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4.7 Biological Uptake in Oceans and Freshwater Reservoirs, and Geo-engineering

The net primary production of marine ecosystems is roughly the same as for terrestrial ecosystems (50GtC/yr for marine ecosystems and 60GtC/yr for terrestrial ecosystems), and there are opportunities to increase the net carbon flow into the marine biosphere. There are fundamental differences between the two systems, however, as the marine biosphere does not include large stores of carbon in the living and dead biomass. There are some 3 GtC in marine biota versus nearly 2500GtC in terrestrial vegetation and soils (Table 4.1). The key to increasing the carbon stocks in ocean ecosystems is thus to move carbon through the small reservoir of the marine biota to the larger reservoirs of dissolved inorganic carbon (the "biological pump") in ways that will isolate the carbon and prevent its prompt return to the atmosphere. The biological pump serves to move carbon from the atmosphere to the deep oceans, as organisms take up CO_2 by photosynthesis in the surface ocean, and release the carbon when the organic material sinks and is oxidized at depth.

Several researchers have suggested that ocean productivity in major geographical regions is limited by the availability of primary or micronutrients, and that productivity could be increased substantially by artificially providing the limiting nutrients. This might involve providing nitrogen or phosphorus in large quantities, but the quantities to be supplied would be much smaller if growth were limited by a micronutrient. In particular, there is evidence that in large areas of the Southern Ocean productivity is limited by availability of the micronutrient iron. Martin (1990, 1991) suggested that the ocean could be stimulated to take up additional CO_2 from the atmosphere by providing additional iron, and that 300,000 tonnes of iron could result in the removal of 0.8GtC from the atmosphere. Other analyses have suggested that the effect may be more limited. Peng and Broecker (1991) examined the dynamic aspects of this proposal and concluded that, even if the iron hypothesis was completely correct, the dynamic issues of mixing the excess carbon into the deep ocean would limit the magnitude of the impact on the atmosphere. Joos *et al*. (1991) reported on a similar model experiment and found the ocean dynamics to be less important, the time path of anthropogenic CO_2 emissions to be very important, and the maximum potential effect of iron fertilization to be somewhat greater than reported by Peng and Broecker (1991).

Some of the concepts of iron fertilization have now been tested with 2 small-scale experiments in the equatorial Pacific Ocean. In experiment IronEX 1 (November, 1993) 480 kg of iron were added over 24 hours to a 64 km^2 area of the equatorial Pacific. In IronEX 2 (May/June, 1995) a similar 450 kg of iron (as acidic iron sulphate) were added over a 72 km^2 area, but the addition occurred in 3 doses over a period of one week.

The IronEx 1 experiment showed unequivocally that there was a biological response to the addition of iron. However, although plant biomass doubled and phytoplankton production increased fourfold, the decrease in CO_2 fugacity (in effect the partial pressure of CO_2 decreased by 10 micro atm) was only about a tenth of that expected (Martin *et al*., 1994; Watson *et al*., 1994; Wells, 1994). In the IronEX 2 experiment the abundance and growth rate of phytoplankton increased dramatically (by greater than 20 and twice, respectively), nitrate decreased by half, and CO_2 concentrations were significantly reduced (the fugacity of CO_2 was down 90matm on day 9). Within a week of the last fertilization, however, the phytoplankton bloom had waned, the iron concentration had decreased below ambient, and there was no sign that the iron was retained and recycled in the surface waters (Monastersky, 1995; Coale *et al*., 1996; Cooper *et al*., 1996; Frost, 1996).

These two experiments have demonstrated that week-long, sustained additions of iron to nutrient-rich, but iron-poor, regions of the ocean can produce massive phytoplankton blooms and large drawdowns of CO_2 and nutrients. While the results of these two experiments cannot be uncritically extrapolated, they suggest a very important role for iron in the cycling of carbon (Cooper *et al*., 1996). The consequences of larger, longer-term introductions of iron remain uncertain. Concerns that have been expressed relate to the differential impact on different algal species, the impact on concentrations of dimethyl sulphide in surface waters, and the potential for creating anoxic regions at depth (Coale *et al*., 1996; Frost, 1996; Turner *et al*., 1996). There is much to be learned of the ecological consequences of large-scale fertilization of the ocean.

Jones and Young (1998) suggest that the addition of reactive nitrogen in appropriate areas, perhaps in conjunction with trace nutrients, would increase production of phytoplankton and could both increase CO_2 uptake and provide a sustainable fishery with greater yield than at present.

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