OCEAN FERTILIZATION: MITIGATING ENVIRONMENTAL IMPACTS OF FUTURE SCIENTIFIC RESEARCH

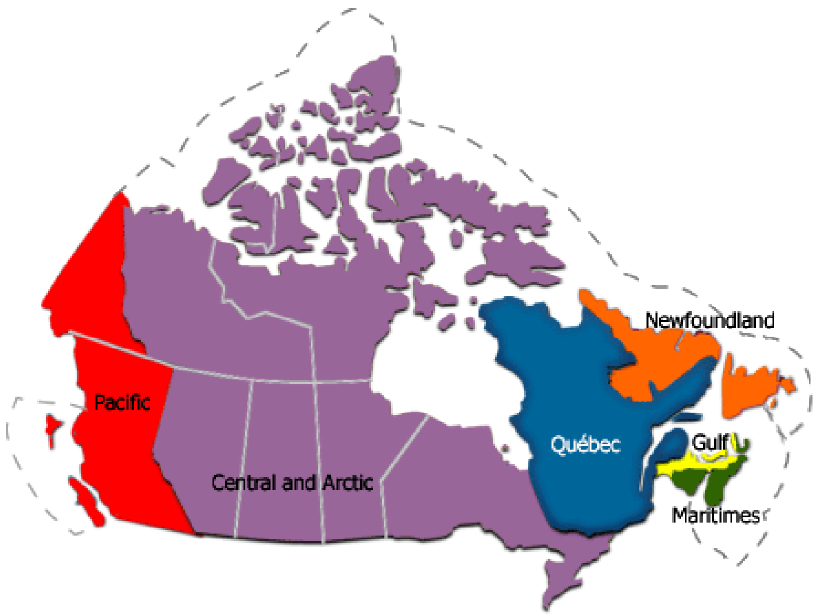

Figure 1: Department of Fisheries and Oceans' (DFO) six administrative regions.

Context :

Geoengineering options are being proposed to decrease the rate of global warming associated with the build-up of greenhouse gases from human activities. Ocean fertilization attempts to sequester atmospheric carbon dioxide to the ocean interior by adding a limiting nutrient to a selected region of the ocean. The nutrient stimulates the growth of phytoplankton; the phytoplankton convert carbon dioxide to organic matter through photosynthesis, whereby the newly formed organic matter is sequestered to the subsurface ocean, primarily as sinking organic particles.

Internationally, the London Convention and London Protocol are regarded as the global instruments with the appropriate authorities to manage ocean fertilization. The London Convention/London Protocol are international treaties designed to govern marine pollution and regulate the dumping of wastes at sea. Environment Canada is the lead federal authority on both treaties and is supported by Fisheries and Oceans Canada, Foreign Affairs and International Trade and Justice. In May 2008, the Scientific and Legal Working Groups of the London Convention/London Protocol were tasked to evaluate the issue of ocean fertilization. Subsequently, the governing bodies recommended proceeding towards the examination of options for the regulation of the activity. The legal working group proposed that Parties "agree to the concept of regulation such that commercially driven activities are prohibited". This concept has not been included in any of the resolution texts, but instead the Meetings of Parties agreed by resolution that ocean fertilization activities are not allowed at this time, with the exception of legitimate scientific research. However, what constitutes legitimate scientific research has not yet been defined.

In February 2009, the Intersessional Technical Working Group on Ocean Fertilization of the London Convention/London Protocol initiated the development of a Draft "Assessment Framework for Scientific Research Involving Ocean Fertilization". The framework provides a tool for assessing scientific research proposals on a case-by-case basis to determine, among other things, if a proposed activity is consistent *with the aims and objectives of the London Convention or Protocol and meets the requirements, as appropriate.*

This document examines the current scientific knowledge and understanding of ocean fertilization, the uncertainties, and fundamental questions required for informed decision making. As part of this evaluation, this document reviews the Draft Assessment Framework created by the London Convention/London Protocol Technical Working Group on Ocean Fertilization.

SUMMARY

- Ocean fertilization has been proposed as a geoengineering method that in some regions of the world ocean may enhance ocean uptake of carbon dioxide from the atmosphere. The US National Academy of Sciences defines geoengineering as “options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry”.

- Ocean fertilization represents one geoengineering approach undertaken by humans with the principal intention of stimulating primary productivity in the oceans. Fertilization proposals are loosely divided into 'micronutrient' and 'macronutrient' additions.

- Addition of the micronutrient iron is by far the best studied artificial ocean fertilization technique; nitrogen is the most likely option for macronutrient fertilization.

- Expected consequences of large-scale ocean fertilization include changes in phytoplankton community composition and food web structure, vertical export of biogenic material, reduction of subsurface oxygen, and production of climate active gases such as nitrous oxide.

- Results from the ocean iron fertilization experiments conducted so far have not determined at what scale fertilization will result in persistent alterations of the ecosystem. However, there is scientific confidence that a “threshold scale” can be determined such that fertilization up to this scale would likely not cause persistent changes to an ecosystem.

- Large-scale fertilization of coastal waters with nitrogen entails high ecological risks and potentially irreversible ecosystem disruptions.

- The London Convention/London Protocol Draft Assessment Framework provides a mechanism for assessing, on a case-by-case basis, proposals for ocean fertilization to determine whether they represent legitimate scientific research.

- It is recommended that there be an examination of the knowledge base for development and application of criteria for conducting environmental assessments of fertilization experiments, and for defining a "threshold scale" below which proposals could be exempted from a full assessment.

- A concern over the capacity of a single nation to implement the Assessment Framework suggests that if possible an international body should be available to assist with assessments.

- Fertilization experiments have been highly valuable for the study of the dynamics and functioning of ocean ecosystems and biogeochemical cycles, but it is unlikely that individual experiments will ever resolve critical questions about the long-term consequences of ocean fertilization for climate change mitigation.

- Future scientific research on ocean fertilization should be encouraged to improve our understanding of the ocean's response to nutrient addition.

INTRODUCTION

With over eight billion metric tons of carbon from fossil fuels emitted annually, reducing the rate of increase of carbon dioxide (CO_2) in the atmosphere and the global warming associated with the increasing CO_2 greenhouse effect continues to be a global challenge.

Carbon offsets are a financial instrument representing the net reduction of greenhouse gas concentrations. Through such instruments, companies or nations unable to meet emission restrictions can purchase carbon offsets equivalent to some fraction of their emissions. Encouraged by such carbon offset programs, ocean fertilization has been proposed as a geoengineering method that in some regions may enhance the oceanic uptake of carbon dioxide from the atmosphere. The US National Academy of Sciences defines geoengineering as "options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry". Ocean fertilization represents one geoengineering approach undertaken by humans with the principal intention of stimulating primary productivity in the oceans. Fertilization proposals are loosely divided into 'micronutrient' and 'macronutrient' additions.

A capability to predict and detect downstream side effects of ocean iron fertilization is required before it is considered a viable technology for climate mitigation. Evaluating such impacts is difficult and it is unlikely that side effects can be predicted with confidence.

The global concern that large-scale ocean fertilization could have negative impacts on the marine environment is demonstrated by the statements, agreements and recommendations made by various international bodies such as the:

Scientific Committee on Oceanic Research;
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection;
Global Ecology and Oceanography of Harmful Algal Blooms; and
Convention on Biological Diversity.

In particular, in 2008 the Conference of the Parties to the United Nations Convention on Biological Diversity restricted ocean fertilization to small scale scientific research studies within coastal waters "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".

For many nations, the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and 1996 Protocol (herein referred to as the London Convention) is regarded as the appropriate regulatory international body on this matter. In 2008, the governing bodies of the London Convention declared that "given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed". In addition, the Meeting of Contracting Parties agreed to further consider a potential legally binding resolution or an amendment to the London Protocol at its session in October 2009. Canada supports the Convention's position on ocean fertilization which recommends proceeding toward regulation of the activity. In October 2009, Contracting Parties were unable to reach consensus as to how best control ocean fertilization activities at that time. Ocean fertilization and its potential regulation will continue to be debated at the London Convention and within other international organizations.

This peer-review was convened to examine the current state of scientific knowledge and understanding of ocean fertilization and its uncertainties. This process examines the subject in the context of establishing some guidance on future experimentation that potentially reduce some of the uncertainties surrounding this issue. The products from the peer-review will assist in developing a Canadian position regarding a regulatory framework which allows for the continuation of ocean fertilization science in international waters. As part of this evaluation, this document considers a Draft Assessment Framework for Scientific Research Involving Ocean Fertilization being developed by the London Convention's Technical Working Group on Ocean Fertilization.

Through the course of a national peer-review process that took place in Ottawa (September 29-30, 2009), government and university scientists were tasked to address the following questions:

1. What are the most significant deleterious intended and unintended consequences of ocean fertilization and what is the level of scientific confidence regarding their impacts?

2. Is there sufficient knowledge to determine at what scale a project would likely not cause irreversible and unacceptable harm to an ecosystem? If so, what are the criteria that would define the upper limit of such a project?

3. Is the Convention's Draft Assessment Framework adequate for assessing scientific research proposals involving ocean fertilization?

4. What are the most pressing or most important research areas on ocean fertilization?

ASSESSMENT

The ocean is by far the largest 'exchangeable' reservoir of carbon on Earth, i.e., exchangeable with the atmosphere on time scales of thousands of years or less. The ocean has absorbed approximately half of the cumulative anthropogenic emissions of carbon dioxide to date from burning of fossil fuels and cement production (total uptake ~118 Gt C as of 1995).

Atmospheric carbon dioxide is controlled in large part by two sets of ocean processes that are known as the 'solubility pump' and the 'biological pump'. These together maintain a strong gradient of dissolved inorganic carbon[1] between the surface ocean and the deep ocean. The solubility pump results from the greater solubility of carbon dioxide gas in cold water, and the fact that the deep ocean is largely ventilated at high latitudes (surface waters sink at high latitudes to large depths, then flow horizontally at depth towards the tropics and subtropics where there is very little exchange between surface and deep waters). The biological pump includes sedimentation of both organic and inorganic particulate carbon, as well as downward mixing and advection of dissolved organic carbon and remineralization and dissolution, the latter occurring in the intermediate and deep ocean. The biological pump stores carbon in the

[1] Dissolved inorganic carbon is the total of the three chemical species that carbon dioxide forms once it enters the ocean from the atmosphere.

deep ocean, away from contact with the atmosphere for decades or centuries; ocean fertilization attempts to artificially enhance the strength of the biological pump.

Remineralization of organic carbon declines with increasing depth and occurs primarily in shallower depth strata. Because shallower waters will normally come in contact with the atmosphere after a shorter time than deeper waters, the sequestration timescale is likely to be fairly short (a few decades at most) on average. Because both the rate of remineralization and the circulation of the subsurface layers in which remineralization occurs are variable and poorly known, any estimate of the sequestration timescale will be highly uncertain.

For ocean fertilization to be successful in sequestering atmospheric carbon, the carbon must be retained at depth for a significant period. Deep ocean renewal time is about 500 years on average, but some subsurface waters are much older. In the North Pacific Ocean, for example, exchange with the atmosphere occurs on timescales of a few decades to depths of around 500 m and densities of 1026.8 kg m^{-3}. This is the upper limit to surface density in the North Pacific, so it is assumed that at greater depths the time scale for atmospheric exchange is longer and these deeper layers would therefore retain sequestered carbon longer.

This assessment examines sequestration through micronutrient and macronutrient fertilization. Addition of the micronutrient iron is by far the best studied artificial ocean fertilization technique; nitrogen is the most likely option for macronutrient fertilization.

Micronutrient fertilization

Iron fertilization as a form of geoengineering originated largely in the work of John Martin (1935-1993) and his collaborators in the 1980s. Martin is widely known as the father of the “iron hypothesis” regarding the formation of high nutrient, low chlorophyll conditions. Martin realized that iron abundance in oceanic phytoplankton were very low (10^{-4}-10^{-5} mol Fe / mol C), which eventually gave rise to the idea that substantial ocean uptake of carbon dioxide could be catalyzed by fairly small additions of iron to high nutrient, low chlorophyll regions.

The first in situ fertilization experiment in the equatorial Pacific was deemed to be a success because it unequivocally demonstrated that iron limited phytoplankton growth in high nutrient, low chlorophyll regions (Martin et al., 1994). Yet it was not successful from a geoengineering perspective because it did not demonstrate enhanced net export of carbon from the surface ocean or enhanced ocean uptake of atmospheric carbon dioxide. Subsequently there have been about a dozen additional experiments, as well as a few others conducted by commercial organizations that did not report any results in the scientific literature. Most of these experiments induced some enhanced export of carbon, however as a prototype demonstration of geoengineering the results have not been particularly encouraging because the sequestration of carbon per unit of iron added is quite low (de Baar et al., 2005; 2008). When measured as net uptake of carbon dioxide from the atmosphere, the values become substantially lower (de Baar et al., 2008).

The aqueous chemistry of iron is very complex. The forms thermodynamically favoured under ocean surface conditions are highly particle-reactive, that is, they will bind to almost any surface they come in contact with, so that iron is constantly being removed from solution and transported downwards by sinking particles (scavenging). As a result, the whole-ocean residence time for iron is estimated as only around 100 years, compared to 3,000 years for nitrogen and 30,000 for phosphorus. The residence time of added iron in the surface ocean (where both oxygen and particulate matter concentrations are high) is much shorter, and in deliberate fertilization experiments a large fraction of the added iron precipitates from solution on a time scale of hours to days.

Macronutrient fertilization

In contrast to the hundreds of scientific papers written on iron, very few papers have been written on macronutrient fertilization. In fact, a landmark evaluation of the global potential of macronutrient fertilization using an ocean model (Matear and Elliott, 2004), has been cited only four times (ISI Web of Science, 2009/08/07), and none of the citing articles deals directly with further evaluation of this strategy. It can reasonably be said that experimental verification of the viability of macronutrient fertilization is in its infancy.

Because over most of the open ocean the ‘limiting nutrient” is thought to be nitrogen, one suggestion has been to fertilize the ocean with nitrogen in order to stimulate algal growth and carbon sequestration. However, fertilization with nitrogen involves a much larger mass of fertilizer than with iron, and so is likely to occur in waters relatively close to shore. A proposal to fertilize the Sulu Sea, Philippines with nitrogen motivated the publication of a scientific article by many experts in the field addressing the potential risk of nitrogen fertilization (Glibert et al., 2008). The authors concluded that the environmental and economic costs of nitrogen fertilization are potentially great and need to be rigorously assessed. Both the viability of macronutrient fertilization as a geoengineering strategy, and the assumption that it will not have extreme adverse ecological consequences, depend on very tenuous assumptions about the evolution of community structure in response to fertilization (Glibert et al., 2008). Large-scale fertilization of coastal waters with nitrogen entails high ecological risks and potentially irreversible ecosystem disruptions.

An important difference between micronutrient and macronutrient fertilization is that micronutrient fertilization seeks to reduce atmospheric carbon dioxide by redistributing macronutrients downward in the ocean, while macronutrient fertilization seeks to increase the total ocean nutrient pool. Partitioning of carbon between the ocean and atmosphere is, at least in the equilibrium state, closely related to the whole-ocean inventory of nitrogen and phosphorus; the biological pump further shifts this partitioning towards the ocean by depleting the variable reserve of unused nutrients in the surface ocean.

The 'downstream' ecological effects of micronutrient and macronutrient fertilization will likely be quite different, although they are highly uncertain in each case. Macronutrient fertilization will in principle increase (macro) nutrient concentrations in newly upwelled thermocline water in the decades following fertilization, while iron fertilization will tend to reduce them. However, macronutrient fertilization with nitrogen only would likely deplete other macronutrients (phosphorus and silicon).

Responses to Specific Questions

1. **What are the most significant deleterious intended and unintended consequences of ocean fertilization and what is the level of scientific confidence regarding their impacts?**

Expected consequences of large-scale ocean fertilization include changes in phytoplankton community composition and food web structure, vertical export of biogenic material, subsurface oxygen and production of climate active gases such as nitrous oxide (Table 1).

Change in phytoplankton community structure and food web

A fundamental change in phytoplankton community structure is an intended consequence of ocean fertilization. The viability of ocean fertilization as a geoengineering strategy, and the expected magnitude of the ecological consequences, depends on assumptions about the evolution of community structure in response to fertilization. These assumptions are untested, and are likely to be incorrect in many cases.

Vertical export of biogenic material

Phytoplankton blooms can generate rapidly sinking pulses of organic matter that are transported to the deep ocean with little remineralization, and if such blooms could be assumed to arise reliably from fertilization, the sequestration timescale would be several hundred years. However, in open ocean fertilization experiments to date this has not occurred, and even detecting enhanced export across the bottom of the euphotic zone has proven difficult (de Baar et al., 2005).

Sub-surface oxygen depletion

Remineralization of organic matter under oxic conditions consumes oxygen. Reduction of subsurface oxygen concentrations is an expected and unavoidable consequence of ocean fertilization, and thus is an intended consequence. If carbon is sequestered, oxygen will be reduced and might be depleted locally. Oxygen in the thermocline has already been observed to be declining in some regions, and will inevitably decline globally as sea surface temperature increases.

Ocean acidification

While there have been claims by both proponents and opponents of fertilization that it will alleviate or exacerbate ocean acidification, respectively, neither claim is supported by scientific evidence. It is likely that fertilization, if successful, would accelerate acidification at depths at which remineralization occurs, and alter the spatial distribution of changes in pH.

Production of climate active gases

Nitrous oxide: Nitrous oxide is a potent greenhouse gas that is produced by microbes during oxidation of ammonium to nitrate (nitrification) and reduction of nitrate to nitrogen gas (denitrification). Nitrification occurs in direct proportion to remineralization of organic nitrogen, and so is generally greatest immediately below the euphotic zone. Any increase in export production will inevitably increase nitrification and associated nitrous oxide production. This will occur predominantly at shallow depths that are ventilated on time scales of a few decades at most unless the remineralization length scale increases substantially. An increase in export production in the vicinity of eastern boundary currents will intensify the suboxic conditions naturally found there and will increase nitrous oxide production by denitrification. It is likely that at least some of this nitrous oxide will escape to the atmosphere but the proportion is not well constrained.

While the concern over the production of climate active gases is often focused on potential nitrous oxide production, other gases potentially produced from fertilization experiments could have significant consequences.

- *Methane:* Methane is another potent greenhouse gas that is produced by bacteria under anoxic conditions. Because of the potential for subsurface oxygen depletion, there has been some concern that ocean fertilization could result in an increased ocean source of atmospheric methane. Our assessment is that this is among the least likely consequences, because of the magnitude of oxygen depletion that would be required to increase significantly the production of methane.

- *Dimethylsulfide:* Dimethylsulfide is a volatile sulfur compound produced by oceanic microbial communities and is the largest natural source of atmospheric sulfate aerosol, which is implicated in cloud formation. Enhanced production of dimethylsulfide by ocean fertilization could potentially reduce global warming by increasing Earth's albedo[2]. It is not known with confidence whether large-scale fertilization would result in increased or decreased production of dimethylsulfide.

- *Methyl halides (halocarbons):* Methyl halides are also produced by marine phytoplankton although their exact biological function is not known. They are both greenhouse gases and catalysts for stratospheric ozone loss. Their atmospheric lifetime is short (~ 1 year), but their global warming potential is large. Enhanced production of methyl bromide has been observed in mesoscale (< 1000 km^2) iron fertilization experiments.

- *Sulfur hexafluoride:* Sulfur hexafluoride is an industrially produced compound that has been added in mesoscale iron addition experiments to help track the patch of fertilized water and to distinguish fertilized from unfertilized waters and estimate mixing of the two. Sulfur hexafluoride is an extremely potent greenhouse gas with a very long atmospheric lifetime. If it were to be used in fertilization experiments, its greenhouse gas contribution would have to be included in the assessment of net reduction of global warming potential.

[2] the albedo of an object is a measure of how strongly it reflects light.

Table 1. Potential deleterious consequences of ocean fertilization. *Increased or decreased efflux of climate active gases is considered a significant impact if the effect on atmospheric radiative forcing exceeds 5% of the radiative effect of carbon sequestration. Mesoscale experiments (e.g., < 1000 km^2) are identified as useful where major outstanding scientific uncertainties can potentially be substantially reduced by such experiments. AGW = anthropogenic global warming; SOD = Stratospheric Ozone Depletion, Y = yes.*

	Impact on	**Consequence**	**Likelihood**	**Confidence**	**Utility of mesoscale expt.**	**Comments**
	Phytoplankton community	changes in plankton community and food web structure	High	Low	Y	some change is virtually certain, trajectory not predictable in detail; mesoscale experiments can reveal much about ecosystem response.
	Oxygen depletion	local subsurface oxygen reduction	High	High	Y	proportional to magnitude of fertilization
		downstream hypoxic/anoxic conditions	Moderate	Low		dependent on location and scale; cumulative effects over decades more difficult to assess
	Ocean acidification	exacerbation of ocean acidification	Moderate	Low	Y	both exacerbation and mitigation possible
Climate active gases	Nitrous oxide (N_2O)	local increase in ocean efflux of N_2O	High	Moderate	Y	proportional to magnitude of fertilization
		downstream increase in ocean efflux of N_2O	Moderate	Low		cumulative effects over decades difficult to assess
	Methane (CH_4)	increase in ocean efflux of CH_4	Low	Moderate to High		
	Dimethylsulfide (DMS)	increase in ocean efflux of DMS	Moderate	Low	Y	both exacerbation and mitigation of AGW possible; scientific understanding of the climatic effects of increased DMS flux is also Low.
	Methyl halides (halocarbons)	increase in ocean efflux of halides	Moderate	Low	Y	both exacerbation and mitigation of AGW and SOD possible
	Sulfur hexafluoride (SF_6)	increase in ocean efflux of SF_6	High	Moderate		continued use is required until alternate technologies emerge

2. Is there sufficient knowledge to determine at what scale a project would likely not cause irreversible and unacceptable harm to an ecosystem? If so, what are the criteria that would define the upper limit of such a project?

There is insufficient knowledge to define an upper limit scale for ocean fertilization experiments. Results from the ocean iron fertilization experiments conducted so far have not determined at what scale fertilization will result in persistent alterations of the ecosystem. However, there is scientific confidence that a “threshold scale” can be determined such that fertilization up to this scale would likely not cause persistent changes to an ecosystem.

Fertilization experiments to date have been of quite limited scale and have largely occurred in high nutrient, low chlorophyll regions of the open ocean. It is impossible to state with confidence that broader ecosystem impacts will not occur, and there have been theoretical studies that suggest that small perturbations can propagate to larger scales through the intrinsic dynamics of the ecosystem. However, such scenarios are highly speculative.

Ocean fertilization does occur naturally, for example near some islands and through dust storms, and at spatial scales much larger than any of the experimental trials conducted to date. However, it is unlikely that they can be used as the sole surrogate for understanding intentional ocean enrichment on the scale for geoengineering; that is why more experiments have been proposed.

The concept of scale is multi-dimensional. Spatial limitations cannot be the only criteria for which intentional ocean enrichment experiments are measured. Consideration of frequency of fertilization events, seasonal and interannual variability, horizontal dispersion of dissolved and particulate materials, and location (e.g. ecosystem composition and proximity to sensitive areas) is necessary to generate an accurate ecosystem-based model of effects.

As the “scale” of an experiment increases, the relevance of the experimental results increases but so too does the risk of changes to the ecosystem. At this time, the upper limit of which ocean fertilization will result in persistent alterations of the ecosystem can only be determined by exceeding it.

In the context of this document, the threshold scale being proposed is a precautionary upper limit. It is unrealistic to expect that a precise point where additional enrichment would cause a persistent alteration to an ecosystem could be determined. There is insufficient knowledge on which to base such a determination. Factoring in the uncertainty, the precautionary threshold proposed below is based on a high degree of confidence that no persistent alterations to an ecosystem would occur.

A research or pilot scale project with the following criteria is considered unlikely to have persistent adverse effects on the environment:

- not exceeding an area of 300 square kilometers;
- limiting quantity of enrichment media (e.g. for iron – not to exceed sixteen tonnes);
- observable effects not exceeding a period of one year; and
- adjacent coastal and marine sensitive areas are identified for potential far-field impacts.

3. Is the London Convention/London Protocol Draft Assessment Framework adequate for assessing scientific research proposals involving ocean fertilization?

The Convention Draft Assessment Framework provides a mechanism for assessing, on a case-by-case basis, proposals for ocean fertilization to determine whether they represent legitimate scientific research. It provides a comprehensive listing of potential impacts, and a systematic framework for assessing these.

In meeting its objectives the framework is attempting to ensure that the research proposal is well founded and structured (e.g. to be at a scale that is no larger than needed to answer the question, that the measurements proposed will enable the question posed to be answered and that appropriate follow-up and peer review are planned), that the research effort will not cause a lasting impact on the marine environment and environmental risks are minimized while benefits are maximized. From this perspective, the framework has identified the key areas that need to be considered, and for the evaluation of a large project, this framework adequately provides for a means to assess a project.

From a practical perspective however, the comprehensive nature of the framework in its current draft will require extensive assessment and reporting and the information sought may not be readily available. Whereas this may be warranted for a large-scale project, both risks and capacity associated with smaller scale work will normally also be lower. The potential to divert capacity and limited research funding to the assessment, particularly as there is no minimum size or risk factor associated with triggering the framework, could result in the unintended consequence of making unfeasible the conduct of small-scale basic research on ocean fertilization aspects. It is recognized that this is likely not an intended or desirable consequence of regulating research.

In reviewing the past research as per question 2, it was noted that it may be possible to establish with some degree of confidence a research project scale below which the risk to the marine environment would be minimal. The adequacy of the framework would be greatly increased by the introduction of a tiered approach based on defined criteria, with the level of information required more closely corresponding with the likely level of risk. This has the potential to reduce the unintended impact on small scale research, while not detracting from the main objectives of the framework. It is recommended that there be an examination of the knowledge base for development and application of criteria for conducting environmental assessments of fertilization experiments, and for defining a "threshold scale" below which proposals could be exempted from a full assessment.

There is an argument for a two-tiered approach for assessments as there is scientific confidence that a “threshold scale” can be established below which an experiment would likely not result in persistent changes to an ecosystem. Therefore, it may be possible to establish criteria that would accommodate a “fast track” assessment process that would be more proportional to the potential risk while still meeting the precautionary intent of the Convention and Protocol Draft Assessment Framework. The full framework assessment would continue to be applied to those proposals that exceed the threshold scale.

There may also be a second practical issue with respect to the experts that would have the capacity to conduct assessments under the framework. The scientific community that is engaged in this type of research remains relatively small. A concern over the capacity of a single nation to implement the Assessment Framework suggests that if possible an international body should be available to assist with assessments. Further emphasis is put on the need for an international body given that there might exist an occasion where scientists appear to be in a conflict of interest with respect to the assessment of a given project. For the process to remain credible, it must meet an acceptable burden of proof that the process is transparent and fair.

4. What are the most pressing or most important research areas on ocean fertilization?

The supplies of key nutrients — nitrogen, phosphorus, silicate, iron — to phytoplankton in surface waters vary significantly by region, with season, and under the influence of atmospheric deposition and coastal runoff. The magnitudes and proportions of these inputs will change with climate and human activities. The impact of nutrient inputs on phytoplankton community structure, sedimentation, and biogeochemical cycles thus remains a lively area of scientific research with important repercussions for humanity regardless of whether ocean fertilization as a geoengineering strategy proceeds. Our ability to monitor and predict ecosystem responses to perturbation is poor, compounded by scientific uncertainty on what constitutes an ecosystem's background state — that is, how spatial and temporal variability of nutrient supply structures ecosystems. There is no shortage of important scientific questions with respect to ocean fertilization.

It was not the intent of this exercise to generate a comprehensive list. Pressing areas with the greatest uncertainty were predominantly discussed. These include the general influence of limiting nutrients on ecological and biogeochemical functions, shifts in community structure and its impact on energy transfer, impacts on pelagic communities, particle remineralization and transport, nitrification and denitrification, understanding the natural variability of the background state, and separating natural variability and dilution effects from direct fertilization effects.

Sources of Uncertainty

The effectiveness of ocean fertilization as a geoengineering strategy remains unproven. There is little confidence that ocean fertilization can enhance ocean uptake of carbon dioxide from the atmosphere at climate-relevant scales, and less that the effects of ocean manipulation on those scales can be predicted and verified for decades.

It is difficult to predict to what extent the intended consequences of ocean fertilization will impact food web composition and function. Even less is known regarding unintended consequences and far-field effects. Presently there is insufficient scientific knowledge to predict the scale at which ocean fertilization will result in persistent alterations of the ecosystem.

CONCLUSION

Fertilization experiments have been highly valuable for the study of the dynamics and functioning of ocean ecosystems and biogeochemical cycles, but it is unlikely that individual experiments will ever resolve critical questions about the long-term consequences of ocean fertilization for climate change mitigation. Future scientific research on ocean fertilization should be encouraged to improve our understanding of the ocean's response to nutrient addition. Innovative experimentation, limited by strict criteria regulated by a recognized international authority, could advance the sciences of oceanography and biogeochemistry with negligible environmental impact.

SOURCES OF INFORMATION

de Baar, H. J. W., et al, Synthesis of iron fertilization experiments: from the iron age in the age of enlightenment, J. Geophys. Res., 110, 10.1029/2004JC002601, 2005.

de Baar, H. J. W., L. J. A. Gerringa, P. Laan, and K. R. Timmermans, Efficiency of carbon removal per added iron in ocean iron fertilization, Mar. Ecol. Prog. Ser., 364, 269-282, 2008.

Boyd, P. W., et al, Mesoscale iron enrichment experiments 1993-2005: Synthesis and future directions, Science 315, 612-617, 2007.

Glibert, P.M., et al. Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin, 56, 1049-1056, 2008.

Martin, J. H., et al, Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean, Nature, 371, 123-129, 1994.

Matear, R. J., and B. Elliott, Enhancement of ocean uptake of anthropogenic CARBON DIOXIDE by macronutrient fertilization, J. Geophys. Res., 109, 10.1029/2000JC000321, 2004.

FOR MORE INFORMATION

Contact: Denis Gilbert
Fisheries & Oceans Canada
Maurice-Lamontagne Institute
850 route de la Mer
Mont-Joli, Québec, Canada, G5H 3Z4
Tel: 418-775-0570
Fax: 418-775-0546
E-Mail: Denis.Gilbert@dfo-mpo.gc.ca

Or

Jim Christian
Fisheries & Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney, BC, Canada, V8L 4B2
Tel: 250-363-8319
Fax: 250-363-8247
E-Mail: James.Christian@dfo-mpo.gc.ca

This report is available from the:

Canadian Science Advisory Secretariat
National Capital Region
Fisheries and Oceans Canada
200 Kent Street
Ottawa, ON K1A OE6

Telephone: (613) 990-0293
Fax: (613) 990-2471
E-Mail: CSAS@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas

ISSN 1919-5079 (Print)
ISSN 1919-5087 (Online)

La version française est disponible à l'adresse ci-dessus.

CORRECT CITATION FOR THIS PUBLICATION

DFO. 2010. Ocean Fertilization: Mitigating Environmental Impacts of Future Scientific Research. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/012.