INTERNATIONAL MARITIME ORGANIZATION

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OCEAN FERTILIZATION

Background and Literature Review Addressing Main Elements in the LC/LP Scientific Groups' Statement of Concern on Ocean Fertilization

Submitted by Canada

SUMMARY	
Executive summary:	This document outlines the potential benefits and impacts of fertilizing the open ocean with iron, nitrogen or phosphorous, or of "ocean pumping" to fertilize surface waters with deep-ocean nutrients for the purpose of sequestering atmospheric carbon. It also looks at criteria that should be considered in assessing these activities as climate change mitigation measures, namely: the duration of likely sequestration, the sustainability of the practice employed, and the method of verifying and measuring carbon sequestration. The references cited in this document can be found in the annex.
Action to be taken:	Paragraph 8
Related documents:	LC/SG 30/14; LC 29/17; LC-LP.1/Circ.20

1 INTRODUCTION

1.1 Early in 2007, the 30th session of the LC Scientific Group, and the 1st session of the LP Scientific Group issued a Statement of Concern (LC/SG 30/14) in response to the commercial iron fertilization projects described later in this document that are proposed as climate change mitigation techniques. "The Scientific Groups of the London Convention and Protocol noted with concern the potential for large-scale ocean iron fertilization to have negative impacts on the marine environment and human health. They, therefore, recommended that any such operations be evaluated carefully to ensure, among other things, that such operations were not contrary to the aims of the London Convention and Protocol" (LC/SG 30/14, paragraph 2.25).

1.2 At the 29th Consultative Meeting/2nd Meeting of Contracting Parties in November 2007, the Statement of Concern was accepted, and a scientific working group was established to address the issue of iron fertilization, and the broader issue of ocean fertilization. The terms of reference for this group to be convened at the 2008 Scientific Group (SG) meetings in Ecuador were decided upon and are contained in LC 29/17, annex 6. Based on these terms of reference, the SGs will discuss and attempt to come to some consensus on:

.1 what constitutes "large scale" in the ocean;

.2 a clear justification of the need for experiments at scales of the order of 200 by 200 km; and

.3 an assessment of the impacts on the oceans of experiments at such scales. (LC-LP.1/Circ 20, paragraph 6).

Also, the Scientific Groups are to assess the potential impacts on the oceans of experiments at such scales, and work with the Legal Intersessional Correspondence Group (LICG) to determine whether further action to regulate iron fertilization should be taken under the LC/LP.

1.3 This document is intended to provide basic information on each of the areas to be discussed by the SGs, and to provide a general overview of the issues. In particular, each of the areas that may potentially be considered in the evaluation of scientific field research proposals will be addressed via a review of available, peer-reviewed scientific literature and reports.

1.4 This document does not explicitly address fertilization with phosphorous, because no commercial proposals to do so are known. However, there is discussion in the oceanographic community of the possibility of fertilizing the ocean with a combination or iron and phosphorous. Because this type of proposal is so new, very little information is available for consideration at this time. However, the LC/LP Scientific Groups may want to note this additional fertilization technique for discussion at a later date.

2 GENERAL BACKGROUND

Climate change

2.1 The surface of the earth is literally "blanketed" by the atmosphere, a complex, layered mixture of gases whose properties create and regulate the climate. Without the atmosphere and the properties of the gases that comprise it, the temperature on the earth's surface would fluctuate wildly and the diversity of life that has evolved could not exist. Of particular note are the "greenhouse gases" (carbon dioxide, methane, and especially nitrous oxide because many authors expect its production and release to the atmosphere to increase with fertilization) that trap a portion of the sun's heat near the earth's surface.

2.2 Data from several sources confirm that the concentration of greenhouse gases, and in particular, of carbon dioxide in the atmosphere has increased significantly since the beginning of the Industrial Revolution due mainly to the burning of fossil fuels. The increased concentrations of greenhouse gases have led to a change in our climate through the retention of a greater portion of the sun's heat in the lower atmosphere, with this in turn leading to an increased number of extreme weather events, a rise in sea levels, and shifts in the distribution and availability of fresh water around the globe.

Iron fertilization

2.3 In light of the many serious and potentially irreversible consequences of climate change, many initiatives to reduce the concentration of carbon dioxide in the atmosphere have been suggested or are underway. One such mitigation technique is the proposed fertilization of the open ocean with iron. This is hypothesized to stimulate the growth of phytoplankton, microscopic organisms that use energy from the sun to convert carbon dioxide to organic molecules through photosynthesis. Increasing global photosynthesis by phytoplankton could possibly provide a means of removing the gas from the atmosphere and storing it in the ocean. This practice would "enhance" a naturally occurring process of ocean regulation of earth's climate. However, the efficacy of this technique for carbon dioxide sequestration and long-term storage is presently unknown.

2.4 Currently, at least two large-scale, commercial iron fertilization projects are being pursued for carbon credits that would be tradable in emerging carbon markets around the globe. Supporters of these projects see iron fertilization as a relatively inexpensive method of sequestering carbon, compared with other available sequestration techniques. If they are correct in their assertions, the potential for profit through carbon credit trading would be significant.

The iron hypothesis

2.5 The idea of fertilizing the ocean with iron as a means of reducing atmospheric carbon dioxide stems from the "Iron Hypothesis" (Martin 1990).

2.6 Approximately one third of the world's oceans are described as "high-nutrient, low-chlorophyll" (HNLC) regions (Martin *et al.* 1990). These areas are characterized by the presence of abundant macronutrients, such as nitrates and phosphates, but constantly low phytoplankton biomass. The "Iron Hypothesis" first proposed by John H. Martin (1990) suggests that phytoplankton do not exploit the excess nutrient resources available in HNLC regions because of the lack of bio-available iron.

2.7 To date, twelve small-scale iron enrichment experiments have been conducted in HNLC regions of the ocean to test the Iron Hypothesis (Boyd *et al*. 2007), and a few studies have been conducted in non-HNLC regions. The results confirm the hypothesis resoundingly, and show that iron supply does indeed limit phytoplankton production in approximately one third of the world ocean. However, none of the studies completed to date have been able to demonstrate conclusively that iron fertilization can increase the sequestration of carbon.

2.8 However, whether the deliberate addition of iron to HNLC regions can result in significant carbon dioxide storage remains uncertain (Chisholm *et al*. 2001). Estimates of the potential global sequestration of carbon dioxide through iron fertilization have been decreasing for 15 years as we learn more from the fertilization experiments, but at the same time estimates for carbon dioxide release into the atmosphere over the next century are increasing (Denman In press; Raupach *et al*. 2007). It is important to note that the studies conducted to date were not designed to assess the efficacy of iron fertilization for carbon sequestration purposes (Chisholm *et al*. 2001), but they have been used in recent modelling analyses to study the efficacy of sequestration at the global scale (Aumont and Bopp 2006; Gnanadesikan *et al*. 2003; Zahariev *et al*. 2008; Zeebe and Archer 2005). Study results can be compared with each other and to observations of natural iron enrichment episodes (Blain *et al*. 2007) for some purposes, but should not be used to extrapolate the outcomes of large-scale and continual iron fertilization schemes (Boyd *et al*. 2007; Chisholm *et al*. 2001). Although the studies used similar general approaches, they were conducted during different seasons (Buesseler *et al*. 2004), with different iron media, and on very small spatial and temporal scales (Boyd *et al*. 2007). Generally, the efficiency of iron fertilization is unknown, and no reliable means of measuring presently exist. In order to assess the effectiveness of iron fertilization, and ocean fertilization, as means of sequestering carbon, it will be crucial to be able to determine the amount of organic matter that sinks to sufficient depths where it can be assured that it will remain there for centuries.

Commercial iron fertilization proposals

2.9 Several organizations are currently pursuing large-scale iron fertilization projects. In principle, such experiments could be used to demonstrate the potential of this technique for carbon sequestration, and to address concerns over the lack of a method for accurately measuring the amount of carbon removed from the atmosphere (such a method will be crucial for the allotment of carbon credits). These projects involve the fertilization of ocean patches that are 40,000 square kilometres in size; this is significantly larger than the 100 square kilometre patches fertilized in any of the scientific studies to date. As a result of the larger fertilization patches, large-scale proposals will necessitate the observation of blooms that diffuse over areas much larger than the 1000 square kilometre areas seen in small-scale studies.

2.10 One organization advocating iron fertilization for carbon credits is the Climos Corporation (www.climos.com). The details of the activities proposed by this group are not explicitly listed on their website.

2.11 The other major player proposing to fertilize the ocean with iron for commercial gain is the Planktos Corporation (www.planktos.com). This group has attracted plentiful and controversial media attention over its highly publicized project plans, which involve the fertilization of a large ocean patch in the vicinity of the Galapagos Islands with both iron sulphide (the same material used in small scale studies to date) and hematite dust (a readily available industrial waste product and abundant mineral intended to mimic volcanic dust) (Planktos 2007). Planktos has recently suspended its operations due to an inability to raise sufficient funds from investors (Courtland 2008).

Commercial nitrogen fertilization proposal

2.12 The following description of the Ocean Nourishment Corporations (ONC)'s commercial nitrogen fertilization proposal was compiled from information available at www.oceannourishment.com; it does not represent conclusions that have been drawn from peer-reviewed, scientific literature, except where specific references are provided.

2.13 To obtain a source of nitrogen with which to fertilize the ocean, and trigger phytoplankton blooms, ONC is proposing to use a process that is widely used in the manufacture of fertilizer for terrestrial agriculture, wherein atmospheric nitrogen is converted to bio-available urea. The liquid urea is mixed with other limiting nutrients to produce a nutrient mix. This mixture would then be introduced "via a marine pipeline to the continental shelf where it [will be] diffused into the photic (sunlit) zone of the ocean." It is estimated that up to two million tonnes of nitrogen would be added to the ocean in this type of project.

2.14 This addition of nitrogen to the ocean is intended to mimic the natural upwelling of nitrogen-rich waters from the deep ocean. By fertilizing surface waters in this way, phytoplankton blooms will be encouraged. These blooms may enable the absorption of atmospheric carbon. ONC claims that this carbon would remain sequestered in the deep ocean for several hundred years, and that five to eight million tonnes of carbon per year would be removed from the atmosphere. This amount is equivalent to one tenth of one percent of global annual fossil fuel emissions based on estimates by (Raupach *et al*. 2007), and suggests that the efficiency of the proposal would be quite low (i.e. having a carbon to nitrogen ratio of six or seven). It is not clear from the information provided why this type of fertilization would result in longer sequestration times than iron fertilization, and ONC does not substantiate this claim. Also, unlike fertilization via the addition of a single nutrient like iron, which has an innate upper-limit for carbon sequestration potential that is dictated by the quantities of other nutrients available, fertilization via a mixture of nutrients as proposed by ONC has no built-in upper bounds (Dr. A. Pena, personal communication, 2008).

2.15 ONC also claims that this fertilization activity would result in increased fish stocks of up to 1.1 tonnes of fish protein per tonne of nitrogen added to the ocean. However, this estimate has been challenged by climate change and ocean biogeochemistry expert Dr. K. Denman (personal communication, 2008) who calculates that only 0.007 tonnes of carbon per tonne of nitrogen would reach fish in a short (three link) food chain. Dr. Denman reached this number assuming a ten percent transfer of biomass to each higher trophic level, and that full 6 to 7 tonnes of carbon per tonne of nitrogen would be available to the phytoplankton.

2.16 According to ONC, their method would be suitable for use in 70% of the world's oceans where nitrogen availability limits productivity, and only at deep sea sites. This contradicts their earlier claim about delivering nitrogen fertilization via the continental shelf, and will influence the assessment of potential impacts (Dr. A. Pena, personal communication, 2008). ONC estimates that their technique will cost US $15-25 per tonne of carbon sequestered. ONC proposes to monitor fertilized areas via satellite imagery and water sampling to collect information with which environmental impact assessments can be completed.

Commercial ocean pumping proposal

2.17 The Atmocean organization is proposing to enhance the natural upwelling of nutrient rich deep-sea water using "ocean pumps". Their proposal is described here based on information provided at www.atmocean.com; it does not represent conclusions that have been drawn from peer-reviewed, scientific literature.

2.18 In Atmocean's ocean pumping proposal, patented "ocean pumps" would be strategically placed in large arrays that would ultimately cover approximately 80% of the world's oceans. The pumps would be constructed from the same materials as ocean buoys, and would be powered by waves. Each pump would be equipped with solar batteries to enable satellite tracking, be three metres in diameter, and reach 2-300 metres deep. Pumps would be spaced approximately two kilometres apart, and would be tethered together at their deepest points to avoid their obstructing navigation. Also, pumps would not be placed in known shipping channels.

2.19 Given particular assumptions about wave amplitude and frequency, ocean mixing ratios, and thermocline depths, Atmocean estimates that over a 30 day period, a single pump could bring enough deep ocean water to the surface to fertilize an area of four square kilometres and 30 metres in depth. The fertilized area would also decrease in temperature by 0.5^{o}C in this time.

2.20 Atmocean claims that 2 billion tonnes of carbon per year could be sequestered using their ocean pumping technique. They also claim that the technique does not involve biogeochemical changes to the ocean, since only local nutrients would be used to enhance phytoplankton production in surface waters. However, no data to substantiate these claims has yet been published, and it is unclear that sustained "ocean pumping" of this sort would not have biogeochemical consequences over time. Because deep ocean waters are enriched with carbon as well as nutrients (Sarmiento and Gruber 2006), pumping these waters to the surface could enable the release of large amounts of dissolved carbon dioxide to the atmosphere, it is not clear that this mechanism can result in net removal of carbon dioxide from the atmosphere (Dr. A. Pena, personal communication, 2008). Moreover, the deep water pumped to the surface would be denser than the surrounding waters and, so it is reasonable to expect that they would soon sink below the surface layer to depths where they would no longer be available for use by phytoplankton.

3 POTENTIAL IMPACTS TO THE MARINE ENVIRONMENT

3.1 This section will address the concerns raised by the SGs directly in section 2 of their Statement of Concern.

.1 the estimated amounts and potential impacts of iron and other materials that may be released with the iron

3.2 Determining the true efficiency of artificial fertilization experiments (that is, the ratio of carbon exported to iron supplied) is crucial to modelling the potential of iron fertilization for carbon sequestration purposes (Zeebe and Archer 2005). However, the current lack of a reliable method for making this determination has been noted by several sources (Boyd 2004; Boyd *et al*. 2000; Buesseler and Boyd 2003; Schiermeier 2003; Smetacek 2001). During natural blooms triggered by the deposition of iron dust from volcanic eruptions, the addition of dissolved iron is slow and continuous (Boyd 2007), whereas iron fertilization experiments involve the rapid addition of large amounts of iron over a very short period of time (Boyd 2004). Several additions are required to maintain elevated iron levels and trigger a phytoplankton bloom, because 80-95% of the material added is lost to precipitation and scavenging over a period of several days to two weeks (Bowie *et al* 2001 in Boyd 2007). This loss of bio-available iron was observed during several Southern Ocean enrichment experiments and a Canadian sub-arctic Pacific study (Boyd *et al*. 2005; Harrison 2006 and documents therein). Also see (Boyd *et al*. 2000).

3.3 The method of supplying iron to the ocean is important, but many additional factors influence the availability of the added iron for use by phytoplankton, and these processes are poorly understood. Advances in our understanding of iron biogeochemistry (the way iron interacts with organisms and water chemistry in the ocean) are improving our ability to predict what happens when iron is added to the ocean today, and determine what happened during natural fertilization events in the geological past, but a great deal of research remains to be done (Boyd *et al*. 2007).

3.4 The amount of iron that needs to be added to the ocean to trigger a phytoplankton bloom is at least double the amount estimated in laboratory experiments (Buesseler and Boyd 2003). Since the relatively low cost of iron fertilization as a sequestration technique is based on these laboratory estimates, it is reasonable to assume that actual field fertilization costs per tonne of carbon removed will be higher.

3.5 There is very little information available on the potential for chemical or toxicological impacts resulting from the addition of iron to the ocean.

3.6 References to various "iron slurries" patented for use in commercial iron fertilization projects were found. Details on the contents of these mixtures or their potential impacts were not readily available.

3.7 Iron sulphide solutions have been used in iron fertilization experiments, and were proposed for use by the Planktos Corporation (Planktos 2007). Iron sulphide is not generally considered a potent toxin, and iron in this form is used in human nutritional supplements.

3.8 Hematite dust, a readily available industrial waste product and abundant naturally occurring mineral, was also proposed for use by the Planktos Corporation (Planktos 2007). It is less reactive than iron sulphide, and so may be more or less effective when used to fertilize the ocean. Hematite, in and of itself, is not a potent toxin, and abounds in the natural environment. The Planktos Corporation (2007) asserts that hematite dust will enable iron fertilization that resembles natural fertilization by volcanic dust. As stated, hematite is not a potent toxin, however, depending on the size of dust particles used, the potential for toxic impacts may be elevated. Sufficiently small dust particles, or nanoparticles, have been proposed in several nanotechnology applications, including medical applications, and have been investigated for their toxic effects. While the results are not conclusive, concern has been raised in many studies; and the potential for toxic effects at relatively low doses has been demonstrated in fish. If the dust particles used are larger than "nano" in size, then these concerns would not apply. It is not likely that dust obtained as a waste product would be processed to become "nano" in size, since this would be very costly to do.

3.9 The United Kingdom's Royal Society and the Royal Academy of Engineering Report "Nanoscience and Nanotechnologies" (2004) has the following general advice on the regulation of nanoparticles:

> "R4: Until more is known about environmental impacts of nanoparticles and nanotubes, we recommend that the release of manufactured nanoparticles and nanotubes into the environment be avoided as far as possible".
>
> "R5: Specifically, in relation to two main sources of current and potential releases of free nanoparticles and nanotubes to the environment, we recommend:
>
> .1 that factories and research laboratories treat manufactured nanoparticles and nanotubes as if they were hazardous, and seek to reduce or remove them from waste streams; and
>
> .2 that the use of free (that is, not fixed in a matrix) manufactured nanoparticles in environmental applications such as remediation be prohibited until appropriate research has been undertaken and it can be demonstrated that the potential benefits outweigh the potential risks."

.2 the potential impacts of gases that may be produced by the expected phytoplankton blooms or by bacteria decomposing the dead phytoplankton

3.10 When considering the potential impacts of ocean fertilization, such as the generation of greenhouse gases like nitrous oxide or methane, it is important to note that the threat may be more or less severe depending on the type of fertilization (e.g., via iron, nitrogen, phosphorous, or a mixture) used, and the specific site being fertilized.

Dimethylsulphide (DMS)

3.11 Phytoplankton blooms in the ocean produce dimethylsulfoniopropionate (DMSP), a precursor of the gas known as dimethyl sulphide (DMS). This gas is oxidised in the atmosphere to become an aerosol that plays a key role in cloud formation and climate regulation (Bates *et al*. 1987).

3.12 In several iron fertilization experiments, dissolved DMS concentrations increased substantially (Boyd *et al*. 2000; Levasseur *et al*. 2006; Wingenter *et al*. 2004); other small-scale enrichments yielded conflicting results (Boyd *et al*. 2007). For example, in the SERIES experiment, DMS concentrations in the fertilized region dropped below levels in unfertilized waters during the diatom bloom, presumably because the species responsible for producing the largest amounts of DMSP had been grazed down by the increase in microzooplankton responding to the initial stages of the bloom (Levasseur *et al*. 2006; Merzouk *et al*. 2006). It is difficult to predict whether the total flux of DMS to the atmosphere would go up or down following long term, large scale iron fertilization (Levasseur *et al*. 2006).

3.13 Wingenter *et al*. (2007) suggest that the climatic effect of excess DMS from ocean fertilization could be larger than that of carbon sequestration, and that the regional impacts could be large and unpredictable.

Nitrous oxide

3.14 A successful iron fertilization episode should result in increased phytoplankton productivity. This, in turn, should accelerate the rate at which other nutrients, like nitrogen, are used by the phytoplankton and cycled through the food web. This increase in nitrogen cycling could then lead to an increase in atmospheric levels of nitrous oxide (N_2O) (Jin and Gruber 2003). This risk is also present with the nitrogen fertilization proposals of ONC (Matear and Elliott 2004), which may intensify low oxygen conditions and increase organic flux over the continental slope in some regions.

3.15 Nitrous oxide is the third longest-lived greenhouse gas, and Chapter 2 of the IPCC AR4 WG1 report estimates its current atmospheric lifetime to be 114 years, with a warming potential per mole of 298 to one, relative to carbon dioxide. Nitrous oxide is also involved in the destruction of the ozone layer (Crutzen 1981 and Shine *et al* 1990 in Fuhrman and Capone 1991).

3.16 It is difficult to predict what nitrous oxide yields from iron induced phytoplankton blooms would be over time. If iron fertilization generated sufficient nitrous oxide, the benefits in terms of climate change could be negated entirely (Jin and Gruber 2003). One of the twelve Southern Ocean enrichment experiments measured dissolved nitrous oxide levels, and found no observable difference between fertilized and non-fertilized areas (Boyd *et al*. 2000). During another Southern Ocean enrichment experiment, (Law and Ling 2001) observed a nitrous oxide increase of approximately seven percent, and calculated that this increase could cancel out 6-12% of the reduction in the radiative effect of carbon dioxide achieved. A modelling assessment of the offsetting effect of nitrous oxide production suggests that it would be dependent on both the region fertilized and the duration of fertilization (Jin and Gruber 2003).

Methane

3.17 Methane also has warming potential much greater than carbon dioxide, although exactly how much more depends on the time scale considered (IPCC AR4). Globally, terrestrial sources of methane dominate over ocean sources (Tyler 1991).

3.18 Methane is produced primarily in reducing sediments, particularly on the continental shelf and slope; enhanced methane production is more likely to arise from the nitrogen fertilization proposals of ONC than from open-ocean iron-fertilization.

3.19 Large areas of the open ocean are supersaturated with methane, but the source is not known (Karl and Tilbrook 1994). Phosponate oxidation is a possible candidate, but very little is known about phosponates in terms of either sources or turnover time (Dyhrman *et al*. 2006). As with nitrous oxide, it is reasonable to assume that a general increase in biogeochemical cycling would increase the rate of this process, but rates are much less well constrained.

.3 the estimated extent and potential impacts of bacterial decay of the expected phytoplankton blooms, including reduced oxygen concentrations

3.20 Shortly after the iron hypothesis was first proposed, a box-model was generated to predict the likelihood that iron fertilization could generate anoxic (very low oxygen) conditions in the subsurface ocean (Peng and Broecker 1991). This model suggested that in certain zones around Antarctica, anoxia would prevail and result in severe impacts on organisms in those zones (Peng and Broecker 1991). A subsequent study predicted that sustained fertilization of the open ocean (in contrast to the short-term experiments conducted to date) would lead to anoxic conditions in the deep ocean. However, a general circulation grid point model showed a reduction in oxygen levels, but not anoxia (Sarmiento and Orr 1991). This finding has been corroborated by subsequent field and modelling investigations wherein there was not a sufficient export of organic matter to depth to remineralize and consume oxygen. However, it has recently been suggested that there is no evidence of such anoxia being generated in the major iron fertilization events of the geological past (Johnson and Karl, 2002).

3.21 The iron enrichment studies conducted to date have not attempted to track or measure oxygen levels, and even if they had, the spatial and temporal scales are much smaller than those that would be involved in large-scale commercial enrichment. The extent of oxygen depletion, were it to occur, would depend on the duration of fertilization, intensity of productivity induced, extent of sinking, and the depth distribution of organic matter (Fuhrman and Capone 1991). The type of fertilization used (e.g., iron, nitrogen, phosphate, or a mixture) may also affect the creation of low oxygen conditions. For these reasons, it does not seem possible to accurately predict whether anoxia will in fact result from iron or other types of ocean fertilization.

3.22 What is clear is that anoxia, even over relatively brief time periods, could be catastrophic for the organisms in affected areas, and could trigger several biogeochemical consequences (Fuhrman and Capone 1991). One review predicted that the creation of anoxic conditions would lead to a shift in microbial (bacterial) communities to favour organisms that produce nitrous oxide and methane (Fuhrman and Capone 1991). Such enhanced greenhouse gas production is especially likely to arise from the nitrogen fertilization proposal of ONC (Matear and Elliott 2004).

3.23 Commercially important fish and shellfish species can be impacted by low oxygen concentrations at concentrations significantly above those associated with true anoxia (Whitney *et al*. 2007).

.4 the types of phytoplankton that are expected to bloom and the potential impacts of any harmful algal blooms that may develop

3.24 Iron fertilization has been shown to change the composition of phytoplankton communities in the small-scale enrichment experiments conducted to date. Initially, it appears that all types of phytoplankton benefit from the addition of iron. Smaller species, however, are grazed upon by predators that can reproduce almost as fast as they can, and so the abundance of smaller species does not continue to increase for long (Coale *et al*. 1996 in Hoffmann *et al*. 2006). In contrast, larger species of phytoplankton, like the diatoms that have dominated the blooms in studies to date (Boyd *et al*. 2000; Cavender-Bares *et al*. 1999, Gervais *et al*. 2002, and Eldridge *et al*. 2004 in Hoffmann *et al*. 2006), are grazed on by organisms that reproduce at a slower rate than they do (Timmermans *et al*. 2001, 2004 in Hoffmann *et al*. 2006). This creates a situation where the prey (the diatoms) have the resources to increase their numbers without being reduced by their predators.

3.25 So, in the short term, iron fertilization shifts phytoplankton communities to favour larger diatom species (Coale *et al*. 2004 in Boyd 2004; de Baar *et al*. 2005) and generally increases the abundance of grazing species (Gall *et al*. 2001a and Gervais *et al*. 2002 in Hoffmann *et al*. 2006). Research is needed on the long-term impacts of these shifts, especially under sustained fertilization conditions (Hoffmann *et al*. 2006). Chisholm *et al* (2001) stress that the oceans are "a tightly linked system" and that these community shifts will alter poorly understood biogeochemical cycles in unintended ways.

3.26 The diatoms that dominate blooms observed to date are constructed of cells that are rich in silicate (Hoffmann *et al*. 2006). Their need for silicate may also limit the longevity of their blooms as silicate resources may become depleted and inhibit further productivity even while iron continues to be abundant. It is likely that silicate depletion will occur before other nutrient resources (like nitrates) are exhausted (Harrison 2006). Also, several studies suggest that atmospheric carbon dioxide releases may actually increase upon the induction of silicate-limited conditions (Boyd *et al*. 2005; Denman *et al*. 2006; Timothy *et al*. 2006).

3.27 Harmful algal blooms (HABs) are predominantly a coastal phenomenon and there is no evidence of such blooms arising from iron fertilization experiments. However, the absolute abundance and total proportion of toxic algae such as *Pseudonitzschia* was higher in the post iron-fertilization communities observed in several experiments (de Baar *et al*., 2005).

3.28 However, it has been shown that nitrogen enrichment can directly stimulate harmful algal blooms (HAB) by enhancing growth and biomass, and indirectly, through alterations in food web and ecosystem dynamics (Gilbert *et al*. 2005). By extension, it is not unreasonable to assume that ocean fertilization has the potential to increase the occurrence of HAB events, even in areas of the ocean where toxic blooms do not occur at present. It is also possible that in areas of the ocean where toxic blooms occur at present, any fertilization activity could favour these "toxic" species and worsen the existing problem.

.5 the nature and extent of potential impacts on the marine ecosystem including naturally occurring marine species and communities

3.29 Phytoplankton are the primary producers of the open ocean. That is, they absorb and use the sun's energy to fix carbon dioxide into organic carbon molecules through photosynthesis. They in turn provide an energy source for their predators, and so on up the food chain. Sinking phytoplankton, dead or alive, and fecal pellets from their predators, are the main mechanisms by which carbon is removed from the ocean surface mixed layer (and from contact with the atmosphere) and transported downwards below the mixed layer.

3.30 It is clear that iron fertilization generates shifts in phytoplankton community composition (de Baar *et al*. 2005; Hoffmann *et al*. 2006), and since phytoplankton are the foundation for many intricately linked marine food chains, it seems likely these shifts will have impacts on other marine species and communities (Chisholm *et al*. 2001). However, it is impossible to predict, given our current knowledge, exactly what those impacts may be and to what extent they may occur.

3.31 Models predict that sustained, long-term iron-induced blooms could lead to the depletion of nitrate and/or silicate supplies in the oceans, which would in turn cause all or part of the phytoplankton community to crash, reducing the efficacy of the ocean as a carbon dioxide sink. Other important marine biogeochemical cycles, such as those that regulate carbon, phosphates and oxygen, could be modified as well. It has also been suggested that altering the foundation of the marine food web could threaten various phytoplankton species and have effects on fish stocks (Chisholm *et al*. 2001).

.6 the estimated amounts and timescales of carbon sequestration, taking account of partitioning between sediments and water

3.32 As noted in the "Possible Benefits of Iron Fertilization" section below, the depth to which aggregates of phytoplankton and zooplankton fecal pellets (i.e. organic carbon particles) sink is critical to the ability of the marine planktonic ecosystem to sequester carbon for long time periods. Long-term sequestration that could last several hundred years or more is thought to begin once organic carbon particles reach depths on the order of 500 metres (Denman *et al*. 1996). No data obtained from the small-scale fertilization experiments conducted to date give robust estimates of the amount of carbon expected to be sequestered by the proposed commercial operations.

.7 the estimated carbon mass balance for the operation

3.33 This is addressed in the "Possible Benefits of Iron Fertilization" section below. In summary, there is no conclusive evidence that iron fertilization is or is not viable as a means of sequestering a portion of the 8 billion tons of carbon dioxide that humans release to the atmosphere annually (Buesseler and Boyd 2003). On the surface, it appears that the estimates provided by geo-engineers are higher than the numbers measured in field fertilization experiments (Boyd 2004; Hurtley and Szuromi 2004).

3.34 Even if it were possible to fertilize the ocean globally, with complete alleviation of iron limitation, the expected impact on atmospheric CO_2 growth under continuing industrial emissions is small (Aumont and Bopp 2006; Zahariev *et al*. 2008); similar results hold for macronutrient fertilization (Matear and Elliott 2004). The actual impact of commercial ocean fertilization would be much smaller (Zeebe and Archer 2005). These findings suggest that even if the logistics are mastered, iron fertilization does not represent a reliable means of sequestering carbon.

Potential Benefits of Increasing Scientific Knowledge

3.35 Human activities are responsible for the release of approximately 8 billion tons of carbon to the atmosphere annually (Raupach *et al*. 2007). To stabilize atmospheric carbon dioxide growth, schemes involving emissions reductions and carbon sequestration techniques are being developed and debated. If accepted as a viable sequestration method, commercial ocean fertilization would represent one of many components that make up such schemes, and would therefore be expected to effectively remove some carbon from the atmosphere for an extended period of time (at least several hundred years). However, many questions remain to be answered with respect to the true sequestration potential of iron fertilization, and ocean fertilization in general.

3.36 A study comparing different methods for removing carbon from the atmosphere suggests that iron fertilization would cost ten to 100 times less than forestation, the next cheapest alternative (Schiermeier 2003). The cost per metric ton of sequestered carbon is expected to be $1 - $2 using iron fertilization (Markels Jr. and Barber 2000 in Buesseler and Boyd 2003). These cost estimates are based on geoengineering models that rely on the ratios of iron added to carbon dioxide sequestered in laboratory experiments (Buesseler and Boyd 2003). These same models suggest that iron fertilization could remove three to five billion tonnes of carbon from the atmosphere each year (an amount representing half or more of current releases), and may be optimistic. Field experiments generally require up to 1000 times as much iron per unit of carbon exported as laboratory experiments, because of abiotic scavenging and precipitation of the dissolved iron (Buesseler and Boyd 2003).

3.37 Results from the small scale field experiments conducted to date indicate that the potential amounts sequestered will be much smaller, and too small to remove significant amounts of anthropogenic carbon from the atmosphere (Boyd 2004; Buesseler *et al*. 2004; Hurtley and Szuromi 2004). For example, the SOIREE iron enrichment experiment suggested that for 2 billion tons of carbon to be sequestered (an amount representing 25% of current annual emissions), an area ten times larger than the entire Southern Ocean (waters south of 50°S) would have to be fertilized (Buesseler and Boyd 2003).

3.38 The temporal and spatial scales involved in the small scale field experiments conducted to date are too limited to enable an accurate determination of the ultimate fate of exported carbon or the efficiency of carbon sequestration (Boyd 2007; Boyd *et al*. 2007; Buesseler and Boyd 2003; Buesseler *et al*. 2004).

3.39 These limitations hinder our ability to extrapolate the results of small-scale experiments to predict the outcomes of larger and longer fertilization projects (Boyd *et al*. 2007; Buesseler and Boyd 2003; Chisholm *et al*. 2001). Although it is “not currently recommended” (Boyd *et al*. 2007, 616), this type of scaling up is often used to assert the potential of large scale iron fertilization projects to effectively sequester carbon.

3.40 It cannot be said with certainty that iron fertilization is or is not a viable strategy for global carbon sequestration. Estimates based on laboratory observations do not reflect what has been observed in the field, and the field observations themselves are hampered by difficulties surrounding the accurate measurement of the sequestered carbon (Buesseler and Boyd 2003; Schiermeier 2003). Global modelling studies suggest that even with very optimistic assumptions about the technical feasibility of large-scale fertilization, the amount of carbon sequestered would be small compared to current industrial emissions (Aumont and Bopp 2006; Zahariev *et al*. 2008).

3.41 Field experiments often rely on measurements of particulate organic carbon (phytoplankton plus fecal pellets and other detrital organic carbon particles) flux beneath a bloom to estimate the amount of carbon exported. It is the sinking of dead phytoplankton and other organic carbon particles that provides a mechanism for storing the atmospheric carbon that these organisms have incorporated. Phytoplankton that are eaten or decomposed by bacteria before sinking will release carbon back to the atmosphere, and so it is only the phytoplankton that escape these processes by sinking that yield a net carbon sink (Smetacek 2001). A Canadian Department of Fisheries and Oceans experiment conducted off the Pacific coast indicated that up to 75% of carbon is recycled at the surface (Timothy *et al*. 2006).

3.42 However, simply measuring the phytoplankton observed sinking beneath a bloom does not provide a complete picture. Decomposition in the ocean's water column can take place over tens or hundreds of years, and so some of this sinking material will still release its carbon to the atmosphere within a relatively short time frame. Depth is crucial to long term carbon sequestration, and it is estimated that only the fraction of phytoplankton that sinks to beneath the surface mixed layer, or more than 100 metres will actually provide a long-term (several hundred years) means of storing carbon. Many of the estimates made to date have not taken measurement depth into account, or have taken measurements at depths of one hundred metres or less (for example (Boyd *et al*. 2000; Buesseler *et al*. 2004; Smetacek 2001).

3.43 Several other factors make it difficult to measure the amount of carbon sequestered following large-scale iron fertilization. Stirring of the iron by natural currents affects the development and spread of the resulting blooms, and the amount of carbon they are able to sequester (Abraham *et al*. 2000); a poor understanding of the nature and extent of stirring that will occur in the open ocean will make it difficult to determine where and how often measurements should be taken. Also, the field experiments conducted to date have often been centred on eddies (tight, circular currents that limit mixing at their centres) that contain a fertilized patch and its resulting phytoplankton bloom to a restricted area (for example, (Hoffmann *et al*. 2006; Smetacek 2001)). This simplifies the process of taking measurements and tracking a bloom's progress. If fertilization is conducted on a much larger scale, the extent of spread will be far greater than that observed in studies to date, and the logistics of making observations over the course of the bloom will present a real challenge. It has been argued that satellite imagery may be used to track very large blooms over long time periods. However, the collection of these images is frequently hindered by cloud cover, especially in the cold water high latitude HNLC waters of the Southern Ocean and the subarctic Pacific Ocean.

3.44 Cautious and independent research to clarify the many remaining uncertainties that surround the usefulness of ocean fertilization as a carbon sequestration technique may help the international community to make an informed decision as to whether these techniques warrant the issuance of carbon credits. However, it is crucial that this type of research is conducted at the smallest spatial scale possible to address the remaining issues, and that any "scaling-up" of studies is done gradually. At this time, it is not clear that experiments whose scale is larger than the studies conducted to date are necessary to begin addressing the remaining uncertainties conclusively, although larger scale studies may be justified to examine ecosystem responses in the future. Also, larger scale studies may still not be able to address the issue of the duration of any sequestration achieved.

3.45 Even if studies can confidently provide estimates of how long fertilization may sequester carbon, consensus as to what should qualify as "permanent" sequestration will be vital to assessing the usefulness of fertilization as a sequestration technique. Agreement on appropriate time scales and methods of verification will also be required to establish an effective regulatory regime.

3.46 It has been suggested that "permanent" sequestration should be defined as "more than 100 years". This definition was provided by the Intergovernmental Panel on Climate Change based on a provision of the Kyoto Protocol, and reflects the estimated duration of sequestration through forestation. It is a minute timeframe when compared to carbon capture and storage techniques, which have the potential to sequester carbon on geological time scales, and in practical terms, only represents a means of offsetting carbon emissions until a later date. If used alone, without implementing plans for simultaneous reductions in emissions and improvements in technology, then "buying-time" in this way does nothing, in and of itself, to reduce the pending impacts of climate change (Mike Bewers, personal communication, 2008).

3.47 Given the current state of knowledge, iron fertilization may be able to meet this 100-year definition of "permanence". It may even be possible to continue fertilizing a given area of the ocean to maintain a phytoplankton bloom over a long period of time, thus lengthening the amount of time it can continue to sequester carbon. If blooms cannot be sustained in this way, then accepting a 100-year definition of "permanence" would require reliance on the view that shifting the atmospheric/oceanic carbon equilibrium to favour the ocean for a relatively short time is sufficient to achieve viable sequestration (Mike Bewers, personal communication, 2007). Iron fertilization studies to date have not considered how long fertilization efforts could continue, or at what intensity, to maintain any reduction in atmospheric carbon that they enable at their start. The resolution of this issue is essential to assess the viability of iron fertilization as a "permanent" sequestration technique, and the potential impacts its practice is likely to have; longer-term and more intensified fertilization activities may well be associated with more severe and longer lasting impacts on the marine environment.

4 OTHER FACTORS AS APPROPRIATE

4.1 Given 1) the uncertainties that surround the potential impacts of fertilizing the ocean over large temporal and spatial scales, 2) the lack of data regarding the amount of time for which these methods could be effectively sustained, and 3) the challenges that need to be overcome in accurately measuring the amount of carbon sequestered, three questions should routinely be addressed when assessing the viability of a particular fertilization method for sequestering carbon:

> "[i] If activities succeed in increasing the carbon in the biosphere, will it stay there (the permanence issue)? [ii] If activities succeed in increasing the rate of carbon accumulation in the biosphere, how long will it be possible to continue at the increased rate (the saturation issue)? [iii] If activities succeed in increasing carbon stocks in the biosphere, is it possible to accurately and precisely measure and affirm that it has been done (the verifiability issue)?" (Schlamadinger and Marland, 2000 in Marland, Fruit and Sedjo, 2001)

5 RECOMMENDED ACTIONS TO ADDRESS SECTION 3 OF THE SGS STATEMENT OF CONCERN

.1 the purposes and circumstances of proposed large-scale ocean iron fertilization operations and whether these are compatible with the aims of the Convention and the Protocol

5.1 Large-scale operations are arguably different from the enrichment experiments conducted so far. Industrial waste may be involved in some of the large scale fertilization proposals, although the promoters of these projects claim that disposal is not their primary goal. Rather, their intentions are threefold.

5.2 First, there is the intention to trigger a phytoplankton bloom, and while this is the likely outcome, it is not guaranteed to occur.

5.3 Second, there is intent to sequester carbon dioxide for long-term storage in the ocean. This second item represents a noble and timely intention; however, the evidence to date does not suggest that the intention is realistic. It remains unknown whether the technique can in fact sequester any carbon, particularly in a sufficient quantity or duration to represent a viable means of removing anthropogenic carbon dioxide from the atmosphere, or whether the climate benefit will be cancelled by other fertilization impacts. If fertilization is shown to have a significant net benefit in the context of global warming, and if the potential ecological consequences have been thoroughly assessed, then perhaps this alternative purpose for the disposal of iron should be considered a legitimate beneficial use.

5.4 Third, the activity is expected to generate profit through carbon credits that can be traded in global carbon markets. At the present time, there is no reliable means of determining how much, if any carbon is sequestered (Hoffmann *et al*. 2006), nor is there an international consensus on what time scale of sequestration is adequate. Until these issues are resolved there is no credible basis for issuing credits. This intention would therefore be unrealistic until measurement and verification techniques improve substantially.

.2 the need, and potential mechanisms, for regulation of such operations

5.5 There is a need to control fertilization operations so that they do not become widespread and sustained. While no single, isolated fertilization event is likely to lead to ecological catastrophe, it is not unreasonable to assume that if fertilization becomes a profitable enterprise, an increasing number of projects will appear (Chisholm *et al*. 2001). The cumulative impacts of these ventures could amount to the type of widespread, sustained fertilization that is associated with the most severe impacts.

5.6 While the need for such control is not immediate, it could become highly pertinent in the future. Centralized, coordinated control would enable the effective monitoring of impacts on the marine environment globally, and could ensure that fertilization events are spread out over time and space in order to reduce impacts.

5.7 Control mechanisms may include requiring permits for projects that would be preceded by assessments that consider the location of the proposed operation, proximity to other operations (spatially and temporally), the material to be used in fertilization, the secondary effects (such as environmental alteration, community shift, and alterations of biogeochemical cycles), and the means of quantifying carbon sequestration and the release of other greenhouse gases. Reporting during and after operations would be critical to effective monitoring.

5.8 Resources for enforcement and monitoring represent challenges to effective control mechanisms, but could be recovered through permit fees.

5.9 Perhaps a preferable alternative would be to advocate for a moratorium on the issuance of carbon credits for iron fertilization operations until the impacts are better understood, and the amount of carbon sequestered can be verified. This will eliminate the economic incentive that is currently driving iron fertilization proponents, at least until the technique is proven and its likely impacts are better understood. Also, this type of control would not impede research efforts to determine precisely what potential iron fertilization may have. If such a moratorium were ever to be lifted, it is proposed that the obligation to verify that carbon has in fact been sequestered, and to quantify other offsetting impacts should rest with the party claiming the credits.

.3 the desirability of bringing to the attention of other international instruments and institutions proposals for such operations

5.10 It is certainly desirable to seek assistance from other international instruments and institutions that would enhance the ability to control and monitor iron fertilization activities. Groups that might be considered include the GPA, MEPC, Regional bodies (MAP, OSPAR, etc.), MARPOL and others.

5.11 It will also be necessary to inform Kyoto and its successor (the group that will administer and control carbon credits) and to suggest the removal of iron fertilization from the list of practices eligible for carbon credits. This group should be informed of proposals and associated estimates of net benefit or harm from them. If this group decides not to award credits for these types of operations, the economic incentive for conducting them will disappear.

6 COMMENTS MADE AT THE IRON FERTILIZATION SYMPOSIUM 2007

6.1 The Woods Hole Oceanographic Institute held an Iron Fertilization Symposium in September of 2007. The information presented at that forum was not expressly reviewed in this document, but represents a thorough overview of the technical and economic issues surrounding iron fertilization. The presentations delivered at the symposium are available at: www.whoi.edu/page.do?pid=14617. Also, the articles published in a special issue of Oceanus that was generated following the symposium can be accessed at: www.whoi.edu/oceanus/viewArticle.do?id=34167&sectionid=1000.

7 CONCLUSIONS

7.1 There is no doubt that climate change represents a severe and pressing threat, and that any means of tackling this threat should not be discarded lightly. However, it is also true that we should not pursue practices that do more harm than they remedy in the name of addressing climate change.

7.2 Very little can be said with certainty when it comes to iron fertilization, its effectiveness as a sequestration technique, or the likelihood and severity of its potential impacts. For this reason, a precautionary approach is strongly advised. This view is reflected in the peer-reviewed literature (Chisholm *et al*. 2001; Fuhrman and Capone 1991; Johnson and Karl 2002; Reay *et al*. 2007).

7.3 If the effectiveness of iron fertilization for the long term storage of carbon is demonstrated, and the practice is determined to be desirable overall, then coordinated control both nationally and globally will be warranted to prevent the intense and sustained fertilization of the ocean through numerous operations, and would enable appropriate reporting and monitoring to be conducted.

8 ACTION REQUESTED OF THE SCIENTIFIC GROUPS

The Scientific Groups are invited to review the information provided with a view to address the Terms of Reference on ocean fertilization.

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ANNEX

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