

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION COMMISSION OCÉANOGRAPHIQUE INTERGOUVERNEMENTALE COMISIÓN OCEANOGRÁFICA INTERGUBERNAMENTAL MEЖПРАВИТЕЛЬСТВЕННАЯ ОКЕАНОГРАФИЧЕСКАЯ КОМИССИЯ

اللجنة الدولية الحكومية لعلوم المحيطات

政府间海洋学委员会

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- To: IOC Member States Action Addresses
- Cc: Chairman, Vice-Chairmen IOC Chairmen, Vice-Chairmen IOC Intergovernmental Subsidiary Bodies Permanent Delegations/Observer Missions to UNESCO of IOC Member States President and Executive Director SCOR Executive Director ICSU Relevant Governmental and Non-Governmental Organizations

Subject: Scientific Summary for Policy-makers of the State of Knowledge on Ocean Fertilization

Dear Madam/Sir,

On behalf of the Intergovernmental Oceanographic Commission (IOC) I have the pleasure in inviting you, in your capacity as representative of your country, to comment on the attached draft "Scientific Summary for Policy-makers of the State of Knowledge on Ocean Fertilization". This invitation responds to the request by the 25th Session of the IOC Assembly to circulate the draft to Member States for comment prior to its final publication and translation.

The draft was prepared for the IOC by the Scientific Steering Committee for the International SOLAS (Surface Ocean - Lower Atmosphere Study) Project, which is an international research initiative comprising of over 1500 scientists in 23 countries.

You are in particular invited to comment from a policy point of view. The scientific peer review of the draft has been made by independent scientists and the Technical Working Group on Ocean Fertilization under the London Convention/London Protocol. The objective is to finalize and present the 'Scientific Summary for Policy-makers of the State of Knowledge on Ocean Fertilization' at the 43rd Session of the IOC Executive Council June 2010.

The deadline for providing comments is 15 May 2010 by e-mail to h.enevoldsen@unesco.org.

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Background:

The IOC Executive Council, at its 41st Session (24 June–1 July 2008), reviewed the Report on the IMO London Convention Scientific Group Meeting on Ocean Fertilization (IOC/INF-1247), including the Statement of the IOC ad hoc Consultative Group on Ocean Fertilization, which provided scientific and technical information about ocean-fertilization experiments, as requested by the London Convention Working Group. The Executive Council recognized the importance of IOC's responsibility in ocean iron-fertilization issues and urged the Executive Secretary to seek additional opportunities to help resolve the scientific uncertainties with respect to this issue. The Executive Council also requested the Executive Secretary to facilitate UN inter-agency coordination on scientific and technical advice, recalling the mandate given by the Commission to the Secretariat to produce, with SCOR, a regular Watching Brief on ocean carbon sequestration.

In fulfilment of these instructions, the Executive Secretary initiated a dialogue with the Secretariats of the IMO London Convention and the Convention on Biological Diversity to discuss the establishment of a mechanism to facilitate UN interagency coordination on this issue. It was agreed that the most effective mechanism would be for the Secretariats to coordinate their efforts in the development of scientific and technical information currently used by each agency.

As a consequence of this agreement, the London Convention Secretariat invited the IOC to participate in the First Meeting of the Intersessional Technical Working Group on Ocean Fertilization (IMO, London, 9–13 February 2009). The Technical Working Group was established by the London Convention/London Protocol (LC/LP) non-binding Resolution (LC-LP.1 (2008)) on the regulation of ocean fertilization, with the purpose to develop an assessment framework on ocean fertilization (Document LC/SG-CO2 3/5, LC/LP Draft Assessment Framework on Ocean Fertilization) and a document summarizing the state of knowledge on ocean fertilization. Dr Luis Valdés (Head, IOC Ocean Sciences Section), Mr Henrik Enevoldsen (IOC Programme Specialist), Dr Ken Caldeira (Carnegie Institute, USA), and Dr Doug Wallace (IfM-GEOMAR, Germany) were part of the IOC delegation to provide their scientific and technical expertise to the meeting. The IOC informed the LC/LP Technical Working Group of its plans to revise the "IOC-SCOR Watching Brief on Ocean Fertilization" to provide a scientific summary for policy-makers on ocean fertilization, in collaboration with SOLAS, the global research programme Surface Ocean-Lower Atmosphere Study sponsored by IGBP, WCRP and SCOR. The LC/LP Technical Working Group on Ocean Fertilization welcomed this initiative and agreed that this technical document could also serve the purposes of the current requirement requested by the parties to the LC/LP. The Technical Working Group on Ocean Fertilization recommended that a draft of this document be submitted to the meetings of the LC/LP Governing Bodies in October 2009. The plan is that the summary of scientific and technical information for policy-makers on ocean fertilization will be translated into the four working languages of the Commission.

The 25th Session of the IOC Assembly confirmed that the already planned revision of the SCOR– IOC Watching Brief on Ocean Fertilization and the development of the LC/LP summary of the state of knowledge on ocean fertilization will be prepared by the IOC in collaboration with SOLAS as one and the same document ("Scientific summary for policy-makers of the state of knowledge on ocean fertilization").

.../...

The 25th Session of the IOC Assembly also noted that the role the IOC is taking in this inter-agency joint effort, responds to the part of the mandate of IOC that calls it to make available the best and most updated scientific knowledge to governments for their decision-making process, one that is only occasionally applied, and further noted that, in the current context, this role is being fulfilled concurrently with provisions of two major UN conventions, the LC/LP and the CBD.

Thank you for your interest and co-operation.

Yours faithfully,

[signed]

Wendy Watson-Wright Assistant Director-General, UNESCO Executive Secretary, IOC

Attachment: DRAFT Scientific summary for policy-makers of the state of knowledge on ocean fertilization.

Ocean fertilization: A scientific summary for policy makers

Draft text version for Member States' comments (21 May 2010) Proposed boxes, images and figures are provided at the end

[Inside front cover]

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 either by directly adding nutrients, or increasing nutrient supply from deep water, or potentially by other means.

This report was commissioned by the Intergovernmental Oceanographic Commission (IOC), which is part of UNESCO. It was prepared with the assistance of the Surface Ocean Lower Atmosphere (SOLAS), an international programme that focusses research effort on air-sea interactions and processes, sponsored by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR), the World Climate Research Programme (WCRP) and the International Commission on Atmospheric Chemistry and Global Pollution (ICACGP). The drafting of this report benefitted from discussions with the secretariat of the International Maritime Organization (IMO) and with the 2009 Intersessional Technical Working Group on Ocean Fertilization of the London Convention/London Protocol (LC/LP), in which IOC participated.

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1. 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 CO₂ 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.

2. Why fertilize the ocean?

For scientific research

To date, 13 small-scale fertilization studies have been performed in the open ocean. Their main purpose 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, on the basis that it should be possible to sequester CO_2 – storing it in the ocean interior – in sufficient quantity and for a sufficient time period to make a significant reduction in the increase of atmospheric CO_2 in a verifiable manner, without deleterious unintended side effects.

For future commercial viability or significant governmental action in this area, a regulatory process that satisfies the Convention on Biological Diversity would first need to be developed, followed by either formal recognition (under UN Framework on Climate Change) of ocean fertilization as a valid option for generating carbon credits, or less structured arrangements for carbon offsetting via a 'voluntary' market. These constraints apply to open ocean fertilization based either on nutrient additions or achieved through artificial upwelling devices (ocean pipes).

For fishery enhancement

Increases in ocean productivity following ocean fertilization might provide additional benefits from a human perspective, since growth enhancement of fish stocks might result, increasing the yield of exploitable fisheries. 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 CO₂ 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'.

Most ocean fertilization approaches 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?

[Fig 2 near here]

Iron addition experiments

The bullets below summarise findings from the 13 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.
- The effect on phytoplankton production and biomass was 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).

Phosphorus addition experiments

There have been two P-addition field studies, 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 $45m^3$ 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 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 Northwest Pacific Ocean.

5. Are there unintended impacts of ocean fertilization?

Changes to the surface ocean ecosystem

The iron fertilization experiments conducted to date primarily stimulated growth of diatoms and are not known to have resulted in harmful algal blooms. However, shipboard experiments in the Northwest Pacific suggest that diatom species that produce the toxin domoic acid might not only increase in abundance in response to iron fertilization, but also could increase their toxin production. 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 significance of such effects is currently unclear.

Far-field effects

Far-field effects, thousands of kilometres from the fertilization site and many months afterwards, include impacts on subsurface waters and sediments into which the fertilized biomass sinks. For small-scale, experimental studies such effects are almost certainly trivial and non-measurable, but they are likely to become significant if large-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. Effects of prolonged, large-scale fertilization for geoengineering could continue years to decades after fertilization initiation. Prediction of effects requires the use of complex models which simulate ocean circulation, biology and chemistry. Model predictions of far-field effects may be almost impossible to verify with direct observations because of the large spatial and time-scales involved (Section 7).

An important far-field consequence of 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 and where natural source of the fertilizing nutrient are available (e.g. iron from shelf sea sediments or atmospheric dust). This 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 with potentially significant consequences that include 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 sinking biomass) may increase the productivity of ecosystems in 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).

[Box 4 near here]

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 enhanced downward carbon export is, inevitably, associated with subsurface oxygen depletion. Decreased oxygen 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.

Effects on seafloor ecosystems

The effect 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 the latter's background state (Fig 3).

[Fig 3 near here]

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 (CH₄), with global warming potentials 320 times and 20 times greater than CO₂ respectively. Thus the release to the atmosphere of small amounts of these gases could offset the desired effects of CO₂ 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 CO₂ before reaching the atmosphere.

The ocean is, however, an important source of N₂O 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 N₂O yield could be large, with an estimated 40 - 70% offset of the benefits of CO₂ 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 N₂O yield during biomass decomposition. Only minor increases in N₂O 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 shortduration 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 model suggest higher efficiencies (70-90%), at least for fertilization of tropical /equatorial waters. Clearly this is an area of continued uncertainty which greatly impacts estimates of the overall sequestration efficiency.

[Box 5 near here]

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.

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 (<500m). 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 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 CO2 drawdown resulting from the initial fertilization will be returned to the atmosphere.

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. 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 and/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, represents 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, through Resolution 62/215 concerning Oceans and the Law of the Sea adopted on 22 December 2007, encourages States to support the further study and enhance understanding of ocean iron fertilization.

The International Maritime Organization (IMO) serves as the Secretariat for the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (known as the London Convention), and its 1996 Protocol (the London Protocol). The parties to both agreements have through Resolution LC-LP.1(2008) on the Regulation of Ocean Fertilization adopted on 31 October 2008, decided that: 1) given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed; 2) they would discuss at future sessions a potential legally binding resolution or an amendment to the London Protocol on ocean fertilization; and 3) they would develop a framework for assessing the compatibility of ocean fertilization experiments with the London Convention and Protocol.

This assessment framework is expected to be adopted in 2010. In relation to ocean fertilization and marine biodiversity, the Parties to the Convention on Biological Diversity have, through decision IX/16 on 30 May 2008, "requested Parties, and urged other Governments, in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing 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". The Secretariat to the CBD has furthermore prepared a scientific synthesis on the impacts of ocean fertilization on marine biodiversity. The Intergovernmental Oceanographic Commission (IOC) of UNESCO is assisting with up-to-date summaries on the state of knowledge of ocean fertilization and its effects.

Further reading

Ocean fertilization: general

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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



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

Box 1. Limitation of oceanic biological production in high and low nutrient regions

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 can then increase the abundance of these N-fixing organisms.

Box 2. Ocean 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 (FeSO₄ ·7H₂O) 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.

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 (NH₂)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.

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 freefloating or tethered to the seafloor, could be distributed across regions with low surface nutrient concentrations.





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

Box 3. The importance of transport and timescales

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.



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 **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 (Box 6).



[some further edits required for the diagram in Box 5]



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

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).



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.



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



ADDITIONAL FIGURES



Satellite images of plankton blooms 10-100km across stimulated by iron fertilization experiments *[for possible use on fron t cover]*



Experimental ocean fertilization using ferrous sulphate on UK-German FeeP study, 2004 [provisionally for inside front cover, but could be used elsewhere]