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COMMENT

Engineering a large sustainable world fishery

Mankind is faced with three interconnected problems, those of rising population, the provision of adequate food and the increasing level of waste carbon dioxide in the atmosphere. The ocean plays an important role at present by annually providing *c.* 90 Mt of high protein food and absorbing about 1000 Mt of carbon dioxide (CO_2) from the atmosphere. By the year 2100 it is predicted by the United Nations (1992) that the world population will have more than doubled its 1990 level of 5.2 thousand million people and will approach 11.5 thousand million. Most of this population increase will occur in the developing countries.

While the World Food Summit in Rome in 1996 estimated that 800 million people already suffer from chronic undernourishment, this number will rise unless the food production of the world is more than doubled by the year 2100. Such a potential crisis calls for human intervention in the environment on an unprecedented scale and for the introduction of new methods of protein production.

The past decades have demonstrated admirably how scientific methods and human intervention have been able to improve the capacity of the land to produce increased crop yields. Why has not similar ingenuity been applied to increasing the ocean's capacity to feed the world's population? We believe the answer lies in part in the organization of economic activities into sovereign states, whereas fish may migrate across national boundaries. Therefore those bearing the costs of any increase in the ocean's productive capacity would not necessarily gain the benefits.

The addition of nitrogen to the soil and technological improvements to agricultural methods have increased the food production from the land. Away from the coastal waters, much of the ocean is a desert, being deficient in the nitrogen needed for phytoplankton growth. The addition of nitrogen to the ocean water could be expected to increase the production of phytoplankton, the first step in the ocean food web. The resulting photosynthesis would draw down the inorganic carbon level in the upper ocean and that carbon would be replaced by a flux of CO_2 from the atmosphere. As the carbon works its way down the food chain, it is converted to seafood suitable for human consumption. It is through the phytoplankton that CO_2 is converted to fish.

Rising atmospheric CO_2 and ocean primary production

Population increases and predicted improvements in living standards will increase the demand for energy. More CO_2 is expected to be produced by fuel consumption, with the anthropogenic emissions rising to 19 Gt C per year within the next century, even after accounting for increased energy efficiency and reforestation. While the Framework Convention on Climate Change has started to address the problem of increasing CO_2, the industrialized nations, acting alone, are unlikely to be able to control the emissions of CO_2 on a global scale, an issue discussed by Young and Jones (1995). It is the developing nations, in their quest for economical energy, that will produce most of the emissions in the future. For example, China, already the world's biggest coal producer (Barnett 1994), can not be expected to leave this economic and easily extracted fossil fuel in the ground when its people's desire to industrialize rapidly is of paramount importance.

The oceans are a major sink of CO_2 as photosynthesis incorporates the carbon into biomass and eventually exports it to the deep ocean as sinking detritus. Ocean circulation returns some of this carbon to the surface where the ocean degases to the atmosphere. The difference between the upwards and downward flux of CO_2 is believed (e.g., Houghton *et al.* 1992) to make the ocean a net sink of atmospheric carbon. This upper ocean primary production supports the food web that leads to commercial fish and crustaceans.

Phytoplankton grow, and consume nitrogen and other chemicals in a fairly constant proportion, known as the Redfield ratio. When phytoplankton die, bacteria decompose the phytoplankton to form reactive nitrogen again. This is in the form of ammonia, urea and some amino acids, that provides the nitrogen for regenerated production. Dissolved organic phosphorus, the other

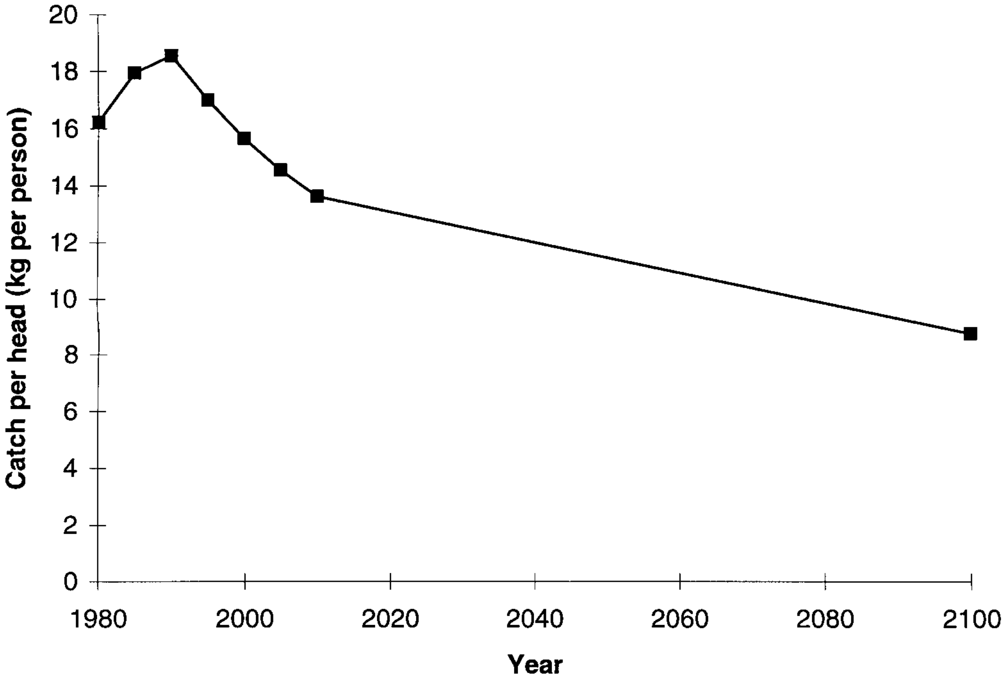

Figure 1 Fish catch (FAO 1994) per head of population. Predictions are based on an assumed constant catch after 1990.

macronutrient, is more readily available, as it is recycled faster than the dissolved organic nitrogen. Thus, while it is generally believed that the supply of nitrogen and phosphorus from upwelled waters has the required nutrients in the Redfield ratio, the surface waters have been observed to contain less nitrogen than Redfield says phytoplankton require. Howarth (1988) points out that the evidence is that nitrogen limits net primary production in most marine situations.

Eppley and Peterson (1979) observe that it is the 'new' primary production that drives both the fish catch and the downward flux of carbon. Fish catch has reached near steady state over the last decade. The historical global total fish catch per head of population calculated from the Food and Agriculture Organization (FAO) statistics is shown in Figure 1. If this trend persists, the catch per person will decrease due to the projected population increase.

Can we increase fish catch per head?

If we provided nitrogen on a large scale to the upper ocean, would it contribute to world food supplies? The ocean biomass is distributed very unevenly, with the coastal parts of the ocean being at least 100 times more productive than the nitrogen-starved central ocean gyres. Nourishing these vast open ocean regions with low concentrations of nutrients would ensure that just modest increases of phytoplankton occurred over large areas. With modest increases in phytoplankton, neither self shading nor red tides would be expected to occur. Nourishing the ocean deserts is an intriguing idea which would be one step in learning how to increase the productivity of the ocean.

The process of ocean nourishment and impact on fisheries

The nutrients required locally to increase primary production could be supplied by pipelines from shore to be swept into the ocean gyres by the prevailing currents. Such nutrient discharge systems would have some of the characteristics of permanent upwelling regions. Because of the small size of the pipe outlet compared with natural upwellings, the rate of initial mixing of the nutrient will be high. Thus ocean turbulence will quickly bring the concentration of nitrogen to the low levels suitable for stimulating growth of the standing stock of phytoplankton. Those species which flourish in richer conditions can be expected to dominate the nourished water as it drifts around the central gyre.

We can calculate the landings needed to maintain the catch at 15 t per 1000 people over the next century. Then, assuming all primary production is nitrogen-limited, and that fish stocks are pro-

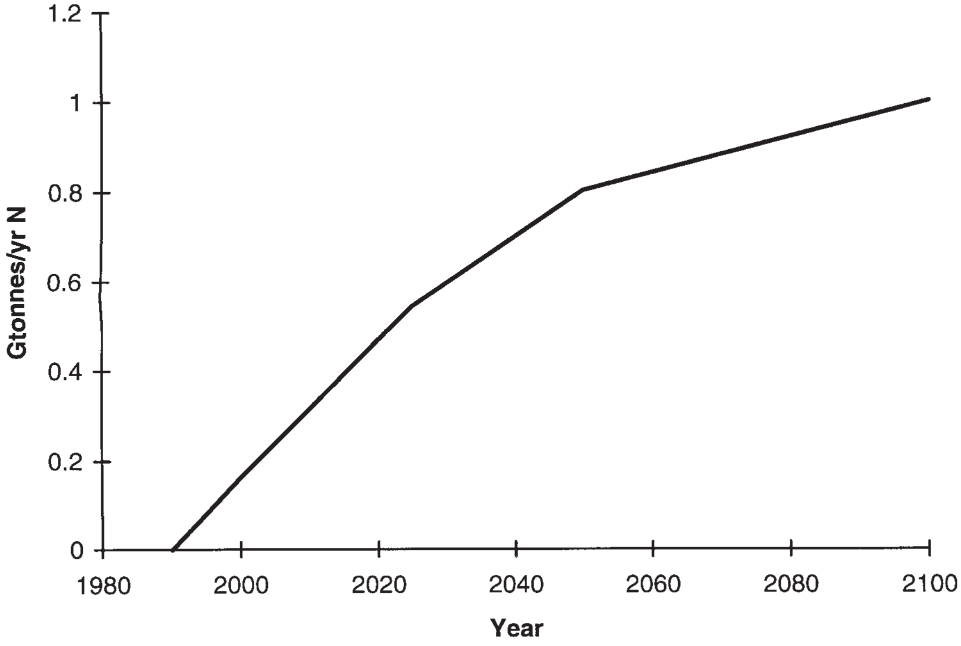

Figure 2 Additional nitrogen needed to keep fish catch per head of population constant, assuming new primary production in the ocean is 4.5 Gt C per year in 1990. The current level of nitrogen manufactured is about 80 Mt per year.

portional to new primary production, how much nitrogen is needed to keep the fish catch per head constant? If the effort per tonne of fish landed were maintained constant in the future, and management remained as effective as it is today, we can calculate the increase in new primary production needed to keep the fish landings constant.

As in Jones (1996), we assume, based on the Redfield ratio, that 1 t C fixed by new primary production needs 1/7 tonne of nitrogen, and that this nitrogen can be supplied with a 70% uptake efficiency. Thus the addition of 1 t of nitrogen is assumed to increase new primary production by 5 tC. If the current level of new production is 4.5 GtC yr^{-1} (Eppley & Peterson 1979) then the nitrogen needed for production to keep pace with population will increase to 1 GtN yr^{-1} in 2100 (Fig. 2). Since the weight of seafood at present taken from the ocean is only 0.08 Gt yr^{-1} this has a negligible impact on the new primary production of 4.5 GtC yr^{-1}. Fish harvesting at this level is, however, having a significant impact on the ocean ecology.

How does the nitrogen needed shown in Figure 2 compare with the current production of 80 MtN yr^{-1} fixed from the atmosphere? Approximately 10 new nitrogen fertilizer plants per year with capacity of 1 MtN yr^{-1} would be needed; the increase is similar to the 11.5% compounded rate of growth of nitrogen fertilizer production that occurred between 1960 and 1970. The pipeline technology needed has been developed by the offshore oil and gas industry. It is possible to imagine nitrogen-fixing plants, connected to pipelines *c.* 0.5 m in diameter releasing reactive nitrogen 100 km or so offshore. The necessary capital, while substantial, is minor compared with the capital required for the 50 new power stations per year for the next decade projected by the International Energy Agency (1995).

Environmental impacts

Large-scale nourishment will cause changes to the ocean, some of which have been canvassed by Fuhrman and Capone (1991), who considered a much greater increase in primary production than we see as appropriate to keep the fish catch proportional to population.

A significant change to the ocean is likely to be the dissolved oxygen (O_2) concentration below the mixed layer. As the dead phytoplankton and detritus of the zooplankton grazers fall through the thermocline to the deep ocean, the organic carbon and nitrogen components decay and consume O_2. The extra O_2 consumption is likely to be related directly to extra carbon sequestered.

In the atmosphere there will be a valuable impact as the increased photosynthesis drives the export of carbon from the upper ocean and its replacement from the atmosphere. A nourishment scheme to keep fish per head constant, would consume about 4 GtC yr^{-1} at the end of the 22nd century, making allowance for the CO_2 produced as a result of nitrogen fixation. This allowance would be *c.* 20% for the nourishment scheme designed by Jones and Oteagui (1997). In the year 2100 the man-made or anthropogenic sources of CO_2 under the scenario IS92b described in Houghton *et al.* (1992) will be 19.1 Gt yr^{-1}; our nourishment scheme would mitigate about 20% of these CO_2 emissions.

The current rise in atmospheric CO_2 implies that the pH of the surface waters is decreasing as the concentration of carbonic acid increases to provide an equilibrium between air and water. The enhanced photosynthesis considered here will mitigate this anthropogenic change in the pH of the upper ocean and restore the level closer to its pre-industrial value.

While there are efforts around the world to reduce uncontrolled nutrient discharges into the ocean, these are in response to local eutrophication and should not be confused with the present discussion on raising the nutrient level in those areas deficient in nitrogen.

Finally, we need to consider if supplying this amount of additional nitrogen to the ocean would lead to a shortage of other nutrients. Phosphorus input to the oceans appears adequate for the levels of nourishment discussed. It has been estimated, by Tiessen (1995) that 33 MtP yr^{-1} is added to the ocean by farming, industry and domestic sewage. Other nutrients, if they become depleted, could be provided with the nitrogen.

Costs and benefits of nourishment

There has been a revolution in the industrial conversion of atmospheric nitrogen to reactive nitrogen. The manufacturing costs have fallen steadily and Kroschwitz (1992) suggests costs of *c.* US\$100–160 tN^{-1}, depending on the cost of feed fuel and capital. We use an optimistic cost for fixing nitrogen of US\$100 tN^{-1} appropriate to large-scale production in optimum locations. The capital and operating costs of the pipelines have been ignored in this analysis, as they are clearly much less than the fixation costs. A design and costing for a practical implementation of an ocean nourishment plant is described in Jones and Otaegui (1997). They use the estimate that 1 t of nitrogen produces 5 tC of new primary production.

With annual fish landings of about 80 Mt and with new primary production of about 4500 MtC, a linear relationship suggests that an increase of primary production by 1 tC will increase fish landings by 18 kg. Thus the \$100 for nitrogen produces 5 t of new primary production which allows an additional 90 kg of fish to be harvested. This is a cost of US\$1.1 per kg of fish. The above figure is crude because it used the global relationship between fish capture and primary production. However, it may also be pessimistic in that most primary production occurs in the open ocean (Valiela 1984), where fish catches are very inefficient. The cost and nitrogen demand would be less if we used a relationship more appropriate for upwelling regions.

Previous experience

Adding nitrogen to ocean waters has been shown to increase photosynthesis in culture experiments and also in mesocosm experiments (Handa *et al*. 1994). Such nourishment is used frequently in aquaculture. Nourishment in the form of primary production, however, is used for a restricted range of products. Primary production was increased on a larger scale in the freshwater lakes of Canada to assist the salmon industry, where increased primary production increased juvenile salmon which in turn increased salmon returns (Parsons *et al.* 1984).

There have been attempts to induce artificial upwelling to bring up nutrient-rich water. Kajikawa *et al.* (1991) pumped deep water from Toyama Bay, Japan, to the surface, but concluded that there was no evidence that nourishment had occurred. Large amounts of water must be transported to bring a small amount of nutrient to the surface, and the deep water contains carbon, as well as nitrogen, which cancels most of the ‘greenhouse gas’ benefits of increased photosynthesis.

The discussion above has focused on the addition of one macronutrient. Areas with adequate nitrogen are limited to about 20% of the ocean surface (Martin *et al*. 1994). Coale *et al.* (1996) experimentally seeded an expanse of surface water in the equatorial Pacific Ocean with iron which triggered a ‘massive’ bloom of phytoplankton, demonstrating that ocean nourishment is a potential mitigator of the effects of ‘greenhouse gas’ emissions. Martin *et al*. (1990) had already suggested iron fertilization of the Southern Ocean as a feasible method of increasing CO_2 uptake. Sorensen (1995) suggested a ‘blue revolution’ for the North Sea.

Sustainable fisheries

Our current practice of exploiting the fish stocks of the ocean without ocean nourishment appears to have been taken beyond the sustainable limit. Fish stocks of aggressively harvested species are collapsing. Nourishment may provide an opportunity to both sequester the excess CO_2 of the atmosphere and provide additional protein for the rising world population.

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