The Global Impact of Ocean Nourishment

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Introduction

Ocean Nourishment is the concept of providing additional nutrients to the desert regions of the ocean to sequester atmospheric carbon dioxide and to increase the sustainable fish catch.

The present annual level of photosynthetic activity of the upper ocean is limited by the supply of macro or micronutrients. These nutrients are recycled in the ocean by upwelling and augmented by inputs from the rivers and the atmosphere. The addition of reactive nitrogen and other nutrients will increase primary production and stimulate the food web. The availability of phosphorus, silica and trace nutrients is assessed by considering the supply of these nutrients via external input to the ocean. The cost of Ocean Nourishment is sensitive to the extent that micronutrients to supplement reactive nitrogen must be provided.

The global population is expected to increase by 2 billion over the next thirty years. This paper explores the scenario of Ocean Nourishment providing sequestration of two thirds of the fossil carbon utilized by and one third of the minimum protein requirement of these additional people.

Scale of intervention

We wish to examine the global impacts of Ocean Nourishment being widely used. The underlying driver in this need for nourishment is the rising world population. The changes over the last few years and the estimates for the future in Fig. 1 show we have passed the peak growth rate. The United Nations predicts the population will almost stabilize in 2050. These additional people will need food and will burn fossil fuels.

Let us look at the protein requirements of these new people. The average fish consumption in Malaysia, according to Chuan, Othman and Fung (1996) is 37 kg per person which provides about half the Malaysian people's animal protein (11% of their total protein, possibly a third of the recommended minimum). This is consumption of twice the world's average fish protein. Let us take supplying 37 kilograms per person as the goal. We then can calculate the new fish landings needed to keep up with the population growth.

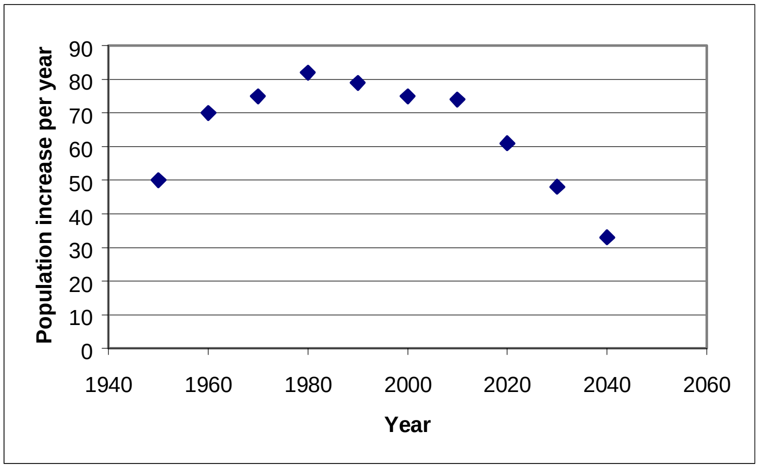

Fig 1 The change in world population estimated from United Nations (1999)

Agriculture is stressing the land with thirty eight percent of the land suffering degradation (FAO, Terrastat, 2000). Only about 20% of the land area is potentially arable while far more of the ocean has the capacity to be more productive. Thus ranching the ocean for extra fish can be carried out much less "intensely" than land agriculture. We have coined the phase *Ocean Nourishment* to describe the processes of increasing the sustainable fish yield from the open ocean.

Impact on nitrogen production

The production of synthetic reactive nitrogen increased rapidly last century mostly as a result of the Green Revolution that allowed world food supplies to keep up with the rising population. In the surface ocean nutrients are in short supply. Nitrogen is most deficient (by weight) and Jones (2001b) has calculated the nitrogen needed to increase the oceanic primary production sufficiently to produce more carnivorous fish for capture, using observations assembled by Iverson (1990). Table 1 shows the reactive nitrogen needed produce clupeids. The production of nitrogen for terrestrial agriculture, reproduced from Jones (1996) is shown in Fig. 2 for comparison with the nitrogen needed to be supplied to the ocean to provide one third of the protein for the expected "new people". From 2050 to 2100 we assume the new nutrient added in the previous years will begin to be recycled and the primary production will stay constant if the additional nutrient decreases linearly. We have not examined the plausibility of this last assumption

To increase the new primary production by the proposed amount, the nitrogen production will need to double during the next 50 years. Shown for comparison in Fig 3 is the projected growth of electrical energy generation. It can be seen that the change in nitrogen production to supply the ocean is modest compared with the projected electric energy supply.

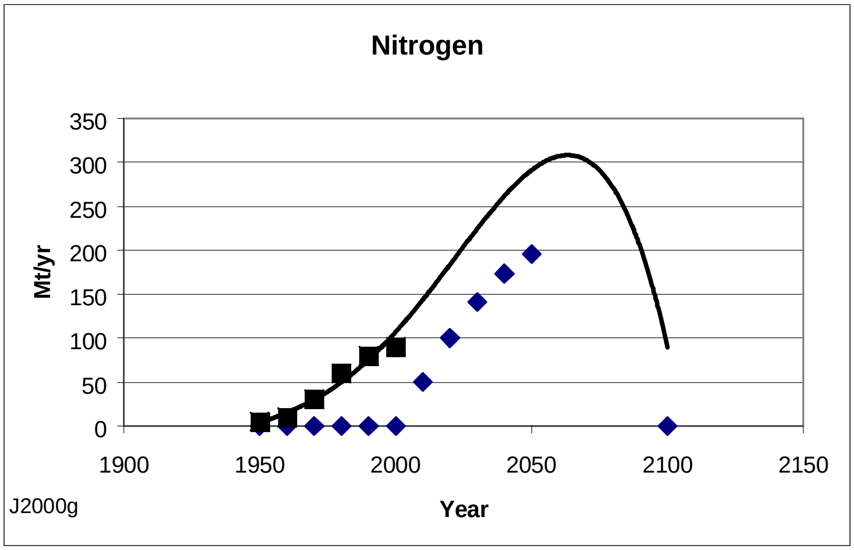

Fig 2 Nitrogen production shown as a line. Assumes land based use of nitrogen stabilizes at the year 2000 value; nitrogen to the ocean ◆; present agricultural use ■.

Carbon dioxide sequestered.

The carbon sequestered in the deep ocean as a result of the increased primary production comes from the fraction of carbon incorporated into the biomasss that falls out of the photic zone. *New primary production* is the term used for the conversion of inorganic carbon to organic material using nutrients that have recently come into the photic zone. Some of these nutrients and the carbon are used over and over again in the photic zone as

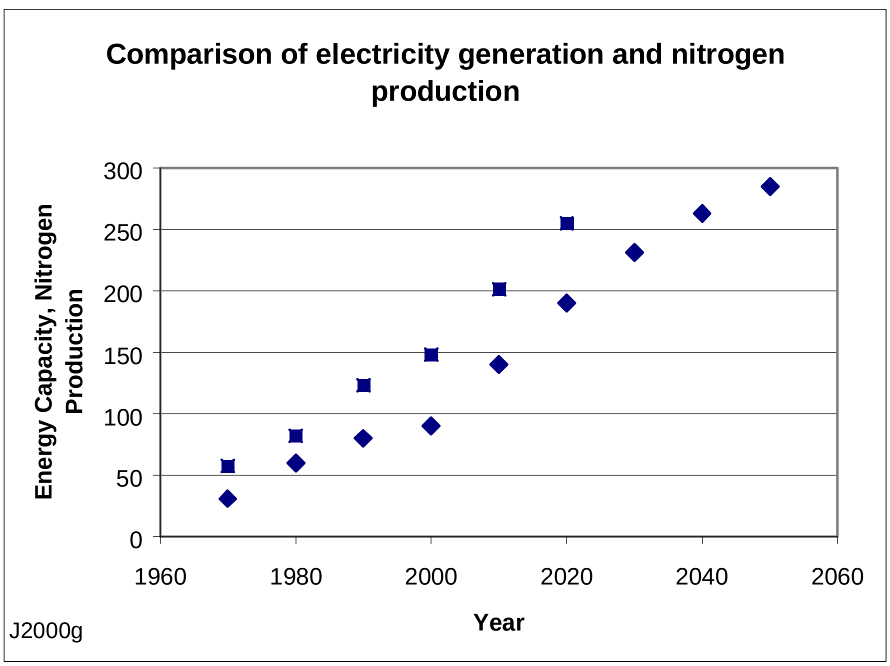

Fig 3 Comparison from IEA (2000) of past and projected electricity capacity, PWh ■ and production of nitrogen for the present scenario, Mt/yr ◆.

the biomass dies and is remineralised. However, eventually the equivalent of all *the new primary production* over the deep ocean falls out of the photic zone. If it did not the level of primary production would be steadily rising and we do not believe this to be the case (on the millenium time scale). Thus the ratio of export carbon to recycled carbon is not important for determining the amount of carbon sequestration.

Table 1 Nutrient demands for our fish for new people strategy.

	Mt/yr	Mt/yr	Mt/yr	Mt/yr	area	Mt/yr		Sequester CO_2	Total capital	Nat Gas Consum.
Year	N	C Redfield	P Redfield	Si*[1]	$10^3 km^2$	O*[2]	#plants	Mt/yr	$million	PJ/yr
2000	0	0	0	0	0	0	0	0	0	0
2010	50	288	6.9	60	1050	950	75	600	25500	1500
2020	100	571	13.8	119	2128	1900	152	1200	51700	3000
2030	141	805	19.5	169	2996	2679	214	1320	72800	4230
2040	173	989	24.0	208	3668	3287	262	2076	89100	5190
2050	195	1116	27.0	234	4340	3705	295	2340	100300	5850
2100	0	0	0	0	0		0	?	0	0
Reference*[4]		4500	33	200	300000	10^7 Mt		22700		64000

** Note 1 Assuming 50% diatoms. Note 2 Oxygen consumption below thephotic zone. Note 3 P = 10^{15}. Note 4 see text.*

To increase the new primary production requires the addition of new nutrients. In terms of the carbon dioxide sequestered, Jones and Otaegui (1997) deduced for a practical system using natural gas as the feed stock, that 1 tonne of Nitrogen (and other nutrients) sequestered 12 tonnes of carbon dioxide. (Note all amounts of sequestered carbon are referred to in terms of carbon dioxide. 1 tonne of carbon dioxide = 0.27 tonne of carbon.)

Thus Table 1 shows that under our scenario of providing 33% of minimum protein for the population increase of Fig 1, the total carbon dioxide sequestered rises to 2.3 Gtonnes/yr in the year 2050.

Thus we can calculate the carbon dioxide sequestered per person under our "fish for new people" program. This is 0.8 tonnes/yr of CO_2 per additional person. Currently in a country with modest food deficiency, India, the average person produces 1.2 tonnes of carbon dioxide per year in 1996 (Marland et al, 2000). We might take this a reasonable average to expect for the "new" people, although it assumes continued poverty. Thus ocean nourishment at this level would be able to absorb about 66% of the emission from new people.

In an earlier simulation of macro-nutrient fertilization in a global atmosphere ocean model, Orr and Sarmiento (1992) assumed a constant increase in export production. An often quoted result is that they found that the carbon sequestered was only 44% of the export production. These authors concluded that an unreasonably large supply of nitrogen would be required. They did not elucidate what was unreasonable about supplying these chemicals but we might assume that they felt that management of atmospheric carbon dioxide did not warrant such expenditures. We will return to the cost issue below.

More recently Matear and Elliot (2001) studied the alternate problem of adding nutrients to the photic zone at a constant rate. This study took into account the nutrient recycled back into the photic zone by upwelling (together with the carbon) and allowed us to calculate an uptake efficiency based on the added nutrients rather than new primary production. When they assumed ocean nourishment only in areas that were nutrient limited they found an efficiency of 90%. In the Jones and Otaegui study, the efficiency was assumed to be 70% to allow for some of the many other issues such as calcium carbonate exported with some types of phytoplankton, extra DMS or methane produced and some denitrification.

Impact on Chemical composition of the upper Ocean

It is imagined that the nitrogen above would be introduced away from the coast lines and adjacent to existing productive fishery areas.

With the aid of the Redfield ratio, the demand for phosphorus and silica have been estimated in Table 1. For silicon consumed we used the ratio 0.18 mole Si per mole C as in Abraham et al (2000) and assumed half the new primary production would be diatoms. If this were the case it would seem the demand for silica would be quite high. It is likely the diatoms would not be favoured in an Ocean Nourishment scheme which did not provide silica.

Shoji and Jones (2001) felt that Ocean Nourishment plants able to sequester 10Mt/yr of carbon dioxide would cost about US$340 million to construct and produce about 0.66 Mt/yr of nitrogen. Such plants need energy and with current technology this is about 30GJ per tonne of nitrogen. Some bench marks can be provided to place in context the figures in Table 1. Current nitrogen manufacture is about 90 Mt/yr. The phosphate down rivers is 33 Mt/yr (Tiessen, 1995). Anthropogenic carbon dioxide emissions to the atmosphere is 22,700 Mt/yr (IEA, 2000). The growth of production of ammonia plants is large but not out of line with projected electricity generation. Electricity will require more new plants of conventional size (1000MW) in a single decade than the nourishment strategy described above. They will each cost about 3 times as much as a nourishment plant. Current production of natural gas is 6400 PJ/yr. New primary production is estimated at about 4.5Gt C/yr by Eppley and Peterson (1979).

If one imagines a model of nutrient rich water upwelled near the coast and depleted of nitrogen by the opportunistic phytoplankton, the question arises if trace nutrients are also depleted. In some areas there is an iron deficiency rather than nitrogen. Howarth (1998) comments on the more rapid recycling of phosphate than nitrogen.

Impact on phytoplankton

In nutrient-poor waters Falkowski et al (1998) point out that picophytoplankton are important in recycling the nutrients. When extra nutrients are added to such areas, the larger phytoplankton can expect to increase in importance. When the nutrients supplied lacks silica, diatoms are not expected to be as important as in areas enriched by naturally occurring upwelling. How well can phytoplankton adapt to lower levels of phosphate, silicate and trace nutrients? Refield et al (1963) looked at luxury consumption of nutrients and how they react to the reduced concentration of a particular nutrient. A series of experiments to culture water samples from target areas are needed to clarify what level of trace nutrients are the most cost effective in Ocean Nourishment. Much as in agriculture, when nutrients are provided to crop lands or pastures, tests need to be done to find the deficient nutrients and provide them in appropriate proportions.

The level of phytoplankton concentration induced by Ocean Nourishment can be controlled by engineering design of the injection system. The size and spacing and depth of the nutrient release points will control the maximum average phytoplankton concentration. For areas adjacent to upwelling regions, a reasonable design goal might be chlorophyll concentrations of 20% of phytoplankton bloom levels or chlorophyll values of 1-2 mg/m^3. At such levels the phytoplankton levels might be 50 –100mg/m^3 of C. The Ocean Nourishment plant discussed above produces 2000t of nitrogen per day (some days are allowed for maintenance). Using the Redfield ratio (7:1) the volume water that can be enriched to support the growth of 50 mg/m^3 of carbon is 28×10^{10} m^3/day of water. Let us take a photic zone of 20m depth. Then the new primary production from the introduced nutrients would occur over an area of 14000km^2/day. The prevailing current sweeps the nutrient away from the plant and diffuses it laterally. After the initial uptake of the nutrients, either export from the photic zone or remineralisation takes place. The fraction exported might be expected to be high, Eppley and Peterson (1979), but if silica is in short supply, the rapidly exported diatoms will be less than in natural upwellings. The regrowth of phytoplankton using the remineralised nutrients will be less intense partly because diffusion has added to export to lower their concentration. Eventually all the nutrients and their associate organic carbon will be exported unless the nourished water is quickly subducted.

The ocean area undergoing nourishment is estimated from the above in Table 1 and reaches about 1% of the surface area of the ocean (3×10^8 km^2). Ocean nourishment can be placed so they secondary uptake of the introduced nutrient does not strongly interact with other nourishment plants. For scenarios aimed at more fish production or larger sequestration goals some care would be needed in the plant placement.

Costs

It is shown that a additional carbon dioxide uptake of about 1 Gt/yr utilises a small fraction of the ocean surface. Initially carbon dioxide sequestration by ocean nourishment is in the range of US$5 to US$15 per tonne (avoided). This cost does not recognise the value of fish produced. For sequestration targets in excess of 4 Gt/yr the cost might be expected to rise due to the need use more than a ten percent of current natural gas production.

The typical costs that might be incurred in nourishing the ocean could be recovered according to Shoji and Jones (2001) by selling carbon credits for the sinks produced by the additional new primary production. New estimates of the uptake efficiencies made by Matear and Elliott (2001), would suggest that in the most favourable situation the storage of carbon could be substantial. This is sequestration for much longer than the overturning period of the intermediate depth ocean as pointed out by Jones(2001a). If the fish harvested had to sustain all the expense of ocean nourishment, the cost would be order US$200 per tonne of pilchards and the like landed.

Martin et al (1990) first suggested the role the ocean might play in managing climate change. Ocean Nourishment to increase both fish catch and sequester atmospheric carbon dioxide has been discussed in Young and Gunaratnam (1996) where increasing the nutrients in the Sulu Sea has been considered in the spirit of a large IRONEX demonstration. Coale et al (1996), reported the results of the iron enrichment experiment.

Risks

Revolutionary processes such as large scale ocean nourishment need demonstrations to reduce the uncertainties inherent in all new concepts. The risks can be managed by introducing such technology progressively and monitoring the risk. Risk is not absolute but relative to other alternative strategies and the reason for the concern about climate change is the risk to food security for the poorer people of the world.

The over nutrification of some coastal waters has been used as example of introducing nutrients and their undesirable consequences. A more relevant example is that of productive upwellings where the nutrients are supplied to the photic zone and the phytoplankton support large pelagic fisheries. One of the issues brought up is the possibility of regime shifts taking place in the nourished areas. This is of course the aim of nourishment as one shifts towards a more productive ecosystem. If the nourishment is adjacent productive upwelling regions the uncertainty of the ecological response is somewhat reduced.

The remineralisation of marine organic matter takes about 17 oxygen molecules for each nitrogen molecule. Shown in Table 1 is the oxygen required by the extra export flux of organic carbon. Much of this oxygen comes from the thermocline which will have reduced oxygen until it is again in contact with the atmosphere. While we see that as a fraction of the total oxygen in the ocean (~10^7 Mt) the extra consumption is small, it may be better to look at numerical model simulations as in Matear and Elliot (2001) to appreciate the issues. At first glance, this consumption of oxygen would not seem severe if the Ocean Nourishment plants were widely distributed.

Societal issues

Such eco-engineering often sparks ethical debates. It involves intervening in the natural order of life. These debates, however, should be a balancing of the rights of people, especially children, to basic needs with the rights of future generations who may have to cope with a changed environment. Will the risks involved in increasing the sustainable yield of protein from the sea be lower than making the same increases on the land? While extra food production does not ensure everyone receives adequate nutrition, food produced locally at low cost is a promising start.

The Future

Avoiding hunger for the extra billions of people can be considered as providing cheaper food than at present, where 800 million cannot afford too purchase adequate food supplies.

In the future the energy for fixing nitrogen might not come from fossil fuel. The current practice of using of fossil fuel bring with a penalty of carbon dioxide that first had to be allowed for before the sequestration gains in Table 1 were calculated. As the nutrients are needed in the ocean, obtaining the energy from the sea may become a cost effective approach for more ambitious sequestration goals.

Conclusion

The sea is 70% of the surface of the globe but provides only 6% of human protein. Can the ocean play a bigger role in providing food security for the people of poorer countries? By combing foreign income for carbon sink credits and fish protein for human consumption, enhancing the productivity of the oceans may be attractive in the near future.

The costs of sequestering carbon dioxide is modest compared with many estimates. Modelled emission trading between Annex B countries gives a permit price of $32 per tonne of CO_2, IEA (2000). At costs of $5 to $15 per tonne, Ocean Nourishment would capture a significant fraction of the market. It provides “permanent sequestration” as described in Jones (2000a).

The fundamental cause of the rapidly rising carbon dioxide problem and the cost of food is the rising population. Despite a wish for decreasing world population, the neglect of educational opportunities, particularly for women, means that those able to reproduce will not be persuaded to limit reproduction. The more fortunate have an ethical need to contribute to feeding these additional people. The extra food production will inevitably require further change of the environment but if done efficiently it might increase the standard of living to allow more education. Providing the nutrients that are in short supply in the sea, as has been done on the land in the Green Revolution, may be the alternative to looking for new methods of producing low cost food on the land.

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