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Climos Background

What Does Climos Do?

Climos is exploring techniques for naturally removing large amounts of CO2 from the atmosphere. One such technique, Ocean Iron Fertilization (OIF), is based on a natural process that is one of the Earth's primary natural mechanisms to remove carbon dioxide. It has very high mitigation potential compared to other available methods, and also has relatively low cost.

OIF works by improving the efficiency of natural phytoplankton production in the open ocean, adding to the very large natural amount of carbon sequestration that takes place in the world's oceans every year. Publicly funded research scientists have investigated aspects of the science behind the technique in twelve small-scale experimental trials since 1993, which have shown that the addition of iron can stimulate large blooms of phytoplankton. Given this promise, a number of scientists and private corporations are calling for moderate scale demonstrations to better understand the efficacy and impact of this mechanism, specifically with the intention of assessing its possible use for climate mitigation[Buesseler et al., 2008; G8+5, 2008]

Buesseler, K.O., et al., ENVIRONMENT: Ocean Iron Fertilization--Moving Forward in a Sea of Uncertainty. Science, 2008. 319(5860): p. 162.

Raloff,G8+5. Joint Science Academies' Statement: Climate Change Adaptation and the Transition to a Low Carbon Society. 2008 [cited].

What Is Climos' Funding/business Model?

Climos believes that there is a strong rationale for commercial participation in determining whether Ocean Iron Fertilization (OIF) is a potential mitigation technique for sequestering atmospheric carbon dioxide that contributes to global warming, ocean acidification, and other environmental change. Publicly funded basic research using OIF was designed to understand the role of iron in controlling the biological productivity of the oceans now and in the past. However, the emerging potential of OIF as an element of the portfolio of market-related approaches to reduce greenhouse gases in the atmosphere is of applied interest, not simply a basic research problem. The models for development of techniques for commercialization include both commercial funding and public/private partnerships in funding, but do not generally rely on public subsidy alone. We believe that either funding model can be successful in the case of OIF and that appropriate regulatory and market-based safeguards can be put in place for development. A phase of development research is essential because it will not only resolve issues related to the efficiency of OIF for carbon mitigation, but also provide information on environmental impact. Learning from this development phase will allow the evolution of safeguards for later deployment of OIF as a mitigation strategy if it proves successful and appropriate.

Climos intends to use emerging environmental markets to help fund the research into OIF. The ultimate purpose of these environmental markets is to protect or restore the environment by creating a financial incentive that will stimulate action and innovation within the private sector. Regulatory carbon markets provide a financial incentive by ensuring that a sufficiently aggressive 'cap' is in place, and maintain integrity by ensuring that traded credits represent an actual environmental benefit. Given the accelerating nature of the GHG emissions problem, and the considerable resources available from the private sector, it makes sense to provide a financial incentive to invest in developing creative and cost-efficient ways to reduce greenhouse gases. In this way, the private sector assumes the financial risk as well as receipt of financial benefits, but most importantly focuses its efforts on seeking ways to solve the climate change problem.

A few private corporations have been launched to explore OIF as a mitigation option. However, OIF will only develop as a commercial business if over the next several years it can also be demonstrated to the satisfaction of the scientific, regulatory and market communities that: 1) OIF sequesters carbon dioxide effectively and can be measured accurately, and 2) the benefit of OIF is greater than its environmental impact. All stakeholders have the joint responsibility to work together to ensure a thorough evaluation of these two primary metrics.

What Are Climos Near Term Plans?

Climos intends to carry out a demonstration program of Ocean Iron Fertilization (OIF) in order to understand the potential of OIF as carbon mitigation tool. We understand and appreciate the interest of scientists, regulators and NGOs in these activities. We have been working with these groups to:

- Explain how OIF can be effective at carbon sequestration;
- Develop future OIF experiments in a transparent manner;
- Show that OIF can be carried out in an environmentally benign manner;
- Suggest how regulatory controls could be established.

The potential sequestration ability of OIF and the impact of OIF at larger scales are separate research questions. We know that these questions cannot be answered with a single large experiment. Instead, we view such an initial experiment as part of a new phase of research focused on the efficacy and impact of moderately-sized experiments (< 200 x 200 km). The demonstration program we are planning will emphasize research related to export and sequestration as well as environmental impact. Only with this information can scientists, regulators and the private sector understand whether deployment of OIF to mitigate CO_2 would be successful and the nature of its impacts at larger scales. If it cannot be demonstrated at this moderate scale that OIF sequesters carbon, and does so with negligible or acceptable ecosystem impacts, it will not be done at larger scales.

Climos proposes to fund a team of scientists from the international academic/research community who are familiar with the science associated with OIF experiments. Climos will fund a workshop to develop measurement strategy and experimental design. The scientific team will design the experiment based on the workshop results, develop a methodology which will be made public, conduct the experiment, and transfer the results immediately to a public data base. Climos employees will not participate in the experiment or handle the data. The two most likely locations for the experiment are the high seas in the northwest Pacific (a site of two previous experiments), or the sub-polar Southern Ocean (where five previous experiments have been completed). The choice of location will depend on the suggestions of the workshop and the time of year during which the experiment can be organized. The duration of the cruise will be about two months in order to allow full characterization of the experimental site before fertilization, during the evolution of the bloom, and during the sequestration or carbon export phase. Multiple measurement and observation strategies, together with modeling, are anticipated for the cruise.

The proposed series of OIF demonstration experiments will significantly advance scientific understanding of the environmental effects of ocean iron fertilization, which will inform the choice on whether OIF is appropriate for deployment on a large scale as carbon mitigation tool.

In the near term, Climos is preparing an Environmental Impact Statement on OIF. This consists of two documents. The first is a Conceptual Model of OIF, which will provide a synthesis of scientific knowledge around OIF and will be used to identify and evaluate the environmental issues associated with proposed ocean iron fertilization activities. The Conceptual Model will be released in late summer 2008. The second document will be the Master Environmental Report (MER), which will include a description of the design of the planned project and the expected benefits. The MER will also cover the expected environmental effects of OIF, such as effects on local marine biota, ocean chemistry, greenhouse gases, and other climate relevant gases such as DMS. Finally, the MER will describe monitoring procedures for these effects, as well as mitigation techniques for potential negative effects.

Climos has made a commitment to obtaining a permit from a signatory to the International Maritime Organization London Convention on Ocean Dumping (IMO LC) prior to any actual demonstration experiment. If we cannot obtain one, and one is required, we will not move forward. However, recognizing that OIF is a unique process that does not easily fit within the pollution prevention framework of the London Convention, Climos has led the development of various essential components to an effective regulatory approach for OIF. These components include:

- The formation of a Scientific Advisory Board (SAB);
- Proposing elements of a "Code of Conduct" last year that lays out many of the requirements we will demand of ourselves;
- A presentation to delegates of the London Convention in November of 2007;
- The development of an early draft framework methodology for quantifying carbon export and permanence. This will evolve over the next year.
- The announcement of our engagement of Tetra Tech to produce a detailed Conceptual Model and Master Environmental Report for OIF that will form the basis of a comprehensive Environmental Impact Assessment;
- Preparation of detailed materials in advance of the London Convention Scientific Group Intercessional meeting in Guayaquil (including responses to the Canadian review and Greenpeace critique of OIF; and other notes concerning the legal status of OIF under the LC as well as the rationale for considering commercialization)

Is OIF A Substitute For Emissions Reductions?

Not even close. Even if after many years, OIF was scaled up to take place in all of the regions for which it would be effective, ocean fertilization could at best result in a small fraction of the total CO_2 reductions necessary to prevent dangerous climate change. However, even this small fraction may represent one of the largest single potential sources of carbon reductions. It is imperative that society accelerate the pace of energy efficiency and renewable energy efforts. There is no technological solution that will allow humanity to continue to emit carbon dioxide at its present rate without severe consequences. Every potential mitigation technology needs to be explored in parallel.

There are no credible suggestions that we are aware of that so-called geoengineering approaches can eliminate the need to reduce CO_2 emissions. At best, these approaches can help buy time while emissions reductions are carried out. The nuanced understanding that these mitigation techniques could be complimentary to emissions reductions, was recently voiced by no less a credible group than no less a credible group than 13 of the world's top National Academies of Science. They wrote, "*There is also an opportunity to promote research on approaches which may contribute towards maintaining a stable climate (including so-called geoengineering technologies and reforestation), which would complement our greenhouse gas reduction strategies.*"[G8+5, 2008]. Further clarification from the US NAS Sec'y of Foreign Affairs, Michael Clegg suggested that this included "approaches to soaking up carbon dioxide," specifically "the so-called fertilization of the oceans with iron"[Raloff, 2008].

G8+5, Joint Science Academies' Statement: Climate Change Adaptation and the Transition to a Low Carbon Society. 2008 [cited].

Raloff, J., Science Academies Call for Climate Action, in Science News. 2008.

Ocean Iron Fertilization Basics

How Does Ocean Iron Fertilization Work?

Ocean fertilization is a technique to sequester carbon dioxide into the deep ocean by stimulating phytoplankton growth. Oceanographers have known for decades that biologic productivity in much of the open ocean is not limited by the supply of macronutrients such as nitrate and phosphate. Since the early 1990's, twelve open ocean experiments have shown that adding iron to these regions results in large blooms of phytoplankton [Boyd et al., 2007]. These experiments mimic the effect of natural iron delivery from deep water upwellings and large dust storms that deposit tens of millions of tons of iron to the ocean annually and thus provide essential nutrients for phytoplankton growth.

feb26sandstorm

Figure 1: Natural dust storms provide a regular source of iron to the deep ocean ocean. Ocean iron fertilization mimics this process.

Iron fertilization works in areas of the ocean where iron supply is the limiting factor for phytoplankton growth. Iron is an essential micronutrient for phytoplankton because it plays a key role in reactions taking place in the cell during photosynthesis [Geider and Roche, 1994]. The OIF experiments used iron sulfate, which contains iron in the ferrous, Fe^{2+}, form that is more soluble in seawater than other common iron compounds and is environmentally benign.

Figure 2: Shows locations of OIF experiments (crosses). Also shows annual surface nitrate concentrations (umol/l). The major iron-limited areas are the Southern Ocean, the northern Pacific, and the eastern equatorial Pacific (yellow, orange, red colors). [Boyd et al., 2007]

Boyd, P.W., et al., Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, 2007. 315(5812): p. 612-617.

Geider, R.J. and J. Roche, The role of iron in phytoplankton photosynthesis, and the potential for iron-limitation of primary productivity in the sea. Photosynthesis Research, 1994. 39(3): p. 275-301.

What Is The Scientific Basis For OIF?

First, the oceans play a central role in the natural carbon cycle of the Earth. Within the global carbon cycle, 45% of annual carbon turnover is driven by the primary productivity of ocean phytoplankton, and the oceans contain 93% of the biologically active carbon within the global carbon cycle. Large-scale variations in the carbon content of the atmosphere have been heavily influenced by the oceans on timescales ranging from thousands to millions of years.

Second, the "biological pump" is the dominant biogeochemical process in the ocean, and the primary means by which carbon sequestration occurs naturally there. It is driven by the growth and subsequent export to depth of biomass dominated by phytoplankton (microscopic marine photosynthesizers). As these organisms bloom, mature, and die in a 60-day life cycle, they either lose buoyancy or are grazed by zooplankton. In either case, a significant fraction of the dead organisms or fecal pellets aggregate into falling particles and sink towards the deep ocean. This process is known as the biological pump, and it moves carbon from the atmosphere into the deep ocean reservoir. This process has been an active component of the carbon cycle since photosynthesis began in the oceans about three billion years ago.

biological pump copy2

Figure 3: The Biological Pump
Schematic shows pathways for carbon to move from the atmosphere into the deep ocean. This is a natural process by which plankton grow at the surface, and then lose buoyancy after they die. Carbon is exported to the deep ocean from the “marine snow” composed of sinking plankton bodies and the fecal pellets from higher level consumers that eat plankton.

Third, the strength of the biological pump is often limited by the availability of iron, which is an essential micronutrient for phytoplankton growth. Since the late Dr. John Martin proposed that iron limits phytoplankton growth in much of the open ocean (the “Iron Hypothesis”) in the late 1980’s, Martin recognized that ocean iron fertilization might sequester large amounts of carbon from the atmosphere by stimulating the biological pump. Since the early 1990’s, twelve open ocean experiments have shown that large blooms of phytoplankton can be stimulated by adding iron to regions of the ocean where phytoplankton populations are lower than would be expected from the standing stocks of macro-nutrients [Boyd et al., 2007].

Fourth, recent science has shown that the biological pump is more effective at storing carbon in the deep ocean than previously thought. Observations of naturally occurring phytoplankton blooms have shown that up to 50% of the carbon in a phytoplankton bloom can be sequestered below 500 meters [Blain et al., 2007; Buesseler et al., 2007; Dunne, Sarmiento, and Gnandesikan, 2007]. At this depth, the permanence of carbon storage is 100 years or more over much of the world’s oceans [England, 1995; Matsumoto, 2007].

Additionally, recent modeling has shown that the majority of the carbon exported from the surface ocean is replaced by atmospheric CO_2 [Jin et al., 2008], describing how ocean fertilization can result in real reductions of atmospheric carbon dioxide. Early ocean fertilization experiments were usually too short to observe the bloom termination, or too small in scale to effectively track the export of carbon [Buesseler et al., 2004].

More recent experiments, such as EIFEX (2004) in the Southern Ocean, measured sequestration efficiency of 50% below 1000m [Smetacek et al., Submitted].

Fifth, changes in iron cycle can influence the carbon cycle, and this effect can be quite large on paleoclimatic timescales. Naturally occurring iron fertilization is one of the primary mechanisms for atmospheric CO_2 removal during the Glacial periods. We know that the rate of aeolian dust bringing iron to the ocean has at least quadrupled during the glacial stages of the past one million years [Petit et al., 1999], and that biological productivity in the oceans has increased during periods of high dust flux [Winckler et al., 2008]. A recent synthesis of measurements and modeling by Cassar and co-authors suggested that “airborne Fe increases production of sub-Antarctic waters, strengthening the link between enhanced Fe delivery and lower CO_2 during the ice ages.” Their research showed that observed increases in iron flux would have resulted in a 40ppm reduction of atmospheric CO_2, which is equal to half of the total CO_2 difference between warm and glacial conditions [Cassar et al., 2007].

Figure 4: Shows the 400,000 year relationship between temperature, CO2, and iron flux (via dust). Glacial periods have much higher dust flux vs. the shorter Interglacial warm periods, and CO2 tends to be lowest when dust flux is highest. Modeling by Cassar et al. suggests that the increased glacial dust flux can remove 40ppm CO2 through natural OIF in the Southern Ocean [Cassar et al., 2007]. Figure is from [Petit et al., 1999].

Finally, there is evidence that the deep Southern Ocean is the historically the largest mobile source and sink of carbon, with staggeringly vast amounts of carbon moving into or out of the ocean during major climate changes. Approximately 500 GtC (1,800 $GtCO_2$) moves into or out of the deep Southern Ocean during transitions between glacial and non-glacial conditions [Piotrowski et al., 2005]. This volume of carbon is significant in comparison to the total volume of carbon in the atmosphere (760 GtC or 2,800 $GtCO_2$), and the terrestrial biosphere (2,260 GtC or 8,275 $GtCO_2$). The Southern Ocean is also iron-limited, and has an abundance of macro-nutrients such as nitrates and phosphates. Paleoclimatic evidence shows a strong correlation between high dust flux to the Southern Ocean and the low temperatures of glacial conditions [Lambert et al., 2008].

The combination of the above factors suggests that ocean iron fertilization could be a viable means of removing carbon dioxide from the atmosphere. The potential volumes that could be sequestered are significant and justify further research directed at understanding the potential of OIF.

Boyd, P.W., et al., Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, 2007. 315(5812): p. 612-617.

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Buesseler, K.O., et al., Revisiting Carbon Flux Through the Ocean's Twilight Zone. Science, 2007. 316(5824): p. 567-570.

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Jin, X., et al., The impact on atmospheric CO2 of iron fertilization induced changes in the ocean’s biological pump. Biogeosciences, 2008. 5: p. 385-406.

Buesseler, K.O., et al., The Effects of Iron Fertilization on Carbon Sequestration in the Southern Ocean. Science, 2004. 304(5669): p. 414 - 417.

Smetacek, V., et al., Massive carbon flux to the deep sea from an iron-fertilized phytoplankton bloom in the Southern Ocean. Submitted, Submitted.

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Winckler, G., et al., Covariant Glacial-Interglacial Dust Fluxes in the Equatorial Pacific and Antarctica. Science, 2008: p. 1150595v1.

Cassar, N., et al., The Southern Ocean Biological Response to Aeolian Iron Deposition. Science, 2007. 317(5841): p. 1067-1070.

Piotrowski, A.M., et al., Temporal Relationships of Carbon Cycling and Ocean Circulation at Glacial Boundaries. Science, 2005. 307(5717): p. 1933-1938.

Lambert, F., et al., Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. Nature, 2008. 452(7187): p. 616-9.

How Would OIF Be Implemented?

What Is The Research Status Of OIF?

Scientific understanding of the potential of OIF comes from a substantial body of peer-reviewed literature on 12 publicly-funded open ocean experiments, as well as a much larger body of work on the "biological pump", which has been the subject of research by multiple decade-long international programs such as VERTEX (e.g. [Knauer et al., 1990], the Joint Global Ocean Flux Study (JGOFS) , [Ducklow et al., 2001], [Karl et al., 2001], and the recent VERTIGO experiments that studied carbon flux into the "twilight zone" of the ocean below the euphotic zone (e.g. [Buesseler et al., 2007]). Studies of the response of the ocean to the 2-20x dust flux to the oceans during glacial periods and the associated decrease in atmospheric CO2 provide useful inference about the impact of OIF could have at larger spatial scales[Cassar et al., 2007]. Finally, a growing body of work on model simulations of OIF also provide scenarios of the response to the ocean to larger-scale OIF, and in the last few years these models have achieved significant advances in explicitly modeling the iron cycle coupled with ocean circulation, biogeochemistry and the resulting ecosystem response (e.g. [Aumont and Bopp, 2006] and [Jin et al., 2008]).

Buesseler, K.O., et al., Revisiting Carbon Flux Through the Ocean's Twilight Zone. Science, 2007. 316(5824): p. 567-570.

Jin, X., et al., The impact on atmospheric CO2 of iron fertilization induced changes in the ocean’s biological pump. Biogeosciences, 2008. 5: p. 385-406.

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What Next Steps Are Being Proposed By The Science Community?

Many in the scientific community have proposed moderate-scale demonstration experiments (at least 100 x 100 km in size) (e.g.[Boyd et al., 2007; Buesseler et al., 2008]), in order to understand and resolve issues related to the efficacy and the impact of OIF at larger scales. Previous experiments were not specifically designed to measure carbon export into the deep ocean, and thus suffered from design issues that greatly reduced the accuracy of export measurements. The last OIF experiment (EIFEX) was larger than prior experiments and was long enough to observe the carbon export phase of the bloom. Not surprisingly, EIFEX observed much high rates of sequestration than prior experiments [Smetacek et al., Submitted]. The EIFEX experiment was a successful design that could be replicated on a moderately larger scale to improve our understanding of the carbon sequestration capability of OIF.

Buesseler, K.O., et al., ENVIRONMENT: Ocean Iron Fertilization--Moving Forward in a Sea of Uncertainty. Science, 2008. 319(5860): p. 162.

Boyd, P.W., et al., Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, 2007. 315(5812): p. 612-617.

Smetacek, V., et al., Massive carbon flux to the deep sea from an iron-fertilized phytoplankton bloom in the Southern Ocean. Submitted, Submitted.

How Would OIF Be Scaled Up?

First, the scale of proposed OIF projects must be defined. We define *small scale* as being significantly smaller than the scale of ocean mixing processes such as eddies, and extremely small compared to ocean basins (i.e. 10-15 km on a side), with one-time fertilization and evaluation of results. The purpose of small scale OIF projects has been to look at the impact of iron on phytoplankton production. We define *moderate scale* as being on the scale of ocean mixing process (i.e., 100-200 km on a side) with the potential for repeated individual experiments over a few years to look at impacts. The purpose of this scale would be to advance the science behind OIF in order to determine the potential for OIF as carbon mitigation strategy. *Large scale* would imply OIF on sizes comparable to significant percentages of ocean regions (e.g., a significant percentage of the Southern Ocean), and for extended time periods (many years to decades or centuries).

Results from previous OIF experiments clearly highlight the need for a series of second generation moderate-scale demonstrations to determine whether OIF would be an effective carbon mitigation technique. Several scientific articles and policy papers have called for further experiments[Boyd et al., 2007; Buesseler et al., 2008; IOC, 2008]). The patch scales described in these documents range from 100x100 km to 200x200 km, approximately the dimension of mesoscale eddies. Conducting OIF experiments on this scale will greatly improve the likelihood that measurements in the patch have the minimum dilution with material outside the patch and will increase the statistical accuracy of carbon sequestration measurements.

Buesseler, K.O., et al., ENVIRONMENT: Ocean Iron Fertilization--Moving Forward in a Sea of Uncertainty. Science, 2008. 319(5860): p. 162.

Boyd, P.W., et al., Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, 2007. 315(5812): p. 612-617.

IOC, STATEMENT OF THE IOC AD HOC CONSULTATIVE GROUP ON OCEAN FERTILIZATION, I.O. Commision, Editor. 2008.

Who Would Decide If OIF Should Be Deployed At Large Scales?

Regulatory frameworks are in place that could provide effective controls on future OIF activities. The primary regulatory framework is the London Convention of 1972, which has 88 signatory countries, however all governments have the ability to regulate the activities of their registered vessels and activities in their ports, whether they are party to the London Convention/London Protocol (LC/LP) or not. In addition, governments that are party to the LC/LP also have mutually agreed guidelines that recognize the importance of the marine environment and ecosystem and that foster good governance for the oceans. The LC/LP and its subsidiary bodies have been encouraged to provide additional guidance specific to OIF for assessment of project proposals and on-site measurement programs that would be required for such projects. This would allow effective regulation of experiments in the development stage. We assume that the LC/LP will actively follow such development experiments and their results. If development efforts identify either 1) methods that must be employed to avoid unacceptable environmental risks or 2) unacceptable environmental risks that cannot be managed, the LC/LP can take further steps to 1) agree to further guidelines for regulation or 2) consider a moratorium. We believe that this strategy is more likely to result in an appropriate pace of development balanced by responsible oversight.

What About The Statement On OIF By The UN Convention On Biological Diversity?

There are reports that the Parties to the Convention on Biological Diversity (CBD) have issued a moratorium on commercial ocean iron fertilization. However, as we understand their statement, it acknowledges the ongoing consideration of OIF by the London Convention over the last year, including the LC interaction with prominent members of the international ocean science community. We further understand that the CBD statement calls for additional scientific research, a precautionary approach and appropriate regulatory controls for OIF activities -- objectives that have been shared by Climos since its inception.

Climos agrees that OIF activities should proceed only where there is an adequate scientific basis to justify them, including assessment of associated risks, and should be subject to an appropriate regulatory framework including any permits required pursuant to the IMO LC process. Climos encourages the LC to develop regulatory guidelines to help assess and control future OIF activities. Moreover, as we have previously stated, no sale of carbon credits from OIF projects should take place unless those projects are shown to be effective and the environmental impacts characterized. Climos looks forward to interacting with the CBD parties and the Subsidiary Body on Scientific Technical and Technological Advice (SBSTTA) to develop and share relevant scientific and technical data relating to these issues, including the information developed as part of the scientific review under the LC process.

Where In The Ocean Would OIF Be Conducted?

The initial iron fertilization paradigm we have chosen is fertilization of a HNLC (High Nutrient Low Chlorophyll) zone. HNLC areas have been the primary focus for eleven of the past twelve OIF research experiments. While other paradigms (such as fertilization to stimulate nitrogen fixation) have been discussed and debated, and while a valid rationale for exploring these paradigms may exist, we intend our first demonstration to be an HNLC OIF.

This selection narrows our potential choice of project locations. While the Equatorial Pacific is an HNLC region, we have chosen not to consider it for the first experiment because of the potential for generating N2O and because models suggest that at least some nutrient depletion could be an issue in this region. This has led us to focus on the North Pacific or Southern Ocean. Successful OIF experiments have been carried out in both areas. We will further limit our choice of sites for the Southern Ocean to those sufficiently north of the latitude indicated by the Antarctic Treaty that our work would not affect the Antarctic continent or its waters. The primary constraint on the choice between a North Pacific and Southern Ocean experiment is seasonal. Phytoplankton require adequate sunlight to grow in addition to adequate nutrient and this naturally limits any intentional stimulation of growth to the summer season for the regions.

The second constraint on site selection is distance from shore. OIF is generally not effective near land because sufficient quantities of iron are supplied by river runoff and/or re-suspension of continental shelf sediment. Further, for carbon to be sequestered with sufficient permanence, water must be deep enough that the exported carbon is removed from further contact with the atmosphere for at least 100 years. In the interest of conservatism, we will only consider project locations in deepwater (at least 2000 meters in depth and more likely ~4000 meters in depth or greater) and at least 500 kilometers away from the nearest land mass (and more likely at least 1000 to 1500 kilometers away). Both of these parameters are elements of the Code of Conduct we proposed.

The third constraint on site selection is proximity to an operating port that can provide an adequate source of working class vessels to perform the distribution of the iron sulfate to our specification. There are a limited number of countries that are both signatories to the London Convention, proximate to either Southern Ocean or North Pacific potential operating locations, and that have working ports of sufficient size to maintain a fleet of vessels available for hire and satisfactory to the work required. As of the writing of this document Climos has had no formal discussions with any nation for the purposes of permitting an OIF project under the London Convention.

Who Would Conduct OIF?

Climos will select and fund a Lead Scientist (Principal Investigator) to lead and coordinate the experimental cruise on our behalf. Our preference is a Lead Scientist with previous experience in conducting OIF experiments. We are discussing the position with a small number of scientists. During the fall of 2008 Climos will hold a workshop for members of the international community familiar with OIF science to discuss the measurements and modeling necessary to quantify export/sequestration. A second workshop will emphasize measurements and modeling to quantify impacts of OIF, including ecological. We anticipate that it will be held during early spring 2009. We have been discussing co-sponsorship with an international global change program focused on interdisciplinary marine ecosystem study.

Using the information and planning from the workshop the Lead Scientist will propose a scientific team to perform the demonstration cruise on our behalf. This team will be chosen for their scientific credentials and recognition within their research focus.

In What Form Would The Iron Be Added?

soluble in seawater than other common iron compounds and is environmentally benign. In order to chelate the iron sulfate and enhance its solubility, the iron sulfate was acidified before dispersing it in the ocean. . Coincidentally, weakly acidic iron sulfate may mimic the form of iron thought to be most likely to enter the ocean from dust deposition [Zhuang and Duce, 1993]. It should be mentioned that the acidity of the iron sulfate solution is immediately diluted upon introduction to the ocean. Subsequent measurements on previous experiments were not able to detect a difference in pH. To the contrary, the increase in pH (decrease in acidity) as a result of the increased production of phytoplankton (and subsequent drawdown of DIC) is many orders of magnitude greater than any immediate effect of the chelating HCl.

Iron sulfate is normally used for a variety of land-based applications such as trace nutrient in plant fertilizer and nutritional supplements for animals. While the iron sulfate does often originally derive from a co-product of either steel manufacturing or titanium dioxide manufacturing, commercial formulators process it further according to specifications appropriate for the use intended. Climos will obtain analyses and provide those to interested parties to document levels of any other trace materials in the solution that will be used. The trace elements in a typical iron sulfate source diluted to the concentrations that we would use for fertilization are very low in comparison with the trace element concentration of seawater.

Table 1: Iron Sulfate Impurities Compared to Background Seawater Concentrations

Element	Maximum concentration in $Fe(SO_4)$ (ppm)	Concentration in 5 nmol $FeSO_4$-H_2O solution (mg/l)	Concentration in seawater (mg/l)	Percent concentration in 5 nmol $FeSO_4$-H_2O relative to seawater
As	1	0.000001	2.60	**0.000%**
Cd	2	0.000002	0.11	**0.002%**
Cr	20	0.000017	0.20	**0.009%**
Cu	17	0.000014	0.90	**0.002%**
Pb	17	0.000014	0.03	**0.047%**
Mg	9600	0.008156	1290000.00	**0.000%**
Mn	2700	0.002294	0.40	**0.574%**
Ni	85	0.000072	6.60	**0.001%**
Zn	2000	0.001699	5.00	**0.034%**

In all of the previous OIF experiments iron sulfate was acidified and mixed with seawater onboard ship. A small stream of this mixture was then released into the prop wash of the ship as it was steaming. The propeller mixed the acidified iron sulfate into the water behind the ship. We propose to use the same technique. Distribution of iron will take place from ships separate from the scientific measurement ship. In order to fertilize a moderate sized patch (as much as 200 x 200 km), we will use multiple distribution ships to minimize the fertilization time.

The materials used for OIF experiments, and the materials that we propose to use are dominated by ions that are either 1) in higher concentration in seawater than the fertilization solution (e.g. SO_4, Cl, trace elements), or 2) are introduced in high concentration but are diluted or precipitate out very quickly (e.g., Fe). While the acidified iron sulfate is more acidic than seawater, it is rapidly diluted and does not result in low pH in the experiment area. For these reasons we believe that the immediate effect of the iron solution itself and the impurities in the iron solution would pose no threat to marine life. The principal effect of iron fertilization in 12 previous experiments was the stimulation of phytoplankton growth.

How Effective is OIF?

How Do We Know That OIF Will Remove Atmospheric Carbon Dioxide?

The reason to engage in OIF is to facilitate the drawdown of atmospheric CO_2. There are two aspects of atmospheric carbon dioxide removal. The first component is carbon uptake into organic carbon as a response to the triggered phytoplankton bloom. This causes the surface ocean to become depleted in inorganic carbon. According to Henry?s Law of Partial Pressures, atmospheric carbon dioxide will equilibrate with the surface ocean resulting in CO_2 uptake by the ocean. The second component is the sequestration of a portion of the phytoplankton organic carbon to deeper waters where it cannot re-equilibrate with the atmosphere.

The fact that organic carbon can be removed from the surface ocean by OIF has been conclusively demonstrated by both artificial experiments, such as the EIFEX experiment which observed high rates of sequestration with up to 50% of the bloom biomass sinking below 1000m depth [Smetacek et al., Submitted], and by observations of natural blooms [Blain et al., 2007]. Recent measurements of carbon export from naturally-occurring seasonal phytoplankton blooms in the northwest Pacific and subtropical Pacific suggest that the biological pump is much more efficient than previously thought. The VERTIGO experiments used the latest equipment and techniques, including neutrally buoyant sediment traps to look at the fate of carbon below the mixed layer, and found that export to the deep ocean (below 500 m) was 2-5 times greater than previously thought[Buesseler et al., 2007]. Similarly, observations of natural blooms stimulated by iron fertilization in the Southern Ocean (e.g. over the Kerguelen plateau) showed extremely high rates of carbon export compared to prior observations [Blain et al., 2007].

Jin and his coauthors (2008) used a modern ocean circulation model with an explicit iron biogeochemical cycle to measure atmospheric uptake efficiency of OIF. By conducting simulations of iron fertilization the Tropical Pacific using a coupled ocean circulation model with biogeochemical and ecological response components, they found that atmospheric carbon dioxide replaces between 75-93% of the organic carbon exported to depth [Jin et al., 2008]. This adds evidence in support of OIF as an effective means of sequestering atmospheric carbon dioxide.

Blain, S., et al., Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature, 2007. 446(26 April): p. 1070-1074.

Buesseler, K.O., et al., Revisiting Carbon Flux Through the Ocean's Twilight Zone. Science, 2007. 316(5824): p. 567-570.

Jin, X., et al., The impact on atmospheric CO2 of iron fertilization induced changes in the ocean's biological pump. Biogeosciences, 2008. 5: p. 385-406.

Smetacek, V., et al., Massive carbon flux to the deep sea from an iron-fertilized phytoplankton bloom in the Southern Ocean. Submitted, Submitted.

How Efficient Is OIF At Removing Atmospheric Carbon Dioxide?

There are two measures commonly used to describe the effectiveness of OIF. The first measure, *atmospheric uptake efficiency*, is the ratio of atmospheric CO_2 absorbed by the ocean to the amount of carbon exported by the biological pump to depths at which it will not re-equilibrate with the atmosphere for long periods of time. We believe this is an important measure of the efficiency of OIF as a carbon sequestration technique, because the goal of a carbon sequestration technique is to remove CO_2 from the atmosphere. Jin et al. [2008] found atmospheric uptake efficiencies of 0.75 – 0.93, which were much higher than earlier and simpler models (e.g., [Gnanadesikan, Sarmiento, and Slater, 2003]).

The second measure commonly referred to is the *iron utilization efficiency*, which is the ratio of carbon exported to iron supplied. We do not believe that this is an appropriate method of determining the amount of carbon sequestered. Iron introduced to the surface water is not directly related to carbon sequestered because an oversupply of iron would not generate a more vigorous response. Beyond a certain threshold, excess iron supplies will precipitate out of the system. The expected *iron utilization efficiency* is important to understand how much iron is necessary to stimulate a phytoplankton bloom in HNLC waters, although this ratio is not relevant for *measuring* carbon export.

Gnanadesikan, A., J.L. Sarmiento, and R.D. Slater, Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. GLOBAL BIOGEOCHEMICAL CYCLES, 2003. 17(2): p. 1050.

How Do We Know The Total CO2 Removal Potential Of OIF?

During the last two years, new computer-based models explicitly simulated the ecological response to the natural iron cycle. When coupled to ocean circulation and biogeochemical models, these simulations provide much more realistic predictions than previously possible. The new models have also shown that a large scale 100-year deployment of OIF could produce enough carbon reductions to be comparable with any other currently envisioned carbon reduction technique [Jin et al., 2008; Aumont and Bopp, 2006].

The results from the Aumont and Bopp [2006] simulations suggest that OIF could remove 33 ppm CO_2 from the atmosphere after 100 years of continuous fertilization. This is a not a small number, as it represents 1/3 of the current elevation of atmospheric CO_2 levels. Zahariev et al. [2008] using a different set of model assumptions calculated that global OIF would absorb approximately 11% of annual anthropogenic emissions

[Zahariev, Christian, and Denman,2008]. Although much smaller, this quantity is still equivalent to that of many other emission reduction strategies, such as moderate and low-penetration wind power. This suggests that OIF has the potential to become one of the single largest individual techniques to mitigate atmospheric CO_2 levels.

Several critiques of OIF have focused on the fact that OIF cannot remove all anthropogenic CO_2. However, OIF should not be expected to shoulder the entire burden of anthropogenic CO_2 emissions removal. This is neither realistic nor desired. Other technologies or techniques such as forestation, deep geologic sequestration, wind turbines, or photovoltaics are not expected to meet this requirement. We believe that this criticism is a legacy of very early suggestions that OIF could be used to draw down a significant portion of the accumulated anthropogenic CO_2. We have never made such a claim. If OIF is assumed to work in parallel with the entire spectrum of other mitigation responses, then the total potential removal is large compared to most other options.

Jin, X., et al., *The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump.* Biogeosciences, 2008. 5: p. 385-406.

Aumont, O. and L. Bopp, *Globalizing results from ocean in situ iron fertilization studies.* Global Biogeochem. Cycles, 2006. 20.

Zahariev, K., J.R. Christian, and K.L. Denman, *Preindustrial, historical, and fertilization simulations using a global ocean carbon model with new parameterizations of iron limitation, calcification, and N2 fixation.* Progress in Oceanography, 2008.

How Permanent Is The Carbon Sequestration From OIF?

There are two components to the question of 'permanence' of carbon sequestration from OIF. The first component is the length of time that sequestered carbon will be prevented from returning to the atmosphere. This time is a function of the ocean circulation patterns at depth below the fertilized patch. Deep ocean mixing is a slow process that occurs on a time scale of hundreds to a thousand years. The ability to associate the depth of the water column with age (of last contact with the atmosphere) and future trajectory of the water is well-established in the oceanographic community. Measurements of the intrusion of manmade tracers (e.g. CFCs) and radioactive elements into world oceans provide calibration data for circulation models. These models can then produce a "residence time vs. depth profile" curve for any area of the ocean in which ocean fertilization is conducted There are two components to the question of 'permanence' of carbon sequestration from OIF. The first component is the length of time that sequestered carbon will be prevented from returning to the atmosphere. This time is a function of the ocean circulation patterns at depth below the fertilized patch. Deep ocean mixing is a slow process that occurs on a time scale of hundreds to a thousand years. The ability to associate the depth of the water column with age (of last contact with the atmosphere) and future trajectory of the water is well-established in the oceanographic community. Measurements of the intrusion of manmade tracers (e.g. CFCs) and radioactive elements into world oceans provide calibration data for circulation models. These models can then produce a "residence time vs. depth profile" curve for any area of the ocean in which ocean fertilization is conducted [England, 1995; Matsumoto, 2007], as well as the general future path of this water.

The residence time of carbon sequestered from OIF is calculated through application of the general circulation models described above. As organic carbon particles sink via the biological pump, the particles undergo a constant dissolution back into a dissolved state. The process is called *remineralization*, because organic material is converted back to its inorganic (or mineral) form. Preferentially, most sequestered carbon is remineralized closer to the surface of the ocean, but a significant fraction can sink to the deep ocean or even the sea floor. The permanence of carbon sequestration from OIF is defined by the future trajectory of the water parcel in which each unit of carbon remineralizes. In order to generate carbon credits from OIF, carbon sequestration should be measured at depth corresponding to a desired permanence time period.

The second component of 'permanence' of carbon sequestration is the definition of a *permanence time period*. The Kyoto Protocol uses 100 years as the arbitrary time horizon for which the GWP of the six regulated GHGs are normalized [UNFCCC, 1997]. This choice by the Kyoto Protocol policy makers incorporated consideration for both long-term benefits and short-term benefits of climate mitigation options [IPCC, 1995] *p.229*, and is the best definition available for viable carbon sequestration. To be consistent global carbon policy, we recommend a depth corresponding to a 100-year residence time for measuring the carbon credits claimed by an OIF project.

Because permanence is such a crucial concept and is often misunderstood, the text of the IPCC discussion on permanence is reproduced below. A key assumption is that permanence is an arbitrary time period chosen to reflect a *policy decision* on the best way to solve the climate change problem.

> *"Policy-relevant climate-change phenomena exist at both ends of the climate-change time spectrum:*
>
> <!--[if !supportLists]-->*1. If the policy emphasis is to help guard against the possible occurrence of*

> *potentially abrupt, non-linear climate responses in the relatively near future, then a choice of a 20-year time horizon would yield an index that is relevant to making such decisions regarding appropriate greenhouse gas abatement strategies. In addition, if the speed of potential climate change is of greatest interest (rather than the eventual magnitude), then a focus on shorter time horizons can be used.*
>
> <!--[if !supportLists]-->*2.* <!--[endif]-->*Similarly, if the policy emphasis is to help guard against long-term, quasi-irreversible climate or climate-related changes (e.g., the very slow build up of and recovery from sea level changes that are controlled by slow processes such as warming of the ocean), then a choice of a 100-year or 500-year time horizon would yield an index that is relevant to making such decisions regarding appropriate greenhouse gas abatement strategies.*
>
> *With this awareness, policies could choose to be a mix of emphases. GWPs with differing time horizons can aid in establishing such a mix. Indeed, that was the case in the Montreal Protocol deliberations, in which the long-lived, high-ODP gases were the initial focus and the shorter-lived, lower-ODP gases were subsequent focus."[IPCC, 1995] p.229*

England, M.H., *The Age of Water and Ventilation Timescales in a Global Ocean Model.* Journal of Physical Oceanography, 1995. **25**(November): p. 2756 - 2777.

Matsumoto, K., *Radiocarbon-based circulation age of the world oceans.* Journal of Geophysical Research, 2007. **112** (C09004).

UNFCCC, *REPORT OF THE CONFERENCE OF THE PARTIES ON ITS THIRD SESSION, HELD AT KYOTO FROM 1 TO 11 DECEMBER 1997*, in *FCCC/CP/1997/7/Add.1*, UNFCCC, Editor. 1997.

IPCC, *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, ed. J.T. Houghton. 1995, Cambridge, U.K.: Cambridge University Press.

Ecological Effects of OIF

Would OIF Result In Anoxia Or "Dead Zones"?

Anoxia is caused by persistent excessive primary biological productivity that can lead to low oxygen conditions as a result of the metabolism of the organic material from biological productivity. Anoxia (or "dead zones") occur in coastal ocean waters, often as a result of the continuous abundant supply of nitrate and phosphate from land that can sustain large blooms of phytoplankton for many months. This generates a large amount of organic matter which decomposes and absorbs oxygen. Anoxia rarely occurs in the open ocean because surface waters do not have a continuous supply of nutrients (e.g., nitrate, phosphate, silicate, iron) that can sustain blooms for extended periods. In the open ocean, natural phytoplankton blooms, as well as artificially stimulated ones die out in a matter of weeks due to limited macronutrients. This effect was also observed in experiments that applied iron to the ocean multiple times and did not observe any increase in phytoplankton productivity compared to experiments that used only one initial application of iron [Boyd et al., 2007].

A second control on the potential for anoxia is the depth of the water column in which the phytoplankton bloom occurs. In shallow water, decomposition of phytoplankton is concentrated in smaller volume of water, thus increasing the level of oxygen depletion per unit volume of water. The "dead zones" in the Gulf of Mexico occur in water that is 10-30m deep. Anoxia is very unlikely to occur with ocean fertilization in non-coastal waters where depths are thousands of meters. Avoiding the possibility of anoxia is one of the reasons why the Climos Code of Conduct for Ocean Iron Fertilization proposes that all OIF projects be "conducted at least 500 km from shore and in waters at least 2000 meters deep." [Climos, 2007].

Even though small to moderate scale OIF in the deep open ocean is very unlikely to acute conditions of create anoxia, there is a complex relationship of the biological pump and deep ocean oxygen levels. More research is needed on the effects of large scale OIF on deep water oxygen levels. A recent synthesis of 12 general circulation models by Najjar et al. demonstrated poor agreement on the effects of biological carbon export on oxygen content, and all but two of the models overestimated the oxygen-depleting effects of biological carbon export [Najjar et al., 2007]. A major conclusion by Najjar et al. is that more sediment trap observations of carbon export are needed to refine the models, particularly in the Southern Ocean. Collecting this data would be a primary focus of our proposed OIF demonstration cruise. With better data, and continually improving models, scientists will be able to make better predictions on the potential effects of large scale OIF on oxygen levels, which will inform future policy decisions on the feasibility of large scale OIF.

Boyd, P.W., et al., Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, 2007. 315(5812): p. 612-617.

Climos. The Climos Code of Conduct. 2007 [cited]

Najjar, R.G., et al., Impact of circulation on export production, dissolved organic matter, and dissolved oxygen in the ocean: Results from Phase II of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP-2). Global Biogeochem. Cycles, 2007. 21.

What Effect Would OIF Have On Ocean Acidity?

OIF would not exacerbate surface ocean acidity, and may have a slight beneficial effect. First, it is important to recognize that ocean acidification is a problem of the upper ocean where organisms that secrete calcareous skeletal material are most common. Second, the deep ocean is naturally elevated in acidity due to its much higher carbon content derived from the continual action of the biological pump. Ocean fertilization provides a net reduction of surface ocean acidity by accelerating the transport of CO_2 out of surface waters to the deep ocean bicarbonate reservoir. This local decrease in surface ocean acidity can persist for approximately eight months before atmospheric CO_2 re-equilibrates with the surface ocean [Jin et al., 2008]. The effect of OIF on deep ocean acidity is very small because of the relative size of the deep ocean carbon pool. To put this in perspective, if the historic total of human CO_2 emissions (~1,700 GtCO230) were sequestered to the deep ocean, this would increase the deep ocean carbon content by 1%.

Jin, X., et al., The impact on atmospheric CO2 of iron fertilization induced changes in the ocean's biological pump. Biogeosciences, 2008. 5: p. 385-406.

Would OIF Cause Harmful Algae Blooms (HABs)?

Ocean fertilization experiments have stimulated the same plankton groups that bloom under natural conditions, especially small photosynthesizers and diatoms. While algae capable of producing toxins exist in most of the ocean, blooms dominated by algae capable of producing toxins generally occur in coastal waters where nutrient levels are high and where shallow waters allow the re-innoculation of waters by resting stages that are present in sediments. Even natural blooms in the open ocean that include diatoms genetically capable of making toxins have not been observed to influence marine organisms, including marine mammals and seabirds. No harmful algal blooms have been identified during ocean fertilization experiments. Ocean fertilization activities should be conducted in the open ocean where harmful algal blooms have not been identified, and measurements should be made to detect the presence of any toxins.

Would OIF Cause Permanent Changes To The Species Of Phytoplankton In The Ocean?

Natural blooms result in temporary changes to the overall species composition compared to non-bloom conditions [Hoffman et al., 2006; Barber and Hiscook, 2006]. After the bloom, the species mix returns to pre-bloom conditions [Barber and Hiscook, 2006]. There is no evidence that individual fertilized blooms have caused permanent changes to species composition. Given the large variability of natural iron delivery over both annual and geologic time scales, and the lack of permanent changes associated with these changes in flux, it is also unlikely that larger scale OIF would cause permanent changes.

Hoffmann, L.J., et al., Different reactions of Southern Ocean phytoplankton size classes to iron fertilization. Limnology and Oceanography, 2006. 51(3): p. 1217 - 1229.

Barber, R.T. and M.R. Hiscock, A rising tide lifts all phytoplankton: Growth response of other phytoplankton taxa in diatom-dominated blooms. GLOBAL BIOGEOCHEMICAL CYCLES, 2006. 20(4).

Would OIF Produce Other Greenhouse Gases Such As Nitrous Oxide And Methane?

Because the greenhouse gases (GHGs), methane and nitrous oxide(N2O), are products of biological metabolism, there has been concern that enhancing phytoplankton productivity might result in concentrations of these gases that would offset the benefit of CO_2 reductions from biological carbon export [Fuhrman and Capone, 1991]. More recent coupled physical/biogeochemical ocean models have shown substantial N2O generation in some regions (e.g. the tropics), and very little generation in other regions (e.g. North Pacific and Southern Ocean) [Jin and Gruber, 2003]. Measurements during two ocean fertilization experiments in the Southern Ocean confirm these results. One experiment showed a small amount of N2O that would offset about 5% of the predicted CO_2 sequestration [Law et al., 2005], the other experiment showed none [Walter et al., 2005].

From the standpoint of quantifying net carbon reduction benefits, leakage from the generation of non-CO_2 gases, such as N2O and CH4, can be quantified through measurements during the project. The CO_2 -equivalent amount can then be subtracted from the total sequestered carbon. In the North Pacific and Southern Ocean, High-GWP gas leakage is estimated to be 5% or less of the total CO_2 reductions. Leakage from the burning of fossil fuels to power the ships and from other direct operations will be deducted and is estimated to be approximately 1% of the total CO_2 reductions.

Fuhrman, J.A. and D.G. Capone, Possible Biogeochemical Consequences of Ocean Fertilization. Limnology and Oceanography, 1991. 36(8): p. 1951-1959.

Jin, X. and N. Gruber, Offsetting the radiative benefit of ocean fertilization by enhancing N2O emissions. Geophysical Research Letters, 2003. 30(24).

Law, C.S., et al., Vertical eddy diffusion and nutrient supply to the surface mixed layer of the Antarctic Circumpolar Current. J. Geophys. Res, 2003. 108: p. 3272.

Walter, S., et al., Nitrous oxide measurements during EIFEX, the European Iron Fertilization Experiment in the subpolar South Atlantic Ocean. GEOPHYSICAL RESEARCH LETTERS, 2005. 32(L23613).

Would OIF Affect Biological Productivity Elsewhere?

The basic premise of most proposals for OIF is that they would be deployed in HNLC (high nutrient, low chlorophyll) regions that have excess nutrients that can only be drawn down by additional supply of iron. Thus the addition of the iron is not affecting local productivity that would have taken place in the absence of OIF, it is adding to that productivity.

Some modeling studies have raised a concern that iron fertilization in one place would take up nutrients that would been taken up at a later time in a different region of the ocean (this is the so-called “downstream” nutrient depletion effect) [Gnanadesikan, Sarmiento, and Slater, 2003]. Two recent modeling studies that used a more complete modeling approach have considered these concerns. The first looked at OIF from a global, long term perspective. In a 100-yr global-scale fertilization simulation, Aumont and Bopp (2006) found that total global biological productivity increased by 20.0 GtC/yr in the first year of fertilization, and remained elevated by 9.8 GtC/yr in the 100th year of fertilization when compared to the unfertilized case [Aumont and Bopp, 2006]. In particular, they found that downstream nutrient depletion did not occur in HNLC regions such as the Southern Ocean, because strong winter mixing of surface and deeper waters restores surface nutrient levels each year. A second modeling study by Jin et al (2008) simulated fertilization of the Tropical Pacific for ten years, and did not find “downstream” depletion of nutrients. These results suggest that OIF would not reduce downstream biologic productivity and therefore reduce carbon sequestration effectiveness. Our point in citing these studies is not that the most recent model is the last word on efficiency of OIF, but that results are model dependent and that they should be used with great caution in developing policy concerning OIF. Further research with larger scale experiments and continually improving models will help inform future policy choices.

Aumont, O. and L. Bopp, Globalizing results from ocean in situ iron fertilization studies. Global Biogeochem. Cycles, 2006. 20.

Gnanadesikan, A., J.L. Sarmiento, and R.D. Slater, Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. GLOBAL BIOGEOCHEMICAL CYCLES, 2003. 17(2): p. 1050.

Would OIF Affect Fisheries?

In the single published case in which the impact of OIF up the food chain to fish was studied (SEEDS), the effects were positive rather than negative:

“Effects of iron enrichment on higher trophic levels, such as fishes, are among the important issues that can be tested only by meso-scale whole ecosystem experiments. Trawl samplings of salmon and other nekton were performed inside and outside of the iron-enriched patch at the end of the experiment (day 14). Although there was no significant difference in salmon catch between inside and outside of the patch, catch of juvenile Northern mackerel was obviously high in the iron-enriched patch.” [Takeda and Tsuda, 2005]

This is also consistent with the historic association between diatom new production and fisheries [Cushing, 1995; Ryther, 1969; Smetacek, 1998]. We are not arguing that OIF will enhance fisheries, but there is certainly no evidence that enhanced diatom production in the ocean is associated with harm to food webs or decreased fisheries production. This is an issue that should be studied in future experiments, but the only published evidence suggests that fisheries are enhanced.

Another recent study suggests positive ecological effects from OIF in the Southern Ocean. Smith et al. studied Antarctic icebergs, around which observed increases in marine life density were found to be the result of ocean fertilization from the release of iron-containing mineral dust entrained in the melting ice [Smith, 2007]. These effects were observed for several kilometers around the icebergs and at many higher levels of the food chain. Their results suggest that iron-containing dust released from free-drifting icebergs can positively affect the pelagic ecosystem of the Southern Ocean and that icebergs can serve as areas of enhanced production and sequestration of organic carbon to the deep sea. This was covered by the popular press in Time Magazine’s article, Islands of Life.

Takeda, S. and A. Tsuda, An in situ iron-enrichment experiment in the western subarctic Pacific (SEEDS): Introduction and summary. Progress in Oceanography, 2005. 64(2-4): p. 95-109.

Cushing, D.H., Population Production and Regulation in the Sea: A Fisheries Perspective. 1995: Cambridge University Press.

Ryther, J.H., Photosynthesis and Fish Production in the Sea. Science, 1969. 166(3901): p. 72-76.

Smetacek, V., Biological oceanography: diatoms and the silicate factor. Nature, 1998. 391(6664): p. 224.

Smith, K.L.J., Free-Drifting Icebergs: Hot Spots of Chemical and Biological Enrichment in the Weddell Sea. Science, 2007. 317(27 July): p. 478-482.

How Do We Know Whether OIF Would Cause Other Unknown Ecosystem Effects?

As with any action in the natural environment, it is impossible to foresee all potential effects, and thus it is conceivable that unexpected consequences can arise. Some have suggested that the threat of potential unknown deleterious effects is reason enough to stop any further OIF demonstrations [Allsopp, Santillo, and Johnston, 2007]. However, it is important to discriminate between moderate scale experimental demonstrations and large scale deployment of OIF as a tool in addressing global change. The existing body of scientific evidence is very clear that small to moderate scale OIF demonstrations in the deep ocean are benign if the demonstration is properly designed [IOC, 2008], and that these demonstrations are vital to further understand whether OIF could become a beneficial climate change mitigation tool [Buesseler et al., 2008]. The data collected by these field trials will be very useful for expanding the predictive capability of computer models [Najjar et al., 2007] which is one of the primary scientific means for predicting the long-term effects of large scale OIF.

With respect to the additional iron, Aumont and Bopp investigated the fate of the added iron in their global OIF simulations, and found that most of the iron is lost to sediments and does not remain in biologic zone. They also found that, “After 10 years, the iron global content is only about 15% higher than in the nonperturbed case. After 90 years, the artificially added iron has been almost entirely washed out of the ocean, resulting in virtually identical ocean Fe content in both cases.” [Aumont and Bopp, 2006].

When considering the potential ecological effects of larger scale OIF, it is important to recognize that large scale OIF is a continuously ongoing natural process. OIF occurs naturally. Artificial OIF would increase the rate of this natural process, by simulating the iron deposition increases that have occurred repeatedly throughout the recent geologic past. The supply of iron to the ocean has increased many fold during ice ages, and these increases lasted for hundreds to perhaps thousands of years [Petit et al., 1999; Lambert et al., 2008]. Deep ocean sediment cores show that biologic productivity also increased in parallel [Winckler et al., 2008]. There is no evidence of negative ecological consequences from these increases; it appears that life in the ocean can easily adapt to the changes in iron supply.

Finally, should OIF be scaled up and then later found to be unacceptable, it can be scaled back rather quickly. Aumont and Bopp investigated the fate of the added iron in their global OIF simulations, and found that most of the iron is lost to sediments and does not remain in biologic zone. They also found that, “After 10 years, the iron global content is only about 15% higher than in the non-perturbed case. After 90 years, the artificially added iron has been almost entirely washed out of the ocean, resulting in virtually identical ocean Fe content in both cases.” [Aumont and Bopp, 2006].

Buesseler, K.O., et al., ENVIRONMENT: Ocean Iron Fertilization--Moving Forward in a Sea of Uncertainty. Science, 2008. 319(5860): p. 162.

Buesseler, K.O., et al., The Effects of Iron Fertilization on Carbon Sequestration in the Southern Ocean. Science, 2004. 304(5669): p. 414 - 417.

Petit, J.R., et al., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature, 1999. 399(June 3): p. 429-436.

Winckler, G., et al., Covariant Glacial-Interglacial Dust Fluxes in the Equatorial Pacific and Antarctica. Science, 2008: p. 1150595v1.

Lambert, F., et al., Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. Nature, 2008. 452(7187): p. 616-9.

Aumont, O. and L. Bopp, Globalizing results from ocean in situ iron fertilization studies. Global Biogeochem. Cycles, 2006. 20.

IOC, STATEMENT OF THE IOC AD HOC CONSULTATIVE GROUP ON OCEAN FERTILIZATION, I.O. Commision, Editor. 2008.

Najjar, R.G., et al., Impact of circulation on export production, dissolved organic matter, and dissolved oxygen in the ocean: Results from Phase II of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP-2). Global Biogeochem. Cycles, 2007. 21.

What Kind Of Research Is Needed To Understand The Ecological Effects Of OIF?

There is already a great deal of research upon which to base our understanding of the effects of OIF. It is clear that a few moderate scale field trials of OIF will have no lasting negative effects, and that these trials will provide valuable scientific data upon which to assess the effects of large scale OIF as a carbon mitigation tool. This sentiment is echoed in the Buesseler et al 2008 Science Policy Forum authored by sixteen senior scientists involved in OIF and ocean biogeochemistry [Buesseler et al., 2008]. They write:

> *"The consequences of global climate change are profound, and the scientific community has an obligation to assess the ramifications of policy options for reducing greenhouse gas emissions and enhancing CO2 sinks in reservoirs other than the atmosphere. … we feel that ocean biogeochemical research will help inform these important policy decisions.[Buesseler et al., 2008]*

Furthermore, Buesseler et. al describe the future research needed for informing these policy decisions

- *Field studies on larger spatial and longer time scales, because ecological impacts and CO_2 mitigation are scale-dependent.*
- *Consideration of OIF in high- and low-nutrient regions to understand a wider range of processes that are affected by iron, such as nitrogen fixation and elemental stoichiometry.*
- *Detailed measurements in the subsurface ocean to verify the fate of fixed carbon, including remineralization length scales of carbon, iron, and associated elements.*
- *Broad assessment of ecological impacts from bacteria and biogeochemistry to fish, seabirds, and marine mammals.*
- *Characterization of changes to oxygen distributions, biophysical climate feedbacks, and cycling of non-CO_2 greenhouse gases, such as methane, nitrous oxide, and dimethylsulfide.Long-term monitoring and use of models to assess downstream effects beyond the study area and observation period.*
- *Improved modeling studies of the results and consequences of OIF, including higher spatial resolution, better ecosystem parameterization, inclusion of other greenhouse gases, and improved iron biogeochemistry.*
- *Analysis of the costs, benefits, and impacts of OIF relative to other climate and carbon mitigation schemes and to the impacts of global change if we take no action [Buesseler et al., 2008]*

By engaging the private sector under the auspices of the emerging carbon market, Climos would accelerate the pace at which the above research can be conducted. To ensure scientific integrity, Climos proposes to fund a team of scientists from the international academic/research community who are familiar with the science associated with OIF experiments. Climos will also fund a workshop to develop measurement strategy and experimental design. The scientific team will design the experiment based on the workshop results, develop a methodology which will be made public, conduct the experiment, and transfer the results immediately to a public data base. Climos employees will not participate in the experiment or handle the data. Participating scientists and those who use data from the database will be free to publish any results in the open literature.

Buesseler, K.O., et al., ENVIRONMENT: Ocean Iron Fertilization--Moving Forward in a Sea of Uncertainty. Science, 2008. 319(5860): p. 162.

Regulatory Aspects of OIF

Is OIF Currently Regulated?

There are no formal existing regulations on OIF specifically, however the London Convention of 1972 is currently investigating the potential to regulate OIF activities. The London Convention is an international framework that is ratified by 88 countries and defines the rules by which signatory nations regulate the dumping and pollution from ships. The London Convention is actively considering whether and how OIF would fall under its purview.

At the 29th Consultative Meeting of the Contracting Parties to the London Convention (LC) in November 2007, the Parties adopted a Statement of Concern on Ocean Iron Fertilization (OIF) and established a scientific working group to address the issue of OIF. That group convened at the meeting of the LC Scientific Group (SG) in Guayaquil, Ecuador the week of May 19. The SG and supporting delegations prepared extensively for its closer review of OIF issues.

At the Guayaquil meeting, Climos presented a detailed briefing on OIF. The briefing addressed the scientific basis for larger and longer experiments as suggested by the international scientific community, including previous research results, responses to the SG's Statement of Concern, and a description of our plan in support of an independent scientific research program and demonstration. In addition, Climos reviewed for delegates its anticipated near term activities, including the development of a detailed Environmental Impact Assessment of OIF by a major environmental consulting and engineering firm to be released later this year. We also provided detailed responses to Greenpeace's critique of OIF that had been released in the intersessional period since the Statement of Concern. (This is available for download at www.climos.com)

Climos understands that the LC will release a report on the deliberations of the Guayaquil SG meeting on OIF in the near future. This report will reflect the group's science-based review of the LC's prior Statement of Concern and further scientific considerations for OIF activities. The SG report is intended to be a key element in the policy discussions on OIF during the next full LC meeting in October 2008. Climos looks forward to continuing to work with the relevant expert bodies under the London Convention as they develop their review of OIF and related issues.

What About The Announcement By The CBD?

Recently, the Parties to the Convention on Biological Diversity (CBD), adopted a statement related to OIF. It acknowledges the ongoing consideration of OIF by the International Maritime Organization London Convention (LC) over the last year, including its interaction with prominent members of the international ocean science community. The CBD statement calls for additional scientific research, a precautionary approach and appropriate regulatory controls for OIF activities.

Climos agrees that OIF activities should proceed only where there is an adequate scientific basis to justify them, including assessing associated risks, and should be subject to an appropriate regulatory framework including any permits required pursuant to the IMO LC process. Climos encourages the LC to develop regulatory guidelines to help assess and control future OIF activities. Moreover, as we have previously stated, no sale of carbon credits from OIF projects should take place unless those projects are shown to be effective and the environmental impacts understood. Climos looks forward to interacting with the CBD parties and the SBSTTA to develop and share relevant scientific and technical data relating to these issues, including the information developed as part of the scientific review under the LC process.

Is A Permit Necessary To Engage In An OIF Project?

Climos has made a commitment to obtaining a permit from a signatory to the International Maritime Organization London Convention on Ocean Dumping (IMO LC), if required, prior to any actual demonstration experiment. If a permit is required, and we cannot obtain one, we will not move forward.

What Voluntary Steps Is Climos Taking To Ensure That OIF Is Carried Out Responsibly?

Our near term focus has been on the outreach and engagement necessary to communicate what we feel is the strong rationale for further scientifically-led, but privately funded, demonstrations. Our activities have included:

<!--[if !supportLists]--><!--[endif]-->

- <!--[if !supportLists]--><!--[endif]-->The formation of a Scientific Advisory Board (SAB);
- Proposing elements of a “Code of Conduct” last year that lays out many of the requirements we will demand of ourselves;
- <!--[if !supportLists]--> <!--[endif]-->A presentation to delegates of the London Convention in November of 2007;

<!--[if !supportLists]--> <!--[endif]-->

- The development of an early draft framework methodology for quantifying carbon export and permanence. This will evolve over the next year.

<!--[if !supportLists]--> <!--[endif]-->

- The announcement of our engagement of Tetra Tech to produce a detailed Conceptual Model and Master Environmental Report for OIF that will form the basis of a comprehensive Environmental Impact Assessment;
- Preparation of detailed materials in advance of the London Convention Scientific Group Intercessional meeting in Guayaquil (including responses to the Canadian review and Greenpeace critique of OIF; and other notes concerning the legal status of OIF under the LC as well as the rationale for considering commercialization)

Following the completion of the Tetra Tech Conceptual Model and Master Environmental Report we intend to explore the possibility of obtaining a permit for a demonstration cruise from a favorable LC signatory that is operationally practical based on our chosen project location.

Relationship to Other Carbon Mitigation Efforts

Will OIF Reduce The Pressure To Reduce Carbon Emissions Through Energy Efficiency And Renewable Energy?

OIF does not take away from efforts to reduce emissions, which must be fundamental. However, since the rate of carbon emissions is much greater than previously thought, the world needs to consider all potential approaches to solving the problem of climate change. OIF provides a complementary approach to reducing emissions, which is a sentiment echoed in a joint statement made by the National Academies of Science from thirteen of the largest countries. In "Joint Science Academies' Statement: Climate Change Adaptation and the Transition to a Low Carbon Society", the Academies describe a sustainable approach to carbon emission reductions and also, "promote research on approaches which may contribute towards maintaining a stable climate (including so-called geoengineering technologies and reforestation), which would complement our greenhouse gas reduction strategies."[G8+5, 2008].

G8+5. *Joint Science Academies' Statement: Climate Change Adaptation and the Transition to a Low Carbon Society*. 2008 [cited]

What Is The Difference Between OIF And Other Ocean Fertilization Techniques?

Ocean fertilization in general works by supplying “missing” nutrients that limit the growth of phytoplankton in any particular region of the ocean. Iron is a trace micronutrient that can stimulate a large volume of carbon uptake for a small amount of iron material added. The theoretical maximum “carbon utilization ratio” is ~100,000 atoms of carbon per atom of iron. Other fertilization techniques add nutrients such as nitrates and phosphates. These have much lower ratios of carbon utilization (~7 atoms of C per atom of N or P), and thus a much larger volume of nutrient material is needed to stimulate an equivalent amount of carbon absorption. Some techniques, such as “Ocean Nourishment” have suggested supplying these nutrients instead of or in addition to iron. However, the larger quantity of nutrients required would make ship-based distribution more difficult, and thus commercial operations using nitrogen and/or phosphorous have typically been planned near coastal areas where pipes can distribute materials from land-based sources. The close proximity to shore suggests other problems, such as anoxia and the difficulty of achieving measurable permanence of removal.

What Is The Difference Between OIF And Artificial Ocean Upwelling?

Primary productivity in the ocean is continuously supplied with nutrients when deep ocean waters mix to the surface, bringing nutrients that have been regenerated from decomposing organic material. This upwelling is one component of vertical nutrient recycling in the ocean. The biologic pump, which moves organic carbon from the surface to deep waters is the other. In some areas of the ocean, vertical mixing is strongest during the winter (e.g. high latitudes), which replenishes nutrients on an annual basis. In other areas, mixing is relatively constant throughout the year (e.g. tropics). In general, upwelled deep waters are richer than surface waters in macro-nutrients such as nitrates and phosphates and micro-nutrients such as iron. Deep waters are also highly enriched in carbon, which can reenter the atmosphere upon upwelling.

“Artificial upwelling” is a technique that uses underwater tubes to uplift deep water to the surface. The upward flow of water through these tubes is driven by flaps which open and close through wave action. As of today, this technology is still very experimental, and it is not known how well it will work to stimulate a phytoplankton bloom or cause a net sequestration of carbon dioxide. There has been no published scientific research on this yet. We note that as of June 2008, Dave Karl of the University of Hawaii was engaged in an open ocean trial of a wave pump modified from those developed Atmocean, a company developing this technology.

Climos encourages research into additional ways that we might safely and effectively make meaningful reductions of atmospheric CO_2 levels.

Philosophical Questions

How Does The Precautionary Principle Apply?

The Precautionary Principle has been widely invoked in support of a variety of viewpoints in relation to climate change and responses to climate change such as OIF and geoengineering. The most commonly known form is from the 1992 Rio Declaration:

> *In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent*

> *environmental degradation.*

The careful reader will notice that here the that while this “precautionary approach” recommends against waiting for “full scientific certainty” in “postponing cost-effective measures to prevent environmental degradation”, that the context of the Rio Declaration in which it was made was concerned primarily with emissions reductions measures, the opposition to which was primarily from those skeptical of climate change. With OIF and other proposed geoengineering measures the sense is somewhat reversed. Here, counter-intuitively, it is primarily those that *are* concerned with the environment which are skeptical of what are seen as climate interventions. They urge precaution in undertaking actions to which they perceive a risk of large scale unintended and perhaps irreversible consequences.

We point out that there are some 19 ‘varieties’ of the precautionary principle frequently cited in the literature [*Lofstedt*, 2003]. However, two ironically opposite interpretations tend to emerge as the most commonly referenced.

The first was adopted by Germany:

> *Uncertainty does not justify inaction. In its most basic form, the precautionary principle is a principle that permits regulation in the absence of complete evidence about the particular risk scenario. [Lack of full scientific certainty shall not be used as a reason for postponing measures to prevent environmental degradation—Bergen Declaration]. [Lofstedt, 2003]*

While the second was adopted by Sweden:

> *Uncertainty requires shifting the burden and standard of proof. This version of the precautionary principle is the most far reaching. It holds that uncertain risk requires forbidding the potentially risky activity until the proponent of the activity demonstrates that it poses no (or acceptable) risk [Lofstedt, 2003].*

The first, above, is elaborated and extended as part of the elements of extropian philosophy advanced by Max More and Natasha Vita-More in what they term the “Proactionary Principle”:

> *People’s freedom to innovate technologically is highly valuable, even critical, to humanity. This implies several imperatives when restrictive measures are proposed: Assess risks and opportunities according to available science, not popular perception. Account for both the costs of the restrictions themselves, and those of opportunities foregone. Favor measures that are proportionate to the probability and magnitude of impacts, and that have a high expectation value. Protect people’s freedom to experiment, innovate, and progress*
>
> *Unpacking the Proactionary Principle*
>
> *… If we pry open the lid of this introductory-level version of the Principle, we will discover [ten] component principles lying within:*
>
> <!--[if !supportLists]-->*1.* <!--[endif]-->***Freedom to innovate:*** *Our freedom to innovate technologically is valuable to humanity. The burden of proof therefore belongs to those who propose restrictive measures. All proposed measures should be closely scrutinized.*
>
> <!--[if !supportLists]-->*2.* <!--[endif]-->***Objectivity:*** *Use a decision process that is objective, structured, and explicit. Evaluate risks and generate forecasts according to available science, not emotionally shaped perceptions; use explicit forecasting processes; fully disclose the forecasting procedure; ensure that the information and decision procedures are objective; rigorously structure the inputs to the forecasting procedure; reduce biases by selecting disinterested experts, by using the devil’s advocate procedure with judgmental methods, and by using auditing procedures such as review panels.*
>
> <!--[if !supportLists]-->*3.* <!--[endif]-->***Comprehensiveness:*** *Consider all reasonable alternative actions, including no action. Estimate the opportunities lost by abandoning a technology, and take into account the costs and risks of substituting other credible options. When making these estimates, carefully consider not only concentrated and immediate effects, but also widely distributed and follow-on effects.*
>
> <!--[if !supportLists]-->*4.* <!--[endif]-->***Openness/Transparency:*** *Take into account the interests of all potentially affected parties, and keep the process open to input from those parties.*
>
> <!--[if !supportLists]-->*5.* <!--[endif]-->***Simplicity:*** *Use methods that are no more complex than necessary*
>
> <!--[if !supportLists]-->*6.* <!--[endif]-->***Triage:*** *Give precedence to ameliorating known and proven threats to human health and environmental quality over acting against hypothetical*

> *risks.*
>
> <!--[if !supportLists]-->*7.* <!--[endif]-->***Symmetrical treatment:*** *Treat technological risks on the same basis as natural risks; avoid underweighting natural risks and overweighting human-technological risks. Fully account for the benefits of technological advances.*
>
> <!--[if !supportLists]-->*8.* <!--[endif]-->***Proportionality:*** *Consider restrictive measures only if the potential impact of an activity has both significant probability and severity. In such cases, if the activity also generates benefits, discount the impacts according to the feasibility of adapting to the adverse effects. If measures to limit technological advance do appear justified, ensure that the extent of those measures is proportionate to the extent of the probable effects.*
>
> <!--[if !supportLists]-->*9.* <!--[endif]-->***Prioritize (Prioritization):*** *When choosing among measures to ameliorate unwanted side effects, prioritize decision criteria as follows: (a) Give priority to risks to human and other intelligent life over risks to other species; (b) give non-lethal threats to human health priority over threats limited to the environment (within reasonable limits); (c) give priority to immediate threats over distant threats; (d) prefer the measure with the highest expectation value by giving priority to more certain over less certain threats, and to irreversible or persistent impacts over transient impacts.*
>
> <!--[if !supportLists]-->*10.* <!--[endif]-->***Renew and Refresh:*** *Create a trigger to prompt decision makers to revisit the decision, far enough in the future that conditions may have changed significantly [Jensen et al., 1996].*

From the Wikipedia entry for the Proactionary Principle:

> *In theory, sufficient study of the variables of any proposed course of action may yield acceptable levels of predictability. In this regard The Proactionary Principle can be looked upon as the philosophical formulation of the accepted mathematical principles of extrapolation and the logical principles of induction.*
>
> *http://en.wikipedia.org/wiki/Proactionary_Principle*

We think this articulates our position well, which we have set forth in the Climos Code of Conduct, available here: http://www.climos.com/standards

We also draw attention to the excellent thinking of Jamais Cascio in his 2006 article "The Open Future: The Reversibility Principle", who suggests a further extension:

> *When considering the development or deployment of beneficial technologies with uncertain, but potentially significant, negative results, any decision should be made with a strong bias towards the ability to step back and reverse the decision should harmful outcomes become more likely. The determination of possible harmful results must be grounded in science but recognize the potential for people to use the technology in unintended ways, must include a consideration of benefits lost by choosing not to move forward with the technology, and must address the possibility of serious problems coming from the interaction of the new technology with existing systems and conditions. This consideration of reversibility should not cease upon the initial decision to go forward to hold back, but should be revisited as additional relevant information emerges.*

Is OIF reversible? Technically, no—few things truly are. However, the additional productivity stimulated by OIF stops immediately when iron is no longer supplied. From that point forward, the system essentially relaxes to its previous equilibrium. Any impacts of OIF, such as additional oxygen or nutrient demand, would begin to abate from that point forward. So, while not reversible, one could very reasonably argue that it can be "turned off" once started.

We note that there is a commonly accepted, mature practice in Environmental engineering called "Adaptive Mitigation" which essentially implies that one establishes a mechanism for understanding whether the action has the intended effect and adapts the mitigation based on the results. This is built in to EIAs as a matter of routine now.

This also suggests an approach to OIF whereby the concerns over long-term potential effects are continually monitored for. If trends begin to develop which suggest that the risks of continued mitigation outweigh the benefits, then the mitigation can be discontinued.

Lofstedt, R.E., The Precautionary Principle: Risk, Regulation and Politics. Process Safety and Environmental Protection/Official Journal of the European Federation of Chemical Engineering: Part B, 2003. 81(B1): p. 36-43.

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