication, harmful algal blooms, secondary greenhouse gas emissions, and changes in the fish species distribution in existing fishing grounds.

Keywords: carbon sequestration, ocean fertilization, ocean nourishment, marine protein.

Introduction

The uncertainty associated with climate change and the need for more protein as the global population rises have led to calls to increase the primary production of the world's oceans.

An extraordinary quadrupling of the wild fish catch over the last 50 years has contributed to feeding the extra billions of people. However, while the population will increase by further substantial numbers in the next 50 years, increased food needs cannot be expected to be satisfied by just hunting and gathering in the sea. Wild fish catches have been constant for the last decade. We have reached the present carrying capacity of the sea.

On land we have increased productivity dramatically, but in the ocean we are still relying on nature. Jones and Young (1997) suggested that we should increase the growth of phytoplankton to both sequester carbon from the atmosphere and increase the base of the marine food web. They examined the use of nitrogen which has potential for some 70% of the deep ocean regions, those in which new primary production is limited by the supply of macronutrients. For the remaining 30% of the deep ocean which is not light limited, Markels and Barber (2001) proposed fertilization with the micronutrient iron.

The rising gross domestic product of the world has been underpinned by the increasing use of fossil fuel. The disposal of the consequent carbon dioxide in the atmosphere is leading to the threat of rapid climate change. If the carbon can be safely stored in the organic carbon cycle in the ocean, rather than in the atmosphere, this would diminish the magnitude of climate change and the consequent threat to food security of subsistence farmers due to changed rainfall patterns.

Classification of Risks

The purposeful modification of the ocean ecology carries risks. Understandably there is apprehension amongst many of rapid change and Glibert et al (2008) exemplifies these concerns. However, the current practice of the storing of waste greenhouse gas in the atmosphere also carries risks as does the increasing fishing effort on existing fisheries (Mace 1997) The demand for food by the 800 million people presently suffering malnutrition, as well as the needs of the additional poor that will be part of the increasing population, makes an adequate supply of low cost protein uncertain.

The risks associated with deploying a new technology such as Ocean Nourishment® can be considered of two types: ecological risks and effectiveness risks. The latter are risks that carbon will not be sequestered

with as great an efficiency as present knowledge suggests, or that fish stocks are not food supply limited (and so may not increase their mass as a result of increased primary production). Another effectiveness risk is that fish may not thrive on the particular plankton species enhanced by ocean enrichment.

The effectiveness risks need not be discussed here as economic reality and the certification process will deal with such risks. The other class of risk is the ecological damage that might occur as a result of ocean enrichment. This risk is addressed in this article.

Glibert et al (2008), although the title of their article only refers to ecological risks of urea fertilization, do not make the distinction between the classes of risk they address. They conclude that plans to enrich the ocean with urea will fail because it will not work. It is likely, they say, that carbon will not sink and the food chain will not be enhanced. These are not ecological risks and fall in our second category of risk.

Ocean Fertilization

The Green Revolution was built on reactive nitrogen generated by the Haber Bosch process. The dominant agricultural fertilizer is urea (which provides nitrogen). Glibert et al (2006) have pointed out how 55 million tonnes nitrogen in the form of urea is used in agriculture each year. This widespread use of urea has been leading to coastal eutrophication, to a level damaging to primary production. Since the primary goal of Ocean Nourishment is to increase primary production, any such eutrophication would be counterproductive. The techniques of Ocean Nourishment are simple. They are to provide additional nutrient away from other sources of nitrogen and control the infusion process as described in Judd et al (2008) to limit the local level of added nutrient. The initial concentration of nutrients continuously decreases with time unless one renourishes the same water mass. Infusion practised in prevailing currents is easily designed to ensure the current sweeps away the enriched water. Ocean fertilization would be performed in deep ocean waters.

Ocean enrichment can be regarded as biomimicry of the organic carbon cycle. In the existing cycle, the upward flux of nutrients into the photic zone leads to new primary production followed by the sinking of carbon under the influence of gravity. Some small fraction of the carbon is incorporated into harvested fish biomass and the carbon in this small fraction is returned to the atmosphere. Adding new nutrients to the upper ocean mimics and supplements this existing process.

The carbon and nitrogen content of the ocean is large. Gruber (2008) has suggested that there is 660 Gigatonnes (660 Gt) of nitrogen in the sea. The present world manufacture of nitrogen is miniscule in comparison, being of order 0.1 Gt/yr of which 0.05 Gt/Nyr is in the form of urea.

The open ocean is a little utilised resource that can be turned to a new use. Hunting and gathering together with the transport of goods and people make up most of the human activities on the open ocean. There is a low opportunity cost in using the ocean more intensively, in contrast in attempting to farm more intensively on the land. We have fished out the large members of the marine ecosystem and now have started fishing down the food chain (Pauly et al 2000). Despite this change to the ecology many still have an aesthetic vision of the ocean as the last pristine wilderness. This view must be weighed against the needs of the abject poor for economical protein.

Urea is often considered as a source of nitrogen because of its low carbon footprint. The process for manufacturing urea can be represented as



While fossil carbon is needed in this process, much of the carbon dioxide is incorporated in the urea. There will be carbon dioxide emission in the supporting processes, but it can be taken up by the additional phytoplankton.

Redfield

Redfield et al. (1963) produced a remarkably robust estimate for the chemical composition of marine biomass. However there appears to be geographical and species differences (Kortzinger et al. 2001). Nitrogen has a multiplier effect, as one unit of weight of nitrogen when teamed with other required nutrients produces about six units of biomass. Iron, in regions where it is the limiting nutrient, has an even larger multiplier effect. As an example, one tonne of nitrogen draws down $6 \times (44/12) = 22$ tonnes of carbon dioxide. Phosphate is also required by phytoplankton, but is generally available in low concentrations. The option exists for ocean enrichment to just provide the nitrogen needed to consume the locally available phosphate. However if more primary production is desired, additional phosphate can also be infused.

When the phytoplankton die they are converted back to inorganic chemicals, to be used again. The regenerated nutrients are in the Redfield ratio but can be in the form of nitrate, ammonia, urea or other forms of nitrogen.

Eutrophication

One would wish to avoid eutrophication as a result of enrichment by choosing deepwater infusion points and low initial concentrations of nutrients. Glibert et al (2008) failed to read accurately the journalist's report (Young 2007) in the *New Scientist* of the goal of Ocean Nourishment. It is unfortunate that with 57 authors not one noticed the error in reading the *New Scientist* article. This oversight led them to include in their Viewpoint a large section on eutrophication which is not relevant to a nourishment scheme designed to limit the maximum concentration of chlorophyll. Glibert et al (2008) thought the goal was to increase the chlorophyll concentration to 200 $\mu\text{g/L}$ when it was the phytoplankton mass density that was quoted in the *New Scientist* article. Such a mass would correspond to a chlorophyll level of about 4 $\mu\text{g/L}$ Chla, (Kiefer and Mitchel, 1983, Cloern et al, 1995) well below the 10 or 15 $\mu\text{g/L}$ levels Glibert et al 2008 suggested for eutrophication and the associated list of undesirable consequences. Because of turbulent diffusion in the ocean, the infusion concentration is the highest concentration of introduced nutrient that occurs.

The 200 $\mu\text{g/L}$ of phytoplankton mentioned by Young (2007) is much less than 1 part per million. Such a low density has little prospect of shading the deeper waters, nor does it carry many of the risks Glibert et al (2008) suggested for intense fertilization. I think we can set aside the issue of eutrophication and focus our attention on other issues surrounding ocean fertilization.

Species Composition

Ocean enrichment hopes to bring about a change in the phytoplankton composition from those typical of oligotrophic waters. When urea is the source of nitrogen, it may encourage one species more than another. When iron is provided to nitrogen poor water, it can encourage nitrogen fixing bacteria such as *Trichodesmium*, Capone et al (1997).

Culture bottle studies of natural assemblages of phytoplankton provided with additional nutrients have been carried out in many locations around the world. A culture bottle study of the Sulu Sea was conducted by Harrison (2007) using ultra clean techniques. The resulting phytoplankton were analyzed by staff from the University of the Philippines in the Visayas who found that urea enrichment led to a dominance of diatoms. They did not find a dominance of organisms such as cyanobacteria or picoeukaryotes.

Harmful Algal Blooms

Harmful Algal Blooms, HAB, in coastal waters cause serious problems and appear to be related to the oversupply of nutrients. For example, they have been observed in the coastal waters of the Sulu Sea by Peralta et al (2006). Cullen et al (2002) suggest that red tide producing dinoflagellates prosper in high nutrient, low turbulence situations.

Is there evidence that urea encourages toxin-producing dinoflagellates over other forms of reactive nitrogen? Toxic marine algae blooms appear correlated with nutrient loading (Burkholder, 1998) but it is not at all clear that this loading need be in the form of urea. There can be no harmful algal bloom without a source of nutrients. Certainly some harmful algae like urea. Kana et al (2004) found organic nitrogen favours the growth of *Aureococcus anophagefferens* a source of brown tide. Glibert et al (2008) show a coincidence of fertilizer application and occurrences of paralytic shellfish poisoning but it is not clear that it is urea, of all the forms of reactive nitrogen, that most encourages toxic organisms. In agricultural applications the urea when applied to the soil quickly breaks down to ammonia and carbon dioxide. The runoff of nitrogen to the coastal ocean is thus unlikely to be urea, negating this argument of Glibert et al. (2006).

Will the urea enrichment over deep water lead to high concentrations of ammonia in the surface ocean? If the initial concentration of urea is arranged to be below 2 $\mu\text{mole/L}$, the maximum concentration of ammonia as a result of fertilization is 4 $\mu\text{mole/L}$. These values are orders of magnitude below those shown by Randall and Tsui (2002) for acute toxicity of marine organisms.

Oxygen Consumption

The addition of nutrients that cause increased photosynthesis leads to the release of oxygen to the atmosphere and reduction of dissolved oxygen in the deep ocean. The vertical transport of water brings young, oxygen-rich water from the surface to deeper water. The dissolved oxygen level decreases during its journey through the deep ocean, as the rain of organic matter from the surface production is remineralized by bacteria. Effective ocean fertilization will decrease the oxygen levels in the thermocline. Steady ocean fertilization will lead to a constantly lower level of oxygen as the replacement with younger water, we assume, will be unchanged by the fertilization. Fuhrman and Capone (1991) were one of the first to make the observation that too rapid sequestration of carbon in the ocean posed a risk to the deep ocean ecology. Since the horizontal motion of the surface layer is decoupled from the thermocline, the rain of organic matter from a sustained enrichment activity is like to be broadly distributed over a region of the thermocline. The nutrient enriched surface water, for instance, will undergo regenerative production over thermocline water in a different region to where the new primary production occurred.

While uncontrolled application of urea in the coastal ocean might lead to hypoxia, this is not the region proposed to be enriched. In coastal upwelling (Wilkerson and Dugdale, 1987) the well-mixed surface layer exchanges oxygen with the atmosphere and strong primary production produces oxygen in the photic zone. It is the detritus trapped in the colder upwelling bottom layer where it is being remineralized that can become short of oxygen and when upwelled, lead to fish death. In the deep ocean, the area being considered for enrichment, the situation is markedly different.

The Redfield ratio allows us to estimate the amount of oxygen transfer from the deep ocean to the atmosphere by ocean enrichment. If this transfer occurs stoichiometrically, as 106 carbon molecules to 150 oxygen molecules, the oxygen transfer will be larger than the carbon sequestered. The oxygen content of the ocean is of the same magnitude as the known reserves of economically extractable fossil fuel (5,000 GtC). With an ocean exchange time of 1,000 years (Sarmiento and Gruber, 2006), the rate of oxygen consumption will need to be limited to carbon sequestration of less than 5 GtC/yr to preserve a desired level of oxygen. The technical challenge is to distribute the oxygen consumption broadly so the local change in oxygen level is small. It will be advantageous to nourish in areas with short replacement times of the thermocline water.

With the extra consumption of oxygen comes extra production of nitrous oxide, a powerful greenhouse gas. The release of extra N_2O to the atmosphere will lower the efficiency of ocean enrichment but does not pose any particular ecological risk. Jin and Gruber (2003), modeling iron enrichment in the tropics, find some circumstances where the climate change effect of iron nourishment is negative. Urea nourishment uses nitrogen more efficiently than iron resulting in N_2O being less of a problem.

Urea Nourishment for Fish

We take it as given that increased new primary production and the subsequent regenerative production is good for fish. Empirical evidence collected by fishermen supports the assertion that upwelling regions high in new primary production support large pelagic fisheries. It is such situations that Ocean Nourishment is trying to mimic. There is a strong correlation between new primary production and the available fish production as pointed out by Jones (2004) who used data generated by Iverson (1990). We can be much less confident about the fish species that will locate the new source of food and prosper. The dominant small pelagic fish species might change, which could lead to reduced catches in the traditional regions of one species and the increase of another.

Sulu Sea

Glibert et al (2008) were particularly concerned about ocean enrichment experiments in the Sulu Sea. However the subsistence fishermen of the Sulu are one group of people particularly in need of increased protein. From satellite studies (Jones, 2002, Wang et al, 2006), we already know the level of primary production is low away from the coastal zone. This tropical sea supports much diversity and contains heritage listed coral reefs. It would be desirable to both increase marine protein production and preserve the natural assets.

However the opposite is occurring. The acidity of the Sulu Sea is rising (SCOR/IOC planning committee, 2004). Small pelagic fish catch per subsistence fisherman per day has been decreasing (Zaragoza, 2004), partly because the number of municipal fisherfolk is rising and partly because of illegal fishing techniques. It is always difficult to regulate a decreasing resource.

Carbon Sequestration

Increased primary production leads to the export of more carbon from the surface ocean into the organic carbon cycle. Of the carbon that is exported to deep water, some is buried, becoming part of the sediments. However, most of this carbon undergoes vertical circulation and reappears at the surface some centuries later.

It is claimed that the iron mesoscale experiments did not show an increase of carbon export below the nourished patch. Boyd et al (2004) in the SERIES experiment found 8 % of the organic carbon produced by enrichment was exported within 25 days.

However for those enrichments which lead to regenerative production we need to recognize that new primary production equals export production on a yearly time scale (Gordon et al, 1997) even though the export from the initial use of the nutrients is only a small fraction of the total. For this reason, the value of the initial fraction is of little consequence in determining the total export of carbon. Of course when you use the trace nutrient iron, which is aggressively scavenged, it might be that the new primary production is the dominant response. In the case of urea, the regenerated nutrients are expected to be typical of those of the upper ocean and thus readily able to be reused in regenerative production.

The new primary production suffers the fate of either being grazed by organisms of higher trophic levels, or dying. The senescent phytoplankton either fall out of the surface layer before it can be remineralized or is changed into inorganic compounds or dissolved organic matter for regenerative production. While some phytoplankton may float near the sea surface with the help of gas vesicles, on senescence we can assume they start to sink. While some phytoplankton may be poor quality food for higher trophic levels, we did not find such phytoplankton in the culture bottle studies.

The large scale export of organic matter from the surface ocean has to be equal to the large scale new production (Sarmiento and Gruber, 2006). The proportions of carbon export that can be ascribed to new primary production or to regenerative production are of little importance for macronutrient nourishment.

Conclusion

The main features of the carbon and nutrient cycles are now understood and are described in detail in text books such as Samiento and Gruber (2006). There are uncertainties in our knowledge of the nature of the ocean carbon cycle, which is the basis of marine protein production and a regulator of climate change. This should not discourage us from using the ocean to provide a better life for poor people but rather suggests we should proceed cautiously using the established approach of increasing the scale and duration of enrichment experiments.

Just as in agriculture it was realized for many centuries that adding fertilizer increased crop yields, it is now becoming clear that relieving the nutrient limitation in the ocean holds out the prospect of increasing its carrying capacity. The possible risks involved in Ocean Nourishment must be balanced by the benefits to mankind if an enhanced supply of sustainable marine protein can be produced. To not examine suitable opportunities for increasing the food supply is to accept increases in malnutrition and starvation into the future.

While the economics of Ocean Nourishment were not discussed above, Shoji and Jones (2001) show that the Haber Bosch process can make and deliver reactive nitrogen at a price that is competitive with other carbon sequestration schemes. The enhancement of the marine protein can be provided at no additional cost.

We disagree with the conclusion of Glibert et al (2008) that urea fertilization poses high ecological risks. Partly, their conclusions were based on a misreading of published work. Partly, we believe that careful, gradual and responsible investigations can be performed to explore the issues. The rewards to mankind are so high that this concept should not be dismissed without thorough investigations. The prospect of increasing the productivity of the open ocean is an exciting one. Now mesoscale patch experiments using reactive nitrogen are needed, followed by longer term studies of resulting changes to the ecology.

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