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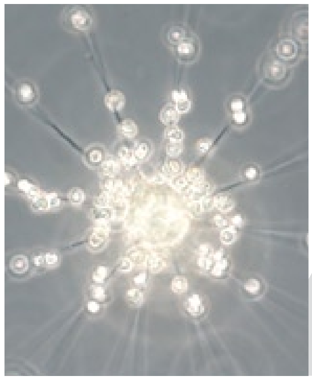
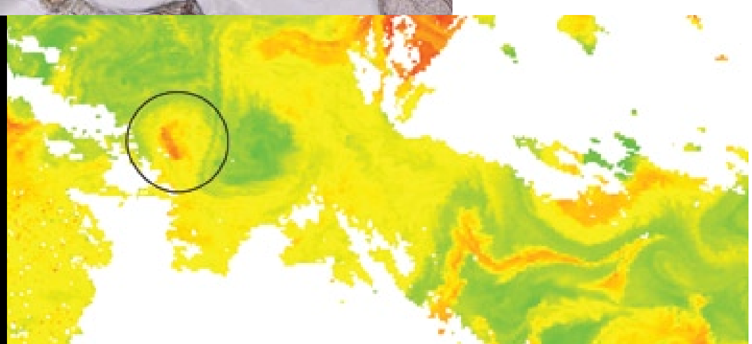


Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity



Convention on
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Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity

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Front cover (top to bottom): (1) Phaeocystis cells freshly attached to the spines of a diatom (*Corethron pennatum*) in the process of colony formation (cells are 0.005 mm)—photo: Marina Montresor, SZN / Alfred Wegener Institute. b) Older colonies overgrowing a diatom cell (the largest colony is 0.05 mm across)—photo: Marina Montresor, SZN / Alfred Wegener Institute. (2) The phytoplankton species *Ceratium pentagonum* from the ice field with diatoms and juvenile copepods in the background—photo: M. Montresor, SZN / Alfred Wegener Institute. (3) Satellite image of sea-surface chlorophyll concentrations with LOHAFEX bloom encircled. Note much larger natural bloom on the upper right and the generally higher values in the southeast than elsewhere—graphic: NASA (http://oceancolor.gsfc.nasa.gov). (4) Iceberg—photo: Kevin Saw, NOCS / Alfred Wegener Institute.

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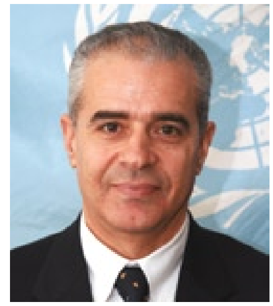
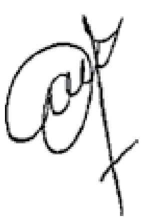


As early as the 1930s, scientists had speculated that iron deficiency could account for areas of the world's oceans with scarce phytoplankton growth. In the 1980s, the studies of the oceanographer John Martin confirmed that the scarcity of iron micronutrients was indeed a major factor in limiting phytoplankton growth and overall productivity in "high-nutrient, low-chlorophyll" (HNLC) areas of the oceans. His research, supported by test experiments, suggested that adding iron to the surface waters of HNLC areas would intensify phytoplankton growth to such an extent that it could reduce atmospheric CO_2 concentrations and thereby mitigate climate change. In 1991, John Martin famously stated "*Give me a half a tanker of iron and I will give you another ice age,*" giving rise to the concept of "ocean fertilization." With the predicted increases in atmospheric CO_2 concentrations and the impact that this will have on humankind and life on Earth, all ideas and concepts to mitigate climate change have to be considered—controversial or not. Ocean fertilization is an intriguing concept: it utilizes the ocean (the largest carbon reservoir on Earth); is based on natural processes; and in theory, suggests that large amounts of CO_2 could be sequestered with relatively little cost.

In recent years, a number of companies have expressed interest in carrying out large-scale ocean fertilization on a commercial basis. This caused policy-makers and stakeholders, including countries, international organizations, and the scientific community, to assess the concept of ocean fertilization in more detail, which highlighted potential benefits but also a range of uncertainties and questions, such as: "*Is large-scale ocean fertilization a feasible and effective option to mitigate climate change? What are the impacts of the intended and unintended changes caused by ocean fertilization? How will the marine environment respond? Will marine biodiversity and ecosystems remain healthy, or will the addition of iron give no net benefit while causing other problems?*" In the ongoing debate about ocean fertilization, the Conference of the Parties to the Convention on Biological Diversity, at its ninth meeting, requested Parties and urged other Governments, in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities. Likewise, many other international organizations and experts have expressed their concerns about the possible adverse impacts of large-scale ocean fertilization activities.

This publication, prepared in direct response to a request by the ninth meeting of the Conference of Parties to the Convention, investigates the scientific basis of these concerns with a view to providing an objective synthesis and analysis of the impacts of ocean fertilization on marine biodiversity. Among other findings, this publication demonstrates that there are uncertainties surrounding the viability of large-scale ocean fertilization as a carbon sequestration tool and potential adverse consequences for marine species, habitats and ecosystem function. There is thus an urgent need to establish a global, transparent and effective control and regulatory mechanism as well as to set in place a thorough prior assessment of the potential impacts of the proposed projects involving ocean fertilization, in order to ensure that such activities do not jeopardize human health or breach the protection, conservation and sustainable management of the marine environment or living resources.



Dr. Ahmed Djoghlaf
Executive Secretary
Convention on Biological Diversity

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EXECUTIVE SUMMARY

The ocean is one of the largest natural reservoirs of carbon, storing about 20 times more carbon than the terrestrial biosphere and soils, and playing a significant role in the regulation of atmospheric CO_2 and climate due to its large heat capacity and global-scale circulation mechanisms. Globally, the oceans have accumulated up to one third of the total CO_2 emissions arising from burning fossil fuels, land use change and cement production, among others, within the last 250 years. Anthropogenic emissions of CO_2 continue to significantly increase atmospheric CO_2 concentration, which in turn is expected to bring about significant global temperature increases with both predicted and unforeseen implications for humans and the environment.

There is a clear need for a reduction in greenhouse gas emissions in line with internationally agreed targets to reduce the rate of climate change, necessitating the implementation of clean energy technologies, supported by a range of mitigation and adaptation measures. According to the Intergovernmental Panel on Climate Change (IPCC), iron fertilization of the oceans may offer a potential strategy for removing CO_2 from the atmosphere by stimulating the growth of phytoplankton and thereby sequestering CO_2 in the form of particulate organic carbon. However, the IPCC states that commercial ocean iron fertilization remains largely speculative, and many of the environmental side effects have yet to be assessed.

Scientific studies into the potential mechanisms for global climate modulation involving ocean fertilization activities have consistently demonstrated the stimulation of phytoplankton biomass through the addition of macro or micro nutrients in certain nutrient-deficient areas of the oceans. However, the consistent and significant downward transport of the captured carbon (biologically fixed carbon) into the deep waters of the ocean, as would be required by an effective commercial CO_2 sequestration tool, is not well substantiated.

The natural variability and fluctuations in biogeochemical processes within the oceans, coupled with an incomplete understanding of the linkages and drivers within this complex system, introduces uncertainty in the extrapolation of experimental observations to the temporal and spatial scales proposed for carbon sequestration by commercial ocean fertilization. A dearth of baseline information in the areas suitable for fertilization, and significant costs and logistical constraints of large-scale commercial ocean fertilization experiments also limit the accurate observation and monitoring of impacts to marine biodiversity resulting from the intentional alteration of chemical and biological processes. This means that unconfirmed modeled simulations are often the only tool available for estimating the longer-term impacts.

Given the present state of knowledge, significant concern surrounds the intended and unintended impacts of large-scale ocean fertilization on marine ecosystem structure and function, including the sensitivity of species and habitats and the physiological changes induced by micro nutrient and macro nutrient additions to surface waters. Accurate assessment of the costs and benefits of commercial ocean fertilization must account for the observed shortcomings in sequestration efficiency and the total economic value of ecosystem function which might be affected due to ocean fertilization activities.

The uncertainties surrounding the viability of large-scale ocean fertilization as a carbon sequestration tool and its potential consequences for marine species, habitats and ecosystem function add significant weight to the case for the wide adoption of an assessment framework for the careful validation of side effects from ocean fertilization activities, and the identification of legitimate scientific research involving ocean fertilization to advance our collective understanding of biogeochemical processes within the vast global oceans. An integrated and coordinated response from the relevant international organizations/bodies is required to ensure that ocean fertilization activities do not jeopardize human health or breach the protection, conservation and sustainable management of the marine environment or living resources.

I. BACKGROUND

The oceans and the organisms they support contain around 38,000 gigatonnes of carbon (Gt C)[1]. The deep oceans presently store about 55 times more carbon dioxide (CO_2) than the atmosphere and 20 times more carbon than the terrestrial biosphere and soils. Driven by the difference in the partial pressure of CO_2 between the atmosphere and seawater, a portion of the atmospheric CO_2 dissolves in the surface layer of the sea and is finally transported into the deep sea by ocean circulation. Furthermore, a proportion of dissolved CO_2 in sunlit ocean surface waters is fixed into biomass through photosynthesis and may sink to the deep sea by gravity and biological processes. As a result, the ocean is the second-largest sink for CO_2 produced from anthropogenic activities, after the atmosphere itself [2,3]. Before industrialization (ca.1750), the ocean was at a state of near equilibrium in terms of carbon efflux and influx and not a CO_2 sink; it released about 0.6 Gt C annually to the atmosphere, while approximately the same amount of carbon entered the oceans from the terrestrial biosphere as organic matter flowing in from rivers[4]. This has since changed. Globally, the oceans have accumulated carbon in the range of 112–118 (+/- 17-19) Gt C since the beginning of the industrial era, representing about 29% of the total CO_2 emissions from burning fossil fuels, land use change and cement production within the last 250 years[5,6].

Anthropogenic emissions of CO_2 have significantly increased atmospheric CO_2 concentrations during the last century, which in turn is expected to bring about significant global temperature increases with both predicted and unforeseen implications for humans and the environment[7,8]. There is a clear need for a reduction in CO_2 emissions, in line with internationally agreed targets, to reduce the rate of climate change, necessitating the adoption of a range of adaptation and mitigation measures. This need has led, *inter alia,* to a portfolio of geo-engineering proposals and options to remove CO_2 from the atmosphere. To be successful, geo-engineering solutions must remove a significant amount of CO_2 from the atmosphere for many decades, in a verifiable manner, without causing deleterious side effects[9]. In past decades, there have been a number of geo-engineering proposals to utilize and increase the functions of the oceans as a sink for atmospheric CO_2, including the proposal to artificially increase the ocean's biological CO_2 pump by stimulating phytoplankton growth via the addition of nutrients to suitable areas of the oceans.

Large-scale Open-ocean Fertilization as a Geo-engineering Solution

Large-scale fertilization of the oceans using micro and macro nutrients has been the subject of recent commercial interest as a potential strategy for carbon sequestration[10], ultimately with the purpose of

1 The Royal Society. (2005). Ocean Acidification due to increasing atmospheric carbon dioxide. Policy document 12/05, June 2005. www.royalsoc.ac.uk

2 Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., *et al.* (2004). The oceanic sink for CO_2. Science, 305:367–371.

3 Iglesias-Rodriguez, *et al.* (2008). Phytoplankton calcification in a high-CO_2 world. Science 320, 336–340.

4 R. Schubert, *et al.* (2006). The Future Oceans – Warming up, Rising High, Turning Sour. Special Report, German Advisory Council on Global Change. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU). 110 pages English version at http://www.wbgu.de/wbgu_sn2006_en.html

5 Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., *et al.* (2004). The oceanic sink for CO_2. Science, 305:367–371.

6 Lee, *et al.* (2003). An updated anthropogenic CO_2 inventory in the Atlantic Ocean. Global Biogeochemical Cycles 17, 1116

7 Huesemann, M. H. (2008). Ocean Fertilization and other climate change mitigation strategies: an overview. Marine Ecology Progress Series Vol. 364: 243–250

8 SCOR/IOC Symposium Planning Committee. (2004). The Ocean in a High-CO_2 World. Oceanography Vol. 17, No 3, Sept. 2004.

9 Denman. K. L. (2008). Climate change, ocean processes and ocean iron fertilization. Marine Ecology Progress Series Vol. 364: 219–225

10 http://www.imo.org/includes/blastDataOnly.asp/data_id%3D19264/14.pdf accessed on 6 May 2009

trading carbon credits. Companies have proposed the fertilization of the open ocean with iron over large scales of 40,000 km^2, attracting controversial media attention. One company proposed to fertilize an area of ocean 560 km west of the biologically diverse Galapagos Islands using 90 tonnes of hematite[11]. However the experiment (planned for May 2007) could not go ahead due to an inability to raise sufficient funds.

The business community is exploring nitrogen fertilization as an engineered solution to climate change in regions where the limiting nutrient is nitrogen[12]. It has also been argued that urea fertilization will benefit fisheries and increase localised productivity. In 2007, one organization announced plans to disperse 500 tonnes of granulated urea into the nitrogen-limited waters of the Sulu Sea, off the coast of the Philippines, via underwater pipes as part of a carbon sequestration and ocean enrichment experiment. It was suggested that each tonne of nitrogen (urea) could sequester 12 tonnes of CO_2, capturing eight million tonnes of CO_2 per year through the sustained fertilization of an area of 20 km[13]. However, the experiment has not yet been implemented. To date, there have been no proposals for fertilizing the oceans with phosphorous with a commercial purpose.

It has also been proposed to enhance the natural upwelling of nutrient-rich deep waters to the surface layers using wave powered "ocean pumps" placed vertically within the water column and reaching down to a depth of 300 metres. It is suggested that two billion tonnes of carbon per year could be sequestered using this method, however this would require pumps to be placed every 2 km across 80% of the world's oceans. These efficiency predictions are, however, not supported in peer-reviewed scientific literature. It is also suggested to use the artificial upwelling of cold, deep water for the preservation of coral reefs (i.e. to counteract high-seas surface temperatures causing coral bleaching), to reduce hurricane intensity (i.e. by placing pumps in hurricane pathways to cool the ocean surface) and to increase plankton growth in support of open-ocean aquaculture[14].

The insufficient knowledge about the potential environmental impacts of such geo-engineering activities raises important questions about the efficacy of these approaches and the immediate and longer term implications for ocean processes, marine living resources, marine biodiversity, food security and human health, and has prompted a number of international organizations and UN agencies to adopt statements, agreements and recommendations for the management of activities involving ocean fertilization[15].

Statement, Agreements and Recommendations Relating to Ocean Fertilization

In 2008, the Conference of the Parties to the Convention on Biological Diversity, in its ninth meeting, adopted decision IX/16 (Biodiversity and climate change). In Part C (Ocean Fertilization), paragraph 4 of this decision, the Conference of the Parties *"…requests Parties and urges other Governments, in accordance with the precautionary approach, to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activi-*

11 Schrope, M. (2007). Treaty caution on plankton plans. Nature, Vol 447:1039.

12 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

13 ETC, SEARICE, Third World Network, Corporate Watch (2007). Backgrounder: Ocean Nourishment Corporation

14 http://www.atmocean.com accessed on 9 September 2009

15 See documents LC30/INF.4 and LC30/Inf.4/Add.1), submitted by UNEP to the 30th . Consultative Meeting of Contracting Parties to the London Convention and 3rd Meeting of Contracting Parties to the London Protocol (London, 27–31 October 2008). http://www.imo.org/includes/blastData.asp/doc_id=10064/INF-4.pdf and http://www.imo.org/includes/blastData.asp/doc_id=10158/INF-4-Add-1.pdf—accessed on 6 May 2009

ties; with the exception of small scale scientific research studies within coastal waters. Such studies should only be authorized if justified by the need to gather specific scientific data, and should also be subject to a thorough prior assessment of the potential impacts of the research studies on the marine environment, and be strictly controlled, and not be used for generating and selling carbon offsets or any other commercial purposes…"[16]

In 2008 UNESCO/IOC ad hoc Consultative Group on Ocean Fertilization suggested that "The restriction of experiments to coastal waters appears to be a new, arbitrary, and counter-productive limitation. (...) There is no scientific basis for limiting such experiments to coastal environments." It is also stated that "A careful science-based 'assessment of associated risks' depends on knowledge that could be gained by further experimentation"[17].

In its decision IX/20 (marine and coastal biodiversity), the Conference of the Parties to the Convention on Biological Diversity "*Taking into account the role of the International Maritime Organization, requests the Executive Secretary to seek the views of Parties and other Governments, and, in consultation with the International Maritime Organization, other relevant organizations, and indigenous and local communities, to compile and synthesize available scientific information on potential impacts of direct human-induced ocean fertilization on marine biodiversity, and to make such information available for consideration at a future meeting of the Subsidiary Body on Scientific, Technical and Technological Advice prior to the tenth meeting of the Conference of the Parties*."[18]

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) is a global framework that contributes to the international control and prevention of marine pollution by prohibiting the dumping of certain hazardous materials and providing permits for the dumping of a number of other identified materials, wastes and matter. The Convention came into force in 1975 and was modernized in 1996 by the more elaborate London Protocol, under which all dumping is prohibited, with exception of a restricted range of acceptable wastes. Both the London Convention and Protocol receive scientific advice on existing and emerging issues of pollution prevention from their Scientific Groups, which meet concurrently.

In 2007, at the 30th Meeting of the Scientific Group of the London Convention and the 1st Meeting of the Scientific Group of the London Protocol, the issue of large-scale ocean iron fertilization operations was considered by the meeting, leading to the release of a "Statement of Concern", which notes the recent commercial interest in the large-scale fertilization of ocean waters in order to sequester CO_2; the indication by the Intergovernmental panel on Climate Change (IPCC) of ocean fertilization as a potential but largely speculative strategy for removing carbon dioxide from the atmosphere; and notes with concern the potential for large-scale ocean iron fertilization to have negative impacts on the marine environment and human health[19].

At the 30th Consultative Meeting of Contracting Parties to the London Convention and 3rd Meeting of Contracting Parties to the London Protocol (London, 27–31 October 2008), recalling the 2007 outcome, this meeting agreed, *inter alia*, that "*the scope of work of the London Convention and Protocol included ocean fertilization, as well as iron fertilization; the London Convention and Protocol were compe-*

16 See http://www.cbd.int/decision/cop/?id=11659, accessed on 6 May 2009

17 Report of the 30th Consultative Meeting of Contracting Parties to the London Convention and 3rd Meeting of Contracting Parties to the London Protocol (London, 27–31 October 2008). http://www.imo.org/includes/blastData.asp/doc_id=10064/INF-4.pdf

18 See http://www.cbd.int/decision/cop/?id=11663, accessed on 6 May 2009

19 See Report of the Thirtieth Meeting of the Scientific Group of the London Convention and the First Meeting of the Scientific Group of the London Protocol, http://www.imo.org/includes/blastDataOnly.asp/data_id%3D19765/14.pdf, accessed on 6 May 2009

tent to address this issue due to their general objective to protect and preserve the marine environment from all sources of pollution (Article I of the Convention and Article 2 of the Protocol); they would further study the issue from the scientific and legal perspectives with a view to its regulation." The meeting also adopted Resolution LC-LP.1 (2008) on the Regulation of Ocean Fertilization[20].

CARBON AND CO_2 UNIT CONVERSION TABLE

Climate change mitigation measures often refer to the natural uptake or engineered capture and storage of carbon (C), while in the context of greenhouse gas emissions it is referred to the gaseous form of carbon, carbon dioxide (CO_2). The relation between the two is as follows:

1 tonne of carbon corresponds to **3.67 tonnes of carbon dioxide**

In this report, tonnes are metric tonnes (i.e. 10^6 grams), and total carbon stores are provided in gigatonnes of carbon (Gt C) and stores per area in tonnes of carbon per m^2 (t C m^2). Carbon fluxes are presented in tonnes of carbon per year (t C per yr) or tonnes of carbon per m^2 per year (t C m^2 per yr).

1 Gt C of carbon corresponds to **10^9 t C.**

A. OBJECTIVES OF THE REPORT

This report presents a review and synthesis of existing literature and other scientific information on the potential impacts of ocean fertilization on marine biodiversity, pursuant to CBD COP 9 decision IX/20, paragraph 3. The final report takes into consideration comments and feedback submitted by Parties, other Governments and organizations as well as the inputs from international scientific experts, who kindly peer-reviewed the report.

In accordance with the requirements set out in decision IX/20, the output of this work shall be submitted to the 14th meeting of the Subsidiary Body on Scientific, Technical and Technological Advice, scheduled for May 2010, for consideration.

The research for this report was conducted by the UNEP World Conservation Monitoring Centre (WCMC) with kind financial support from the Government of Spain.

B. DEFINITION(S) OF OCEAN FERTILIZATION

Despite a wealth of literature, descriptions and statements on ocean fertilization, there are few internationally agreed definitions of the term. This synthesis uses the definition agreed by the Parties to the London Convention and London Protocol for the purpose of Resolution LC-LP.1 (2008) on the Regulation of Ocean Fertilization, which defines ocean fertilization as: ***any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans, not including conventional aquaculture, or mariculture, or the creation of artificial reefs***[21].

It should be noted that the above definition of "ocean fertilization" excludes other human activities which might cause fertilization as a side effect, for example by pumping cold, deep water to the surface for cooling or energy-generating purposes (Ocean Thermal Energy Conversion—OTEC). The latter utilizes the significant temperature difference between shallow and deep waters to produce renewable energy.

20 See Report of the Thirtieth Consultative Meeting and the Third Meeting of Contracting Parties, http://www.imo.org/includes/blastData.asp/doc_id=10689/16.pdf, accessed on 6 May 2009

21 Ibid.

Furthermore, the definition of ocean fertilization in resolution LC-LP.1 (2008) does not cover all processes that might be explored through the addition of material to the marine environment, e.g. (1) the addition of iron to the ocean to study geochemical aspects; and (2) the addition of particulate materials that cause the adhesion and subsequent settling of dissolved or suspended organic matter. Nor does it include the input of nutrients to coastal waters from agricultural runoff of fertilizers, or the input of municipal sewage.

C. SCIENTIFIC HYPOTHESIS FOR OCEAN FERTILIZATION

The ocean is one of the largest natural reservoirs of carbon, and as such plays an important role in the regulation of atmospheric CO_2 and greenhouse forcing of the Earth's climate. Gases are readily exchanged across the air-sea interface due to differences in the partial pressure of CO_2 (pCO_2) between the ocean and the atmosphere. Temperature, salinity and biological activity can all influence the partial pressure of CO_2. For example, the uptake of CO_2 by marine algae during photosynthesis creates a deficit of CO_2 in surface ocean waters, driving the dissolution of CO_2 from the atmosphere into the surface ocean to restore the equilibrium[22,23]. As a result of this and other processes, the ocean absorbed approximately one-third of the CO_2 released from all human activities between 1800 and 1994, leading to an increase in the total inorganic carbon content of the oceans in the range of 112 to 118 (+/- 17–19) Gt during this period[24].

Density stratification separates the shallow surface water layers (~ a few hundred metres deep) from the deep water layers (~ a few kilometres deep) across the global oceans, except in polar regions during winter. Large-scale, three-dimensional ocean circulation creates pathways for the transport of heat, fresh water and dissolved gases such as CO_2 from the surface ocean into the density-stratified deeper ocean, thereby isolating them from further interaction with the atmosphere for several hundreds to thousands of years and influencing atmospheric CO_2 concentrations over anthropogenic timescales.[25,26] In addition to advection and mixing, the ocean can alter atmospheric CO_2 concentration through two basic mechanisms: the "biological pump" and the "solubility pump," as discussed below.

The Biological Pump

A fraction of the surface ocean, a few tens of metres up to 200 metres is sufficiently sunlit to support photosynthesis by marine plants, termed the "euphotic zone." Macro algae and rooted plants are confined to shallow coastal waters, while phytoplankton is the dominant form of plant in the open ocean. Using sunlight for energy and dissolved inorganic nutrients, phytoplankton convert dissolved inorganic carbon (DIC) (the sum of bicarbonate ions, dissolved CO_2 and carbonate ions*)* in seawater into organic matter through photosynthesis, driving global marine food webs and prompting the "drawdown" of additional carbon dioxide from the atmosphere.

22 Chisholm, S. W. (2000). Stirring times in the Southern Ocean. Nature. Vol 407.

23 Suzuki, A. (1998). Combined effects of photosynthesis and calcification on the partial pressure of carbon dioxide in seawater. Journal of Oceanography. Vol 54:1-7.

24 Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., *et al.* (2004). The oceanic sink for CO_2. Science, 305:367–371.

25 Cassar, N., Bender, M. L., Barnett, B. A., Songmiao, F., Moxim, W. J., Levy II, H., Tilbrook, B. (2007). The Southern Ocean Biological Response to Aeolian Iron Deposition. Science. Vol 317, pp1067–1070, 24 August 2007.

26 Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quere, S. Levitus, Y. Nojiri, C.K. Shum, L. D. Talley and Unnikrishnan, A. (2007). Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., D. Qin, M. Manning, Z. Chen, M, Marquis, K. B. Averyt, M, Tognor and H. L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom.

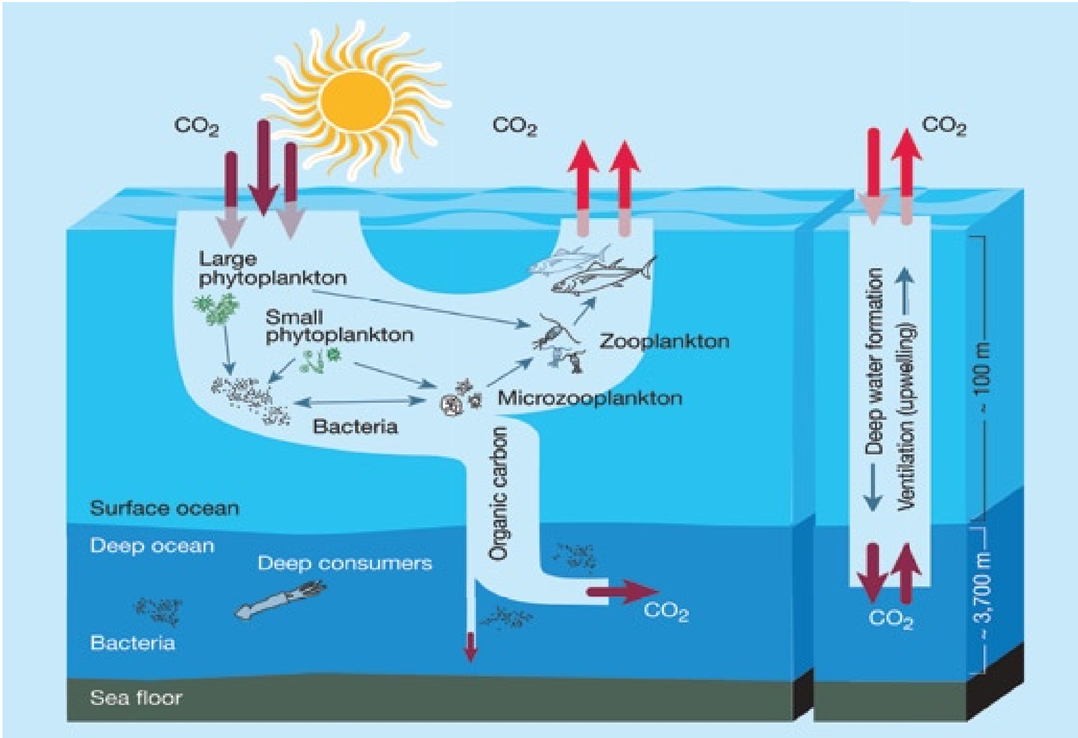

FIGURE 1: The solubility pump (right) and the biological pump (left) help to maintain a sharp gradient of CO_2 between the atmosphere and the deep oceans where 38×10^{18} g of carbon is stored. Using sunlight for energy and dissolved inorganic nutrients, phytoplankton convert CO_2 to organic carbon, which forms the base of the marine food web. As the carbon passes through consumers in surface waters, most of it is converted back to CO_2 and released to the atmosphere. But some finds its way to the deep ocean where it is remineralized back to CO_2 by bacteria. The net result is transport of CO_2 from the atmosphere to the deep ocean, where it stays, on average, for roughly 1,000 years. The food web's structure and the relative abundance of species influences how much CO_2 will be pumped to the deep ocean. This structure is dictated largely by the availability of inorganic nutrients such as nitrogen, phosphorus, silicon and iron. (Figure modified from a graphic by Z. Johnson.) *Source: Strong, A.L., Cullen, J.J. & Chisholm, S.W. (2009). Ocean Fertlization, Science, Policy, and Commerce, Oceanography, Vol. 22, No. 3, pp. 236-261.*

In oceanic biogeochemistry, the "biological pump" is the sum of a suite of biologically mediated processes that transport carbon from the surface euphotic zone to the deep ocean[27]. The concept of ocean fertilization is based on artificially increasing the natural processes by which carbon is sequestered from the atmosphere into marine systems, through the stimulation of primary production in surface ocean waters.

Primary production is limited by light availability and the supply of essential nutrients for growth (e.g., nitrate, phosphate, silicic acid), which restricts the distribution of phytoplankton to the shallow euphotic zone. Much of the carbon "fixed" as organic matter within the phytoplankton during photosynthesis is converted back to CO_2 and released to the atmosphere by the respiration of phytoplankton, bacterioplankton and grazing zooplankton in the mixed surface layers.

27 Volk, T., M. I. Hoffert, (1985). Ocean carbon pumps: analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes, in *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present*, edited by E. T. Sundquist and W. S. Broecker, pp. 99–110, Geophysical Monograph 32, American Geophysical Union, Wash., D.C., 1985.

Carbon export occurs when organic material sinks before it is consumed and converted back into CO_2 and dissolved nutrients. Particulate organic carbon (POC), particulate inorganic carbon (PIC) and dissolved organic carbon (DOC) is exported in the planktonic debris to deeper waters at a rate of ~10PgC per year[28]. Much (~90%) of the remaining organic matter is remineralized into DIC by microbial degradation within a depth range of 100 to 1000m in the water column, releasing mineral nutrients which, via mixing, become available for further photosynthesis when returned to the surface euphotic zone[29]. A proportion of the POC will sink into the density-stratified deeper ocean before it decays, where it will remain as DIC, isolated from further interaction with the atmosphere for an estimated 1,000 years[30], until deep ocean currents and upwelling processes return the deep water to the surface[31,32]. In addition to this gravitational settling, some of the newly formed DOC is transported to the deeper ocean waters by vertical mixing processes[33]. The transfer of carbon into the deep ocean is regulated by the rate of gravitational settling and mixing alongside the rate and location of its conversion back to dissolved inorganic carbon (DIC) by metabolic processes[34]. It is estimated that only a very small amount of the planktonic debris (0.1%) ever reaches the ocean sediments and is lithified to form hydrocarbon deposits (Figure 1)[35].

The Solubility Pump

The solubility pump is another important mechanism for controlling the inventory of carbon in the ocean. CO_2 reacts with water and carbonate to form bicarbonate ions. The sum of bicarbonate ions, dissolved CO_2 and carbonate ions is dissolved inorganic carbon, or DIC[36]. The solubility pump reflects the temperature dependence of CO_2 solubility (i.e., solubility is greater in colder water) and the thermal stratification of the ocean[37]. Large-scale density driven (thermohaline) circulation is driven by the formation of deep water at high latitudes where cold, dense waters sink and flow into the deep ocean basins. Since these deep water masses are formed under the same surface conditions that promote carbon dioxide solubility, they contain a high concentration of DIC, accumulated at the surface, which is transported to the deeper parts of the oceans as the water mass sinks.

Deep water masses accumulate further DIC as they travel across the ocean basins. As such, concentrations of DIC are approximately 10-15% higher in deep waters than at the surface, and lower in the Atlantic than the Indian Ocean, with the highest concentrations found in the older deep waters of the North Pacific[38]. The upwelling of deep ocean waters driven by wind or topography brings the DIC-laden waters to the surface, often resulting in an efflux of CO_2 to the atmosphere.

28 Bishop, J. K. B, Davis, R. E., Sherman, J. T. (2002). Robotic observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific. Science 298, 817.

29 De Baar, H. J., Gerringa, L. J. A., Laan, P., Timmermans, K. R. (2008). Efficiency of carbon removal per added iron in ocean iron fertilization. Mar Ecol Prog Ser, Vol 364:269–282.

30 Chisholm, S. W. (2000). Stirring times in the Southern Ocean. Nature. Vol **407.** 12 October 2000.

31 Denman. K. L. (2008). Climate change, ocean processes and ocean iron fertilization. Marine Ecology Progress Series Vol. 364: 219–225

32 Coale, K. Open Ocean Iron Fertilization for Scientific Study and Carbon Sequestration. Adapted from: Encyclopedia of Ocean Sciences (Eds. Steele, Yentch and Turekian).

33 Hansell, D. A. and Carlson, C. A. (2001). Marine Dissolved Organic Matter and the Carbon Cycle. Oceanography 14. pp. 41–49.

34 Herring, P. 2002. The Biology of the Deep Ocean. Oxford Univ. Press, NY. 314 pp

35 Feely, R. A., Sabine, C. L., Takahashi, T., Wanninkhof, R. (2001). Uptake and Storage of Carbon Dioxide in the Ocean: The Global CO_2 Survey. Oceanography, Vol. 14 (4) 18–32.

36 Le Queré, C. and Metzl, N. (2004). Natural Processes Regulating the Ocean Uptake of CO_2. In: The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. (C. B. Field and M. R. Raupach, Eds.) Island Press: Washington, D.C., USA. pp. 243–255

37 Ito, T., Follows, M. J. (2003). Upper ocean control on the solubility pump of CO_2. Journal of Marine Research, 61:485–489.

38 Feely, R. A., Sabine, C. L., Takahashi, T., Wanninkhof, R. (2001). Uptake and Storage of Carbon Dioxide in the Ocean: The Global CO_2 Survey. Oceanography, Vol. 14 (4) 18–32.

The Biological and Solubility Pumps in Future, Warmer Oceans

Climate variability influences ocean ecosystems in many ways and in synergy with the pervasive anthropogenic stresses to these systems[39]. The overall capacity of the ocean as a carbon sink is predicted to diminish with increasing atmospheric CO_2[40]. Carbon models have shown that the rate of natural uptake of CO_2 by the global oceans may be reduced by 9% as a consequence of climate change impacts[41]. For the Southern Ocean, a weakening of the carbon sink appears to have been observed during the last two decades, which is attributed in one study to the influence of changes in wind patterns affecting the intensity of upwelling processes[42]. Whether this trend will continue or reverse at some point is uncertain[43]. A rapid decline in the CO_2 buffering capacity has been reported from the North Sea, and models suggest it is likely that the capacity in the Gulf Stream/North Atlantic Drift regions may also be in decline[44].

Increasing sea-surface temperatures and enhanced freshening, as predicted under future climate change scenarios, enhances the thermal stratification of the ocean and reduces vertical mixing, which translates into warm surface waters that dissolve less carbon dioxide and have a concurrently reduced nutrient supply from deeper ocean layers[45]. A dramatic decline in the nutrient supply to the euphotic layer is predicted in the coming century[46]. These factors combined will likely result in both decreased primary productivity and consequently, carbon uptake by the biological pump.

The solubility of CO_2 in water correlates negatively with water temperature. Different climate models predict ocean temperature increases throughout the century[47], meaning that less CO_2 can be absorbed at the surface in the formation of deep and bottom water and more CO_2 may be released in upwelling areas. Model outcomes suggest that the strength of the solubility pump is highly correlated with surface and mean deep-ocean temperatures[48]. In the long term the solubility of CO_2 may decrease, or in the worst-case even interrupt, the ocean's solubility pump. This would seriously influence the ocean's carbon absorption capacity and in turn, the potential impact of large-scale ocean fertilization activities on the concentration of CO_2 in the atmosphere.

High-Nutrient, Low-Chlorophyll (HNLC) Regions

The physiological nutrient and trace element requirements of marine phytoplankton must be met from within the water column. The mean elemental ratio of phytoplankton, known as the Redfield ratio, is

39 Cullen, J. J., Boyd, P. W. (2008). Predicting and verifying the intended and unintended consequences of large scale ocean iron fertilization. Mar Ecol Prog Ser, Vol364:295–301.

40 Fung, I. Y., Doney, S. C., Lindsay, K., and John, J. (2005). Evolution of carbon sinks in a changing climate. Proceedings of the National Academy of Sciences 102, 11201–11206

41 Ridgwell, A. J., Maslin, M., and Watson, A. J. (2002). Reduced effectiveness of terrestrial carbon sequestration due to an antagonistic response of ocean productivity. Geophysical Research Letters 29, 1095

42 Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet. M., Nakazawa, T., Metzl, N., Gillett, N., Heimann, M. (2007). Saturation of the Southern Ocean CO_2 Sink due to Recent Climate Change. Science Vol 316 (5832):1735–1738.

43 Le Queré, C., Roedenbeck, C., Bruitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M. (2008). Response to comments on "Saturation of the Southern Ocean CO_2 Sink due to Recent Climate Change". Science 319, 570c

44 Thomas, H., Prowe, A. E. F., van Heuven, S., Bozec, Y., De Baar, H. J. W., Schiettecatte, L.-S., Suykens, K., Koné, M., Borges, A. V., Lima, I. D., and Doney, S. C. (2007). Rapid decline in CO_2 buffering capacity in the North Sea and implications for the North Atlantic Ocean. Global Biogeochemical Cycles 21, GB4001.

45 Crueger, T., Roeckner, E., Raddatz, T., Schnur, R., and Wetzel, P. (2008). Ocean dynamics determine the response of oceanic CO_2 uptake to climate change. Climate Dynamics 31. pp. 151–168

46 Cermeno, P., Dutkiewicz, S., Harris, R. P., Follows, M., Schofield, O., and Falkowski, P. G. (2008). The role of nutricline depth in regulating the ocean carbon cycle. *Proceedings of the National Academy of Sciences* **105**, 20344–20349

47 Matthews, H. D. and Caldeira, K. (2008). Stabilizing climate requires near-zero emissions. Geophysical Research Letters 35, L04705

48 Cameron, D. R., Lenton, T. M., Ridgwell, A. J., Shepherd, J. G., Marsh, R., and Yool, A. (2005). A factorial analysis of the marine carbon cycle and oceanic circulation controls on atmospheric CO_2. Global Biogeochemical Cycles 19, GB4027

106C/16N/1P by atoms and is highly conserved[49]. The world's oceans contain vast reservoirs of nutrients, however these are found primarily at depths below 200 metres, where there is insufficient light for (net) photosynthesis to occur. Nutrient fluxes from deep waters to the sunlit surface waters are low in open ocean areas, and one of the nutrients essential to photosynthesis is almost always exhausted at some time during the growing cycle. The relief of limitation by one nutrient will normally allow production to increase only to the point where it is limited by another[50].

Over 20% of the world's open-ocean surface waters are characterized by the presence of adequate nitrate, phosphate and silicate in the euphotic zone, but a relatively low corresponding phytoplankton biomass. These areas, termed "high-nutrient, low-chlorophyll" (HNLC) areas, are observed in the equatorial and subarctic Pacific Ocean, the Southern Ocean and in some strong upwelling regimes, such as in the equatorial Pacific. Grazing pressure from herbivores has been suggested as a mechanism that prevents the phytoplankton from fully utilizing the available nutrients, alongside strong turbulence (at higher latitudes), which may mix the phytoplankton below the euphotic zone, resulting in light limitation of growth[51].

In addition to these factors, Martin and colleagues predicted, and later validated via bottle incubations and mesoscale iron (Fe) enrichment experimentation, that micronutrients, such as Fe, which are catalytic components in a wide variety of electron transport and enzymatic systems in phytoplankton, are a limiting factor in phytoplankton photosynthesis[52]. Subsequent experimentation has supported the proximate control of biological productivity by iron (The "iron hypothesis"), suggesting that iron availability may regulate ocean production in HNLC areas, thus influencing the associated uptake of carbon over large areas of the ocean. The Southern Ocean is the largest HNLC area of the global ocean and is of significant importance in the regulation of the global climate system due to its potential as a carbon sink.

Low-Nitrate, Low-Chlorophyll (LNLC) Regions

The surface waters of sub tropical and tropical oceans have low sea surface concentrations of nitrate (NO_3^-) and chlorophyll, and are characterized by low rates of organic matter production and export of POC and DOC to the deep ocean. As the magnitude of fluxes in the carbon cycle of these habitats is determined by the supply of inorganic nutrients, these "low-nitrate, low-chlorophyll" (LNLC) areas have no expectation of further primary productivity and represent the global ocean minima in carbon sequestration potential[53]. However, given that these regions occupy approximately 50% of the ocean they are important in the global marine carbon export budget[54].

A strong vertical stratification insulates the upper water layers of these vast seascapes from the large pool of NO_3^- in deeper waters. Nitrogen-based (N_2) new production requires an ample supply of energy, iron (Fe) and phosphorous (P). In well illuminated and stratified NO_3^- depleted regions where there is adequate phosphate (PO_4^{3-}), the addition of Fe may enhance the growth of nitrogen (N_2) fixing organisms (diazotrophs) and promote N_2 based carbon export and sequestration. Alternatively the addi-

49 Falkowski, P. G., *et al.* (1998). Biogeochemical Controls and Feedbacks on Ocean Primary Production. Science 281, 200.

50 Lampitt, R. S. *et al.* (2008). Ocean fertilization: a potential means of geoengineering? Phil. Trans. R. Soc. A. 366, 3919–3945

51 Martin, J. H. *et al*. (1994). Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature, Vol. 371. pp123–129.

52 Kobler, Z. S., Barber, R.T., Coale, K. H., Fitzwater, S. E., Greene, R. M., Johnson, K. S., Lindley, S., Falkowski, P.G. (1994). Nature, Vol. 371. pp145–148.

53 Karl, D. M., Letelier, R. M. (2008). Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. Mar Ecol Prog Ser, Vol 364:257–268.

54 Cullen, J. J., Boyd, P. W. (2008). Predicting and verifying the intended and unintended consequences of large scale ocean iron fertilization. Mar Ecol Prog Ser, Vol 364: 295–301.

tion of phosphate to Fe-containing, phosphate-depleted waters also should stimulate N_2 fixation. These characteristics of the latter are observed in oligotrophic waters downwind from continental dust sources or areas impacted by hydrothermal inputs of Fe from shallow underwater volcanoes[55].

Natural Oceanic Iron Sources

Natural inputs of Fe are supplied to the marine environment via a range of sources: river runoff; the re-suspension of bottom sediments in coastal ocean environments; melting sea ice; atmospheric deposition of dissolved iron; and iron-rich deep water via vertical mixing and upwelling processes[56]. Windblown terrestrially derived dust, mainly from the great deserts of the world, is a major source of external Fe input for the open oceans. Dust particles are transported over thousands of kilometres, creating strong deposition gradients across the oceans. It has been estimated that 26% of the global dust generated each year (1,700Tg/year^{-1}) is deposited in the oceans, with the South Atlantic, South Pacific and Southern Ocean receiving the smallest aeolian dust inputs (Figure 2)[57]. Long-distance transport of Fe to open-ocean environments from re-suspended shelf sediments has also been observed and may contribute similar or greater Fe inputs to that of aerosol sources[58].

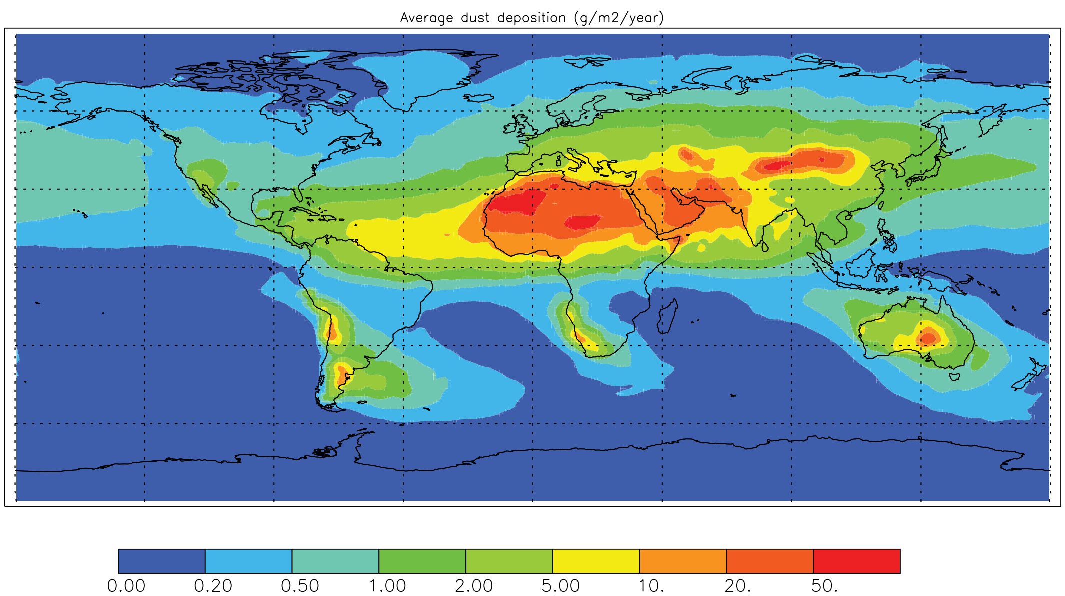

FIGURE 2: Average dust deposition (g/m$_2$/year). *Source: Jickells et al. 2005. Global Iron Connections Between Desert Dust, Ocean Biogeochemistry, and Climate. Science 308 (5718), pp. 67–71*

Contemporary ocean observations support the theory that natural iron fertilization elevates biomass standing stock *in situ*. Separate multidisciplinary studies around the Crozet Islands and the Kerguelen plateau in the Southern Ocean observed elevated biomass, and also elevated export of carbon to the deep

55 Karl, D. M., Letelier, R. M. (2008). Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorphyll seascapes. Mar Ecol Prog Ser, 364:257–268

56 Blain et al. 2007. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature 446:1070–1074.

57 Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., la Roche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., Torres, R. (2005). Global Iron Connections Between Desert Dust, Ocean Biogeochemistry, and Climate. Science Vol. 308. no. 5718, pp. 67–71

58 Lam, P.J., Bishop, J.K.B. 2008. The continental margin is a key source of iron to the HNLC North Pacific Ocean. Geophysical Research Letters 35, L07608, doi:10.1029/2008GL033294

sea, in response to natural iron inputs[59,60]. In 2001, chlorophyll retrievals from NASA's SeaWiFS satellite and two robotic Carbon Explorer floats observed the rapid growth of phytoplankton in the upper layers of the North Pacific Ocean in response to a passing storm, which deposited iron-rich dust from the Gobi Desert into surface waters. An increased POC concentration was observed in the mixed surface layer five days after the dust input, with POC levels exceeding by a factor of two to four those recorded in previous ship-based observations[61]. While not a new discovery, the robotic floats provided high frequency, continuous monitoring data of the upper ocean, facilitating for the first time the direct continuous observations of the upper ocean biological response to an episodic natural fertilization event.

The examination of aeolian dust particles obtained from ice and sediment cores suggests that during glacial periods the supply of Fe to the world oceans was higher than during interglacial periods. Martin and colleagues proposed that increasing iron supply from dust during glacial periods stimulated primary productivity, which in turn led to a decrease in atmospheric CO_2 levels and further global cooling[62]. It is estimated that this increase in Fe induced productivity could have accounted for 30% of the 80 ppm decrease in atmospheric CO_2 during glacial maxima[63,64]. This "iron hypothesis" has sparked much interest in the potential of specific ocean regions to mitigate further climatic warming by improving the efficiency of the biological pump to draw down CO_2 from the atmosphere through the intentional fertilization of ocean surface waters with quantities of macro and micro nutrients.

Both high and low carbon export efficiencies (defined as the amount of carbon exported below the mixed water column for a given nutrient supply) have been observed in studies of natural iron fertilization in the Southern Ocean, creating uncertainty about the efficiency that can ultimately be achieved by artificial large-scale ocean fertilization experiments. The CROZEX study returned export efficiencies 18 times greater than that of a phytoplankton bloom induced artificially by adding iron in the SERIES study, but 77 times smaller than that of another bloom initiated, like CROZEX, by a natural supply of iron[65].

A recent study conducted within the Southern Ocean presents evidence for two intervals of enhanced upwelling concurrent with two intervals of rising atmospheric CO_2 and suggests a direct link between increased ventilation of deep water and the deglacial rise in atmospheric CO_2. A displacement in wind

59 Blain, S., Quéguiner, B., Armand, L., Belviso, S., Bombled, B., Bopp, L., Bowie, A., Brunet, C., Brussaard, C., Carlotti, F., Christaki, U., Corbière, A., Durand, I., Ebersbach, F., Fuda, J.L., Garcia, N., Gerringa, L., Griffiths, B., Guigue, C., Guillerm, C., Jacquet, S., Jeandel, C., Laan, P., Lefèvre, D., Lomonaco, C., Malits, A., Mosseri, J., Obernosterer, I., Park, Y.-H., Picheral, M., Pondaven, P., Remenyi, T., Sandroni, V., Sarthou, G., Savoye, N., Scouarnec, L., Souhaut, M., Thuiller, D., Timmermans, K., Trull, T., Uitz, J., van-Beek, P., Veldhuis, M., Vincent, D., Viollier, E., Vong, L., Wagener, T., 2007. Impacts of natural iron fertilisation on the Southern Ocean. Nature 446, 1070–1074, doi:10.1038/nature05700.

60 Pollard, R.T., I.Salter, Sanders, R.J., Lucas, M.I., Moore, C.M., Mills, R.A., Statham, P.J., Allen, J.T., Baker, A.R., Bakker, D.C.E., Charette, M.A., Fielding, S., Fones, G.R., French, M., Hickman, A.E., Holland, R.J., Hughes, J.A., Jickells, T.D., Lampitt, R.S., Morris, P.J., Nédélec, F.H., Nielsdóttir, M., Planquette, H., Popova, E.E., Poulton, A.J., Read, J.F., Seeyave, S., Smith, T., Stinchcombe, M., Taylor, S., Thomalla, S., Venables, H.J., Williamson, R., Zubkov, M.V., 2009. Southern Ocean deep-water carbon export enhanced by natural iron fertilization. Nature 457, 577–580, doi:10.1038/nature07716.

61 Bishop, J. K., Quequiner, B., Armand, L., *et al.* (2002). Robotic observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific. Science 298, 817.

62 Martin, J. H. *et al.* (1994). Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature, Vol. 371. pp123–129.

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

64 Sigman, D. M., Boyle, E. A. (2000). Nature 407, 859.

65 Pollard, R.T., I.Salter, Sanders, R.J., Lucas, M.I., Moore, C.M., Mills, R.A., Statham, P.J., Allen, J.T., Baker, A.R., Bakker, D.C.E., Charette, M.A., Fielding, S., Fones, G.R., French, M., Hickman, A.E., Holland, R.J., Hughes, J.A., Jickells, T.D., Lampitt, R.S., Morris, P.J., Nédélec, F.H., Nielsdóttir, M., Planquette, H., Popova, E.E., Poulton, A.J., Read, J.F., Seeyave, S., Smith, T., Stinchcombe, M., Taylor, S., Thomalla, S., Venables, H.J., Williamson, R., Zubkov, M.V., 2009. Southern Ocean deep-water carbon export enhanced by natural iron fertilization. Nature 457, 577–580, doi:10.1038/nature07716.

direction and intensity, and the corresponding influence this has in the ventilation of deep water in the Southern Ocean are suggested to have a governing role in this process[66]

Removal of Atmospheric CO_2

To stabilize CO_2 concentrations in the atmosphere in line with internationally agreed targets and reduce the resultant rate of climate change, carbon emissions must be dramatically reduced[67]. For carbon sequestration technologies to be considered effective, they should be capable of removing atmospheric CO_2 for a minimum period of 100 years in a verifiable manner, and stabilizing net CO_2 emissions to provide a buffer period for the reduction of global CO_2 emissions and the global uptake of clean fuel infrastructure and technologies[68].

Modelling studies have predicted that the sustained fertilization of HNLC areas (~30% of the global oceans), over decadal timescales, could temporarily sequester at most 0.5Gt C yr^{-1}. Oligotrophic (LNLC) areas (~50% of the global oceans) offer further potential to sequester carbon in the ocean by enhancing the growth of phytoplankton through nutrient addition or by stimulating nitrogen fixation[69].

These efficiency estimates, however, have not been reflected by the open-ocean fertilization experiments to date, which have required more than twice the predicted amount of Fe to trigger a phytoplankton bloom, leading to the estimation that to sequester approximately 30% of the annual anthropogenic CO_2 emissions, an area of $10^9 km^2$, corresponding to more than an order of magnitude larger than the size of the entire Southern Ocean, would need to be fertilized each year[70]. These conservative estimates suggest that even with sustained fertilization of open oceans, only a minor impact on the increase in atmospheric CO_2 will be possible[71].

66 Anderson, R. F., Ali, S., Bradtmiller, L. I., Nielson, S. H. H., Fleisher, M. Q., Anderson, B. E., Burckle, L. H. (2009). Wind-Driven Upwelling in the Southern Ocean and the Deglacial Rise in Atmospheric CO_2. Science Vol 323 (5920):1443–1448.

67 Denman. K. L. (2008). Climate change, ocean processes and ocean iron fertilization. Marine Ecology Progress Series Vol. 364: 219–225

68 Ibid.

69 Cullen, J. J., Boyd, P. W. (2008). Predicting and verifying the intended and unintended consequences of large scale ocean iron fertilization. Mar Ecol Prog Ser, Vol 364: 295–301.

70 Buesseler, K. O., Boyd, P. W. (2003). Will Ocean fertilization work? Science 300: 67–68.

71 Zahariev, K., Christian, J., Dennman, K. (2008). Preindustrial, historical and fertilization simulations using a global ocean carbon model with new parameterizations of iron limitation, calcification and N_2 fixation. Progress in Oceanography, Volume 77, (1):56–82

II. REVIEW OF OCEAN FERTILIZATION APPROACHES AND POTENTIAL IMPACTS ON MARINE BIODIVERSITY

The role of iron and macronutrients in carbon cycling has been assessed to date using laboratory and ship-based incubations, mesoscale fertilization experiments, studies of naturally fertilized waters and model simulations of the dynamic ocean environment. These studies have established the fundamental role of iron in regions of the oceans and advanced scientific understanding of ocean biogeochemistry. However, the direct experimental demonstration that ocean fertilization induces an increased downward transport of biogenic carbon has remained largely elusive[72].

The verification of the exact quantities of carbon that would be sequestered in the deep ocean presents significant scientific and technical challenges, and cannot be measured by any simple means. Ship-dependent ocean observations of biogeochemical processes and carbon dynamics have to date been conducted over short timeframes of days to weeks and over a limited scale, precluding the accurate extrapolation of results to the larger ocean basin or global scales proposed for carbon sequestration by ocean fertilization for the purpose of climate mitigation[73].

Assessment of the long-term, large-scale processes affected by ocean fertilization is only feasible through detailed modelling of the physics and biogeochemistry of the fertilized and downstream waters. The current state of knowledge is insufficient to place much confidence in the predictions of available models, which have yielded significantly different scenarios for the effect of ocean fertilization in the global oceans[74]. Recent research also highlights the role of observational field studies in further reducing experimental limitations and improving the accuracy and predictions of existing model simulations.

Overestimations of fertilization efficiency have propelled the notion of ocean iron fertilization technology as a rapid and low-cost climate mitigation strategy, most marked in commercial proposals for ocean fertilization technologies. However, the uncertainties surrounding the efficiency of ocean fertilization to influence the significant downward transport of captured carbon presents significant cost implications for the scaling up of ocean fertilization from scientific (test) experiments to commercial-scale operations. Moreover, there are significant concerns for the intended and unintended impacts on marine ecosystem structure, function and dynamics, including the sensitivity of species and habitats and the physiological changes induced by large-scale micronutrient and macronutrient additions to surface waters.

A range of ocean fertilization methods using the addition of iron, nitrogen, phosphate, and silica are considered below in the context of the biogeochemical changes, organism responses and ecosystem considerations of fertilized and downstream water for each fertilization method.

A. IRON FERTILIZATION

A total of 13 scientific iron fertilization studies have been undertaken over time and space scales of weeks and kilometres, between 1993 and 2009 in polar, sub-polar and tropical HNLC areas (Figure 3).

72 Jin, X., Gruber, N., Frenzel, H., Doney, S. C., and McWilliams, J. C. (2008). The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump. Biogeosciences, 5, 385–406.

73 Bishop, J. K., Quequiner, B., Armand, L., *et al.* (2002). Robotic observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific. Science 298, 817.

74 Watson, A. J., Boyd, P. W., Turner, S.M., Jickells, T. D., Liss, P. S. (2008). Designing the next generation of ocean iron fertilization experiments. Mar Ecol Prog Ser, Vol 364:303–309.

The results of these experiments (Annex 1) have confirmed a direct biological response of HNLC regions to iron enrichment through increased phytoplankton biomass. Early experiments were conducted and monitored over very short timeframes (just nine days in IRON EX I in 1993), and were conducted principally to understand the nature of the controls of primary production and ecosystem function in HNLC waters, not to assess the potential of carbon sequestration for the purpose of climate manipulation[75]. Subsequent experimentations have tested the "iron hypothesis" across more HNLC areas, adapted experimental methodologies in response to limitations, and attempted to monitor carbon export flux into deeper waters and the impacts on local nutrient concentrations. While artificial enrichment experiments have each used a common framework to enable comparison, there have been no direct replications of experiments undertaken to date[76].

In January 2009, a larger-scale scientific iron fertilization experiment, LOHAFEX, was conducted in the Southern Ocean, releasing six tonnes of dissolved iron into a 300 km^2 patch. The bloom was followed for a period of 39 days[77].

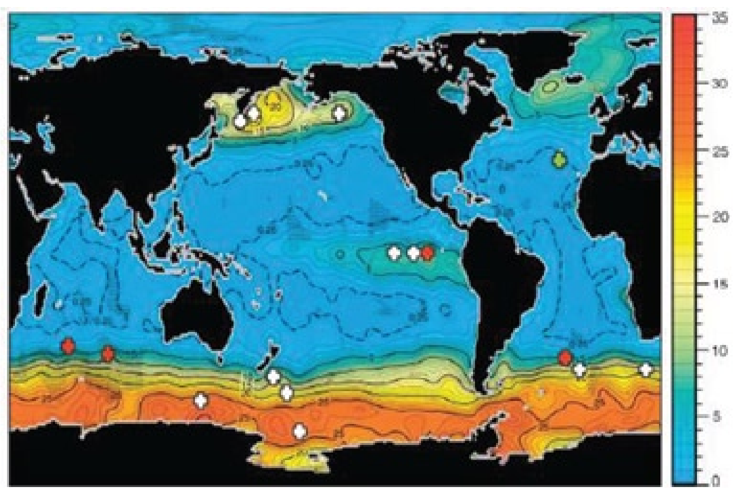

FIGURE 3: Approximate site locations of 12 mesoscale Fe fertilization experiments (1993-2007) (white crosses) relative to annual surface mixed-layer nitrate concentrations in units of mmol liter−1. Shipboard Fe experiments (red crosses), and a joint Fe and P enrichment study of the subtropical LNLC Atlantic Ocean (FeeP; green cross). Mesoscale Iron addition experiments (FeAX) shown are SEEDS I and II (northwest Pacific; same site but symbols are offset), SERIES (northeast Pacific), IronEX I and II (equatorial Pacific; IronEX II is to the left), EisenEx and EIFEX (Atlantic polar waters; EIFEX is directly south of Africa), SOIREE (polar waters south of Australia), SOFEX-S (polar waters south of New Zealand), SOFEX-N (subpolar waters south of New Zealand), and SAGE (subpolar waters nearest to New Zealand). Natural Fe addition experiment sites shown are the Galapagos Plume (equatorial Pacific), Antarctic Polar Front (polar Atlantic waters), and the Crozet and Kerguelen plateaus (Indian sector of Southern Ocean; Crozet is to the left of Kerguelen). *Source: Boyd et al., 2007. This figure is taken directly from the literature and does not include information on LOHAFEX conducted in 2009.*

75 Martin, J. H. *et al.* (1994). Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature, Vol. 371. pp123–129.

76 Boyd, P. W., *et al.* (2007). Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions. Science, Vol 315:612.

77 Alfred-Wegener-Institut (2009). Press Release: Lohafex provides new insights into plankton ecology (www.awi.de).

The following tables provide summaries of key data about the scientific iron fertilization experiments carried out so far. Further information about these experiments is given in Annex 1.

TABLE 1: Summary of the amounts and scales of previous iron fertilization activities

	Initial size of dispersal area	Amount of Fe supplied	Temporal nature	Injection frequency	Duration of monitoring
Past activities	64–1000 km^2	350 kg (SEEDS I)[78] 1-2000kg (LOHAFEX)[47]	Days-weeks	Single (e.g. IRON Ex I) and pulsed injection of Fe (0,3, 7 days) (e.g. SOIREE)	Maximum of 2 months

TABLE 2: Summary of materials used in iron fertilization

<table>
<tr><th></th><th>Typical sources*</th><th>Typical physical forms</th><th>Typical impurities</th><th>Typical ancillary input materials for verification or monitoring</th></tr>
<tr><td>Ferrous sulphate</td><td>Manufactured</td><td rowspan="3">Powder</td><td rowspan="5">• Phosphate
• Trace Elements
• Trace Organics</td><td rowspan="5">SF_6</td></tr>
<tr><td>Fe-chelate (organically complexed)</td><td>Manufactured</td></tr>
<tr><td>Iron sulphide</td><td>Manufactured</td></tr>
<tr><td>Hematite dust</td><td>(i) Manufacturing process
(ii) Naturally occurring</td><td>Fine powder or nano-particle</td></tr>
<tr><td>Propriety nutrient supplements</td><td>Not readily known</td><td></td></tr>
</table>

*The purity of the iron compound being used for fertilization should also be known to ensure that it does not introduce other elements or organic compounds that would endanger marine ecosystems.

Source: Report of the 31st Meeting of the Scientific Group of the London Convention and the 2nd Meeting of the Scientific Group of the London Protocol, 2008[79]

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

79 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

Observed and Predicted Impacts of Iron Fertilization on Marine Biodiversity

A literature review revealed the following information on observed or predicted impacts of iron fertilization on marine biodiversity (Table 3).

TABLE 3: Summary of observed and predicted impacts of iron addition to the marine environment

	Observed or predicted(*) impacts to fertilized area	**Observed or predicted (*) downstream impacts**
Organism responses	Diatoms have responded to Fe additions with the greatest increase in biomass in 5 out of 12 experiments[80]. Diatoms have a siliceous shell and a strong tendency to sink out of the surface waters driving sequestration.	Depletion of silicic acid from surface waters limits further diatom production despite the availability of other macronutrients and Fe[81]
	Diatoms did not proliferate during the LOHAFEX experiment, leading to limited CO_2 drawdown[82].	
	Increased grazing pressure of small crustacean zooplankton (copepods) prevented further growth of the phytoplankton bloom during the LOHAFEX experiment[83].	
	No evidence of harmful algal bloom (HAB) production in any of the 12 meso-scale enrichment experiments. However, HAB forming phytoplankton were observed in bottle incubations at the SEEDS location in the North Pacific[84].	
Nutrient field changes	Fe induced phytoplankton bloom in HNLC surface waters confirmed by high chlorophyll levels.	The absorption of solar radiation by plankton can have a substantial warming effect on the ocean surface in the fertilized area—comparative to the radiative forcing from CO_2.[85]
	Depletion of macro nutrients in the surface layer by phytoplankton bloom.	Predicted reduction in availability of nitrates in downstream waters extending for thousands of kilometres*[86]. Model ROMS BEC Downstream reduction in productivity due to lateral resupply of surface macronutrients to fertilized location.
	Surface nitrate depleted. Reduction of surface DIC by >30mmol^{-1} leading to a drop in pCO_2 of >40µatm and the drawdown of CO_2*[87]—model ROMS-BEC	
	Below the mixed layer nitrate and DIC increase relative to surrounding water due to remineralization of sinking organic matter*[88] Model ROMS-BEC	Potential for increased remineralization and bacterial processes to reduce oxygen concentrations within sub surface waters*[89].

80 Boyd, P. W., *et al.* (2007). Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions. Science, Vol 315:612

81 Ibid.

82 Ibid.

83 www.awi.de

84 Wells, M. L., Trick, C. G., Bill, B. D., Cochlan, W. P., Trainer, V. L., Pickell, L. P. (2009). Iron enrichment stimulates toxic diatom production in the high nitrate low chlorophyll Eastern Subarctic Pacific. Proceedings of the ALSO Aquatic Sciences Meeting, Nice, France, 25–30 January 2009.

85 Frouin, R., and S. F. Iacobellis (2002), Influence of phytoplankton on the global radiation budget, *J. Geophys. Res.*, 107(D19), 4377, doi:10.1029/2001JD000562.

86 Jin, X., Gruber, N., Frenzel, H., Doney, S. C., and McWilliams, J. C. (2008). The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump. Biogeosciences, 5, 385–406.

Impact on climate gases	The increase of DMSP and DMS production, which can affect cloud formation and the reflective properties of clouds, was seen in IronEx II, SOIREE, and EisenEx[90]	
	During SERIES, a minor increase in DMS concentration was observed with subsequent decline to 1 order of magnitude below surrounding unfertilized waters, creating a sink for atmospheric DMS[91]. However, not all species of phytoplankton produce DMS[92]	
	A 7% increase in N_2O production was observed in upper pycnocline in the SOIREE experiment, but no such increase was observed during the EIFEX experiment[93].	N2O, a greenhouse gas with greater warming potential than CO_2, can offset any benefits obtained from atmospheric CO_2 drawdown[95, 96]
	An 8% increase in N_2O was observed between 30 and 50 metres in the SERIES experiment[94].	Model estimations suggest the remineralization of the additional carbon fixed during SOIREE would produce 2.1 to 4.1t of N_2O*[97]
		Increased particle flux from widespread ocean iron fertilization could promote oxygen depletion and the regeneration of nutrients and CO_2 in subsurface waters, which could lead to increased production and efflux of N_2O and methane*[98]
		Observed release of Isoprene, an ozone precursor, which may have a substantial effect on clouds through the formation of secondary aerosols[99]
Ecosystem considerations	An increase in amphipods—zooplankton predators—was observed during LOHAFEX. The dominant species, *Themisto gaudichaudii*, plays an important role in the food web of the Southern Ocean[100].	Amphipod *Themisto gaudichaudii* is the main food of squid and whales in the Southwest Atlantic[101]

87 Ibid.

88 Ibid.

89 Jin, X., and N. Gruber (2003), Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions, Geophys. Res. Lett., 30(24), 2249, doi:10.1029/2003GL018458

90 Levasseur, M., Scarratt, M. G., Michaud, S., et al. (2006). DMSP and DMS dynamics during a mesoscale iron fertilization experiment in the Northeast Pacific—Part 1: Termporal and vertical distributions. Deep-Sea Research II 53, 2353–2369.

91 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283-288.

92 Fuhrman, J. A., Capone, D. G. (1991) Possible biogeochemical consequences of ocean fertilization. Limnol. Oceanogr. 36 (8): 1951-1959.

93 Smetacek, V., Naqvi, S. W. A. (2008). The next generation of iron fertilization experiments in the Southern Ocean. Phil. Trans. R. Soc. A doi:10.1098/rsta.2008.0144.

94 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

95 Fuhrman, J. A., and D. G. Capone. 1991. Possible Biogeochemical Consequences of Ocean Fertilization. Limnol. Oceanogr. 36: 1951-1959.

96 Jin, X., and N. Gruber (2003), Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions, Geophys. Res. Lett., 30(24), 2249, doi:10.1029/2003GL018458

97 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283-288.

98 Fuhrman, J. A., Capone, D. G. (1991) Possible biogeochemical consequences of ocean fertilization. Limnol. Oceanogr. 36 (8): 1951–1959.

99 Rayfuse, R., et al. (2008). Ocean Fertilization and Climate Change: The Need to Regulate Emerging High Seas Uses. The International Journal of Marine and Coastal Law, 23, 297–326.

100 www.awi.de.

101 www.awi.de.

Early results from shipboard incubations in HNLC waters presented compelling, but equivocal evidence that phytoplankton growth was limited by Fe availability[102], demonstrating that the addition of iron to seawater samples stimulated the growth of phytoplankton, especially diatoms. A shift in the phytoplankton community from one dominated by smaller planktonic species to one dominated by diatoms was observed in five out of the 13 iron addition experiments, as detailed in Annex 1. The enhanced phytoplankton bloom proliferates for a limited duration prior to decline, for example 37 days in EiFEX[103].

As the phytoplankton bloom progresses, the macro nutrients phosphate, nitrate and silicate are utilized in the fertilized surface waters. Mesoscale iron experiments have exhibited a wide range of nutrient uptakes, with the lowest rates observed in polar regions. Iron-mediated diatom blooms in mesoscale experiments and natural conditions can deplete silicate but not nitrate, which has led to the bloom decline[104]. Global ocean models have predicted that ongoing fertilization would lead to depletion of macronutrients in the downstream water column. In the case of a decadal model simulation for the tropical eastern Pacific, which combined a Regional Oceanic Modelling System (ROMS) with a Biogeochemical Elemental Cycling (BEC) model, depletion of nitrates in the surface waters of the fertilized area led to reduced nitrate concentrations downstream for several thousand kilometres[105]. This means that if iron-addition removes carbon and nutrients from HNLC surface waters, it could lead to a reduction of nutrients (and thereby phytoplankton production) in other areas.

The response of trace gas emissions to iron fertilization is currently uncertain. Nitrous oxide (N_2O) observations were made during two mesoscale iron fertilization experiments conducted in the Southern Ocean. The remineralization and sinking of particulate organic matter during the bloom decline caused an increase in trace gas emissions of N_2O in one experiment, but not the other[106]. Observation of a naturally induced phytoplankton bloom in the Southern Ocean suggests that secondary organic aerosols formed by the oxidation of phytoplankton-produced isoprene during a bloom, can influence cloud formation and thus affect the Earth's radiation budget and climate[107]. The production of these gases has the potential to affect climate feedbacks (negatively and positively) and air quality, thus any assessment of the overall climate benefit to be obtained from large-scale open ocean fertilization must include these effects. The magnitude and the nature of the feedback will be strongly dependent on the location as well as duration of fertilization[108].

An early global ocean model predicted that wide areas of the subsurface ocean would become anoxic under large-scale continuous iron fertilization[109]. Furthermore, hypoxia and anoxia have been associated with algal blooms in many aquatic environments, leading to fish kills in coastal environments, signaling this as a potential concern for artificial nitrogen fertilization in the ocean[110]. However, given that

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

103 Ibid.

104 Ibid

105 Jin, X., Gruber, N., Frenzel, H., Doney, S. C., and McWilliams, J. C. (2008). The impact on atmospheric CO_2 of iron fertilization induced changes in the ocean's biological pump. Biogeosciences, 5, 385–406.

106 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

107 Meskhidze, N., Nenes, A. (2006). Phytoplankton and cloudiness in the Southern Ocean. Science, Vol 314(5804):1419–1423.

108 Jin, X. and N. Gruber (2003). Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions, Geophys. Res. Lett., 30(24), 2249, doi:10.1029/2003GL018458

109 Sarmiento, J. L., Orr, J. C. (1991). Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO_2 and ocean chemistry. Limnol. Oceanogr. 36:1928–1950.

110 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056

the export efficiency of open ocean fertilization has been shown to be significantly lower than predicted, the magnitude of the projected oxygen impact has decreased.

B. PHOSPHORUS FERTILIZATION

Nearly 80% of the surface waters of the global ocean are considered nitrate (NO_3^-) depleted. Chronic NO_3^- limitation in the upper layer of the water column, where light is available to support photosynthesis, favours the growth of microorganisms that are able to utilize dissolved organic nitrogen or dissolved N_2, termed "diazotrophs." The nitrogen fixation by these organisms requires an ample supply of iron and phosphorous. To date there have been two open-ocean field trials designed to assess the Fe/P fertilization effects on microbial assemblages and elemental fluxes:

1. The cycling of phosphorus (CYCLOPS) project, which added PO_4^{3-} to a Fe-sufficient portion of the eastern Mediterranean Sea;
2. The FeeP project, which added Fe and Fe/PO_4^{3-} to a region in the Northeast Atlantic Ocean to investigate if N_2-fixing phytoplankton are simultaneously limited by Fe and P.

The following tables provide summaries of key data about the phosphorous fertilization experiments carried out so far.

TABLE 4: Summary of the amounts and scales of previous ocean fertilization activities

	Initial size of dispersal area	Amount of Phosphate added	Temporal nature	Injection frequency	Duration of monitoring
CYCLOPS[111]	16km^2	No data	Days to weeks	Single release	9 days
FeeP[112]	2 patches of 25km^2	(i) 20 tonnes P (ii) 5 tonnes of Fe followed by 20 tonnes P	Days to 2 weeks	2-stage release	3 weeks

TABLE 5: Summary of materials used in phosphorus fertilization

	Typical chemical compounds	Typical sources	Typical physical forms	Typical impurities	Typical ancillary input materials for verification or monitoring
Phosphorus	Phosphoric acid Anhydrous monosodium phosphate	Unknown	Solid, liquid or dissolved in solution	• Mixed with other limiting nutrients • Trace metals and organics	SF_6

Source: Report of the 31st Meeting of the Scientific Group of the London Convention and the 2nd Meeting of the Scientific Group of the London Protocol, 2008 [113]

111 Thingstad, T. F., et al. (2005). Nature of Phosphorus Limitation in the Ultraoligotrophic Eastern Mediterranean. Science, Vol 309:1068-1070.

112 Rees, A. P., Nightingale, P. D., Ownes, N. J. P, PML FeeP Team (2007). FeeP—An in situ PO43—and Fe addition experiment to water of the sub tropical north east Atlantic. Geophys Res Abstr 9:01440.

113 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

The export rate of particulate matter to the deep sea was not measured during either the CYCLOPS or FeeP experiments, thus the potential impact on CO_2 sequestration from these fertilization experiments and the enhanced N_2 fixation triggered is unknown[114].

A literature review revealed the following information on observed or predicted impacts of phosphorous fertilization on marine biodiversity (Table 6).

Observed and Predicted Impacts of Phosphorous Fertilization on Marine Biodiversity

TABLE 6: Summary of observed and predicted impacts of phosphorus addition to the marine environment

	Observed impacts to fertilized area	**Predicted (*) downstream impacts**
Organism responses	40% decrease in chlorophyll-a observed in the fertilized CYCLOPS patch following addition of PO_4^{3-}.	
	Decrease in primary production and phytoplankton (Picopytoplankton and nanophytoplankton) growth rates. Increase in bacterial production and copepod egg abundance inside the patch (CYCLOPS).	Differential access to pools of the next limiting nutrient can cause unexpected community shifts*.
Nutrient field changes	Increase in particulate phosphate observed during CYCLOPS.	
	Microbial phosphate uptake and nitrogen fixation increased by up to 6 times and 4.5 times during both FeeP additions[115].	Potential for increased bacterial processes to reduce oxygen concentrations within sub surface waters*.
Impact on Climate Gases	DMS was observed to decrease during the first nutrient addition of the FeeP study[118].	
Ecosystem considerations	Chlorophyll decrease may have resulted from increased grazing by copepods.	Changes in copepod populations could potentially affect commercially important fish species.

Source: Adapted from Thingstad, T. F., et al. (2005). Nature of Phosphorus Limitation in the Ultraoligotrophic Eastern Mediterranean. Science 309: 1068-1070.

The phosphate addition to surface waters in an ultraoligotrophic area of the Mediterranean during the CYCLOPS experiment resulted in an unexpected decline in primary production from phytoplankton and an increase in bacterial production and copepod (egg) abundance (small, mostly planktonic, crustaceans). Ammonium addition via on-deck microcosm experiments with water from inside the fertilized patch induced a phytoplankton bloom, suggesting that the natural system was co-limited by N and P in non-diazotrophic taxa[117], despite an excess of N in surface waters. Thingstad *et al.* (2005) suggest that phosphorus may have "bypassed" the phytoplankton through the microbial food web directly to copepods. This unexpected response is not well understood, but may indicate a coupling of copepods

114 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

115 Rees, A. P., Nightingale, P. D., Ownes, N. J. P, PML FeeP Team (2007). FeeP—An in situ PO_4^{3-} and Fe addition experiment to water of the sub tropical north east Atlantic. Geophys Res Abstr 9:01440.

116 Ibid.

117 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

to lower trophic levels and emphasizes that the effect of phosphate additions on ecosystem food web dynamics is currently unpredictable[118].

C. NITROGEN FERTILIZATION

This fertilization concept is based on the observation that in certain regions of the oceans the lack of sufficient nitrogen is the main factor limiting phytoplankton growth, which therefore might be enhanced by adding nitrogen (in form of urea, ammonia or nitrate). Macronutrient fertilization with nitrogen has been discounted in the past because it needs to move more material than iron fertilization in phosphate-deficient LNLC regions (where diazotrophs need phosphate and sometimes Fe) or than iron fertilization in HNLC regions (where phytoplankton need Fe).

To date, there have been no scientific experiments involving nitrogen fertilization. The following tables provide summaries of key data about proposed nitrogen fertilization experiments.

TABLE 7: Summary of the amounts and scales of proposed ocean fertilization activities

	Initial size of dispersal area	**Amount of addition**	**Temporal nature**	**Injection frequency**	**Duration of monitoring**
Proposed activities	20 km^2	500 tonnes	Sustained fertilization	30-day period	No data

Source: www.oceannourishment.com

TABLE 8: Summary of potential materials used in nitrogen fertilization

	Typical chemical compounds	**Typical sources**	**Typical physical forms**	**Typical impurities**	**Typical ancillary input materials for verification or monitoring**
nitrogen	Urea Ammonia Nitrate	Manufactured commercially	Solid, liquid or dissolved in solution	• Mixed with other limiting nutrients • Trace metals and organics	SF_6

Source: Report of the 31st Meeting of the Scientific Group of the London Convention and the 2nd Meeting of the Scientific Group of the London Protocol, 2008 [119]

The inferences in Table 9 are based on laboratory experiments, observed responses to coastal nutrient inputs from land runoff, sewage outfalls and other sources. They are not derived from actual nitrogen fertilization experiments.

118 Thingstad, T. F., *et al* (2005). Nature of Phosphorus Limitation in the Ultraoligotrophic Eastern Mediterranean. Science, Vol. 309:1068-1070.

119 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

Predicted Impacts of Nitrogen Fertilization on Marine Biodiversity

TABLE 9. Summary of predicted impacts of nitrogen fertilization.[120,121]

	Predicted impacts to fertilized area	Potential downstream impacts
Organism responses	Alteration in species composition of stimulated bloom. Predicted that urea enrichment would preferentially lead to enhancement of cyanobacteria, picoeukaryotes and dinoflagellates rather than diatoms.	Enhanced microbial loop where nutrients and carbon are not effectively transferred up the food chain to higher levels.
	Potential for ammonium/ammonia toxicity to fish. However it is unlikely that toxic ammonium concentrations would be reached.	Implications for food security and human health.
Biogeochemical changes	Stoichiometry limit to biomass production from Nitrogen enrichment.	
Biogeochemical fluxes	Many cyanobacteria and dinoflagellates are positively buoyant and do not easily sink from the euphotic zone limiting sequestration potential.	CO_2 may also be produced in the manufacture of ammonia from coal or petroleum based materials.
Ecosystem considerations	Large-scale biomass concentrations may reduce light levels required to support sustained productivity in the euphotic zone.	Alteration of subsurface N:P ratios could have important and at present, unknown influences on the structure of the pelagic food web[120]. Predicted increase in fish biomass—one tonne of fish will be produced for every tonne of reactive nitrogen added to the ocean in the form of urea[121]
	Potential for eutrophication due to heavy N_2 loading as observed in coastal areas.	Nitrogen loading in coral reef areas can lead to community shifts towards algal overgrowth of corals and ecosystem disruption.
	Potential for increase in toxin-producing dinoflagellates and HAB production raising food chain and human health concerns.	Ammonia can be volatilized to the atmosphere and carried from the site of original application and re-deposited with precipitation.

Source: Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

Nitrogen stimulates the production of phytoplankton biomass, where light and other nutrients are in adequate supply. The efficiency of nitrogen fertilization to sequester carbon from the atmosphere will depend on the species composition of the stimulated bloom. Urea enrichment is likely to result in a loss of phytoplankton biodiversity. Furthermore, urea is preferentially used as a N_2 source by some cyanobacteria, dinoflagellates, and pelagic picoeukaryotes in sub-tropical areas. These groups have been associated with harmful or toxic algal blooms (HABs) observed in the vicinity of urea and nitrogen runoff from agricultural lands[122].

120 Arrigo, K. R. (2005). Marine microorganisms and global nutrient cycles. Nature 437:349–355

121 Young, E., 2007. Can 'fertilizing' the ocean combat climate change? Companies are planning to boost the ocean's plankton, hoping they will harvest more CO_2 from the air. But will it work? New Scientist, September 15, 2007, pp. 42–45.

122 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

Urea is an organic compound commercially derived from ammonia (NH_3) and carbon dioxide (CO_2). Large quantities of CO_2 are produced in the manufacture of ammonia from coal or petroleum-based raw materials, creating downstream impacts for CO_2 emission budgets.

Nitrogen fertilization bears the risk that nitrogen can reach coastal areas, where it is known to cause eutrophication. Such nitrogen loading in sensitive areas such as coral reefs stimulates the proliferation of algae and the overgrowth of corals, with significant implications for the continued provision of ecosystem services.

A correlation between average chlorophyll concentration and typical fish catch is suggested,[123] leading to a hypothesis that potential fish biomass is limited by available organic carbon and is likely to be increased following ocean fertilization[124]. Young (2007) estimates that one tonne of fish will be produced for every tonne of reactive nitrogen added to the ocean in the form of urea[125].

D. UPWELLING OF DEEP SEA WATER

It has been suggested that purposeful delivery of deep water nutrients to the euphotic zone, via controlled or artificial upwelling, might enhance primary production and export production, thereby constituting an effective mechanism for CO_2 sequestration in the open ocean[126].

In relation to this argument, earlier work is worthy to mention. Five ship-based experiments were conducted in the North Pacific Ocean in 2003, in which nutrient-replete water was obtained from below 700 metres and mixed with nutrient poor mixed layer water[127]. The following tables provide summaries of key data about these experiments.

TABLE 10: Summary of the amounts and scales of previous controlled upwelling activities

	Incubated H_2O volume	Amount of addition	Temporal nature	Injection frequency	Duration of monitoring
Past activities	Total water volume $25dm^{-3}$	5%–10% deep sea water.	Days to weeks	Single	5–7 days

Source: McAndrew, P. M., Bjorkman, K. M., Church, M. J., Morris, P. J., Jachowski, N., Williams, P. J. Le B., Karl, D. M. (2007). Metabolic response of oligotrophic plankton communities to deep water nutrient enrichment. Mar Ecol Prog Ser 332: 63-75.

TABLE 11: Summary of materials used in fertilization via controlled upwelling

	Typical chemical compounds	Typical sources	Typical physical forms	Typical impurities	Typical additional consideration
Deep water	Relatively high nutrient, total inorganic carbon, certain trace metals	Deep water from between 100-1000 m depth	Liquid, dissolved	• Trace metals	Sources and materials of physical devices, e.g. pipes

Source: Report of the 31st Meeting of the Scientific Group of the London Convention and the 2nd Meeting of the Scientific Group of the London Protocol, 2008 [128]

123 Ware. D. M., Thomson, R. E. (2005). Bottom-Up Ecosystem Trophic Dynamics Determine Fish Production in the Northeast Pacific. Science, 308, 1280–1284

124 Jones, I S F (2004) The Enhancement Of Marine Productivity For Climate Stabilization and Food Security. Ed. Amos Richmond Handbook of Microalgal cultures. Chap 33 Blackwell, Oxford

125 Young, E., 2007. Can 'fertilizing' the ocean combat climate change? Companies are planning to boost the ocean's plankton, hoping they will harvest more CO_2 from the air. But will it work? New Scientist, September 15, 2007, pp. 42–45.

126 Lovelock, J. E., Rapley, C. G. (2007). Ocean pipes could help the earth to cure itself. Nature 449:403.

127 McAndrew, P. M., Bjorkman, K. M., Church, M. J., Morris, P. J., Jachowski, N., Williams, P. J. Le B., Karl, D. M. (2007). Metabolic response of oligotrophic plankton communities to deep water nutrient enrichment. Mar Ecol Prog Ser, Vol 332:63–75.

128 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

Observed and Predicted Impacts of Ocean Fertilization Via Controlled Upwelling on Marine Biodiversity

A literature review revealed the following information on observed or predicted impacts of ocean fertilization via controlled upwelling on marine biodiversity (Table 12).

TABLE 12: Summary of observed and predicted impacts of ocean fertilization via controlled upwelling

	Observed or predicted (*) impacts to fertilized area	**Observed or predicted (*) downstream impacts**
Organism responses	Bloom of phytoplankton (typically diatoms) supported by NO^{3-} [129] Hypothesis that controlled upwelling will lead to a 2-staged bloom with a second, N_2 fixing bacterial bloom*[130] Proliferation of cyanobacteria observed at Station ALOHA—a typical LNLC site[131]. Additional nitrogen fixation by micro organisms*[132]	Potential for increased remineralization and bacterial processes to reduce oxygen concentrations within sub-surface waters*[133].
Biogeochemical changes	Excess DIC brought into surface waters at Station ALOHA (relative to NO^{3-}).[134]	If pCO_2 in the surface waters is at or above equilibrium with the atmosphere, the addition of excess DIC may result in a net transfer of CO_2 from the ocean to atmosphere*[135] However, the surface waters at Station ALOHA are nearly always under-saturated with respect to atmospheric CO_2[136] and so the excess DIC will likely be retained[137].
Impact on climate gases		Potential secondary impacts may include the production of nitrous oxide via N_2 fixation-nitrification, a greenhouse gas with greater warming potential than that of CO_2*[138] The aerobic production of methane (CH_4), a potent greenhouse gas is possible*[139, 140].
Ecosystem considerations	Toxin production by diatoms and diazotrophs is possible*[141]	

129 McAndrew, P. M., Bjorkman, K. M., Church, M. J., Morris, P. J., Jachowski, N., Williams, P. J. Le B., Karl, D. M. (2007). Metabolic response of oligotrophic plankton communities to deep water nutrient enrichment. Mar Ecol Prog Ser, Vol 332:63–75.

130 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

131 Karl D. M. (1999) A sea of change: biogeochemical variability in the North Pacific Subtropical Gyre. Ecosystems 2:181–214

132 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

133 Ibid.

134 Ibid.

135 Takahashi, T., Feely, R. A., Weiss, R. F., Wanninkhof, R. H., Chipman, D. W., Sutherland, S. C., Takahashi, T. T. (1997). Global air–sea flux of CO_2: an estimate based on measurements of sea–air pCO_2 difference. Proc Natl Acad Sci USA 94:8292–8299.

136 Dore. J. E., Lukas, R., Sadler, D. W., Karl, D. M. (2003) Climate-driven changes to the atmospheric CO_2 sink in the subtropical North Pacific Ocean. Nature 424:754–757.

137 Ibid.

138 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

139 Ibid.

140 Karl, D. M., Beversdorf, L., Bjorkman, K,. Church, M. J., Martinez, A., DeLong, E. (2008). Aerobic production of methane in the sea. Nat Geoscience 1:473–478.

141 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

During all five ship-based experiments, a consistent increase in phytoplankton biomass and primary production increase was observed following fertilization, with a demonstrated shift in phytoplankton communities from small (<2µm diameter) to large (>10µm diameter) diatom cells. These observations are supported by long-term study of Station ALOHA, a typical LNLC habitat with non-limiting Fe concentrations that experiences episodic natural upwelling. Karl and Letelier (2008) later hypothesized that the controlled upwelling of low NO^{3-}:PO_4^{3-} seawater from below 300 metres in LNLC areas will trigger a two-stage phytoplankton bloom: the first stage characterized by NO^{3-} supported diatoms and the second stage by a N_2 fixing bacterial bloom, leading to enhanced N_2 fixation, organic matter production and net carbon sequestration of 32.7mmol C m^{-3} upwelled water[142].

The biogeochemical consequences of sustained upwelling of this nature are uncertain. Deep waters are known to contain high concentrations of DIC derived from long-term decomposition of sinking particulate matter, causing most natural upwelling sites to result in a net ocean-to-atmosphere transfer of CO_2[143]. However due to the regional and seasonal variations in deep-water DIC concentrations, the observed impacts will be site and depth specific.

The artificial upwelling of deep waters also bears the risk of increasing ocean acidification and degassing of CO_2. Colder deep waters absorb larger amounts of CO_2 (cf. section on solubility pump above, and separate synthesis on ocean acidification), which decreases the pH and the calcium carbonate saturation of these waters. Recent hydrographic surveys along the continental shelf of western North America from central Canada to northern Mexico confirm that seawater, undersaturated with respect to aragonite, upwells onto large portions of the continental shelf, reaching all the way to the surface off northern California. Although seasonal upwelling of the undersaturated waters onto the shelf is a natural phenomenon in this region, the ocean uptake of anthropogenic CO_2 has increased the areal extent of the affected area[144]. The artificial up-welling of undersaturated deep water would accelerate the spreading of ocean acidification into areas which so far have not yet been impacted. Also, if carried out in tropical areas, the CO_2 sequestered by increased phytoplankton growth may be offset by the CO_2 released to the atmosphere due to the warming of the deep waters reducing the CO_2 solubility (depending on the localized pCO_2).

142 Ibid.

143 Ibid.

144 Feely, R. A., Sabine C. L., Hernandez-Ayon, J. M., Ianson, D. and Hales, B. (2008). Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. Science 320, pp. 1490-1492.

III. SYNTHESIS OF FINDINGS

A. ORGANISM RESPONSES

Iron fertilization has been shown to change the composition of phytoplankton communities in the small-scale enrichment experiments conducted to date. All types of phytoplankton potentially benefit from the addition of iron in HNLC areas, however smaller species are more rapidly consumed by predators, favouring the bloom of larger diatom species[145,146]. Diatoms have responded to iron additions with the greatest increase in biomass in five (out of the 13) iron-enrichment experiments.

Diatoms, which require silicate for growth, have a strong tendency to sink as intact cells or zooplankton fecal pellets from surface waters[147]. The depletion of surface water silicate by diatoms, however, is likely to limit the longevity of blooms and inhibit further productivity, despite the availability of other macro nutrients and iron, indicating that an increased Fe supply as observed during glacial periods may not have been the only prerequisite to sustain blooms of siliceous algae[148]. Furthermore, the influence of silicic acid depletion may negate the impact of repeated iron enrichment on diatom stocks[149]. Trull *et al.* suggest that silicate macro nutrients are already fully consumed from upwelling waters in the HNLC regions of the global ocean, and thus stimulating diatoms via iron fertilization in these locations will not influence the overall magnitude of carbon sequestration[150]. More information is needed on the succession of phytoplankton community structure, beyond the point of silicate depletion, in order to predict the impact of sustained fertilization on productivity and the macronutrient inventory[151].

Boyd *et al.* (2007) noted little observed change in the grazer community within the timescale of mesoscale iron enrichment experiments[152]. However, heavy grazing pressure by macrozooplankton has been observed in upwelling regions where a continuous (months) nutrient supply maintains high productivity systems. The 2009 LOHAFEX experiment also observed that the phytoplankton community stimulated was rapidly limited by the heavy grazing pressure of amphipod *Themisto gaudichaudii*, an important food source for squid and fin whales in the South West Atlantic. Diatoms did not proliferate following fertilization in LOHAFEX, due to the depletion of silicic acid in the surface waters by previous natural blooms, leading to reduced productivity and low atmospheric CO_2 drawdown. This suggests that other algal groups may not be able to sustain bloom biomass equivalent to those of diatoms in response to iron fertilization[153].

145 Hoffmann L. I., Peeken, Lochte, K. (2006). Different reactions of Southern Ocean phytoplankton size classes to iron fertilization. Limnology and Oceanography 1(3):1217–1229.

146 de Baar, H. J. W., Boyd, P. W., Coale, K. H., Landry, M. R., Tsuda, A., Assmy, P., Bakker, D. C. E., Bozec, Y., Barber, R. T., Brzezinski, M. A. et al. (2005). Synthesis of iron fertilization experiments: From the iron age in the age of enlightenment. Journal of Geophysical Research Vol 110, C09S16, doi:10.1029/2004JC002601

147 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

148 Boyd, P. W., Law, C. S., Wong, C. S., et al. (2004) The Decline and Fate of an iron induced subarctic phytoplankton bloom. Nature, Vol 428: 549–552.

149 Ibid.

150 de Baar, H. J. W., Boyd, P. W., Coale, K. H., Landry, M. R., Tsuda, A., Assmy, P., Bakker, D. C. E., Bozec, Y., Barber, R. T., Brzezinski, M. A. et al. (2005). Synthesis of iron fertilization experiments: From the iron age in the age of enlightenment. Journal of Geophysical Research Vol 110, C09S16, doi:10.1029/2004JC002601.

151 Boyd, P. W., *et al.* (2007). Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions. Science, Vol 315:612.

152 Boyd, P. W., *et al.* (2005). Limnol. Oceanogr. 50, 1872.

153 Alfred-Wegener-Institut (2009). Press Release: Lohafex provides new insights into plankton ecology (www.awi.de).

The increase of cyanobacteria populations, as predicted through the enrichment of surface waters with urea, may be less effective in influencing carbon sequestration[154]. Furthermore, many cyanobacteria and dinoflagellates are considered to be poor quality food for zooplankton grazers that support oceanic food webs[155]. Highly efficient nutrient and carbon cycling within the microbial community can prevent the effective transfer of essential components up the food chain. However, given the current status of knowledge, the extent of impacts is hard to predict[156].

Changes to phytoplankton and bacterial communities could have unpredictable pathways and consequences for the global ocean food chains (depending on location), favouring, for example, the proliferation of opportunistic, less commercially viable species such as jellyfish[157].

Well designed and comprehensive nutrient perturbation experiments that examine all aspects of microbial metabolism likely to be influenced by, for example, controlled upwelling, need to be conducted in order to determine whether diazotroph manipulation can be promoted as a potential climate mitigation strategy[158].

Recent studies confirmed that marine viruses play a crucial role in the marine food web and the biogeochemical cycling/flows of carbon and nutrients. It is as yet unknown whether and how marine viruses would respond to the changes and impacts caused by ocean fertilization[159].

Harmful Algal Blooms (HABs)

Some species of toxic dinoflagellates, responsible for fish kills and the accumulation of toxins in fish and shellfish, can proliferate in areas of high urea loading[160]. The Philippines suffered massive fish kills as a result of a dinoflagellate (*Cochlodinium spp*) bloom in 2005, and has experienced over 2000 intoxication events and 123 human deaths as a result of contaminated seafood consumption between 1983 and 2005[161].

There has been no evidence of such blooms arising from fertilization experiments, however a shift in the plankton community composition to favour heterotrophic dinoflagellates was observed during the SEEDS iron enrichment experiment[162]. Potentially toxic dinoflagellates known to form red tide blooms off the coast of California have been shown to utilize and be supported by urea and its degradation product, ammonium[163]. These organisms may proliferate over time through the production of cysts which may initiate new blooms in isolation of fertilization, germinating from bottom sediments in shallow waters. If cyst forming species were to proliferate following ocean fertilization experiments, the

154 Mulholland, M. R. (2007). The fate of nitrogen fixed by diazotrophs in the ocean. Biogeosciences, 4:37–51.

155 Azam, F., Fenchel, T., Field, J. G., Gray, J. S., Meyer-Reil, L. A., Thingstad, F. (1983). The ecological role of warter-column microbes in the sea. Mar Ecol Prog Ser, 10:257–263.

156 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

157 Powell, H. (2008). What are the possible side effects? Oceanus 46:14–17.

158 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

159 Suttle, C. A. (2005). Viruses in the sea. Nature, 437:356–361.

160 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

161 Bajarias, F.F., Relox Jr., J., Fukuyo, Y. (2006). PSP in the Philippines: three decades of monitoring a disaster. Coastal Marine Science 30 (1), 104–106.

162 Boyd, P. W., *et al*. (2007). Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions. Science, Vol 315:612.

163 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

probability of future blooms of toxic species will increase with significant implications for human health and food security[164].

Dinoflagellate blooms have been found in association with cyanobacteria blooms and are thought to benefit from the dissolved organic nutrients released by the latter. These downstream effects are an important consideration in relation to urea enrichments[165]. Cyanobacteria responded to nutrient enrichments in the FeeP Fe/PO_4^{3-} enrichment experiment[166]. However, some HAB species, more particularly toxic dinoflagellates have been found to be mixtotrophs (i.e., able to ingest small phytoplankton as nutrient sources) and may use cyanobacteria as nutrient sources[167]. This variable positioning in the trophic network makes their relationship with nutrients highly complex.

Adding iron to HNLC waters in bottle and mesoscale experiments consistently stimulates rapid growth of pennate diatoms of the genus *Pseudo-nitzschia*. While coastal *Pseudo-nitzschia* species often produce the neurotoxin domoic acid (DA), oceanic *Pseudo-nitzschia* species are believed to be non-toxic. A sparse diatom community at Ocean Station PAPA (50°N 145°W) produced up to 48 pg DA L^{-1} during multi-day sampling of the photic zone. Cell numbers and toxicity increased with nanomolar iron amendments, and further by co-additions of trace copper, indicating that low purity of iron substrates used in commercial fertilizations may generate unwanted ecosystem responses[168].

Direct toxicity from urea degradation products (ammonium and ammonia) in fish is also suggested as a potential side effect of urea fertilization. Toxicity of NH_3 to fish increases with concentration (and associated oxygen decrease), with effects more marked in juveniles compared to adults. Cultured fish are especially vulnerable given the low oxygen environments around culture cages and their inability to escape from the immediate environment[169].

B. BIOGEOCHEMICAL CHANGES

Oxygen

The evolution and decline of a phytoplankton bloom is likely to increase oxygen demand in the underlying waters due to the consumption and degradation of organic matter. A decrease in oxygen concentrations can lead to increases in anoxic bacterial processes such as denitrification, SO_4^{2-} reduction and methanogenesis, the latter of which could lead to additional release of methane from the ocean[170]. The mesoscale iron enrichment studies did not record oxygen concentrations throughout the water column. However, model predictions have indicated the potential for oxygen to decline in the sub-surface ocean as a result of fertilization. The extent of such hypoxia would be dependent on the duration of fertilization, the intensity of productivity induced, the extent of sinking and the depth distribution of the de-

164 Ibid.

165 Ibid.

166 Karl, D. M., Letelier, R. M. (2008) Nitrogen fixation-enhanced carbon sequestration in low-nitrate, low-chlorophyll seascapes. Mar Ecol Prog Ser Vol 364:257–268.

167 Stoecker, D., Tillman, U., Granéli, E. 2006. Phagotrophy in harmful algae. In Ecology of harmful algae, Granéli, E. & Turner, J.T. (Eds.), pp. 177–187, Springer-Verlag, Berlin

168 Wells, M. L., Trick, C. G., Bill, B. D., Cochlan, W. P., Trainer, V. L., Pickell, L. P. (2009). Iron enrichment stimulates toxic diatom production in the high nitrate low chlorophyll Eastern Subarctic Pacific. Proceedings of the ALSO Aquatic Sciences Meeting, Nice, France, 25–30 January 2009.

169 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

170 Fuhrman, J. A., Capone, D. G. (1991) Possible biogeochemical consequences of ocean fertilization. Limnol. Oceanogr. 36 (8): 1951–1959.

caying organic matter[171]. However, anoxic conditions have not been observed in connection with major natural iron fertilization events in the past[172].

A three-dimensional Ocean Carbon Cycle model was used to investigate the efficiency of macronutrient fertilization at enhancing the rate that anthropogenic CO_2 is sequestered by the ocean. The study predicted an increase of 17.5% in the volume of anoxic water after 80 years of fertilization[173]. These increases in anoxic water were confined to regions that presently have large areas of anoxic water (e.g., eastern equatorial Pacific and Indian Ocean) which suggests that these changes would not greatly impact the marine ecosystems in these areas. The small scale and limited observation of sub surface oxygen concentrations in ocean fertilization experiments to date does not allow extrapolation to accurately predict the impacts of large-scale commercial enrichment applications on oxygen concentrations throughout the water column and on the sea floor[174].

Nutrients

Observations have shown that iron alters the uptake ratio of nitrate and silicate at very low levels. It is thought that this is caused by the differing reproduction rates of phytoplankton and zooplankton communities, and an increase in nitrate uptake rates relative to silica[175]. The shift in ratios of N:P or N:Si and phytoplankton community structure may create an imbalance in production and consumption at larger trophic levels, or could contribute to altered species composition and the geographical and temporal expansion of harmful algal blooms.

It is necessary to determine the quantity of the natural macronutrient stores that are used up in the fertilized patch during the phytoplankton bloom evolution, as these would no longer be available for photosynthesis in downstream ocean regions. This requires complex ocean models relating large-scale physical processes, and the predicted impacts cannot be validated through small perturbations such as patch experiments[176]. Some models have predicted that Southern Ocean fertilization would change patterns of primary productivity globally by reducing the availability of N and P in the equatorial Pacific.

Deep water forms in certain high latitude regions by the sinking of highly saline, cold surface waters, driving the "conveyor belt" ocean circulation processes. Increased surface nutrient depletion in areas where deep water is formed can lower the concentration of preformed nutrients in the sinking water masses[177]. Thus, the reduction of nutrients in surface waters could re-emerge to challenge the sustainability of future primary productivity, thousands of kilometres away from the fertilized site and many years after experimentation, as deeper waters recirculate to the surface layer[178]. Projections by

171 Fuhrman, J. A., Capone, D. G. (1991) Possible biogeochemical consequences of ocean fertilization. Limnol. Oceanogr. 36 (8): 1951–1959.

172 Johnson, K. S., Karl, D. M. (2002). Is Ocean Fertilization Credible and Creditable? Science, 296(5567):467–469.

173 Matear, R. J., Elliot, B. (2000). Enhancement of Oceanic Uptake of Anthropogenic CO_2 by Macro-Nutrient Fertilization, in D. Williams, et al. (Eds.) Greenhouse Gas Control Technologies, CSIRO, Syd. 451–456, ISBN: 0643066721

174 Buesseler, K. O., Boyd, P. W. (2003). Will Ocean fertilization work? Science 300: 67–68

175 Coale, K. Open Ocean Fertilization for Scientific Study and Carbon Sequestration. Adapted from Encyclopedia of Ocean Sciences (Eds. Steele, Yentch and Turekian).

176 Chisholm, S. W, Falkowski, P. G., Cullen, J. J. (2001). Discrediting ocean fertilization. Science, Vol 294: 309–310.

177 Marinov, I., Gnanadesikan, A., Toggweiler, J. R., Sarmiento, J. L. (2006). The Southern Ocean biogeochemical divide. Nature 441:964–967.

178 Powell, H (2008). Dumping Iron and Trading Carbon. In: Buesseler K, Doney S, Kite-Powell H, editors. Oceanus Magazine: The Ocean Iron Fertilization Symposium, Woods Hole Oceanographic Institution (WHOI); 2007 Sep. 26–27; Woods Hole, MA.

Gnanadesikan *et al.* (2003)[179], Aumont and Bopp (2006)[180], and Zahariev *et al.* (2008)[181] all indicate a reduction in primary production and in biological export of carbon on the multi-decadal to century timescale, due to the reduction in available macronutrients returning to the surface ocean, which (taking into account the large time scales over which commercial ocean fertilization activities would have to be carried out) could represent a significant reduction in harvestable marine resources[182].

Ocean Acidification

The oceans are naturally alkaline, with an average pH of 8.2. The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic with an average decrease in pH of 0.1 units[183], which equals an increase of 30 per cent in hydrogen ions[184]. The continued increase in atmospheric CO_2 concentrations will reduce ocean pH further in the forthcoming decades, influencing the depth distribution of remineralization back to DIC, and reducing biocalcification in shells, bones and skeletons of marine organisms, which could result in potentially severe ecological changes. Initial estimations indicate that the Southern Ocean and subarctic Pacific Oceans will become undersaturated with respect to aragonite by 2100[185]. However, new models show that certain parts of the Arctic Ocean will be undersaturated as early as 2016[186]. Ocean fertilization activities which seek to intentionally increase the amount of CO_2 stored within the ocean have the potential to accelerate ocean acidification, with significant and unforeseen feedbacks for ocean ecosystems and the global community.

However, exactly how certain species and parts of the marine environment would be affected by a change in pH due to an artificial increase in phytoplankton and biological processes remains subject to scientific research, discussion and controversy. For example, an increase in the photosynthetic uptake of CO_2 would actually increase the pH in surface layers[187], making them more alkaline. In addition, scientific research results need careful analysis and interpretation, depending on how this research was conducted (e.g. modelled calculations versus measurements; laboratory versus in-situ experiments; single versus multi parameter studies). Laboratory experiments which subjected the coccolithophore species *Emiliania huxleyi* to increased water acidity showed that with decreasing pH, the calcareous plates (coccoliths) of this single-celled plankton organism (which can form huge blooms) weaken and deform — indicating that this species would suffer from ocean acidification. However, observations under different laboratory set-ups suggest that calcification and net primary production of *E. huxleyi* is significantly increased by high CO_2 partial pressures, as anticipated in future oceans. This observation is consistent with field evidence obtained from deep-ocean sediment cores, which suggests a 40% increase in aver-

179 Gnanadesikan, A., Sarmiento, J. L., Slater, R. D. (2003). Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. Global Biogeochem Cycles 17:1050.

180 Aumont, O., Bopp, L. (2006). Globalizing results from ocean *in situ* iron fertilization studies. Global Biogeochem Cycles 20:GB2017.

181 Zahariev, K., Christian, J., Denman, K. (2008). Preindustrial, historical carbon model with new parameterizations of iron limitation, calicification and N_2 fixation. Prog Oceanogr, 77:56–82.

182 Denman. K. L. (2008). Climate change, ocean processes and ocean iron fertilization. Marine Ecology Progress Series Vol. 364: 219–225

183 IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

184 Nelleman, C., Hain, S., Adler, E. (2008). In Dead Water—Merging of Climate Change with Pollution, overharvest and infestations in the World's Fishing Grounds. UNEP, GRID Arendal, Norway.

185 Orr, J. C., Fabry, V. J., Aumont, O., *et al.* (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437 (7059):681–686.

186 Steinacher, M., Joos, F., Frölicher, T.L., Plattner, G.-K. and Doney, S.C. (2009). Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, Vol. 6. pp. 515–533.

187 Wootton, J.T., Pfister, C.A., Forester, J.D. (2008) Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. PNAS December 2, 2008 vol. 105 no. 48 18848–18853.

age coccolith mass over the past 220 years following rising atmospheric CO_2 concentrations. Therefore, coccolithophores may indeed positively respond to rising atmospheric CO_2 partial pressures[188].

Climate-active Gases

N_2O: The production of trace gases such as nitrous oxide (N_2O) is influenced by the remineralization of sinking particulate matter during the phytoplankton bloom decline and export phase, and as such responds to ocean fertilization on large temporal and spatial scales. Elevated mid-water remineralization and oxygen consumption as observed during the fate of induced phytoplankton blooms supports accelerated nitrogen cycling and N_2O production[189]. The N_2O produced is ultimately ventilated to the atmosphere, where it is long lived and has a global warming potential of between 290–310 times that of CO_2[190]. N_2O is also recognized as contributing to ozone depletion[191].

As highlighted in annex 1, few ocean fertilization experiments to date have recorded N_2O concentrations and emissions. No significant increase in mixed-layer N_2O concentration and emissions was observed in two Southern Ocean iron fertilization experiments; however, an increase in N_2O saturation was identified during the Southern Ocean Iron Release Experiment (SOIREE), suggesting iron-induced stimulation of N_2O production. Excess N_2O was not recorded during the European Iron Fertilization Experiment in the Southern Ocean (EIFEX). An increase in N_2O saturation was identified during the Sub-arctic Ecosystem Response to Iron Enrichment Study (SERIES) in the Gulf of Alaska[192]. Extrapolation of N_2O responses to predict the downstream consequences of iron addition experimentation is complicated by the paucity of data and the natural spatial variability of N_2O in the water column. However, recent models have provided some insight into the longer term effects of ocean iron fertilization and have predicted that the remineralization of carbon fixed during the SOIREE experiment subsequently produced 2.1 to 4.1 t of N_2O which, in light of its high global warming potential, could offset the reduction in radiative forcing achieved by 6-12%[193].

Caution has also been expressed that small-scale and or shorter-term fertilization may not reduce N_2O production and emissions proportionally; that the cessation of fertilization will not bring N_2O production back to baseline levels in the short term; and that N_2O production hotspots may relocate[194]. The verification of the N_2O response is therefore an important consideration in future ocean fertilization experimentation.

DMS: Dimethylsulphide is released by several species of marine phytoplankton into the atmosphere, where it becomes oxidized to sulfate (SO_4), an important component of aerosols, thought to influence the nucleation, lifetimes, and optical properties of clouds. DMS is supersaturated in surface waters, and

188 Iglesias-Rodriquez, M. D., Halloran, P. R., Rickaby, R. E. M., Hall, I. R., Colmenero-Hidalgo, E., Gittins, J. R., Green, D. R. H., Tyrell, T., Gibbs, S. J., von Dassow, P., Rehm, E., Armbrust, E. V., Boessenkool, K. P. (2008). Phytoplankton calcification in a CO_2 accreting ocean. Science, Vol 320:336–340.

189 Chan, F., Barth J. A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W. T., Menge, B. A. (2008) Evidence of anoxia in the California Current Large Marine Ecosystem. Science 319:920

190 Fuhrman, J. A., Capone, D. G. (1991) Possible biogeochemical consequences of ocean fertilization. Limnol. Oceanogr. 36 (8): 1951–1959.

191 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

192 Ibid.

193 Law, C. S., Ling, R. D. (2001) Nitrous oxide fluxes in the Antarctic Circumpolar Current, and the potential response to increased iron availability. Deep-Sea Res II 48:2509–2528

194 Jin, X., and N. Gruber (2003), Offsetting the radiative benefit of ocean iron fertilization by enhancing N_2O emissions, Geophys. Res. Lett., 30(24), 2249, doi:10.1029/2003GL018458

emission to the atmosphere by marine phytoplankton has been proposed to reduce the radiative flux to the Earth's surface[195].

The production of DMS and its precursor dimethylsulphonopropionate (DMSP) were measured in nine of the 12 iron fertilization experiments. Early experiments confirmed a trend of rapidly increased DMSP and DMS production in the fertilized patch within days to weeks after the fertilization event[196]. Following the five-fold increase in DMS observed during the SOFeX experiment, scientists estimated that a 2% iron fertilization of the Southern Ocean could increase DMS production by 20% and influence a temperature decrease of 2˚C in surface waters[197]. However, no significant change was observed in DMS concentrations between the iron enriched patch and surrounding waters in the SEEDS experiment in the northwest Pacific. Also, further variation was noted in the SERIES experiment in the northeast Pacific, where elevated levels of bacterial production and associated sulphur demand resulted in the utilization of DMSP and DMS inside the fertilized patch. The results demonstrate fundamentally different trends in biogenic sulphur cycling between various HNLC regions and highlight that iron addition to HNLC waters may not always lead to conditions that are more favourable to mitigating climate change[198].

CO_2: Ocean fertilization methods must account for carbon emissions generated in the process of creating reductions, termed "leakage" (e.g., fuel used to transport Fe to site), and they must also account for any greenhouse gases generated as a result of fertilization[199]. As noted in Table 9, the manufacture of ammonia (used in nitrogen based fertilization) from coal or petroleum based materials cause a significant leakage of CO_2 to the atmosphere[200].

Methane: Methane is produced in reducing sediments on the continental shelf and slope. Methane has a higher global warming potential than CO_2. An increase in methane production, as may occur during nitrogen fertilization, may offset the benefits of CO_2 drawdown from the atmosphere. However, Kock *et al.* (2008) indicate that even large changes in methane production may not be a problem in this context; emissions of methane would have to increase by 16 Tg CH4 yr−1 to offset 20% of a 0.5 Gt C yr−1 carbon sequestration. This is well over 10× the estimated marine source of methane to the atmosphere[201].

Other gases: Ocean fertilization may also influence the production of volatile methyl halides (CH_3Cl, CH_3Br, CH_3I). These compounds photolyze to produce reactive halogens which are believed to contribute to depletion of stratospheric ozone[202].

Temperature: Concern has been raised about the potential of ocean fertilization to directly affect the atmosphere, i.e. the ocean system radiative budget. An extreme scenario of removing 600μmol/mol of CO_2 through long term (100 years) fertilization over 30% of the world's oceans would require a

195 Levasseur, M., Scarratt, M. G., Michaud, S., *et al.* (2006). DMSP and DMS dynamics during a mesoscale iron fertilization experiment in the Northeast Pacific—Part 1: Termporal and vertical distributions. Deep-Sea Research II 53, 2353–2369.

196 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

197 Wintenger, O. W., Elliot, S. M., Blake, D. R. (2007). New directions: enhancing the natural sulphur cycle to show global warming. Atmos Environ 41:7373–7375.

198 Levasseur, M., Scarratt, M. G., Michaud, S., *et al.* (2006). DMSP and DMS dynamics during a mesoscale iron fertilization experiment in the Northeast Pacific—Part 1: Termporal and vertical distributions. Deep-Sea Research II 53, 2353–2369.

199 Leinen, M. (2008) Building relationships between scientists and business in ocean iron fertilization. Mar Ecol Prog Ser, Vol 364:251–256.

200 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

201 Kock, A., Gebhardt , S., Bange, H. W. (2008) Methane emissions from the upwelling area off Mauritania (NW Africa). Biogeosciences Discuss 5:297–315.

202 Vogt, R., Crutzen, P. J., Sander, R. (1996) Nature 383, 327.

sustained increase in photosynthetic energy equivalent to ~1.5W/m^2 over the fertilized region[203]. It is suggested that, given photosynthesis is an endothermic process, this could result in the transfer of this energy as heat to the ocean's surface waters through respiration, with corresponding sea surface temperature change[204].

C. EXPERIMENTAL ADVANCES AND MODELLING

Manipulative experiments involving ocean fertilization are important tools in furthering the understanding of the marine environment. Small-scale patch fertilizations have enabled the improved knowledge of ecological and biogeochemical processes, their interrelations, and the validation of ecosystem dynamic models[205]. However, experiments to date were not well designed to prove the role of ocean fertilization in CO_2 mitigation,[206] nor to monitor the side-effects and impacts on marine biodiversity resulting from these experiments. The IOC *ad hoc* Consultative Group on Ocean Fertilization called for such research to be permitted to continue with minimum regulatory interference so as to allow advancement of knowledge[207].

Modelling the long-term and large-scale (remote) effects of iron fertilization requires high-resolution, global climate models coupled with suitable ecosystem models. In order to be effective as management tools, the models need to undergo rigorous validation to ensure that the assumptions employed are realistic and lead to reliable predictions[208]. Models of progressively increasing resolution and realism have been developed in order to evaluate the potential for iron fertilization of HNLC regions as a means of consuming nutrients and sequestering carbon. Early simplistic models indicated a possible reduction in atmospheric CO_2 of 50–100ppm[209]; however, recent studies with higher resolution three-dimensional models coupled to ecosystem dynamics, including iron, have suggested that addition of iron is much less efficient (order of 10ppm) because the other limiting factors of light and grazing become dominant[210].

A new model of DMS dynamics was developed during SERIES, providing a better understanding of the complex interplay of physical, photochemical and biological processes affecting the evolution of DMS concentrations within the mixed surface layer[211]. It has also been suggested that in order to characterize and take into account the seasonal and regional variability in marine DMS, establishing the atmospheric sulphur and aerosol composition is an important pre-requisite for future ocean iron fertilization experiments, so that the origin of regional variations can be determined[212].

203 Lawrence, M. G. (2002). Side Effects of Oceanic Iron Fertilization. Science. Vol, 297: 1993.

204 Ibid.

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

206 Leinen, M. (2008) Building relationships between scientists and business in ocean iron fertilization. Mar Ecol Prog Ser, Vol 364:251–256.

207 UNESCO/IOC (2008). Statement by the IOC ad hoc Consultative Group on Ocean Fertilization. Available at http://ioc3.unesco.org/oanet/OAdocs/IOC_OF_Statement%20with%20add.pdf, accessed on 10 May 2009

208 Lampitt, R. S. *et al.* (2008). Ocean fertilization: a potential means of geoengineering? Phil. Trans. R. Soc. A. 366, 3919-3945

209 Peng. T. H, Broecker. W. S. (1985). The utility of multiple tracer distributions in calibrating models for uptake of anthropogenic CO_2 by the ocean thermocline. J. Geophys. Res.-Oceans. 90, 7023–7035

210 Aumont, O., Bopp, L. (2006). Globalizing results from ocean *in situ* iron fertilization studies. Global Biogeochem Cycles 20:GB2017.

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

212 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

Simulation models based around phytoplankton ecology have been performed independently for iron enrichment experiments IronEx I, SEEDS, SERIES, and SOIREE. The individual models vary significantly in design and objectives, and comparison between the models can facilitate their improvement and the development of common scenarios for validation[213].

213 SCOR (2006). Proposal for a SCOR Working Group (submitted to SCOR at 28 May 2006): The Legacy of in situ Iron Enrichments: Data Compilation and Modeling. Available at http://www.scor-int.org/2006GM/2006-Iron.pdf, accessed on 10 May 2009.

IV. UNCERTAINTIES AND OTHER CONSIDERATIONS

There are a number of uncertainties and other considerations which have to be taken into account when assessing the impact of ocean fertilization on marine biodiversity and the prospect of ocean fertilization as a climate change mitigation measure.

Location: Natural fertilization of coastal waters occurs through the upwelling of nutrient-rich, deeper waters, from rivers and seabed sediments, or via the aeolian deposition of nutrients into surface ocean waters via dust. Human-induced open ocean iron fertilization will only work where there are unutilized macro nutrients in the sunlit surface layers of the ocean. These only occur in large enough quantities in the Southern Ocean, the sub-Arctic North Pacific and in the equatorial Pacific, although the return cycle in the equatorial areas seems to be much shallower and shorter, and therefore less attractive[214]. A three-dimensional Ocean Carbon Cycle model was used to investigate the efficiency of macronutrient fertilization at enhancing the rate that anthropogenic CO_2 is sequestered by the ocean. The study showed that macronutrient fertilization is site dependent, and that by adding macro nutrients to regions where these nutrients do not limit biological production would not stimulate production or increase oceanic CO_2 uptake[215].

Early observations from the LOHAFEX iron fertilization experiment confirms the importance of co-limitation of nutrients, and suggests that due to the low silicic acid content of surface waters in the sub-Antarctic zone, iron fertilization in this vast region is unlikely to result in the removal of significant amounts of CO_2 from the atmosphere[216].

The IOC warns that an ocean fertilization activity might be damaging even if conducted over one square kilometre, if in the vicinity of a sensitive habitat such as a coral reef, just as another ocean fertilization activity might be benign even though conducted over many thousands of square kilometres[217].

Dependency on local, site-specific conditions: The physical and biogeochemical conditions vary with location and factors such as mixed layer depth, proximity to oceanic fronts and degree of eddy activity. The impact of ocean currents and physical transport in diluting signals as the fertilized patch gets larger can make it difficult to detect the byproducts of decaying algal bloom over the background variability of downstream waters[218].

Geographic scope/range: The concept of ocean fertilization is of relevance only in certain areas of the oceans where the deficiency of certain micronutrients (e.g. iron or nitrate) is the main factor limiting plankton growth. However, ocean currents and water mass exchanges will spread any desired effects and potential impacts over time and space, especially if ocean fertilization is being carried out on a large scale and repeatedly.

214 Denman. K. L. (2008). Climate change, ocean processes and ocean iron fertilization. Marine Ecology Progress Series Vol. 364: 219–225

215 Matear, R. J., Elliot, B. (2000). Enhancement of Oceanic Uptake of Anthropogenic CO_2 by Macro-Nutrient Fertilization, in D. Williams, et al. (Eds.) Greenhouse Gas Control Technologies, CSIRO, Syd. 451–456, ISBN: 0643066721.

216 Alfred-Wegener-Institut (2009). Press Release: Lohafex provides new insights into plankton ecology (www.awi.de).

217 UNESCO/IOC (2008). Statement by the IOC ad hoc Consultative Group on Ocean Fertilization. Available at http://ioc3.unesco.org/oanet/OAdocs/IOC_OF_Statement%20with%20add.pdf, accessed on 10 May 2009

218 Watson, A. J., Boyd, P. W., Turner, S.M., Jickells, T. D., Liss, P. S. (2008). Designing the next generation of ocean iron fertilization experiments. Mar Ecol Prog Ser, Vol364:303–309

Linkages with other climate change effects in the marine environment: The effectiveness of ocean fertilization to sequester and store CO_2 in the deep sea depends on two main processes, the ”biological pump” and the ”solubility pump” (see chapter 2). Whether and how these processes will be affected by other climate change impacts in the marine environment (e.g. changes in water temperature, chemistry and density, alterations in local, regional and global ocean current regimes) is still subject to scientific research and debate. There are indications that especially physical, density-driven mechanisms such as the solubility pump or the cascading of dense shelf water[219], will become weaker over the next decade due to an increase of temperature stratification (layering) and an increase in density gradients between the upper and lower water column, thereby reducing the amount of water (and CO_2) reaching the deep ocean.

Viability: In order to reduce atmospheric CO_2 concentrations in quantities large enough to mitigate climate change, large-scale ocean fertilization activities would have to be (i) effective and (ii) repeated on a continuous basis. Early model calculations based on mesoscale experiments for iron fertilization significantly overestimated the CO_2/carbon sequestration efficacy[220], which could not be confirmed in field experiments.

Lack of knowledge: The general components and functions of ocean fertilization are known. However, the more detailed geophysical, chemical and biological factors, sub-processes and linkages to other small- and large-scale mechanisms which drive the biological pump (and other relevant processes) are not yet sufficiently understood to guarantee ocean fertilization as a viable climate mitigation strategy. The informative outcomes of the recent LOHAFEX experiment, alongside the decrease in chlorophyll observed during phosphate addition in the CYCLOPS experiment, demonstrate this.

Determination of the baseline: In order to assess the effectiveness and risks of ocean fertilization activities, a baseline of the physical, chemical and biological variables which are or could be affected has to be established prior to commencing the ocean fertilization activities. Most previous ocean fertilization experiments (cf. annex 1) measured and described the environmental conditions in the upper water column over a short period of time before (= experimental baseline) and after the experiment with a view to determining whether and what effect the experiment had. However, in most cases the experimental baseline was not determined for the lower part of the water column and the sea bed, including vulnerable marine biodiversity dependent on these habitats.

Risks: Ocean fertilization,by definition, intends to change and interfere with natural processes, and thereby bears the likelihood of effects or outcomes (adverse or beneficial) on marine biodiversity. In order to characterize, assess and evaluate the nature, probability and magnitude of potential risks, the physical, chemical and biological parameters (including their natural variability) which are or could be affected have to be determined to establish a risk assessment baseline. SCOR and GESAMP agreed that any deliberate large-scale addition of nutrients to the ocean must be conducted in such a way that the outcomes of these experiments are statistically quantified and independently verified with respect to the full range of organism and ecosystem changes observed in fertilized and downstream waters[221]. In addition, there is the uncertainty that ocean fertilization activities could unintentionally affect other

219 Cameron, D. R., Lenton, T. M., Ridgwell, A. J., Shepherd, J. G., Marsh, R., and Yool, A. (2005). A factorial analysis of the marine carbon cycle and oceanic circulation controls on atmospheric CO_2. Global Biogeochemical Cycles 19, GB4027

220 Boyd, P. W. (2008). Implications of large scale iron fertilization of the oceans. Mar Ecol Prog Ser, Vol 354:213–218

221 SCOR and GESAMP (2008). OCEAN FERTILIZATION Press Release—Position of SCOR and GESAMP on Deliberate Nutrient Additions to the Ocean. In document LC/SG 31/INF.2, available at http://www.sjofartsverket.se/pages/15453/31-INF2.pdf, accessed on 10 May 2009.

elements and processes coupled with the carbon cycle, which play critical roles in climate regulation[222]. Compared to the short-term experimental baseline (cf. above), these risks call for the collection of data over a longer (multi-year) period of time, especially to determine any (chronic) impacts from repeated ocean fertilization activities.

Monitoring: Previous ocean fertilization experiments monitored the environmental conditions for a few days / weeks after the experiment to determine the development and fate of the bloom. Repeated ocean fertilization activities on a large scale, however, would require the development of a comprehensive, long-term field monitoring approach and strategy. While certain parameters could be monitored via airborne or satellite-based remote sensing, the impacts on marine biodiversity in the deeper waters and on the seafloor would require repeated ship-based observations and sampling in remote and offshore locations. This has implications for the viability and cost/benefit balance of ocean fertilization. The use of modern autonomous underwater vehicles alongside other technologies may be used to reduce the amount of ship time required.

Cost/benefits: Ocean fertilization, especially iron fertilization, has been suggested by commercial entities as a cost effective strategy for mitigating climate change. However, the cost-benefit ratio of ocean fertilization needs an in-detail comparison with other mitigation strategies, before it can be considered a viable tool for carbon offsets. Appraising the relative merits of geo-engineering designs in a transparent way is essential, but little progress is evident[223]. Estimates must consider the costs of the potential total economic value (including use and non-use values) of any marine biodiversity and ecosystem function which might be impacted or influenced due to ocean fertilization, alongside the costs for assessing side-effects via determining of baselines, risk assessment and monitoring.

Carbon Export Efficiency: The study of regions of high phytoplankton biomass stimulated by natural iron inputs from shallow topography or islands, such as the Kerguelen Ocean and Plateau Compared Study (KEOPS), has demonstrated carbon export efficiencies at least ten times higher than those previously estimated for short-term blooms induced by iron-addition experiments[224]. Blain *et al.* (2007) observed that phytoplankton biomass increased until iron availability was again limiting, and suggest that the efficiency of the KEOPS bloom was linked to the mode and duration of the iron supply (slow and continuous), which differs from purposeful additions[225]. The observations of a naturally fertilized bloom during the CROzet natural iron bloom and EXport (CROZEX) experiment also returned a sequestration efficiency of 8,600 mol mol^{-1}, which is 18 times greater than that in the comparable SOIREE experiment in the same Southern Ocean region[226]. Early estimates of carbon sequestration efficiency were demonstrated to be significantly overestimated by mesoscale experimentation, thus the cost has likely been underestimated[227]

A comparison of modes of iron supply in Fe and N enrichment experiments and naturally occurring perturbations reveals a wide variety in the magnitude, residency and spatial and temporal scales of iron supply. It is hypothesized that the magnitude of iron available to the biota will ultimately be determined

222 Chisholm, S. W, Falkowski, P. G., Cullen, J. J. (2001). Discrediting ocean fertilization. Science, Vol 294: 309–310.

223 Boyd. (2008). Ranking geo-engineering schemes. Nature geosciences, Vol 1:722–724.

224 Blain, S., Quéguiner, B., Armand, L., *et al.* (2007). Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature, Vol 446.

225 Ibid.

226 Pollard, R. T., Salter, I., Sanders, R. J., *et al.* (2009). Southern Ocean deep-water carbon export enhanced by natural iron fertilization. Nature, Vol 457:577–581.

227 Boyd, P. W. (2008). Implications of large scale iron fertilization of the oceans. Mar Ecol Prog Ser, Vol 354:213–218.

by the mode of supply and the mobilization and retention of Fe-ions by upper ocean processes[228]. Furthermore, it is suggested that the reduced efficiency of mesoscale experiments is likely a function of the loss of iron via precipitation, physical scavenging, and patch dilution during experimentation[229].

Given the Redfield ratios (see section HNLC regions in chapter 2), it is estimated that for each unit of nitrogen that is added to a nitrogen-limited region, only ~7 units of carbon biomass will be produced. In comparison, for each unit of iron that is added to an iron-limited region, an estimated 1,000,000 units of carbon biomass can be produced in regions where Fe is low[230]. In order to use oceanic production to sequester 1% of the anthropogenic carbon produced each year, an estimated 1-2x10^{13}g N per year would be required, equivalent to 10% of all the nitrogen fertilizers used in agricultural applications globally[231].

The production of excess bioavailable nitrogen in the form of ammonium and dissolved organic nitrogen, as observed in summer blooms of diazotrophs in LNLC regions, is proposed to ensure the efficient scavenging of residual phosphorous and lead to efficient carbon export, provided light and iron are available[232]. However, over extended timescales of continuous upwelling, the export and remineralization of particulate organic matter with elevated C:P and N:P ratios may eventually alter the nutrient ratios of the sub euphotic zone, thereby reducing the efficiency of controlled upwelling as a method of carbon sequestration[233].

The phosphate fertilization of Fe-sufficient regions may require much larger nutrient loads than the iron fertilization of P-sufficient regions, due to the high P:Fe molar stoichiometry of living organisms. The addition of PO_4^{3-} to enhance N_2 based carbon export therefore imposes significant logistical constraints and greater costs than iron fertilization[234].

The short observational periods as well as other intrinsic limits and artifacts of the small scale export fertilization techniques have prevented the effective validation of the efficiency of carbon sequestration and preclude extrapolation to longer timescales[235].

Scale: Ocean iron fertilization activities have been conducted on spatial scales of between 64 and 1,000km^2, with the addition of 350 to 2,000 kg of iron. However, spatial scale is not on its own a sufficient determinant of impacts, and a broader consideration of factors including rate of addition, amount, concentration, duration, composition of chemical, location and time of year, should be recognized as jointly determinative of the oceanic impact[236].

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

229 Aumont, O., Bopp, L. (2006). Globalizing results from ocean *in situ* iron fertilization studies. Global Biogeochem Cycles 20:GB2017.

230 Glibert, M. P., Azanza, R., Burford, M., et al. (2008). Ocean urea fertilization for carbon credits poses high ecological risks. Marine Pollution Bulletin 56: 1049–1056.

231 Ibid.

232 Karl, D. M., Letelier, R. M. (2008). Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. Mar Ecol Prog Ser, Vol 364:257-268.

233 Karl, D. M. (2002). Nutrient dynamics in the deep blue sea. Trends Microbiol 10:410–418.

234 Karl, D. M., Letelier, R. M. (2008). Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. Mar Ecol Prog Ser, Vol 364:257-268.

235 Blain, S., Quéguiner, B., Armand, L., *et al*. (2007). Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature, Vol 446, 26 April 2007.

236 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

There is currently no well established definition of "large scale." When considered in terms of physical ocean processes, large scale applies to a length of tens of kilometres[237]. Recently, Law (2008) defined large scale ocean fertilization as continuous additions to an area greater than 40,000 km^2 for periods of more than one year[238]. The Scientific Groups of the London Convention and Protocol state that generally, large-scale ocean fertilization is difficult to define, subject to multiple interpretations, and that a broader view is now applied to the concept of scale when considering ocean fertilization[239]. The IOC *ad hoc* Consultative Group on Ocean Fertilization suggest that as yet, there is no well established meaning of "large scale" that would allow it to usefully distinguish between activities that would and would not damage the ocean environment[240].

The results of small-scale experiments (tens of kilometres) are strongly influenced by the dilution of unfertilized water into the patch, which makes it difficult to extrapolate the results to larger scales/timeframes. Additionally, many of the processes observed do not scale linearly[241]. This is particularly true for carbon sequestration estimates. Experimentations in the order of 200 km x 200 km are larger than typical ocean eddies, and may provide more realistic representation of impacts likely from commercial-scale fertilization experiments. The assessment of the influence of surface manipulations on the sinking fluxes of particles may be more effective when the experiments are on this scale[242].

237 UNESCO/IOC (2008). Statement by the IOC ad hoc Consultative Group on Ocean Fertilization. Available at http://ioc3.unesco.org/oanet/OAdocs/IOC_OF_Statement%20with%20add.pdf, accessed on 10 May 2009

238 Law, C.S. (2008). Predicting and monitoring the effects of large scale ocean iron fertilization on marine trace gas emissions. Mar Ecol Prog Ser. Vol 364:283–288.

239 See document LC/SG 31/16, available at http://www.imo.org/includes/blastData.asp/doc_id=9938/16.pdf, accessed on 10 May 2009.

240 UNESCO/IOC (2008). Statement by the IOC ad hoc Consultative Group on Ocean Fertilization. Available at http://ioc3.unesco.org/oanet/OAdocs/IOC_OF_Statement%20with%20add.pdf, accessed on 10 May 2009

241 Leinen, M. (2008) Building relationships between scientists and business in ocean iron fertilization. Mar Ecol Prog Ser, Vol 364:251–256.

242 UNESCO/IOC (2008). Statement by the IOC ad hoc Consultative Group on Ocean Fertilization. Available at http://ioc3.unesco.org/oanet/OAdocs/IOC_OF_Statement%20with%20add.pdf, accessed on 10 May 2009

V. CONCLUSIONS

The main conclusion which can be drawn from this study is that, despite the amount of literature available on ocean fertilization, sound and objectively verifiable scientific data on the impacts of ocean fertilization on marine biodiversity are scarce. There are several reasons for this:

(i) Ocean fertilization stimulates primary production for a limited duration only in areas of the oceans where the deficiency of certain nutrients (e.g. iron or nitrate) is the main factor limiting plankton growth. These areas are usually remote and far offshore, and therefore have not been studied in as much detail as, for example, coastal areas. For most potential ocean fertilization areas, there is only limited knowledge available about the natural environmental conditions (including their variability / fluctuations over time) and the organisms and communities which live in the surface layer, the water column and on the seafloor. This lack of information makes it difficult, if not impossible, to determine baselines against which any short- or long-term changes and impacts resulting from ocean fertilization activities could be measured and monitored.

(ii) Ocean fertilization purposefully alters both the chemistry and biological processes in the marine environment, which raises a number of fundamental uncertainties and questions, especially as the role of the oceans in the global carbon cycle is still not fully understood. Changes and impacts on water chemistry (e.g. carbonate concentrations and pH) and abotic parameters follow known stoichiometric, thermodynamic and kinetic reactions, and therefore can be measured, modeled and predicted with reasonable certainty and accuracy. For example, it would be possible to determine the increase in ocean acidification in relation to the amount of CO_2 sequestered by ocean fertilization. However, the impact on biological processes and marine biodiversity is much more difficult to forecast. Knowledge of complex and dynamic biogeochemical marine processes (e.g. the "biological pump") is mostly limited to the general components and functions, and does not include the biological sub-processes, linkages and drivers, which ultimately determine whether and how marine biodiversity and ecosystems will be affected.

(iii) The extent and duration of the impact caused by ocean fertilization on marine biodiversity and ecosystems and related processes and functions also depends on how organisms and communities affected by the environmental changes will react. Again, this is something which at present can only be estimated vaguely (at best) because of the lack of detailed information about the dynamic functioning of marine ecosystems and processes, including the ecology, life cycles and resilience of marine species and communities. Short-term (days to weeks) impacts, especially on planktonic organisms and communities in the surface layers around the fertilization site, could be measured by vessel or traced by remote sensing. However, it would be very costly and resource intensive to measure medium- (months to years) to long-term (years to decades) impacts, especially in the deeper water column and on the seafloor. There is a need for long-term monitoring in these environments to determine any ecological effects, as most deep-sea organisms have a long life time and slow reproduction. At present, the medium- to long-term effects of large-scale ocean fertilization on higher levels of the marine food chain remain poorly understood and researched.

(iv) Most of the ocean fertilization experiments carried out so far, especially the early experimentations, had the objective to test the concept of ocean fertilization (i.e. whether it was possible to stimulate plankton growth) and to gain a better scientific understanding of the development and dynamics of the artificially created plankton blooms. The focus, design and duration of these experiments was not suitable to monitor and provide data on the actual impact of ocean fertilization to marine biodiversity.

(v) In order to get a better understanding on the actual and potential impacts of ocean fertilization on marine biodiversity, more extensive and targeted field work and better mathematical models of ocean biogeochemical processes would be required, not only to determine whether significant sequestration has taken place, but also to interpret field observations and to provide reliable predictions and answers about the side effects and impacts of large-scale fertilization. There is also a need for research to advance our understanding of marine ecosystem dynamics and the role of the ocean in the global carbon cycle. Advances in both of these basic research areas are critical to understanding climate change and should be fostered regardless of whether or not ocean fertilization activities contribute to mitigating climate change.[243]

Ocean fertilization, whether carried out as legitimate scientific research or on a commercial basis, presents serious challenges for the law of the sea, a fundamental objective of which is to ensure that activities conducted on, in or under the oceans do not create hazards to human health and the marine environment, or harm living marine resources[244,245]. Ocean fertilization is one of many recently proposed or emerging uses of the oceans which require an integrated, concerted response from stakeholders and relevant international bodies/organizations to ensure that our oceans and their resources are protected, conserved, managed and used in a sustainable way.

243 LC/LP Scientific Groups (2008) Outcome of the Working Group on Ocean Fertilization, Annex 2 of LC/SG 31/16, Guayaquil, Ecuador, May 2008.

244 Verlaan, P.A. (2006). Experimental activities that intentionally perturb the marine environment: Implications for the marine environmental protection and marine scientific research. Marine Policy. Vol 31: 210-216

245 Rayfuse, R., *et al.* (2008). Ocean Fertilization and Climate Change: The Need to Regulate Emerging High Seas Uses. The International Journal of Marine and Coastal Law, 23, 297-326.

ANNEX

TABLE 1: Overview of biological parameters of ocean fertilization experiments (executed)* [78]

Iron fertilization experiment	Year	Bacterial biomass max/ initial	Bacterial production	Microzoo-plankton biomass	Microzoo-plankton grazing rate	Floristic shift phyto-plankton	Faunistic shift microzoo-plankton	Mesozoo-plankton biomass	Mesozoo-plankton grazing	Cyano-bacteria biomass	Hapto-phyte biomass	Diatom biomass	Primary produc-tion (Max/Min)	Algal net growth (max per day)	Algal growth dilution
Iron Ex I	1993	n.d.	n.d.	1.5	n.d.	cyanobacteria to diatoms	no change	not measured	not measured	n.d.	n.d.	n.d.	4	0.4	2.5
Iron Ex II	1995	1.6	3	10.3	3–4	cyanobacteria to diatoms	heterotrophic nanoflagel-lates to heterotrophic ciliates	3	2–3	2*	4*	100	6	0.9	10
SOIREE	1999	1.6	3	2.6	7	picoeukaryotes to diatoms	heterotrophic nanoflagel-lates to heterotrophic ciliates	n.c.	n.c.	3*	6*	10	9	0.15	3
EisenEx	2000	1.6	2–3	2.2	n.d.	no change	n.d.	n.d.	n.d.	n.d.	n.d.	5.1	4	0.2	1.5–6.1
SEEDS	2001	2.7	n.d.	1.7	n.d.	green algae to centrics	heterotrophic nanoflagel-lates to heterotrophic dinoflagellates	n.c.	18	n.d.	n.d.	50	4	0.6	14
SOFeX South	2002	1.8	2	n.d.	n.d.	no change	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6	0.15	2.8
SOFEX North	2002	2.1	4	n.d.	n.d.	flagellates to diatoms	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	10	0.1	2.1
SERIES	2002	10.6	14.9	11.9	n.d.	cyanobacteria to diatoms	n.d.	in-creased	n.d.	n.d.	n.d.	n.d.	10	0.4	3.5–6.7
EIFEX	2004	n.d.	n.d.	1.7	1.5	no change	n.d.	n.d.	n.d.	n.d.	n.d.	2.9	2	<0.1	n.d.
SEEDS II	2004	n.d.	n.d.	n.d.	n.d.	more diatoms	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
SAGE	2004	no change	no change	n.d.	n.d.	no change	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2	0	n.d.
FEEP	2004	n.d.	n.d.	n.d.	n.d.	no change	n.d.	n.d.	not measured	n.d.	n.d.	n.d.	n.d.	0	n.d.
LOHAFEX†	2009	n.d.	n.d.	n.d.	n.d.	Diatoms did not proliferate	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

* For a detailed cruise report from the CROZEX study please visit: http://www.noc.soton.ac.uk/obe/PROJECTS/crozet/cruiserept/index.php
† Preliminary observations. Findings not yet published.
n.c. = no change; n.d = no data

TABLE 2: Summary of physical parameters of ocean fertilization activities* [78,115]

Property	IronEX I	IronEX II	SOIREE	EisenEx	SEEDS I	SOFEX-S	SOFEX-N	EIFEX	SERIES	SEEDS	SAGE	FeeP	LOHAFEX^	CYCLOPS	DEEP WATER UPWELLING
Region	East equatorial Pacific Ocean	East Equatorial Pacific Ocean	Southern Ocean (Australian sector)	Southern Ocean (Atlantic sector)	Northwest Pacific Ocean	Southern Ocean (Pacific sector)	Southern Ocean (Pacific sector)	Southern Ocean	Northeast Pacific Ocean	Western subarctic Pacific	Subpolar waters nearest to New Zealand	Sub-tropical North East Atlantic Ocean	South Atlantic	Eastern Mediterranean	North Pacific Ocean
Year	1993	1995	1999	2000	2001	2002	2002	2004	2002	2001	2004	2004	2009	2002	2003
Addition	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	$FeSO_4$	Fe	Fe	Fe SO_4	Phosphoric acid	5-10% nutrient-replete water
Addition (kg)	450	450	1750	2350	350[246]	1300	1700	2820	490	350[247]	1100	1840	10,000	n.d.	
Patch size (km^2)	64	72			80	225	225			80			300	16	
Temperature (°C)	23	25	2	3 to 4	11	–1	5	4 to 5	13	9 to 12	11.8	21			
Season	Fall	Summer	Summer	Spring	Summer	Summer	Summer	Summer	Summer	Summer	Fall	Spring	Spring	Spring	Summer
Light climate (mmol quanta $m^2 s^1$)	254 (Max)–230 (Min)	216–108	59–33	82–40	178–39	103–62	125– 74	n.d.	173–73	n.d.	59–52	n.d.			
Dilution rate (day–1)	0.27	0.18	0.07	0.04–0.43	0.05	0.08	0.1	n.d.	0.07–0.16	n.d.	n.d.	0.4		1.0 to 1.2	
Chlorophyll t=0 (mg m^3)	0.2	0.2	0.2	0.5	0.9	0.2	0.3	0.6	0.4	0.8	0.6	0.04		0.18	
Chlorophyll max (mg m^{-3})	0.6	3.3	2.3	2.8	23.0	2.5	2.4	3.0	5.5	2.4	1.3	0.07		0.1	
Bloom phase (duration days)	Evolving (5) subducted	Decline (17)	Evolving (13)	Evolving (21)	Evolving (10)	Evolving (28)	Evolving (27) subducted	Partial decline, evolving (37)	Decline (25)	Evolving (25)	No bloom	No bloom			
dDIC (mmol m^3)	6	26	17	14	58	21	13	n.d.	36	n.d.	n.c	<1			
dDMS (mmol m^3)	0.8	1.8	2.9	1.3 then to 0†	n.c.	n.c.	Increased	n.d.	8.5, then to –5.7†	n.c.	n.c.	n.c.			
Dominant phytoplankton	Mixed	Diatom	Diatom	Diatom	Diatom	Diatom	Mixed	Diatom	Diatom	Mixed	Mixed	Cyanobacteria *Prochlorococous*	*Themisto gaudichaudii*	Cyanobacteria	
Export	n.c.	Increase	n.c.	n.c.	n.c.	Increase	Increase	Increase	Increase	n.c.	n.c.	n.d.			
Mesozooplankton stocks	Increase‡	Increase	n.c.	n.c.	n.c.	n.c.	n.c.	Increase	Increase	Increase	n.c.	n.c.			
Primary production (max/min ratio)	4	6	9	4	4	6	10	2	10	n.d.	2	1.7			

* For a detailed cruise report from the CROZEX study please visit: http://www.noc.soton.ac.uk/obe/PROJECTS/crozet/cruiserept/index.php
† An initial increase in DMS concentration followed by a decline by the end of the study. ‡ Based on anecdotal evidence.
§ Increased export was mainly associated with a subduction event. ^ Preliminary observations. Findings not yet published.
n.c. = no change; n.d = no data; blank = information not located during this study

Sources: Boyd, P. W., et al. (2007). Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions. Science, Vol 315:612-617; Rees, A. P., Nightingale, P. D., Ownes, N. J. P, PML FeeP Team (2007). FeeP – An in situ PO_4^{3-} and Fe^{2+} addition experiment to waters of the sub-tropical north-east Atlantic. Geophys Res Abstr 9:01440.

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