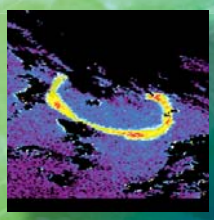
United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission

Ocean Fertilization

A scientific summary for policy makers



Experimental ocean fertilization using ferrous sulphate on UK-German FeeP study, 2004

OCEAN FERTILIZATION:

action to deliberately increase planktonic production in the open ocean. Fertilization might be carried out over a range of scales for a variety of purposes; it can be achieved by directly adding nutrients, or increasing nutrient supply from deep water, or potentially by other means.

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p 2 (Box 1): World Ocean Atlas (2005); US National Oceanographic Data Center

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p 9 (Box 3): Philip Boyd, in Encyclopedia of Sustainablility Science & Technology

p 10 (Box 4) World Ocean Atlas (2009)

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OCEAN FERTILIZATION context and key messages

Concern over human-driven climate change and the lack of success in constraining greenhouse gas emissions have increased scientific and policy interest in geoengineering – deliberate interventions in the Earth's climate system that might moderate global warming. Proposed approaches involve either removing carbon dioxide (CO_2) from the atmosphere by biological or chemical means (to reduce the forcing of climate change), or reflecting part of the sun's energy back into space (to counteract the forcing, by altering Earth's radiation budget).

Here we consider the practicalities, opportunities and threats associated with one of the earliest proposed carbon-removal techniques: large-scale ocean fertilization, achieved by adding iron or other nutrients to surface waters, directly or indirectly. The intention is to enhance microscopic marine plant growth, on a scale large enough not only to significantly increase the uptake of atmospheric carbon by the ocean, but also to remove it from the atmosphere for long enough to provide global climatic benefit. This suggestion grew out of scientific ideas developed in the late 1980s, based on analyses of natural, longterm climate changes (ice age cycles) and experiments that provided new insights into the natural factors that limit ocean productivity, and thereby control the cycling of carbon between sea and sky.

Proposals for large-scale application of ocean fertilization have been controversial, attracting scientific and public criticism. Upholding the precautionary principle, the Convention on Biological Diversity (CBD) decided in 2008 that no further ocean fertilization activities for whatever purpose should be carried out in non-coastal waters until there was stronger scientific justification, assessed through a global regulatory mechanism.

Such a regulatory framework is now being developed, through the London Convention and London Protocol (LC/LP). To assist that process, an overview of our scientific understanding is timely. The following headline messages are considered to represent the consensus view, discussed in greater detail in the main text and based on assessments of the published literature and extensive consultations:

- Experimental, small-scale iron additions to high nutrient regions can greatly increase the biomass of phytoplankton and bacteria, and the drawdown of CO_2 in surface water. The scale of these effects depends on physical and biological conditions, and the levels of other nutrients.
- Because scientific studies to date have been short-term and of relatively small scale, it is not yet known how iron-based ocean fertilization might affect zooplankton, fish and seafloor biota, and the magnitude of carbon export to the deep ocean is still uncertain. There is even less information on the effectiveness and effects of fertilizing low nutrient regions, either directly or by using mixing devices. No experimental studies have been carried out at the larger spatial and temporal scales envisioned for commercial and geoengineering applications.
- Large-scale fertilization could have unintended (and difficult to predict) impacts not only locally, e.g. risk of toxic algal blooms, but also far removed in space and time. Impact assessments need to include the possibility of such 'far-field' effects on biological productivity, sub-surface oxygen levels, biogas production and ocean acidification.
- Whilst models can be developed to improve predictions of both benefits and impacts, the totality of effects will be extremely difficult – and costly – to directly verify, with implications for the confidence and cost-effectiveness of commercial-scale applications.
- Estimates of the overall efficiency of atmospheric CO_2 uptake in response to iron-based

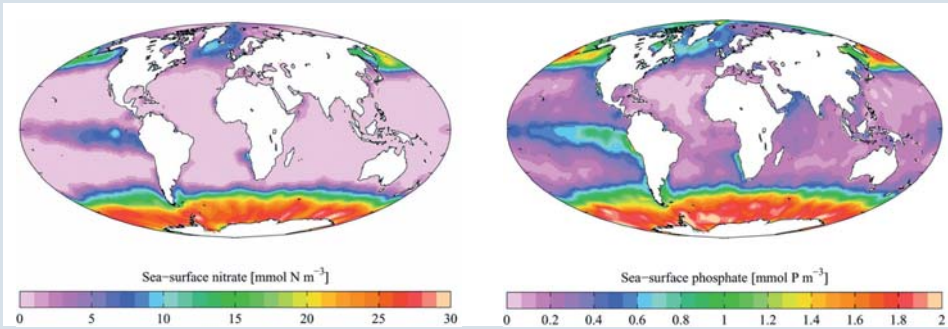
ocean fertilization have decreased greatly (by 5 – 20 times) over the past 20 years. Although uncertainties still remain, the amount of carbon that might be taken out of circulation through this technique on a long-term basis (decades to centuries) would seem small in comparison to fossil-fuel emissions. Fertilization achieved through artificial upwelling is inherently less efficient for sequestration.

- Monitoring must be an essential component of any large-scale fertilization activity, both to check claims of carbon sequestration (for intended geoengineering benefit) and to assess ecological impacts. Monitoring will need to: i) include a wide range of sensitive parameters; ii) take into account natural variability, preferably by including comparison with several otherwise similar but non-fertilized regions; and iii) continue over appropriate time and space scales, potentially over several years and covering many thousand square kilometres.

This document focuses on scientific issues. Whilst socio-economic, ethical and legal considerations are also highly important, they are not given equivalent attention here. Where estimates of likelihood or certainty/uncertainty are given, they are intended to be equivalent to definitions used by the Intergovernmental Panel on Climate Change; however, there has been no formal process to quantify risks and probabilities.

box 1

Limitation of oceanic biological production in high and low nutrient regions



Average levels of available nitrogen (as nitrate, left) and phosphorus (as phosphate, right) in the surface ocean

Biological production in the ocean usually refers to growth of planktonic (drifting) microorganisms that fix carbon by photosynthesis. This requires light and a range of essential elements or nutrients. Since carbon (C), nitrogen (N) and phosphorus (P) are required in relatively large amounts, they are known as macro-nutrients.

The amount of biomass produced in the sunlit, upper ocean is controlled by the availability of the scarcest nutrient. In low nutrient regions – shown above in light purple – N or P is the limiting macro-nutrient. Such areas are effectively biological deserts, since their surface waters receive very low (re-)supply of N and P, mostly by slow mixing with deeper, nutrient-rich water. In other regions, macro-nutrient supply, and plant biomass, may be larger but with a strong seasonal cycle, e.g. with mixing caused by winter storms.

There are also large areas of the surface ocean – shown above in red, yellow and green – where N and P levels remain well above their limiting concentrations year-round. In these high nutrient regions, the concentration of iron (Fe) can instead be limiting. Since phytoplankton need around a thousand times less Fe than either N or P, it is known as a micronutrient.

Addition of limiting nutrient(s) to an ecosystem can have a fertilizing effect. If limitation is by a micronutrient, such as iron, much less needs to be added to stimulate plant growth.

In some low nutrient regions, limitation by N can be overcome by specialised microorganisms that can use dissolved nitrogen gas in seawater. Fertilization with iron and/or phosphate may then increase the abundance of these N-fixing organisms.

>2<

WHY FERTILIZE the ocean?

For scientific research

To date, 13 small-scale fertilization studies have been performed in the open ocean. They have each affected a few hundred square kilometres for a few weeks, on a similar scale (and with similar consequences) to natural blooms of phytoplankton. The main purpose of these studies has been to improve scientific understanding of nutrient limitation, a factor closely connected to marine ecosystem structure, productivity and resource exploitation, and the global cycling of carbon and other key elements. A major achievement has been the conclusive demonstration that the supply of a micronutrient, iron – that constitutes 35% of the mass of the Earth as a whole – controls biological production in high nutrient regions of the ocean (Box 1).

For deliberate carbon sequestration

The oceans will, over thousands of years, take up almost all of the CO_2 that will be released through the burning of fossil fuels. Ocean fertilization for the purpose of geoengineering aims to enhance the rate of ocean uptake of atmospheric CO_2 in order to slow down climate change. This could (in theory) be achieved by large-scale fertilization, applied continuously or semi-continuously to many millions of square kilometres for decades. The aim would be to increase the oceanic sequestration of CO_2 — its storage in the ocean interior — in sufficient quantity and for a sufficient time period to make a climatically-significant reduction in the increase of atmospheric CO_2. This would require verification and also confirmation that there would be no deleterious unintended side effects. Trials to test the viability of such ideas would need to be at the scale of thousands of square kilometres; they have yet to be attempted.

For fishery enhancement

Increases in ocean productivity following large-scale ocean fertilization might provide additional benefits from a human perspective, since growth enhancement of fish stocks might result, increasing the yield of exploitable fisheries. If this were the main objective, the fertilization application would be on a regional, rather than global basis, with a clear need to demonstrate commercial cost-effectiveness. However, the science is still highly uncertain, the supposed benefits have yet to be demonstrated, and 'ownership' issues for open ocean fishery enhancement have yet to be resolved.

>3<

HOW IS THE OCEAN FERTILIZED and how could CO_2 be sequestered?

Nutrients are supplied naturally to the surface ocean from external sources (rivers, submarine volcanoes and seeps, glacial ice and atmospheric dust) and also internally, through nutrient recycling in the surface, mid- and deep ocean. The recycling involves the decomposition of dead marine plants, animals and microbes, releasing the nutrients and CO_2 that were previously used for plant growth in the upper, sunlit waters (Fig 1). About a quarter of the nutrient release takes place in the sub-surface ocean, as a result of sinking downward of biological material, mostly as small particles; this export of carbon from the upper ocean is referred to as the 'biological pump'.

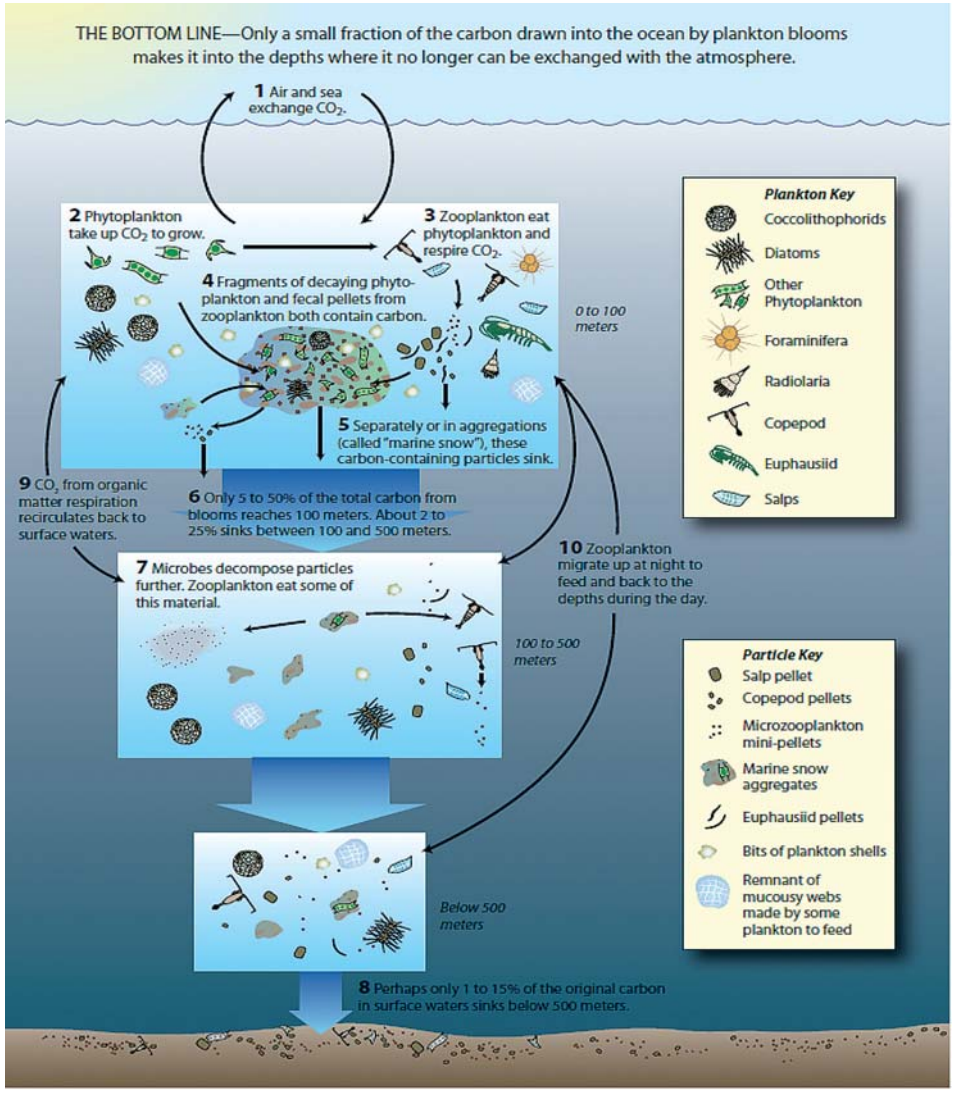


Fig 1. *Processes involved in biological production, decomposition and nutrient cycling in the open ocean.*
Interactive version at www.whoi.edu/oceanus/viewFlash.do?fileid=30687&id=23452&aid=35609

box2

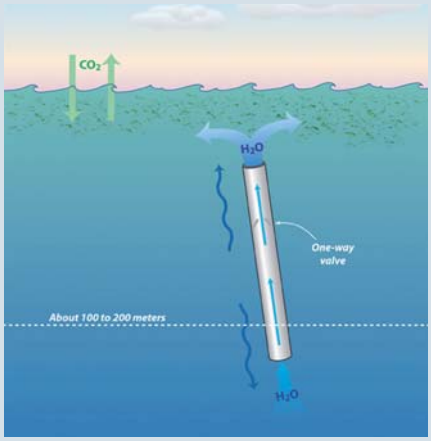
Artificial fertilization techniques

Iron in seawater is mostly in an insoluble form which precipitates and sinks out of the surface ocean rapidly. For fertilization experiments, iron has been added as iron sulphate ($FeSO_4 \cdot 7H_2O$) which is a common agricultural fertilizer and relatively soluble. The iron sulphate is dissolved in acidified seawater, and pumped into the ocean behind a moving vessel. The acidic solution is neutralised rapidly upon mixing with ambient seawater and the iron is transformed chemically into its insoluble form, more rapidly in warmer waters. Commercial fertilization activities might add chemical complexing agents to keep iron in solution for longer.

Artificial upwelling: floating pipes (right) have been proposed, incorporating one-way valves that exploit wave energy or oceanic temperature and salinity gradients to bring deeper water to the near-surface. Typical dimensions suggested for the pipes are ~10 m diameter with lengths of 100–300 m or longer. Networks of pipes, either free-floating or tethered to the seafloor, could be distributed across regions with low surface nutrient concentrations.

Phosphorus addition experiments have used concentrated phosphoric acid mixed with sodium bicarbonate, or direct addition of anhydrous monosodium phosphate. The solutions are pumped into surface waters behind a moving vessel.

Nitrogen: addition of urea $(NH_2)_2CO$ has been commercially-proposed, either as a liquid mixed with phosphate solution and seawater and pumped into the ocean or as spherical grains spread over the ocean surface.



Most ocean fertilization approaches (by small-scale experiments and by models) have to date focused on increasing the external supply of nutrients. However, acceleration of the internal recycling of nutrients is also being explored, using artificial upwelling to bring to the surface naturally nutrient-rich deeper waters (Box 2), or by using optical devices to increase light penetration.

There is an important distinction between fertilization with external or recycled nutrients. An increase of the external supply of nutrients to surface waters can, potentially, reduce their concentration of dissolved CO_2 – hence increasing ocean uptake of CO_2 from the atmosphere via air-sea gas exchange. In order that any additional CO_2 uptake from the atmosphere can subsequently be considered to be sequestered, it should be stored at least below the depth to which seasonal mixing occurs, and generally, the deeper the better (Box 3). In contrast, artificial upwelling not only pumps nutrients upwards, but also the CO_2 released from previous cycles of production/export and sinking/ decomposition. Although some net uptake of carbon may be possible, e.g. if nitrogen-fixation is stimulated, the drawdown of CO_2 from the atmosphere by artificial upwelling is inherently limited.

>4<

WHAT HAPPENS when the ocean is fertilized?

Iron addition

The bullets points below summarise findings from the 13 small-scale, iron addition experiments carried out to date by independent researchers (Fig 2). These studies initially fertilized patches of surface ocean in high nutrient regions over the range 40 - 300 square kilometres. Two pilot studies using iron have also been carried out by commercial organisations, on a similar scale. Full-scale demonstrations or deployments for geoengineering or fishery enhancement would, however, need to be very much larger, involving fertilization of around 10,000 square kilometres.

- Levels of the plant pigment chlorophyll increased in all experiments, by 2-25 times, with associated increases in carbon fixation. Some of the artificially-induced blooms of phytoplankton were visible to satellite-based ocean colour sensors.
- Phytoplankton responded to the iron addition by an increase in photosynthetic efficiency and by altered rates of nutrient uptake.
- Effects on phytoplankton production and biomass were greater in shallower surface mixed layers due to the more confined depth range and, consequently, higher average light intensity experienced by the fertilized plankton. Response was more rapid in warmer waters.
- In most of the experiments, the dominant phytoplankton group changed, with a shift in community composition from smaller groups (cyanobacteria), via medium-sized phytoplankton (haptophytes), to larger diatoms.
- Although diatoms usually dominated species composition after iron addition, the most abundant diatom species varied between locations and experiments. This may reflect regional species differences of initial 'seed' populations as well as competition under a range of ocean conditions.
- Bacterial biomass increased during most of the experiments (by 2-15 times). A transient increase in the stocks of small grazers, microzooplankton, was also reported from some experiments.
- The duration of the experiments was usually too short to allow larger zooplankton to respond. However, grazing increased in two experiments with high pre-existing stocks of medium-sized zooplankton (copepods), and played a major role in controlling the development of these blooms.
- There is, as yet, no information from experimental studies on responses further up the food chain (e.g. by fish).

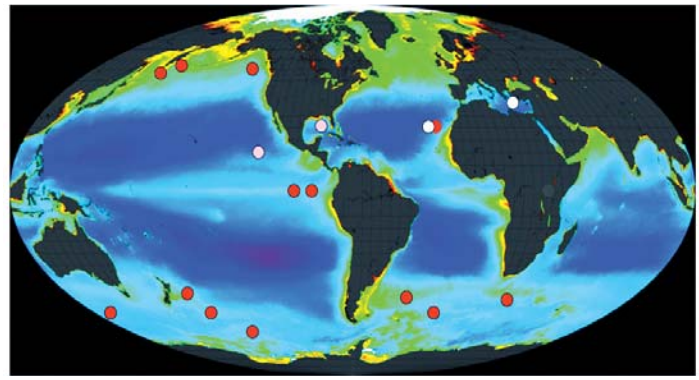


Fig 2. *Sites of the 13 iron fertilization experiments (red), two commercial trials using iron (pink) and two phosphate addition studies (white) carried out to date, on map of satellite-based ocean primary production (yellow/green, high; dark blue, low).*

Phosphorus addition experiments

There have been two small-scale field studies involving P-additions, both in low nutrient waters. In the Eastern Mediterranean, the experiment resulted in rapid increases in bacterial production and zooplankton biomass, and a moderate increase in rates of nitrogen-fixation. However, there was

a slight decrease in phytoplankton biomass and chlorophyll (in contrast to a predicted increase).

Similar effects on bacteria and phytoplankton were observed off NW Africa when phosphate was added alone and with iron. These results are not yet fully explained; they suggest alternative food-chain pathways and/or additional complex limitations operating in low nutrient systems subject to P limitation.

Artificial upwelling

Technologically-robust designs for 'ocean pipes' would be needed to operate in the way envisaged for artificial upwelling systems. Those developed to date have delivered pumping rates of 45 m^3 per hour, but for less than a day – too short for the expected biological and biogeochemical responses to be observed. Modelling studies have been undertaken, but with major uncertainties concerning ecosystem response; in particular, whether induced upwelling of water with high P levels might stimulate nitrogen-fixation, with potential for net CO_2 drawdown. Overall, it seems more likely that artificial upwelling will become a tool to study marine ecosystem responses to nutrient perturbations and changes in mixing regimes, rather than a cost-effective measure to counteract climate change.

Nutrient depletion and co-limitation following fertilization

The addition of a limiting nutrient will, ultimately, result in another factor becoming limiting. In the case of iron additions to high nutrient regions, macronutrients such as silicate (required by diatoms) and nitrate (required by all phytoplankton) subsequently became depleted. In several experiments, the diatom bloom either crashed within two weeks of fertilization or, in one case, did not develop at all – due to a lack of silicon. Light can be an additional limiting factor, especially in polar regions, due to season, cloud cover, deep mixing and self-shading caused by phytoplankton themselves. For phosphate addition experiments in low nutrient regions, the biological response was probably limited by nitrogen availability.

Fate of the added nutrients

The fate of externally-added nutrients depends on their chemical nature. Several experiments with iron required re-fertilization because the added iron rapidly 'disappeared', either through formation of organic complexes or through adsorption onto particles which sank. Thus added iron can be lost from surface waters before it is used by plankton, and much may be removed from the ocean permanently through burial of particles in sediments. In the case of fertilization with phosphate or nitrogen, the added nutrients are expected to be incorporated rapidly into biomass, to be subsequently recycled and released through decomposition in surface or subsurface waters, with relatively little being lost to sediments.

CO_2 drawdown and carbon export

Increases in phytoplankton biomass due to experimental fertilization have been accompanied by reductions in CO_2 levels in surface water, promoting CO_2 drawdown from the atmosphere by gas exchange. The amount of CO_2 drawdown has varied greatly between studies, depending on: the amount of nutrient added; whether other factors limited the biomass increase; the nutrient-carbon ratio of the enhanced biomass; the extent to which there were additional removal processes for the added nutrients; conditions at the air-sea interface (e.g. wind speed, wave characteristics); the depth of the surface mixed layer; and the time that fertilized waters remained in direct contact with the atmosphere. Most experiments did not continue for a sufficiently long time period to follow the decline of the stimulated phytoplankton bloom and associated carbon export. Two studies did report increased carbon export, but of different proportions.

Unexpected responses

The experiments to date show that the biological and chemical responses to nutrient fertilization are variable and difficult to predict. Examples include the unexpected decrease in chlorophyll levels in response to phosphate addition in the Mediterranean; and the observation that markedly different phytoplankton communities and total biomass resulted from two iron addition experiments conducted a year apart at the same site in the north west Pacific Ocean.

>5<

ARE THERE UNINTENDED impacts of ocean fertilization?

Changes to the surface ocean ecosystem

The iron fertilization experiments conducted to date are not known to have resulted in harmful algal blooms. However, shipboard experiments in the north west Pacific suggest that diatom species that produce the toxin domoic acid might increase in abundance in response to iron fertilization, and their rate of toxin production might also be raised. This possibility requires further investigation. 'Non-deliberate' ocean fertilization with nitrogen-containing urea, through sewage, is known to favour the growth of cyanobacteria and dinoflagellates, including toxic species.

As already indicated, fertilization experiments have been of insufficient duration and spatial scale to reveal changes at higher levels within the food chain. Thus any suggestions of either positive or negative impacts on fish stocks remain speculative.

Production of climate-relevant gases in the surface ocean

Ocean fertilization has been observed to increase the surface water concentrations of a range of climate-relevant gases associated with phytoplankton growth. Of these, the best studied is dimethylsulphide (DMS) which, after emission to the atmosphere, might influence climate via the formation of particles that promote cloud formation. Most iron fertilization experiments have shown increased DMS production. Results have been extrapolated to suggest that fertilization of 2% of the Southern Ocean could decrease temperatures by ~2°C in that region. However a fertilization study in the sub-Arctic Pacific observed a DMS decrease, and recent modeling analyses indicate that the linkage between DMS and climate is relatively weak. Several other trace gases have been observed to have altered concentrations after fertilization, with potential implications for atmospheric ozone concentrations. The overall significance of such effects is currently unclear.

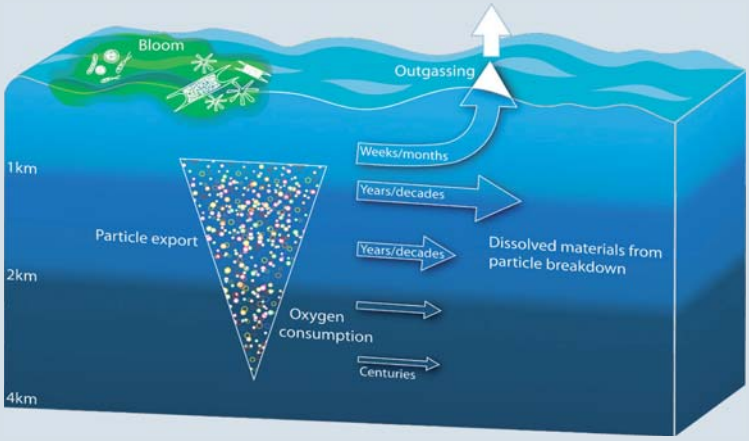
Far-field effects

Far-field effects, hundreds or thousands of kilometres from the fertilization site and occurring months, years or decades afterwards, include potential impacts on subsurface waters and sediments into which the fertilized biomass sinks. For small-scale, short-term experimental studies such effects are almost certainly trivial and non-measurable, but they are likely to become significant if large-scale, longterm fertilization is carried out. Prediction and assessment of far-field impacts requires information on biomass production and sinking as well as on the circulation and mixing of both the fertilized surface waters and the subsurface waters beneath the fertilized location; such information can then be used in complex models which simulate ocean circulation, biology and chemistry. However, model predictions of far-field effects will be extremely difficult to verify with direct observations because of the large spatial and time-scales involved (Section 7).

An important far-field consequence of large-scale fertilization with limiting nutrients (e.g. with iron in a high nutrient region) involves the depletion of other non-limiting nutrients, such as nitrate or phosphate. This depletion can, in turn, reduce the productivity of remote regions downstream of the fertilization location, particularly where natural sources of the fertilizing nutrient are available (e.g. iron from shelf sea sediments or atmospheric

box3

The importance of transport and timescales



Vertical and horizontal transport processes over a range of timescales affect the fate of biologically-fixed carbon in the ocean

A key characteristic of the oceanic ecosystem is transport over long distances associated with mixing, sinking of particles (on a timescale of weeks to months), and ocean circulation. A consequence is that changes at one place in the surface ocean can impact deeper water a few kilometers away in the vertical and thousands of kilometers away in the horizontal.

Oceanic mixing also causes impacts to spread, so that fertilization of a relatively small area could, to some degree, ultimately impact vast regions of the ocean. There can be long time delays as well as large distances separating large-scale fertilization and its impacts, with associated difficulties for the attribution of impacts or verification of effects.

dust). This potential far-field impact has been referred to as 'nutrient robbing'. Thus it is possible that fertilization of an open ocean location in international waters could reduce productivity around islands and countries not involved with the fertilization activity. Models have examined the scale of such effects and, for scenarios involving large-scale fertilization over long periods, large reductions in far-field productivity are indicated. These reductions could have significant consequences, including a re-distribution or overall decrease in fish production.

The other side of the coin to 'nutrient robbing' in the surface ocean is that increased nutrient levels in deep ocean waters (due to decomposition of the biomass that was increased by fertilization) may enhance the productivity of ecosystems in other remote regions, where these waters are eventually returned to the surface ocean by upwelling or mixing.

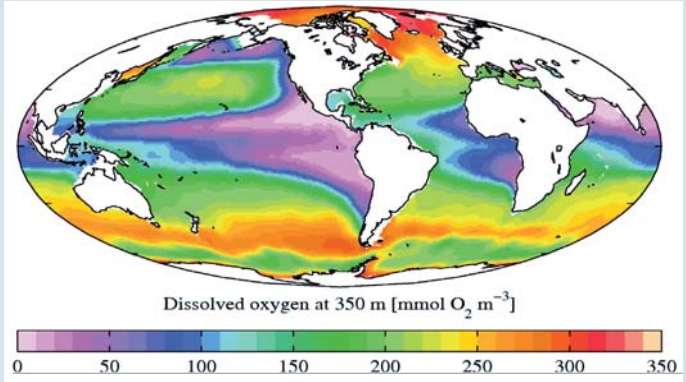
In an analogous way, any additional CO_2 taken up locally due to the fertilization can potentially 'rob' regions downstream of their CO_2 uptake capacity due to the reduced, far-field, biological production. This must be considered in determining the overall CO_2 sequestration efficiency of any fertilization (Section 6).

Subsurface oxygen decrease

Decomposition of any fertilization-enhanced biomass will decrease oxygen levels in the sub-surface ocean, with impacts that may be local or remote, depending on the regional circulation, and could lead to critical thresholds or tipping points being crossed (Box 4). Mid-water oxygen depletion has not been reported for fertilization experiments conducted to date due to their limited scale and duration, but additional oxygen demand is an inevitable consequence of enhanced downward carbon export. Decreased oxygen

box4

'Tipping points' relevant to ocean fertilization



Global distribution of oxygen at 350 m. Red/purple areas show oxygen minimum zones

There are at least two critical thresholds or 'tipping points' relevant to ocean fertilization impacts:

Oxygen. The abundance of dissolved oxygen in the oceanic water column and sediments is a key control for life in the sea as well as for an array of chemical processes, including nutrient recycling. Subsurface waters, not in direct contact with the atmosphere, have reduced oxygen levels representing the balance between oxygen supply by ocean circulation and the cumulative demand due to respiration processes. Critical threshold concentrations of oxygen are process-dependent, but are greater than zero and generally in the range 5-40 µmol O_2 per litre. Increased organic carbon supply due to large-scale ocean fertilization could, potentially, drive far-field oxygen concentrations below these threshold concentrations in regions that are removed from close contact with the atmosphere via mixing.

Carbonate concentration. The tendency of carbonate minerals to dissolve in seawater, including the carbonate shells of both living and dead marine organisms, is governed by a critical concentration of the carbonate ion (CO_3^{2-}) as well as by temperature and pressure. Release of CO_2 to subsurface seawater during decomposition of organic carbon reduces pH (acidification) and carbonate ion concentration. Increased organic carbon supply to the deep ocean could, therefore, alter the depths and locations where these critical carbonate concentrations are reached in the ocean interior.

levels close to the site of fertilization might precondition subsurface waters so that they cross a critical threshold during subsequent transport through the ocean interior (e.g. towards oxygen minimum zones).

Early studies using highly-simplified 'box models' predicted that large volumes of the subsurface ocean would become anoxic as a consequence of large-scale and continuous fertilization. More sophisticated models, based on more likely fertilization scenarios, predict a less dramatic scenario involving growth of the extent of low-oxygen regions rather than oceanic anoxia. Fertilization-induced oxygen depletion of mid-depth waters that supply certain upwelling systems and oxygen minimum zones could, however, cause increased frequency and intensity of near-shore hypoxia and, as a consequence, significant mortality of marine organisms. Important within-ocean nutrient recycling processes might also be altered. The changes of subsurface oxygen concentrations are dependent on the location as well as the scale of the fertilization in relation to ocean circulation patterns and existing oxygen distributions, and can only be assessed using complex models. These models have inherent limitations in their ability to represent existing oxygen distributions and hence predictions of change in oxygen levels must be considered uncertain.

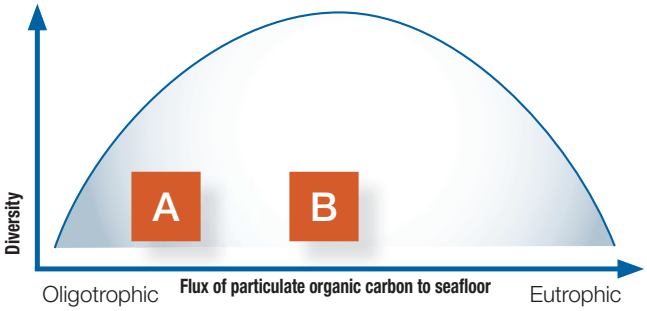


Fig 3. *The greatest seafloor biodiversity occurs when organic carbon export from the upper ocean is midway between very productive (eutrophic) and very unproductive (oligotrophic) conditions. The additional biomass stimulated by large-scale ocean fertilization could therefore increase biodiversity if initial state was at A, or decrease it if at B.*

Effects on seafloor ecosystems

The effect of large-scale ocean fertilization on seafloor ecosystems depends critically on the water depth where the fertilization takes place and the sinking speeds of the particulate biomass produced. In deep waters, a large proportion of any enhanced carbon flux will be decomposed before reaching the sea floor. The enhanced carbon flux to the seafloor is likely to increase the amount of seafloor biomass, as long as oxygen is not depleted; this might have either a positive or negative effect on seafloor biodiversity, depending on its background state (Fig 3).

Production of climate-relevant gases and greenhouse gas 'offsetting'

Decomposition of sinking biomass can produce the long-lived, greenhouse gases nitrous oxide (N_2O) and methane (CH_4), with global warming potentials 320 times and 20 times greater than CO_2 respectively. Thus the release to the atmosphere of relatively small amounts of these gases could offset the desired effects of CO_2 sequestration. Methane is considered the lower risk, since most of this gas naturally produced within the ocean is used as an energy source by other marine microbes and converted to CO_2 before reaching the atmosphere.

The ocean is, however, an important source of N_2O and any enhanced production is likely to be emitted to the atmosphere. The far-field impact of large-scale fertilization has been simulated by models. If fertilization takes place over waters that are already low in oxygen (e.g. the tropics), the N_2O yield could be large, with an estimated 40 - 70% offset of the benefits of CO_2 reduction after 100 years. The offsetting would be much lower (~10%) for fertilization of waters underlain with higher oxygen concentrations, such as in the Southern Ocean. Assessments of overall climate forcing depend critically on the accuracy of ocean circulation models, the representation of oxygen in these models, and our limited knowledge of N_2O yield during biomass decomposition. Only minor increases in N_2O production have been observed during iron addition experiments; at this scale only transient and highly dispersed effects are likely, without ecological or climatic significance.

Ocean acidification

If large-scale fertilization were to lead to substantive additional CO_2 sequestration at depth, this would increase the acidification of ocean interior waters. Such changes would alter the depth at which carbonate biominerals start to dissolve (Box 4), potentially restricting the habitat of deep-ocean organisms that build shells and other structures out of these biominerals, e.g. deep-sea corals.

>6<

HOW EFFICIENT IS LARGE-SCALE OCEAN FERTILIZATION for sequestering atmospheric carbon?

Efficiency with addition of external nutrients

Twenty years ago, fertilization of surface waters with iron looked like a highly efficient process for stimulating export of large amounts of carbon, via sinking particles, to the deep ocean where it would be isolated from the atmosphere for 100 - 1000 years. This early view was based on the calculation that 1 tonne of added iron might sequester more than 100,000 tonnes of carbon, i.e. a carbon export ratio (Box 5) greater than 100,000:1.

However, the one experimental fertilization carried out to date that gave detailed data on carbon export indicated a much lower estimates of this efficiency, at less than 5,000:1. This could be due to rapid grazing or decomposition of the enhanced phytoplankton growth. An additional factor, observed in other studies, was the rapid loss (of up to 75%) of the added iron, by its precipitation and scavenging onto particles before it could be utilized for phytoplankton growth. Improved delivery mechanisms for iron, such as the use of chemical complexing agents, could improve this efficiency, but with cost implications.

The atmospheric uptake efficiency (Box 5) based on the CO_2 drawdown measured during these short-duration experiments was only 2 - 20%. These may be lower bound estimates to this efficiency given that uptake of CO_2 is likely to have continued for a period of time after measurements ended. On the other hand, ~50 % of the exported biomass is likely to decompose above a depth of 500m. In several of the high nutrient oceanic regions that might be considered for fertilization, water mixing in wintertime extends to at least this depth so that much of the CO_2 from the exported biomass would return to the atmosphere within a year of fertilization.

How long exported carbon remains sequestered strongly affects the atmospheric uptake efficiency and can only be addressed with models. Such models have undergone steady development so that estimates of the atmospheric uptake efficiency are still changing as new processes are investigated and more realistic models are implemented. Early models, based on very simple treatments of nutrient uptake, suggested atmospheric uptake efficiencies of less than 10-40% whereas more recent models suggest higher efficiencies (70-90%), at least for fertilization of tropical waters. Clearly this is an area of continued uncertainty which greatly impacts estimates of the overall sequestration efficiency.

However, even using the highest estimates for both carbon export ratios and atmospheric uptake efficiencies, the overall potential for ocean fertilization to remove CO_2 from the atmosphere is relatively small. Thus recent calculations of cumulative sequestration for massive fertilization effort over 100 years are in the range 25-75 Gt (gigatonnes) of carbon (Fig 4), in comparison to cumulative emissions of around 1,500 Gt carbon from fossil fuel burning for the same period under business-as-usual scenarios.

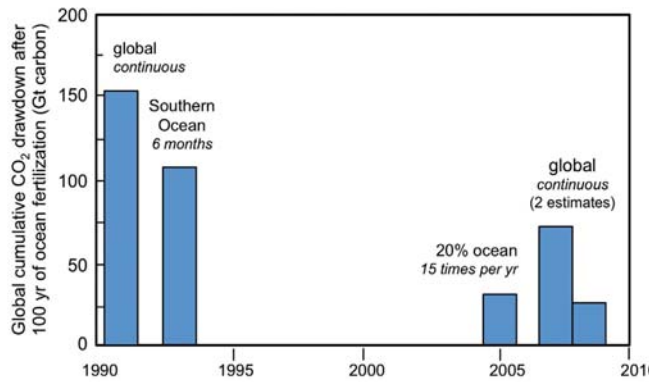


Fig 4. *Model-based estimates of the effectiveness of carbon sequestration (cumulative drawdown over 100 yr) for large-scale, iron-based ocean fertilization. Dates relate to year of publication.*

box 5

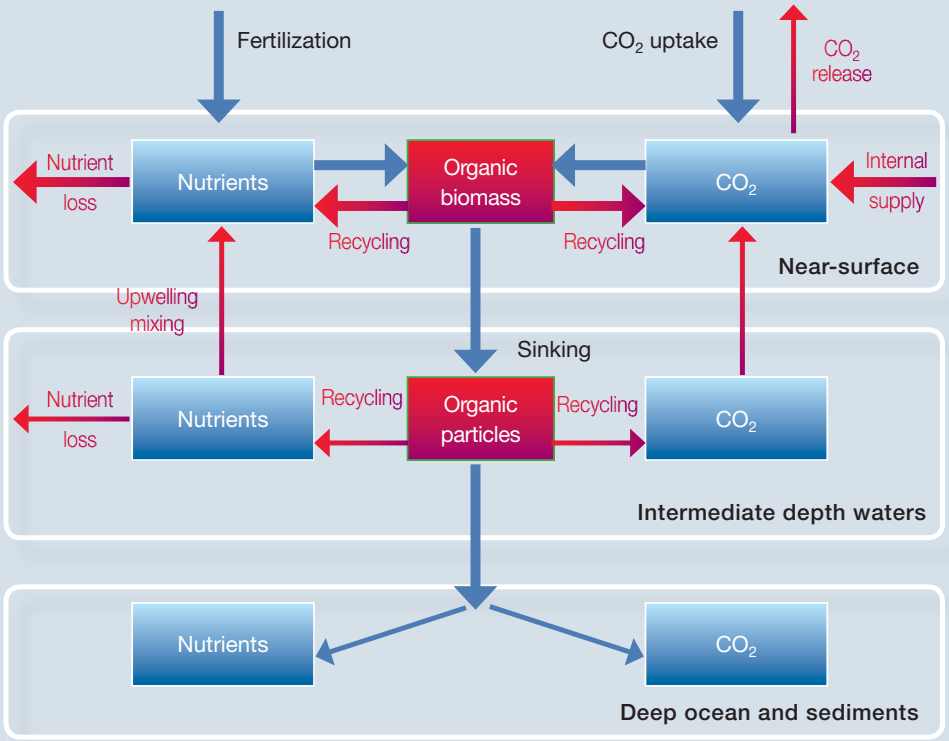
Sequestration efficiency

The overall efficiency of ocean fertilization as a means to sequester atmospheric CO_2 is the product of two difficult-to-estimate factors: 1) how much additional (net) carbon is exported from surface waters into the deep ocean for a given addition of nutrient (the carbon export ratio), and 2) what proportion of the additional carbon export is, ultimately, resupplied by carbon taken up from the atmosphere (the atmospheric uptake efficiency). Some sources of inefficiency are depicted schematically as red arrows in the figure below, the thicker red arrows indicating inefficiencies that occur relatively rapidly, and the thinner red arrows those that may take years or decades.

The **carbon export ratio** is controlled by nutrient loss processes, the carbon:nutrient ratio in fertilized biomass, and the proportion of biomass resulting from fertilization which sinks into the deep ocean.

The **atmospheric uptake efficiency** depends on factors such as wind and waves which determine the rate of air-sea gas exchange and the depth to which exported carbon sinks before being decomposed (with higher efficiency at greater depths).

The efficiency of sequestration over decadal to century timescales depends also on whether the fertilizing nutrient is recycled or lost from the ocean.



Principle processes and inefficiencies involved with fertilization for carbon sequestration. Blue arrows represent the intended sequestration pathways whereas red arrows represent pathways by which the efficiency of sequestration is reduced.

Carbon export efficiency with artificial upwelling

The proposed enhancement of the biological pump by artificial upwelling is less efficient for CO_2 sequestration. Initial modeling has indicated that global deployment of pipes could result in large changes to biological production and export of carbon, but relatively small changes to the air-sea CO_2 uptake. This is because most of the additional exported carbon is decomposed and recycled close to the surface (<500 m). Alternative scenarios, yet to be investigated, could involve manipulation of the nutrient supply rate, or stimulation of nitrogen-fixing organisms or organisms that can sink deep into the ocean.

Long-term (century-scale) sequestration

Most model simulations for large-scale fertilization are for periods of 10-100 years. The CO_2 sequestration potential for longer periods depends on what happens when artificially CO_2 enriched deep waters are eventually returned to the ocean surface. This in turn depends on the nature of the nutrient used for fertilization. If the nutrient is re-released to deep waters via decomposition in the same proportion to carbon as used for growth, then the added nutrient can be considered to be recycled. When such recycled nutrient is upwelled, it can fuel another cycle of growth, carbon uptake and sinking so that the original extra carbon remains in the ocean. However, if the fertilizing nutrient is removed permanently from the ocean by burial in sediments (the likely fate of added iron), then the nutrient is unavailable when the CO_2-enriched deep water is brought to the surface again by upwelling processes — and much of the extra CO_2 drawdown resulting from the initial fertilization will be returned to the atmosphere.

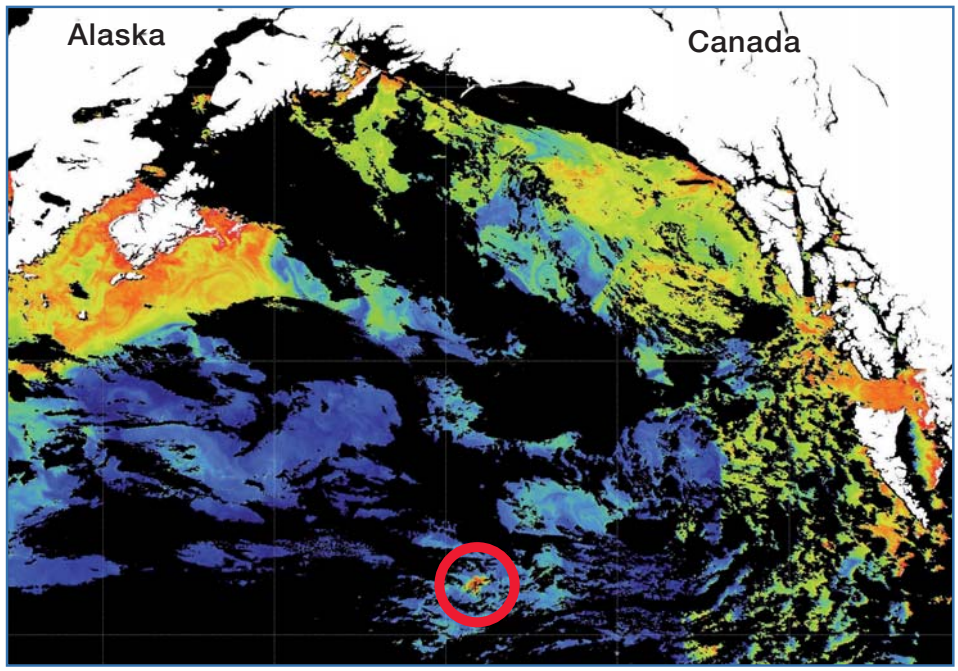


Fig 5. *Satellite image of the phytoplankton bloom stimulated by the SERIES iron fertilization experiment in the North East Pacific (circled). Black areas are cloud cover. The red/orange colours south of Alaska and in other coastal areas are natural blooms. This SeaWiFS image was acquired 19 days after initial addition of iron (on 29 July 2002); five days later, the patch was barely visible.*

>7< MONITORING FOR verification and reversibility

Verification

If the objective of fertilization is to claim 'credit' for enhanced sequestration of carbon then verification must include measurement-based estimates of the amount of carbon sequestered. Alternatively, if the objective is to increase the amount of biomass at a particular trophic level of the ecosystem (e.g. of a harvestable marine resource, such as fish), then the increase in biomass of the target species must be measured, to show that the desired effect has been achieved. In both cases, verification requires:

- monitoring of changes in the downward carbon export or fish biomass in both the fertilized areas and adjacent areas that were not fertilized but were otherwise similar
- long-term (months to years) and far-field monitoring to determine if there are subsequent rebound effects that might offset some of the initial change or might have negative impacts.

Monitoring must be sufficiently extensive to provide defensible verification that fertilization objectives have been achieved without unacceptable or unintended negative impacts. Verification should address far-field effects on the concentrations of oxygen and nitrous oxide (Section 5) as well as far-field reductions in surface nutrient levels that might decrease carbon sequestration and productivity elsewhere ('nutrient robbing' and 'CO_2 sink robbing').

Effective monitoring of the short-term, near-field intended effects of large scale fertilization will itself be costly. In the opinion of several scientists who have been involved in past iron fertilization experiments, adequate verification cannot yet be achieved with currently available observing capabilities.

Reversibility

There is a consensus within the scientific community that none of the small-scale iron fertilization experiments conducted to date are likely to have resulted in long term alteration of ocean ecosystems. Thus the individual fertilizations of several hundred square kilometres of ocean surface, each with ~10 tonnes of iron sulphate, represent a scale comparable to natural bloom events, having effects limited to a few months. However, the findings from small scale fertilization experiments cannot be directly scaled up to the much larger scales envisioned for commercial and geoengineering applications. Purposeful fertilization on a scale large enough to cause a measurable change in atmospheric carbon dioxide concentration will also cause major alterations to the structure of regional planktonic ecosystems, since large-scale sequestration of carbon requires a major shift in plankton community composition.

Would such an artificial change to a marine ecosystem be reversible if it were later judged to be deleterious? For comparison, a 'regime shift' associated with natural variability was documented in the subarctic North Pacific ecosystem in 1977 with a return to more or less the initial state observed in 1989. The biological indicators of the regime shift were more clearly obvious than the physical factors, which were presumed to have been the causative factors. In general, we rarely understand the factors and mechanisms that cause large-scale, natural regime shifts within marine ecosystems. Hence it is arguable that we have insufficient knowledge, let alone technique, to purposefully manipulate an ecosystem to reverse any large scale, long term changes to ecosystems that might be have been initiated by deliberate ocean fertilization.

>8<

GOVERNANCE and policy

The United Nations General Assembly has encouraged States to support the further study and enhance understanding of ocean fertilization (Resolution 62/215; December 2007). Four UN bodies and associated secretariats have major interests in this topic: the Intergovernmental Oceanographic Commission of UNESCO (IOC), the Convention on Biological Diversity (CBD), the International Maritime Organization (IMO) and the UN Convention on Law of the Sea (UNCLOS). Together they cover the spectrum of marine science, marine conservation and pollution regulation.

In response to concerns that large-scale ocean fertilization might be attempted before its consequences were fully understood, the CBD requested Parties, and urged other governments, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities. This justification should include an assessment of associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities, with the exception of small scale scientific research studies within coastal waters (Decision IX/16; May 2008). The 'coastal waters' exception was intended to recognise that territorial seas and other maritime jurisdiction zones already gave states the responsibility for conserving and managing their own marine resources.

The CBD Secretariat subsequently published a review of the impacts of ocean fertilization on marine biodiversity, with its main conclusion being that sound and objectively verifiable scientific data of such impacts are scarce. To provide such information, the CBD review considered that more extensive and targeted field work, and better models of marine processes, were needed – whilst recognising that ocean fertilization presents serious regulatory challenges, to avoid harm to the marine environment.

The IMO is addressing such challenges in its role as Secretariat for the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (the London Convention) and its 1996 Protocol (the London Protocol; together known as LC/LP). In October 2008, the LC/LP Parties decided that: 1) given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed; 2) they would develop a potential legally binding resolution or an amendment to the London Protocol on ocean fertilization; and 3) they would also develop a framework for assessing the compatibility of ocean fertilization experiments with the London Convention and Protocol. The IMO definition of ocean fertilization excluded "conventional aquaculture, or mariculture, and the creation of artificial reefs".

The IOC has considered issues relating to ocean fertilization at its 25th Assembly (June 2009) and its 43rd Executive Council (June 2010). The IOC has been closely involved in the CBD and IMO discussions. IOC Member States have agreed that the precautionary principle is fundamental to the regulation of ocean fertilization, and reasserted that IOC's main role is to respond to requests for scientific or technical information and advice from relevant bodies or Member States. The current review provides an example of such contributions to the overall process.

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Main commercial interests

Atmocean Inc (wave-driven ocean upwelling system) www.atmocean.com

Ocean Nourishment Corporation Pty Ltd (macronutrient additions to enhance fish stocks and carbon sinks) www.oceannourishment.com

Climos (potential application of ocean iron fertilization) www.climos.com

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