

A satellite-style photograph of the ocean and ice. The left side shows a large, textured ice shelf or glacier. The right side shows the ocean with varying shades of blue and green, indicating different depths or water conditions. The text is overlaid on the right side of the image.

Position Analysis

OCEAN FERTILISATION



ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE



Position Analysis: Ocean Fertilisation

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Cover image: Satellite image of a phytoplankton bloom off the coast of South America (NASA)

The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.



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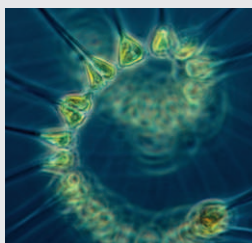
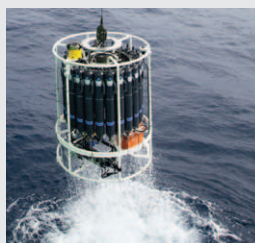
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The aims of this document are to:

1. Inform Australian federal and state governments and the broader community about the growing pressure to use the oceans for geoengineering in general and ocean fertilisation specifically;
2. Provide an update on research concerning ocean fertilisation; and
3. Identify issues for consideration in science and policy development.

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INTRODUCTION

Concern over human-driven climate change and the lack of success in constraining greenhouse gas emissions (Figure 1) has led to growing interest in marine geoengineering as part of a potential solution. Marine geoengineering, a deliberate intervention in the Earth's climate system via either carbon dioxide removal (CDR) or solar radiation management, has been the focus of a number of recent appraisals by leading scientific bodies including the Royal Society (2009), National Research Council (2010) and the Intergovernmental Panel on Climate Change (2012).

One of the most prominent among the proposed CDR interventions is ocean fertilisation, which targets the removal of carbon dioxide by the addition of nutrients such as iron, nitrogen or phosphorus compounds to stimulate the growth of marine phytoplankton. When marine phytoplankton die and sink into the deep-ocean, their carbon is sequestered where it may remain out of contact with the atmosphere for decades to millennia (i.e., via the 'biological pump', Figure 2).

The expectation is that ocean fertilisation could contribute to a portfolio of strategies to combat the enhanced greenhouse effect from increasing global carbon emissions until the world achieves emission reductions and develops more

RECENT HISTORY OF ATMOSPHERIC CO₂

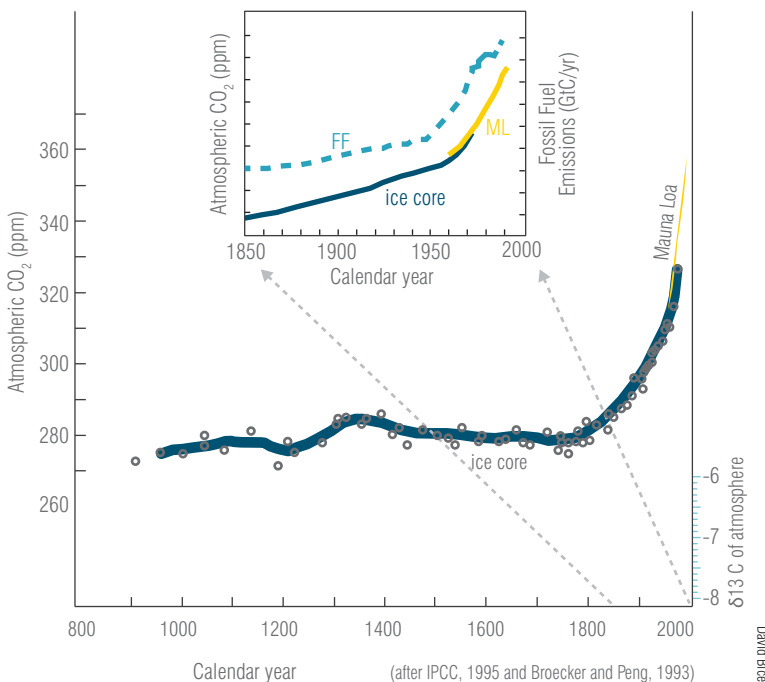


FIGURE 1: The recent history of atmospheric CO₂, derived from the Mauna Loa observations back to 1958, and ice core data back to 900, shows a dramatic increase beginning in the late 1800s, at the onset of the Industrial Revolution. The inset shows a more detailed look at the last 150 years, where we can see that the rise in CO₂ coincides with the rise in the burning of fossil fuels. After a brief respite during the global financial crisis in 2009 (not shown), the rates of CO₂ emissions have continued to rise.

Source: www.e-education.psu.edu/earth103/node/1018. Also see Global Carbon Project www.globalcarbonproject.org (Le Quére et al., 2015).

permanent carbon-capture projects. There is growing recognition that such strategies may be required in order to limit global mean temperature increases to 2°C relative to pre-industrial levels, as appears necessary to minimise dangerous climate impacts on natural systems and allow adaptation to climate change for many human systems at globally acceptable economic, social and environmental costs (IPCC, 2012).

Proposals for large-scale (> 100 km²) application of ocean fertilisation, some of which have been led by commercial enterprises, have been controversial, attracting criticism from scientists, environmental groups and the public (e.g., The Guardian, 2012). Important questions regarding efficacy, risk and legal issues remained unanswered (Boyd, 2008a; Royal Society, 2009; Wallace et al., 2010). The United Nations General Assembly has encouraged States to support further study and enhance understanding of ocean fertilisation (Resolution 62/215; December 2007). Several international bodies and associated secretariats have major interests in this topic, including the Intergovernmental Oceanographic Commission of UNESCO (IOC),¹ the United Nations Convention on Biological Diversity (UN CBD),² the International Maritime Organization (IMO) via the London Convention/

London Protocol (on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter),³ and the UN Division for Oceans Affairs and the Law of the Sea (DOALOS).⁴ Together they cover the spectrum of marine science, marine conservation, and pollution regulation and offer a variety of perspectives on ocean fertilisation. The most advanced efforts at regulation have come from the IMO and UN CBD, both of which have urged their member states to voluntarily apply a moratorium on activities, though not scientific experiments, until the risks are better understood (see Table 2 for details of international bodies interested in ocean fertilisation).

- 1 http://www.unesco.org/new/en/natural-sciences/ioc-oceans/single-view-oceans/news/ocean_fertilization_we_cannot_afford_to_gamble_with_the_ocean/#.Vw2_90J969I
- 2 www.cbd.int/
- 3 www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx
- 4 www.un.org/depts/los/doalos_activities/about_doalos.htm

BIOLOGICAL PUMP

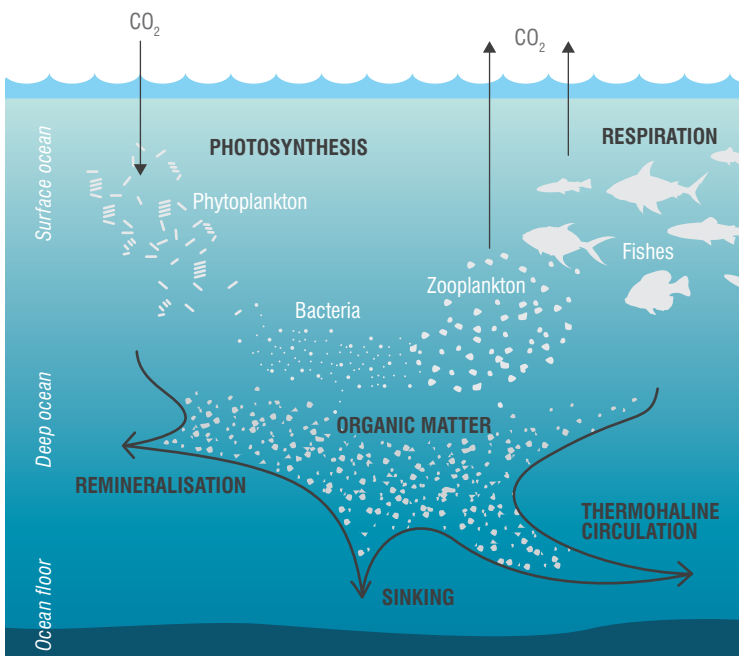


FIGURE 2: CO₂ is converted into organic matter during photosynthesis by phytoplankton (microscopic plants) growth in the surface ocean. A small amount of this material reaches the deep sea where it is sequestered from the atmosphere, either as organic carbon or back in the form of dissolved CO₂ after bacterial remineralisation. The overall effect is known as the ‘biological pump’ (Volk and Hoffert, 1985). The deeper the carbon is transported into the ocean interior the longer it remains isolated from the atmosphere. Ocean fertilisation stimulates the first step of photosynthetic primary production, with the intention that the entire pump increases. Consumption of the produced organic matter offers the potential additional benefit of enhanced fisheries, but also reconverts much of the carbon to CO₂ by respiration.

The immediacy of the policy issues was highlighted in July 2012, when a controversial large-scale ocean fertilisation experiment was undertaken in international waters off the west coast of Canada

Deliberate (also known as 'artificial' or 'purposeful') ocean fertilisation has been carried out in more than a dozen scientific field experiments since 1994, and other studies have examined biological pump processes in areas that receive natural nutrient inputs (Figure 3). These efforts include the SOIREE (Boyd et al., 2000) and KEOPS (Blain et al., 2007) research projects in the Southern Ocean, activities in which ACE CRC scientists Boyd, Trull and Bowie have been key investigators. Such studies have advanced the understanding of the processes involved and our knowledge on the role of iron supply in altering global climate in the geological past, but have not yet resolved many uncertainties regarding the efficacy, capacity and risks of ocean fertilisation as a carbon dioxide removal strategy (as reviewed in more detail in the next chapter (The Genesis of International Regulation of Ocean Fertilisation)). Many of the fertilisation experiments have been carried out in the Southern Ocean. This is because it is the largest region where macro-nutrients are abundant and only small amounts of the micro-nutrient iron are required to stimulate production. The primacy of the Southern Ocean as a target region elevates the importance of ocean fertilisation for Australia, as does the fact that much of these waters are beyond national jurisdiction (Figure 4) and therefore Australia's interests must be protected via both domestic legislation and international agreements.

The immediacy of the policy issues was highlighted in July 2012, when a controversial large-scale ocean fertilisation was

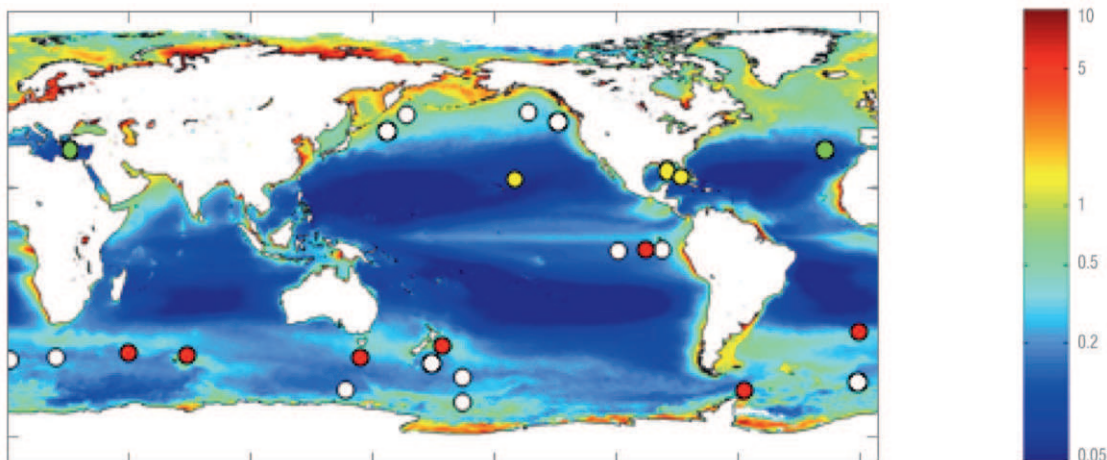


FIGURE 3: A map of satellite-derived mean annual chlorophyll concentration (units are mg chl m⁻³). Phytoplankton contain chlorophyll, so these maps are used as an indicator of ocean plant biomass. The white circles are the locations of 15 deliberate ocean iron fertilisation (OIF) experiments performed since 1993. The green circles indicate phosphorous enrichment. The red circles show sites where natural iron fertilisation studies have been carried out. The yellow circles show oceanic geoengineering trials or pilot studies, including iron fertilisation (Markels and Barber, 2001) and nutrient upwelling using ocean pipes (Lovelock and Rapley, 2007; White et al., 2010). Adapted from Strutton P. (2012) and Boyd et al. (2012).

undertaken in international waters off the west coast of Canada (Tollefson, 2012; Xiu et al., 2014). About 120 tonnes of iron (reported as 'iron sulphate' and 'iron oxides') was released into an area roughly one km² in size, 100 nautical miles outside Canada's exclusive economic zone (Figure 5). Lead proponents had previously championed fertilisation for carbon sequestration (Schiermeier, 2003) and the project received backing from the Haida First Nation for the purpose of restoring salmon stocks in the waters off the Haida Gwaii in the Queen Charlotte archipelago. No application for approval was submitted to the Canadian government – a signatory to both the UN Convention on Biological Diversity and the London Protocol and Convention. When news of the activity broke, it drew attention to the ongoing debates in scientific and political circles regarding the appropriateness of the research, the level of risks, and the effectiveness of regulatory frameworks. To date, there has been no conclusive evidence to show the higher trophic levels benefitted from the fertilisation (Batten and Gower, 2014).

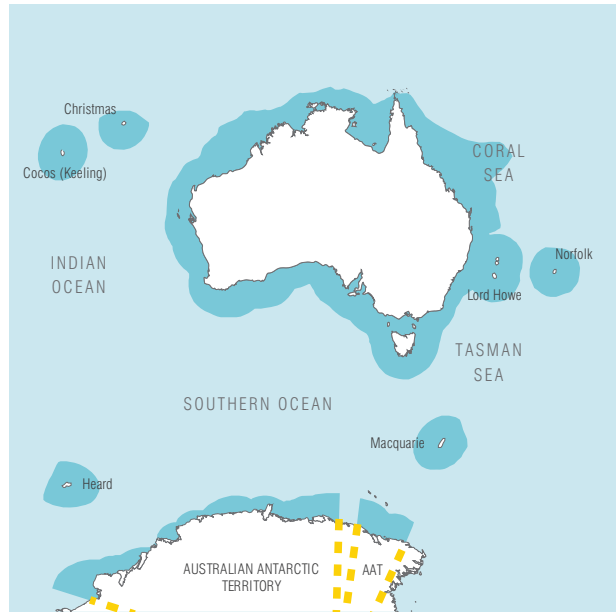


FIGURE 4: A depiction of Australia's marine jurisdiction. Australia's Exclusive Economic Zone (EEZ) is one of the largest in the world with the total marine area of about 10 million km². It is made up of 8.2 million km² off Australia and its remote offshore territories, and two million km² off the Australian Antarctic Territory. It extends to a distance of not more than 200 nautical miles from the territorial sea baseline.
Source: <http://www.ga.gov.au/scientific-topics/geographic-information/dimensions/oceans-and-seas#heading-1>

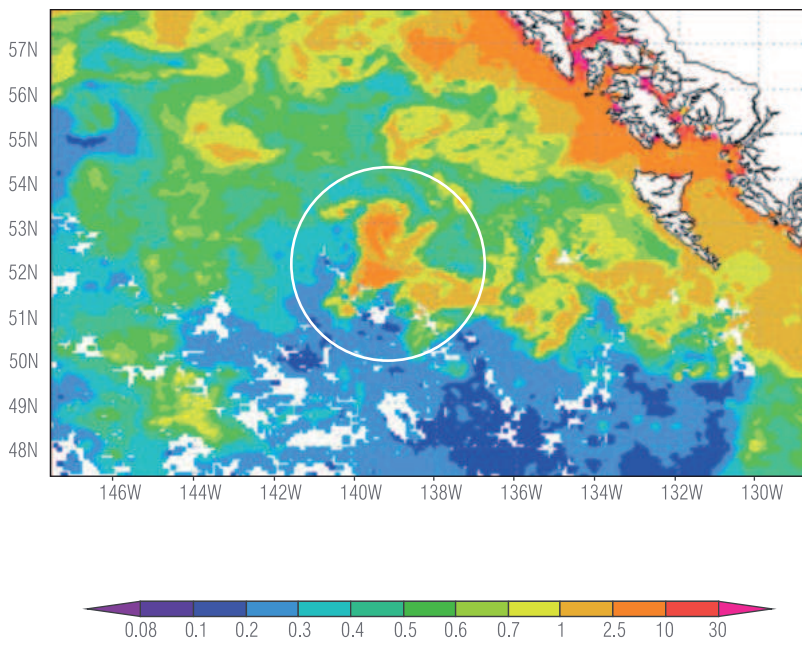


FIGURE 5: Yellow and brown colours show relatively high concentrations of chlorophyll (units are mg chl m⁻³) in August 2012, after iron sulphate was released into the Pacific Ocean as part of a controversial geoengineering scheme off the west coast of Canada. This fertilisation induced the most intensive phytoplankton bloom of the past 10 years in the region, ~2× stronger than that caused by iron aerosols from Kasatochi volcano in 2008, ~5× that typically observed in the region, including any induced by passing Haida eddies of previous years (Xiu et al., 2014).

THE GENESIS OF INTERNATIONAL REGULATION OF OCEAN FERTILISATION

In 2008, a decision was made at the 9th Conference of Parties (CoP) to the Convention on Biological Diversity (CBD) that: **requests Parties and urges other Governments, in accordance with the precautionary approach, to ensure that ocean fertilisation activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small scale scientific research studies within coastal waters** (Decision IX/16 2008).

This decision is not legally binding. Shortly thereafter at the 30th Conference of Parties to the London Protocol, which regulates dumping at sea, the Parties augmented this recommendatory moratorium from the Convention on Biological Diversity (which addresses biodiversity conservation) by adopting a resolution on the regulation of ocean fertilisation. Two very significant actions underpinned the concept of regulation. The first was the adoption of a definition of *ocean fertilisation*: “any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans”. The second, the significance of which is specifically related to the mandate of the London Protocol to prevent pollution caused by dumping at sea, was the declaration that ocean fertilisation was “placement of matter for a purpose other than mere disposal” under the Protocol – that is, it was not “dumping” *per se* (LC-LP.1 2008). While this decision did not alter the fact that LC-LP Parties accepted authority over ocean fertilisation, under paragraph 8 of LC-LP.1 2008, ocean fertilisation for purposes other than legitimate scientific research is considered ‘contrary to the aims’ of the LC and LP. The key objective of the LP is contained in its article 2: to ‘protect and preserve the marine environment from all sources of pollution’.

By October 2010, the London Protocol Parties had adopted the non-binding ‘Assessment Framework for Scientific Research Involving Ocean Fertilisation’ (LC-LP.2 2010), which proposed that, in accordance with paragraph four of Resolution LC-LP.1 2008, scientific research proposals should be assessed on a case-by-case basis using the Assessment Framework. The value of this framework is that it gave Parties directions on whether an ocean fertilisation proposal would qualify as ‘legitimate scientific research’.

Also in 2010, the States Parties to the Convention on Biological Diversity adopted a further non-binding decision with regards to geoengineering (Decision X/33). This decision covered all types of geoengineering, including ocean fertilisation. In summary, the decision requested that states refrain from engaging in any geoengineering activity that may affect biodiversity. Small scale studies of geoengineering in controlled settings might have been exempt from this

provision; however they would still have been subject to environmental impact assessment in accordance with article 3 of the CBD.

And conclusively, in October 2013 the Parties added a new Article 6. The new article 6bis read: *Contracting Parties shall not allow the placement of matter into the sea from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering activities listed in Annex 4, unless the listing provides that the activity or the sub-category of an activity may be authorised under a permit.*⁵

It therefore became necessary to define the term “marine geoengineering” and the following was also adopted under Article 1(5bis): *a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe.*

This definition reflects a widespread concern about the unknown but potential environmental impacts from new activities such as ocean fertilisation and other geoengineering techniques (Boyd, 2008a). However, the definition also potentially excludes activities ‘where the manipulation of natural processes is not directly intended, but is only a side effect’ and activities that have a purpose other than addressing climate change, such as the Haida Gwaii project (Ginzkey and Frost 2014: 85).

These decisions have categorised artificial ocean fertilisation with geoengineering broadly under a new Annex (4) to the Protocol, which prohibits operational activities but enables scientific research that meets permit conditions through the assessment framework (new Annex 5) to continue. Even though the new Annex (4) refers to



Video of iron being released into the ocean off the coast of Canada in 2012

geoengineering activities broadly, ocean fertilisation is the only activity currently listed within. It defines ocean fertilisation and determines that only legitimate scientific research activity will be permitted. The States Parties have permitting authority and should report ocean fertilisation activities in their own territory and any that might impact other countries to the LP Secretariat. This certainty promotes confidence in the growing regulatory regime since the burden of proof is on the proponents to ensure their proposals fit within the assessment framework.

Finally, the most recent meeting of the CBD’s Subsidiary Body on Scientific, Technical and Technological Advice in November 2015 recommended maintaining the status quo and reinforcing the previous moratoria until scientific research provided better understanding of possible impacts on biodiversity and ecosystem services (Recommendation XIX/7).⁶

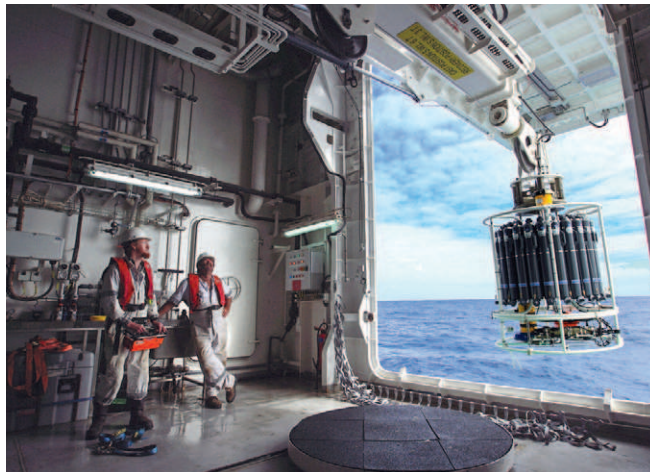
The CBD’s Decision X/33 paragraph 8(w) relates to a moratorium on all climate related geoengineering techniques, and work is continuing on considering a range of possible regulatory measures.⁷

5 The formal proposal for the amendment was submitted by Australia, Nigeria and the Republic of Korea. Australia therefore played a central role in negotiating this amendment.

6 <https://www.cbd.int/recommendation/sbstta/default.shtml?id=13427>

7 UNEP/CBD/SBSTTA/19/INF/2, Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework, <https://www.cbd.int/doc/?meeting=sbstta-19>

THE SCIENCE OF OCEAN FERTILISATION



Crew aboard *RV Investigator* retrieve a CTD from waters around Heard Island in the Southern Ocean in February 2016

Ocean fertilisation has been the subject of many papers, reports and reviews including Convention on Biological Diversity (2009), Enhanced Carbon Storage in the Ocean working group (2011), National Oceanographic and Atmospheric Administration (2010), Wallace *et al.* (2010) and Williamson *et al.* (2012). Most of the scientific activity has focused on whether fertilisation works in terms of increased phytoplankton production, accumulation, CO₂ uptake, carbon export to the ocean interior, and to a lesser extent whether higher trophic levels also respond. A few experiments have also begun to measure ecosystem changes and associated risks. No experiments or assessments have yet been sufficient to resolve many of the uncertainties to determine whether ocean fertilisation should be considered or rejected as a viable carbon dioxide removal mechanism (Güßow *et al.*, 2010). This is partly because the experiments to date have been too small.

Most research has focused on fertilisation with the micro-nutrient iron, because only very small amounts (parts per trillion) are needed to achieve a disproportionately large response (in other words, a large ratio of carbon sequestered per unit iron added) in regions where unused macro-nutrients such as nitrogen and phosphorus are available (including upwelling regions such as the eastern tropical Pacific and most of the Southern Ocean). These ocean regions, which are effectively “anaemic”, are termed “high nutrient low chlorophyll” (HNLC) regions, and adding iron can stimulate production, and thus nutrient and carbon dioxide consumption. Interest also has been growing in the addition of nitrogen and phosphorous in regions such as the sub-tropical gyres where nitrogen and/or phosphorous are in limiting supply, to extend the overall purview and capacity of ocean fertilisation (Karl and Letelier, 2008).

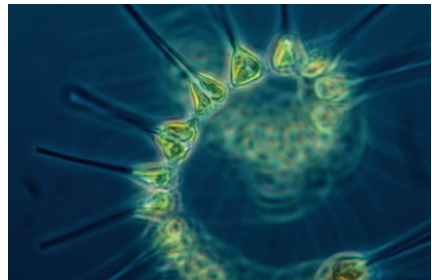
Iron addition

All but one of the 14 experiments to date (Figure 3) have added iron (the exception added phosphorous), and all but one of the iron additions have observed increased growth rates of phytoplankton. Almost all have also shown increases in phytoplankton stocks and carbon fixation, promoting carbon dioxide drawdown into the ocean from the atmosphere by gas exchange. Some of the artificially-induced blooms of phytoplankton extended to nearly 1000 km² in area and were visible to satellite-based ocean colour sensors.

Thus, a major achievement has been the conclusive demonstration that oceanic scarcity of iron controls biological production in nearly one third of the global ocean (Boyd *et al.*, 2007). The biological responses were more dramatic in warmer waters with shallower mixed layer depths and higher average light intensities. In most experiments, all phytoplankton types increased in abundance, but with stronger accumulations of larger sized cells in particular diatoms which form a silica shell (Trull *et al.*, 2001; de Baar *et al.*, 2005).

Despite the increased phytoplankton growth, few experiments were able to observe increased carbon export to the ocean interior, in part because the duration of experiments was generally too short to address the associated foodweb processes (Boyd *et al.*, 2007), but also because export processes are complex, time-varying, and often decoupled from production (Boyd and Trull, 2007). To fill this gap, and also to assess the possibility for differences between short-term and persistent fertilisation, some reliance has been made on studies of regions experiencing natural iron fertilisation from islands and shelf sediments (e.g., Blain *et al.*, 2007; Pollard *et al.*, 2007; Charette *et al.*, 2013; Bowie *et al.*, 2009, 2015). These suggest carbon export is likely to be increased by iron fertilisation, although estimates of the additional carbon that is exported from surface waters into the deep ocean for a given addition of iron vary enormously – by up to two orders of magnitude (Morris and Charette, 2013) (see ‘Major Uncertainties’ below).

This wide range of carbon sequestration efficiencies is due, in part, to the rapid loss of iron during deliberate fertilisations which have added iron in sulphate form, a common agricultural fertiliser that is relatively water soluble, and dissolved the iron sulphate in acidified seawater (Bowie *et al.*, 2001). In most of the experiments, the iron solution was pumped into the ocean behind a moving research vessel over a few hundred km², a similar scale to that of a natural phytoplankton bloom. Despite dissolving the iron, its chemistry meant it returned to a solid form that readily sticks onto other marine particles and hence was rapidly lost from the system through sinking permanently into the deep sea, with this happening more



Marine phytoplankton



Large-scale addition of synthetic urea has been proposed for fishery enhancement

rapidly in warmer waters. These scientific experiments have revealed that other ways to keep the added iron dissolved for longer are required and are likely available.

Macronutrient addition

The ability of macro-nutrient (nitrate, phosphate, silicate) addition to achieve carbon sequestration is even less well understood than that of iron fertilisation. There have been only two small-scale (10-100 km length scales) field studies involving phosphorus additions, both in waters low in phosphorous. The experiments resulted in rapid increases in bacterial production and zooplankton biomass, and a moderate increase in rates of nitrogen fixation. Surprisingly, there was a slight decrease in phytoplankton stocks.

These results are not yet fully explained, and may suggest alternative food-web pathways and complex limitations operating in low macro-nutrient systems. So far, no ocean fertilisation experiments have added nitrogen in a biologically available form. Large-scale addition of synthetic urea has been proposed for fishery enhancement (Judd *et al.*, 2008), and it has been suggested that this type of fertilisation may be more effective for longer term carbon storage (compared to iron) and easier to verify (Lawrence, 2014).

The addition of urea or ammonia may present greater ecological risk than adding nitrate, because there is already widespread evidence in the coastal ocean of the effects of nitrogen-rich run off (eutrophication) in



Photo: iStock

Proposals include a network of robust 'ocean pipes', either free-floating or tethered to the seafloor in regions with low surface nutrient concentrations

stimulating harmful algal bloom events (Gilbert *et al.*, 2008). Phosphorous fertilisation is not currently under widespread active consideration, since in some regions it is already in increasingly short supply for terrestrial agriculture.

Biogeochemical modelling of the effects of large-scale macronutrient fertilisation has indicated that the efficiency of this process is subjected to complex factors (Matear and Elliot, 2004). Nitrogen and phosphorous added to the sub-tropical gyres is expected to stimulate production and carbon export, but then to be rapidly recycled in subsurface waters, allowing resupply to the surface ocean to fuel additional cycles of production and export. This is in contrast to iron fertilisation, the benefits of which are expected to persist for a decade at most before the iron is lost to deep-sea sediments, whereas phosphorous and nitrogen additions may deliver benefits for millennia (Lawrence, 2014).

Artificial upwelling

As an alternative source of nutrient supply, there have been proposals to bring deeper, nutrient-rich water to the sunlit upper ocean. Many of these concepts involve mechanical devices powered by wave energy and one-way valves, or strategies that involve altering temperature and salinity (and therefore density) gradients to drive upwelling.

Proposals include a network of robust 'ocean pipes', either free-floating or tethered to the seafloor in regions with low surface nutrient concentrations (Lovelock and Rapley, 2007). Enhanced primary production has been demonstrated over a short period in some pilot projects, however devices developed to date have not been deployed for long enough for the expected biological responses to be observed, and the long-term robustness of the devices remains to be demonstrated (White *et al.*, 2010).

Modelling studies suggest net atmospheric CO₂ drawdown may actually be low, primarily because high concentrations of dissolved inorganic carbon will be brought to the surface in the upwelled water together with the nutrients.

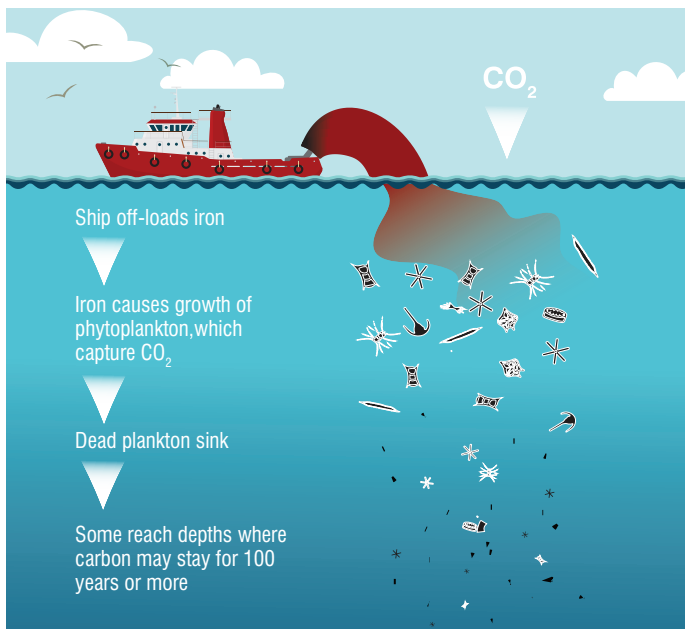
Fertilisation effects might be partly indirect; for instance high phosphorous levels in upwelled water could stimulate nitrogen fixation (Karl and Letelier, 2008; Oschlies *et al.*, 2010a). Surface temperature and salinity will also be affected, and if enhanced upwelling is carried out on a sufficiently large scale, the associated cooling could have significant climatic implications (Oschlies *et al.*, 2010b). It looks very likely that artificial upwelling will become a useful tool to study marine ecosystem responses to nutrient perturbations and changes in mixing regimes, and possibly to produce localized cooling, but is rather unlikely to be a cost-effective measure for carbon dioxide removal from the atmosphere.

MAJOR UNCERTAINTIES

Efficiency and capacity

The efficiency of ocean fertilisation as a means to sequester atmospheric carbon dioxide is commonly calculated as the additional (net) carbon that is exported from surface waters into the deep ocean for a given addition of nutrient. This is termed the 'carbon sequestration efficiency' and is controlled by nutrient loss processes, the carbon/nutrient ratio in fertilised blooms, and the proportion of biomass resulting from fertilisation which sinks into the deep ocean. There are several factors which lower efficiency, with shallow recycling of organic particles and subsequent CO₂ release back to the atmosphere, being the most important. The economic attractiveness of ocean fertilisation for geoengineering will be greater if sequestration efficiency is high and this can be measured easily. Estimates range from below \$US5 a tonne of carbon sequestered to above \$US200 a tonne, which ranges from highly attractive to prohibitively expensive for investors (see Harrison, 2013, and discussion in Boyd, 2008b). Macronutrient fertilisation has been estimated in 2010 as costing in optimal conditions US\$20 per tonne of carbon (Jones, 2014), although permitting and monitoring costs were not included.

Results from deliberate ocean iron fertilisation experiments show carbon sequestration efficiencies (C:Fe) in the range 650-25,000:1 (de Baar *et al.*, 2008), and are considerably less efficient than earlier estimates. This is likely due to the loss of the added iron via absorption on to sinking particles and rapid grazing of phytoplankton. In contrast, some studies of naturally iron-fertilised waters has found higher efficiencies (e.g., Blain *et al.*, 2007), but again with considerable variability among naturally fertilised regions (Morris and Charette, 2013), perhaps



The Hope

Plankton populations rebound to historic levels, reviving fisheries and sequestering vast amounts of carbon

The Fear

Iron leads to depletion of deep-water oxygen, alters food chain, and promotes toxic species; CO₂ soon resurfaces

FIGURE 6: Cartoon depicting potential outcomes of ocean iron fertilisation. It is not yet known whether fertilisation might generally enhance ecosystem production and drawdown of CO₂ ('the hope'), or whether this might lead to substantial and unwanted ecosystem changes that ultimately might do little or nothing to enhance CO₂ drawdown ('the fear').

Source: <http://www.motherjones.com/files/legacy/news/outfront/2008/03/dumping-iron-1000.jpg>

as a result of differences in the supply mechanisms or the maturity of the ecosystems (Trull *et al.*, 2015). Enhancement of the biological pump by artificial upwelling is less efficient, because the upwelled nutrients are accompanied by high initial CO₂ contents (Oschiles *et al.*, 2010a).

The estimates of Buesseler *et al.* (2008) estimated an upper bound for carbon sequestration of 0.5 gigatonnes of carbon per year, corresponding to a reduction of 0.24 parts per million (volume) atmospheric carbon dioxide per year (Cullen & Boyd 2008), which represents less than 5 per cent of the cumulative emissions of carbon from fossil fuel burning. Notably, this sequestration estimate was based on a modelling study of global ocean iron fertilisation (Aumont and Bopp 2006), a scale that may be unachievable. For a fuller discussion, see Boyd (2008b), de Baar *et al.* (2008)

(i) Ecosystem changes

Although ocean iron fertilisation experiments conducted to date have resulted in changes to ecosystem community structure, no harmful algal blooms have been observed. However, shipboard experiments in the North Pacific have shown that diatom species which produce the toxin domoic acid might increase in abundance following iron addition (Silver *et al.*, 2010). Inadvertent nitrogen fertilisation of the coastal ocean by urea in sewage favours the growth of cyanobacteria and dinoflagellates species, some of which may be toxic (Glibert *et al.*, 2008). Open-ocean deliberate fertilisations have been of insufficient temporal and spatial scales to reveal biodiversity changes at higher trophic levels within the food chain, and therefore we do not presently know whether there will be positive or negative impacts on ecosystems as a whole or on fisheries (Figure 2), although the healthy state of naturally iron fertilised waters provides a basis for optimism.

(ii) Production of climate-relevant gases

Ocean fertilisation may increase the atmospheric concentrations of a range of climate-relevant gases associated with phytoplankton growth. These include dimethylsulphide (DMS) which influences climate via the formation of particles that promote cloud formation. Other volatile trace gases may affect tropospheric ozone concentrations. The links between trace gas production and climate, and thus the overall significance of such effects, is currently unclear. Long-lived greenhouse gases such as nitrous oxide and methane may also be produced at mid- and deep- waters upon decomposition of additional sinking biomass, particularly under low oxygen conditions

such as in the tropics. These gases have global warming potential which are orders of magnitude greater than carbon dioxide, and this may offset the desired effects of CO₂ sequestration if they reach the sea surface and are emitted to the atmosphere. However, only minor increases in nitrous oxide production have been observed during iron addition experiments (Law *et al.*, 2001), and thus negative ecological or climatic risk has not been demonstrated.

(iii) Far-field effects

Vertical and horizontal transport and mixing processes in the ocean will result in effects being observed many hundreds or thousands of kilometres from the fertilisation site, and several months, years or decades afterwards. Effects will become more significant with increases in scale and duration of fertilisation. For example, the addition of iron to the iron-limited Southern Ocean will result in depletion of other non-limited nutrients (such as nitrogen and phosphorous), which will reduce the productivity of regions downstream of the fertilisation location, including closeby countries not involved with the fertilisation activity (referred to as "nutrient robbing"). Similarly, additional carbon dioxide taken up locally due to fertilisation can result in a reduced carbon uptake capacity in a remote region ('CO₂ sink robbing'), and this must be budgeted in determining the overall CO₂ sequestration enhancement (Gnanadesikan *et al.*, 2003). Potential impacts on subsurface waters and sediments require an accurate knowledge of biomass production and sinking alongside ocean circulation and mixing. These are major difficulties for the attribution of impacts and verification of sequestration. Modelling will be the best tool to use to assess far-field effects.

and the 2008 thematic section on ocean iron fertilisation in the journal *Marine Ecology Progress Series*.

Risks

Ocean fertilisation may result in several unintended and undesirable impacts. This aspect has greatest degree of uncertainty and therefore requires further investigation (Figure 6).

Potential problems, discussed below, have been identified in several reviews (Secretariat of the Convention on Biological Diversity, 2009; Williamson *et al.*, 2012), but evaluations are lacking.

(iv) Subsurface oxygen decrease

Decomposition of sinking plant biomass and enhanced downward carbon export following fertilisation will decrease sub-surface oxygen concentrations, which could, at least in shallow waters, lead to critical oxygen thresholds being crossed (for instance, anoxia leading to significant mortality of marine organisms). Mid-water oxygen depletion has not been reported for fertilisation experiments conducted to date due to their limited scale and duration, although models demonstrate an increase in the extent of low-oxygen regions following large-scale fertilisation (Oschiles *et al.*, 2010b).

(v) Effects on seafloor ecosystems

Large-scale ocean fertilisation may have a positive or negative effect on seafloor ecosystems, depending on water depth, particle sinking rates, rate of biomass decomposition and its background state (Lampitt *et al.*, 2008). This will be extremely difficult to monitor because of the remoteness of the deep seas.

(vi) Ocean acidification

Substantive carbon sequestration following fertilisation would affect the extent and distribution of ocean acidification, with a reduction in the rate of acidification in the upper ocean (which tracks atmospheric levels) but with waters in the deep ocean interior becoming more acidic. Thus ocean fertilisation may act to ameliorate ocean acidification in surface waters where most of the marine life is located (Cao and Caldeira, 2010). But in deeper waters, negative impacts are to be expected, including the shallowing of the 'saturation horizon' for carbonate minerals, thereby reducing the ability of deep-sea organisms such as corals to build shells and other structures.

MONITORING: VERIFICATION, ATTRIBUTION AND REVERSIBILITY OF IMPACTS

In addition to the uncertain understanding of fertilisation efficiency, capacity and risk, there are significant issues regarding the assessment of fertilisation outcomes and the assessment of whether fertilisation experiments should be allowed.

Monitoring

Trials to properly assess the effectiveness of large-scale ocean fertilisation are likely to be needed at the scale of approximately 10,000 km², with measurements over several months to years (Watson *et al.*, 2008). Monitoring must be sufficiently extensive to provide defensible verification that fertilisation objectives have been achieved without unacceptable or unintended negative impacts. Effective monitoring will be costly, will present considerable logistical challenges, and cannot be achieved with currently available observing capabilities.

Verification

Ocean fertilisation activities will need to be matched by an accurate assessment of their effectiveness. To use results from ocean fertilisation in any carbon trading scheme which would permit the claiming of “carbon credits”, verification must be based on measurements of the amount of carbon sequestered to the deep sea – and for the length of time such sequestration occurs. Where the objective is to increase biomass at a particular trophic level – such as for the purposes of fisheries enhancement – then the increase in biomass of the target species must be measured.

In all cases, verification requires monitoring of changes in both the fertilised areas and adjacent areas that were not fertilised but were otherwise similar, and far-field monitoring to determine if there are subsequent rebound effects that might offset some of the initial change (e.g., “nutrient robbing” and “CO₂ sink robbing”) or might have negative impacts. For carbon accounting, the benefits from ocean fertilisation need to be quantified within pre-agreed confidence limits, and show not only the additional amount of carbon initially exported, but also the average time period for which it will be sequestered. Long-term monitoring over decades will also be needed to determine whether deleterious side effects are within acceptable limits.

Reversibility

Reversibility is an important consideration affecting the acceptability of ocean geoengineering proposals (Boyd, 2008a). Although none of the iron fertilisation experiments have demonstrated long-term alteration of ocean ecosystems, and the scale and duration have mimicked natural bloom events, the results of these studies cannot be directly extrapolated to the much larger scales envisioned for operational geoengineering. Large-scale regime shifts may occur within marine ecosystems following deliberate



Pete Harmsen/MNF

Australian researchers deploy equipment for studying Southern Ocean chemistry

CARBON TRADING

It has been suggested that the sequestration of atmospheric CO₂ via ocean fertilisation – once it is verified as a concept with a proven range of metrics such as how much, for how long and where – might be used in a carbon trading scheme, using carbon credits.

The Australian Securities and Investment Commission describes carbon trading as:

Carbon trading is when you buy and sell carbon credits (also called carbon offsets). Carbon credits are tradable units that often relate to emissions reduction or sequestration activities, such as tree planting, improving energy efficiency or capturing methane from landfill.

Source: <https://www.moneysmart.gov.au/investing/complex-investments/carbon-trading>

fertilisation, but it may not be possible to attribute impacts to events, distinguish cause and effect, or to restore the system to its previous condition. The ability to halt any undesirable effects will depend on the length of time that the agent of perturbation (e.g., iron) remains in the environment. Given that a key term in international environmental law is ‘precaution’, without a significant understanding of and confidence in these factors, it is unlikely that geoengineering of this kind will be permitted.

SUMMARY OF KEY MESSAGES

TABLE 1



Marine phytoplankton diatoms

The issue

What we know

Efficacy

Experiments have shown that iron additions to high nutrient low chlorophyll regions can greatly increase phytoplankton and bacterial productivity and biomass, and draw down CO₂ in surface waters.

Capacity

The amount of carbon that might be taken out of circulation via iron fertilisation, on a long-term basis (decades to centuries) is small (<1 GTC/yr) in comparison to anthropogenic emissions (~9GTC/yr).

Risk

Large-scale fertilisation could have unintended and difficult to predict impacts, not only locally, but also far removed in space and time. The potential for negative impacts is expected to increase with the scale and duration of the fertilisation.

Mother nature has been shown to carry out iron fertilisation of open-ocean waters without any known deleterious effects, in fact natural Fe fertilisation underpins high value biodiversity and fisheries in the Southern Ocean, although macronutrient additions in other coastal regions have negative impacts (e.g., eutrophication).

Verification

Monitoring must be an essential component of any large-scale fertilisation activity, both to check claims of carbon sequestration (for intended geoengineering benefit) and to assess ecological impacts.

International legal status of ocean fertilisation activities

Ocean fertilisation is deemed to be "placement" not "dumping" under LP and there is a recommendatory moratorium on operational activity. This can be lifted simply by the agreement of the Parties to do so.

The IMO moratorium allows for and provides guidelines to assess 'legitimate scientific research'. The UN CBD has a moratorium in place, which is poorly worded. It appears to allow research in coastal waters (where some impacts are likely to be most deleterious) but not in open ocean waters.

What we don't know

The fraction of carbon exported from surface to the deep ocean is uncertain. This is largely because scientific experiments to date have been short-term (weeks) and of relatively small scale (up to 100 km²).

Natural experiments have been shown to have a high carbon sequestration efficiency, but it is uncertain whether this can be achieved artificially.

The additional CO₂ uptake capacity from nitrogen fertilisation is probably similar to that of Fe fertilisation, because lack of phosphate ultimately limits both, but no studies have been carried out.

It is not yet known how artificial ocean fertilisation would affect zooplankton, fish and seafloor biota. Risks include toxic algal blooms, oxygen depletion, changes to ocean acidification patterns and the production of greenhouse gases such as nitrous oxide and methane that would offset the value of CO₂ uptake.

Optimal fertilisation strategies to avoid these impacts have not been developed. Reversibility may not be as simple as stopping the fertilisation, if ecological responses were to become self-sustaining in some way.

While models can be developed to improve predictions of both benefits and impacts, the totality of effects will be extremely difficult to either predict or verify, with implications for the confidence and cost-effectiveness of large-scale applications.

There is no formal process for assessing when it would be safe to lift the moratorium. The components that should be included in the definition of 'legitimate scientific research' are debatable, e.g. should only government-funded research be permitted; should the research only be conducted within national jurisdiction; should the research only be approved by an independent scientific body; or should approval be based solely on the principles within the Assessment Framework?

What is required

An understanding of factors controlling the penetration of carbon to ocean depths, with more focus on mesopelagic processes.

More knowledge of the coupled interactions of ocean circulation and both trace and major nutrient biogeochemical cycles are needed.

Impact assessments need to include the possibility of unwanted effects on biological productivity, subsurface oxygen levels, biogas production and ocean acidification, at both local and remote scales. Future experiments need to assess the relative probability of each of these deleterious effects.

More science on the links between primary productivity resulting from fertilisation and fisheries is required by tracing the impact up the food chain.

Results should inform the future status of existing moratoria.

Monitoring will need to assess benefits and risks and:

- (i) include a wide range of sensitive parameters;**
- (ii) take into account natural variability, preferably by including comparison with several otherwise similar but non-fertilised regions; and**
- (iii) continue over appropriate time and space scales, potentially over several years and covering many thousand km²**

Scientific research must continue to play a significant role in informing the status of ocean fertilisation activities.

Conflicting definitions leading to competing jurisdictions between various organisations and regimes, e.g. the IMO and the CBD, should be resolved.

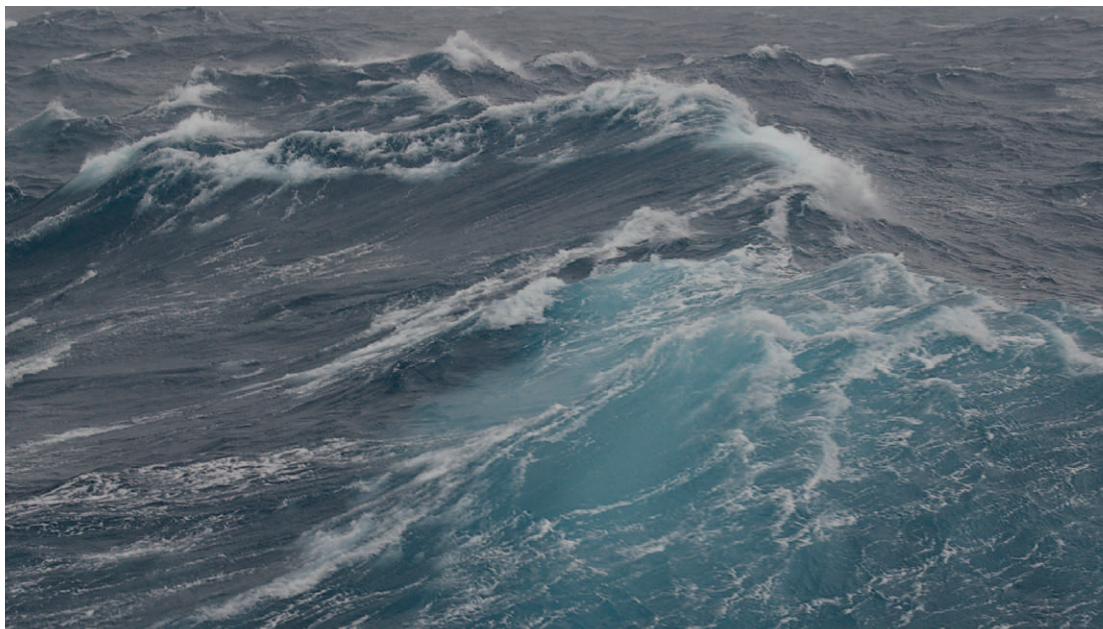
Further research is needed to define, in the context of geoengineering, the scope, scale, intensity, duration, location, environmental and ecological impacts and objectives of "legitimate scientific research".

COMPARISON WITH OTHER MARINE GEOENGINEERING SCHEMES

This document focuses on ocean fertilisation, but there are also other geoengineering schemes that use the ocean for carbon dioxide removal. Slight extensions to the fertilisation idea include adding 'complexing agents' to keep iron in solution, and seeding ocean regions with fast growing phytoplankton or seaweeds with high carbon/nutrient ratio compositions (perhaps produced by genetic modification).

Other proposals focus on chemical processes, for instance adding alkaline substances such as lime, limestone, or basaltic rocks, to enhance the solubility of carbon dioxide. Useful overviews and comparisons of these and other schemes have been published, which include commentary on the risks and relative merits of such schemes (e.g., Boyd, 2008a; Royal Society, 2009; Vaughan and Lenton, 2011; Mathesius *et al.*, 2015; Matear and Lenton, 2015).

The London Protocol adoption of a general approach to the regulation of marine geoengineering could cover these possibilities. Simply injecting liquid or solid carbon dioxide directly into the deep sea has also been considered but this has restrictions attached to it and concerns over transport are considerable. At the LC35 Meeting of Parties in 2013, the meeting adopted in principle the "Guidance on the implementation of article 6.2 on the export of carbon dioxide streams for disposal in sub-seabed geological formations for the purpose of sequestration". This will regulate an activity that would otherwise be prohibited: "the export of carbon dioxide streams for disposal in accordance with Annex 1 may occur, provided that an agreement or arrangement has been entered into by the countries concerned" (LC35 Report).



Steve Hinchou

LEGAL AND POLICY ISSUES

International Approaches

Organisations as diverse as the International Oceanographic Commission and the Intergovernmental Panel on Climate Change, with a range of different responsibilities, have taken a serious interest in the concept of ocean fertilisation since the early 2000s. A number of multilateral legal conventions have direct relevance to artificial ocean fertilisation and its potential consequences including the UN Convention on the Law of the Sea – UNCLOS, the Convention on Biological Diversity (CBD), and the International Convention for the Prevention of Marine Pollution from Ships – MARPOL. The one that has proven most appropriate to regulate the activities that are undertaken during artificial ocean fertilisation is the London Convention/London Protocol. It is the action of placing potentially unacceptable foreign material into the marine environment that is the primary determinant for regulation. What occurs as a result of that initial action may be deemed under this or other legal regimes as a pollution event or an activity that might cause harm to marine species and the marine environment.

Even though regulation that prevents an activity is likely to be the most effective, there are several problems stemming from accepting LC-LP as the legal instrument of authority in this case. The first is that there are only 45 contracting parties, out of a potential 200, and significant non-parties are the United States and Russia. Secondly, there are jurisdictional limits which do not include the high seas, or ships flagged to non-parties, for example, and they broaden the potential for active non-compliance (Ginzkey and Frost 2014: 93). In any case, preventing or minimising harm is the customary law obligation on states regarding potential transboundary pollution.

Statements of concern from disparate organisations have encouraged further scientific study of iron fertilisation experiments/activities to address efficacy, capacity, risk, verification and reversibility because of the high level of uncertainty that remains. The London Protocol parties have accepted their primacy in regulating ocean fertilisation and as a consequence have taken the front running by defining ‘ocean fertilisation’, deeming it to be ‘placement of matter for a purpose other than mere disposal’ rather than ‘dumping’ (LP4.8, Annex 4.), providing, of course, that the placement itself is not in contravention of the objectives of the Protocol. They have also developed assessment framework. The framework for the environmental assessment of proposals for ocean fertilisation research on a case-by-case basis is based on the agreed definition and compliance with the aims and objectives of the Protocol (LC-LP2, 2010). London Protocol Parties are encouraged to use the assessment framework to determine “with utmost caution” the acceptability of a proposal. Under LP4(8)3, an initial assessment should determine whether or not the proposal is in fact a legitimate scientific research project involving “ocean fertilisation”. If it is, a risk analysis should

be undertaken using variables such as problem formulation, site selection, exposure assessment, effects assessment, risk characterisation and risk management to provide the basis for a decision. Monitoring will be an integral part of any approved 'legitimate scientific research' activity. In addition, under the Assessment Framework rules, Contracting Parties are obliged to consult with states that might be affected by any such research, and to obtain their consent when necessary before issuing permits.



Southern Ocean seafloor ecosystem

If Parties adopt the environmental assessment framework domestically, then together with their extant legislation, sufficient controls on ocean fertilisation should be achievable in the short term. London Protocol Parties reaffirmed the use of the Assessment Framework in the 2013 amendment of the Protocol to regulate ocean fertilisation.

Australian Domestic Approaches

As a party to the London Protocol moratorium the Commonwealth government has legislation it should invoke to curtail or prevent rogue ocean fertilisation activities like the Haida experiment off Canada in Australian waters (Table 3). Depending upon where activities were to be conducted, in addition to any state legislation which applies to coastal waters (within 3 nm), the Commonwealth can rely on the *Environment Protection (Sea Dumping) Act 1981*, as amended (*Sea Dumping Act*) and the *Environment Protection and Biodiversity Conservation Act 1999*, as amended (EPBC Act).

Any ocean fertilisation activities proposed for Australian territorial sea, exclusive economic zone and waters above the continental shelf by an Australian national or company on any vessel, using a substance that is a 'controlled material' under the *Sea Dumping Act* would require a permit. Additionally, an Australian vessel operating outside Australia's national jurisdiction would also require a permit. The meaning of "controlled material" is the same in the *Sea Dumping Act* as in the LP – the latter prohibits dumping except for a list of materials for which dumping may be considered under a permit. The substance descriptions "*inert, inorganic geological material*" (such as iron) and "*organic material of natural origin*" (such as urea) are the two most likely to be relevant to this discussion. The LP parties (including Australia) encourage legitimate scientific research and if activities are assessed as not contrary to the aims of the Protocol (and deemed to be placement rather than dumping), it might be thought probable that permits would be achieved under this Act.

However, Australia can also manage and regulate ocean fertilisation activities through the EPBC Act and its *national interest* provisions. According to these provisions, ocean fertilisation could be deemed an *action* causing a *likely*

significant impact on a matter of national environmental significance (particularly in relation to threatened species and the marine environment) that would require assessment and approval under the EPBC Act before it could be undertaken. Further, a requirement to take account of the *precautionary principle* (s391) would almost certainly preclude permission, simply on the basis of the levels of scientific uncertainty described earlier in this document.

Relevant Australian Legislation

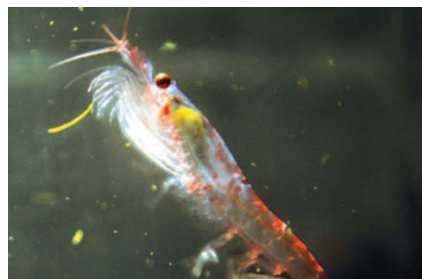
Obtaining a permit for sea dumping

The *Sea Dumping Act* implements Australia's international obligations under the London Protocol. Under the *Sea Dumping Act*, all dumping at sea is prohibited, except for possibly acceptable wastes which may be considered under a permit. Irrespective of the fact that the London Protocol has defined the actions carried out during ocean fertilisation as "placement" there is still the requirement to determine whether such placement is contrary to the aims of the London Protocol, and hence a permit may still be required.

The London Protocol Annex 1 lists the following waste categories that may be considered for a permit:

- 1 Dredged material;
- 2 Sewage sludge;
- 3 Fish waste, or material resulting from industrial fish processing operations;
- 4 Vessels and platforms or other man-made structures at sea;
- 5 Inert, inorganic geological material;
- 6 Organic material of natural origin;
- 7 Bulky items primarily comprising iron, steel, concrete and similarly unharmed materials for which the concern is physical impact, and limited to those circumstances where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other than dumping;
- 8 Carbon dioxide streams from carbon dioxide capture processes for sequestration (noting that carbon dioxide streams may only be considered for dumping if: disposal is into a sub-seabed geological formation; and they consist overwhelmingly of carbon dioxide (they may contain incidental associated substances derived from the source material and the capture and sequestration processes used); and no wastes or other matter are added for the purpose of disposing of those wastes or other matter).

Currently under the *Sea Dumping Act*,⁵ the matter to be placed under an ocean fertilisation activity would need to fall under one of the waste categories above for a permit to be considered.



Antarctic krill

⁵ <http://www.environment.gov.au/topics/marine/marine-pollution/sea-dumping/sea-dumping-act>

Australia has not yet ratified the 2013 amendment to the Protocol to regulate ocean fertilisation, but is committed to the 2008 and 2010 resolutions to regulate ocean fertilisation

Relationship with EPBC Act

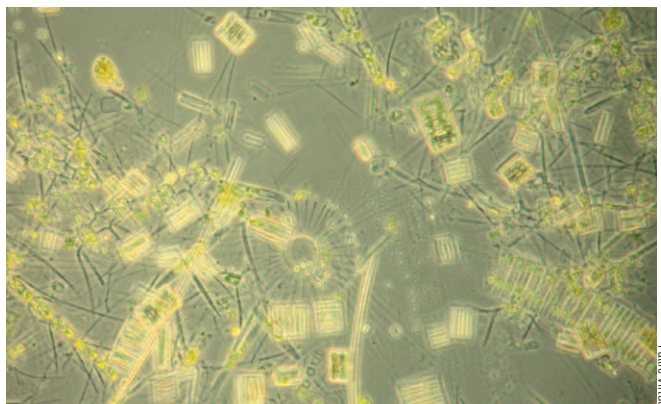
At the same time an application for a permit is reviewed by the Sea Dumping authority, it is also reviewed for impacts covered under the *EPBC Act*'s 'national environmental significance' charter (Figure 7). Chapter 2, §23.1 of this Act outlines how the Minister might decide whether an action has, will have, or is likely to have, a significant impact on a matter of national environmental significance – in this case the Commonwealth marine environment. The decision is achieved by prohibiting a person from taking an action without Ministerial approval or by the Minister making a decision that approval is not needed. In short, a person must not take an action that has, will have, or is likely to have, a significant impact on a matter of national environmental significance such as the Commonwealth marine environment.

There are guidelines that provide direction in how to evaluate the meaning of significance:

*A 'significant impact' is an impact which is important, notable, or of consequence, having regard to its context or intensity. Whether or not an action is likely to have a significant impact depends upon the sensitivity, value, and quality of the environment which is impacted, and upon the intensity, duration, magnitude and geographic extent of the impacts.*⁶

Australian scientific researchers would theoretically need to gain a permit under the *Sea Dumping Act*, but more likely, approval under the *EPBC Act*. Invoking the precautionary approach because of the lack of scientific certainty, approval under the latter would then be available only at the Minister's discretion. Considering that more scientific research is required, gaining approval this way is a possibility.

Should the government wish it, a domestic moratorium on ocean fertilisation scientific experiments could be accomplished simply by withholding permission under the *Sea Dumping* and/or *EPBC Acts*. This would also apply to commercial operations.



Palmer Virtue

⁶ <http://www.environment.gov.au/epbc>

Sea ice algae

The Haida Gwaii activity occurred without the knowledge of the Canadian or provincial governments, however, and it is possible to evade regulation by conducting activities offshore, far from monitoring capabilities, such as in the Southern Ocean. In addition, the London Protocol treaty amendment of 2013 (Ginzky and Frost, 2014) only applies to those that are contracting parties (and still only in a voluntary way until Parties have ratified or acceded to the amendment). It also needs to enter into force (when 2/3 majority of parties have ratified or acceded). It is interesting to note there have to date been no ratifications or accessions to the 2013 amendment to the Protocol to regulate ocean fertilisation, however in adopting the amendment, the Parties (including Australia) reaffirmed that the 2008 and 2010 resolutions continue to apply for all Contracting Parties, pending the entry into force of the 2013 amendments (i.e., that commercial activities are prohibited, and only legitimate scientific research could be considered if assessed through the Assessment Framework for Scientific Research Involving Ocean Fertilisation). Any research that involves addition of substances in the marine environment is likely to require assessment under the Environment Protection Biodiversity Conservation Act 1999 and the Environment Protection (Sea Dumping) Act 1981.

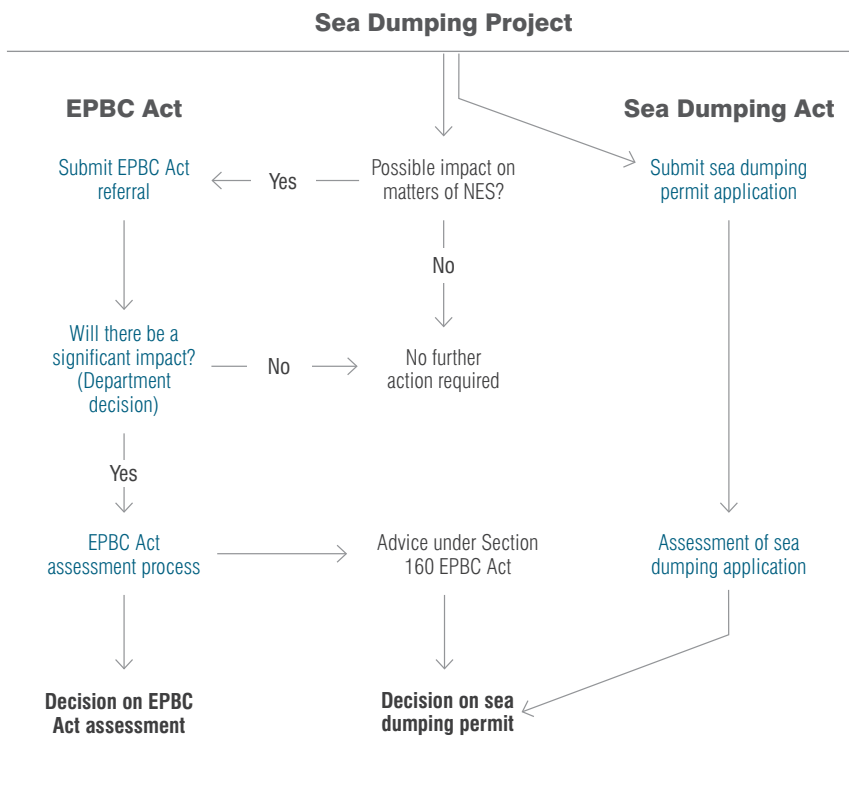


FIGURE 7: Relationship between EPBC Act and Sea Dumping Act. Source: <http://www.environment.gov.au/coasts/pollution/dumping/relationship-epbc.html>

FUTURE RESEARCH NEEDS AND STRATEGIES

Ocean fertilisation experiments have been highly valuable for studying the dynamics of marine biogeochemical cycles and the functioning of ocean ecosystems (Figure 8). There have, however, been no scientific ocean fertilisation experiments since Lohafex in 2009 (Martin *et al.*, 2013). This is in part due to the UN Convention on Biological Diversity de facto moratorium, but also due to an increasing recognition that individual small-scale experiments are unlikely to ever resolve critical questions about the long-term consequences of ocean fertilisation for climate change mitigation (Watson *et al.*, 2008; Smetacek and Naqvi, 2008).

Recently, the Committee on Geoengineering Climate (National Research Council) highlighted several important future research directions (National Research Council, 2015; p. 62-3, from Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration):

- Understanding the effectiveness of iron inputs on stimulating biological organic carbon production and increasing carbon export;
- Determining the fate of the sinking organic carbon and iron in the subsurface ocean as a result of deliberate ocean iron fertilisation;



Australian researchers deploy equipment for studying Southern Ocean chemistry

Pete Hamson/MNF

- Assessing potential downstream effects that may limit biological productivity or change other aspects of biogeochemistry in other regions;
- Detection and accounting of net changes in subsurface ocean carbon sequestration and the effective lifetime of the carbon sequestration; and
- Understanding the ecological and biogeochemical consequences of extended and large-scale iron fertilisation.

The committee concluded:

“In summary, current limitations of ocean iron fertilisation as a viable CDR method include the limited knowledge regarding the method’s effectiveness in regard to carbon capture, concerns regarding the environmental impacts and cost of large-scale and sustained OIF, and the associated ethical and legal issues. Although about a dozen ocean iron fertilisation field experiments have been conducted, their purpose was fundamental scientific research primarily related to the basic controls on ocean biology and biogeochemistry. Many unresolved issues remain regarding scalability, efficacy, verification, and environmental impacts. Given these limitations and

unknowns, the committee concludes that the risks and costs currently outweigh the benefits. The committee considers this an immature CDR technology with high technical and environmental risk.”

There remains, however, much to be learnt through future scientific research on ocean fertilisation and scientists should be encouraged to improve our understanding of the ocean’s response to nutrient addition.

The best path forward for this may be through examination of ‘natural’ iron fertilisation, which have included multiple recent studies in the Southern Ocean (e.g., FeCycle (Boyd *et al.*, 2005), SAZ-Sense (Bowie *et al.*, 2009), CROZEX (Pollard *et al.*, 2007), Blue Water Zone (Zhou *et al.*, 2010), KEOPS (Blain *et al.*, 2007)).

Circa 1990

Today

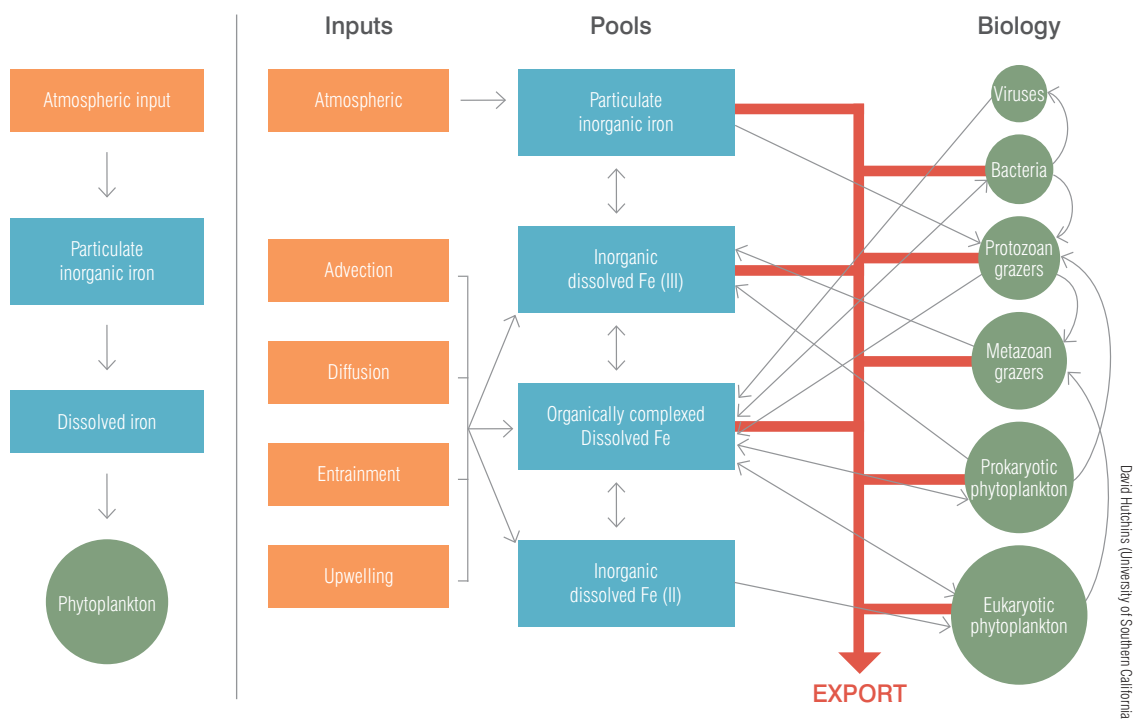


FIGURE 8: Evolution of our understanding of the marine biogeochemical cycle.

The natural iron fertilisation studies in the Southern Ocean (Figure 9) have focused on areas where iron was supplied to the upper ocean through natural processes such as sedimentary resuspension (de Baar *et al.*, 1995), island run-off (Bowie *et al.*, 2015), glacial melt (Raiswell *et al.*, 2008) and sea ice melt (Lannuzel *et al.*, 2015). Sea ice covers about 40 per cent of the Southern Ocean during winter and triggers massive seasonal blooms in the marginal ice zone during spring. The oceans around Australia also receive large amount of terrestrial aerosols such as iron-laden dust particles which are transported far out to sea in dust storms (Jickells *et al.*, 2005). Tracking these iron sources and quantifying their effects on carbon sequestration and ecosystem health is an important path forward. The scales of natural iron fertilisation studies are essential controlled by the scale of natural iron supply, and thus can provide better analogues to widespread fertilisation than individual experiments. In addition, the maturity of the ecosystems receiving iron through natural processes should

There will be natural changes in iron fertilisation of the ocean in the next century as the climate evolves. Understanding the magnitude and effect of such changes on ocean biogeochemical cycles is important

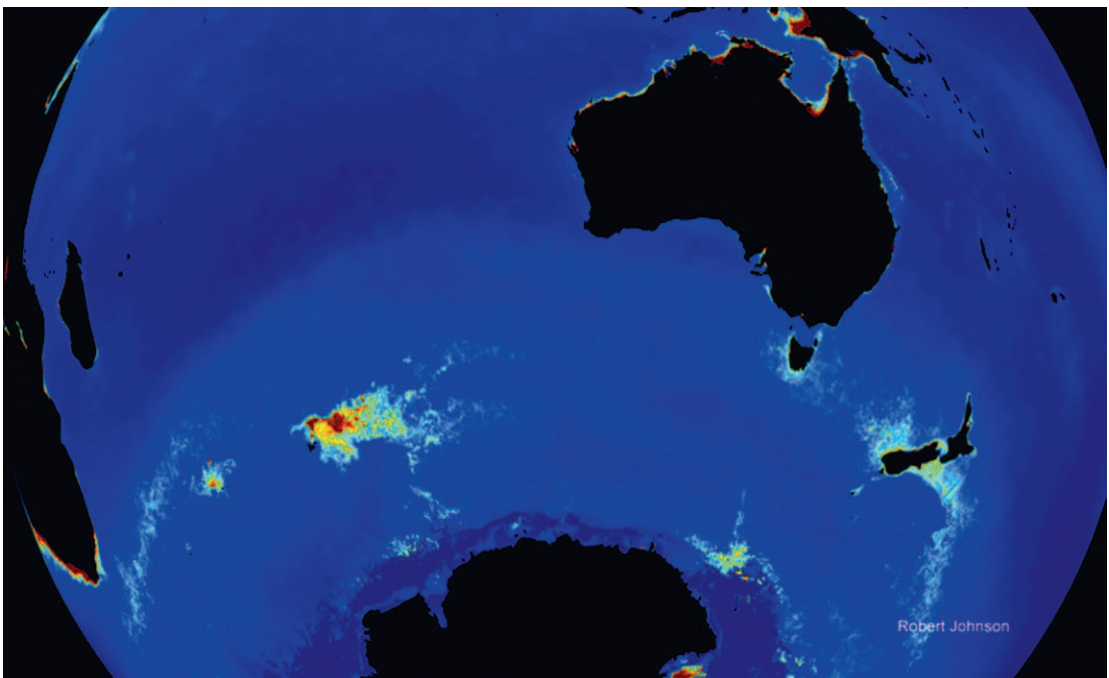


FIGURE 9(a): Satellite image of the Southern Ocean showing phytoplankton blooms hundreds to thousands square kilometres in size downstream of Tasmania, New Zealand, Antarctic islands, and especially the Kerguelen plateau. This region has been the focus of two major French-Australian natural iron fertilisation studies called “KEOPS” which have observed enhanced carbon sequestration and healthy ecological conditions.

provide a good guide to longer-term ecological impacts, both positive and negative.

Whether natural experiments are the right way to evaluate future geoengineering through ocean fertilisation is still being debated, and at present we do not know enough from natural iron work to inform governments about the efficacy of ocean fertilisation as a potential and safe CO₂ mitigation strategy. Regardless, there will be natural changes in iron fertilisation of the ocean in the next century through an evolving climate (e.g., increased dust delivery, strengthening boundary currents, deoxygenation, acidification, sea level rise, sea ice reduction, and glacial melt) and understanding the magnitude and effect of such changes on ocean biogeochemical cycles is important in its own right.

Since the ACE CRC's previous Position Statement on Ocean Fertilisation in 2008 (Trull *et al.*, 2008) which contributed to the formulation of the position of the Australian delegation to the IMO, our understanding has evolved from condemnation based on potential risk (which is looking increasingly overstated) to one of lack of demonstrable/verifiable/affordable benefit. That in itself raises challenges for future regulatory processes.

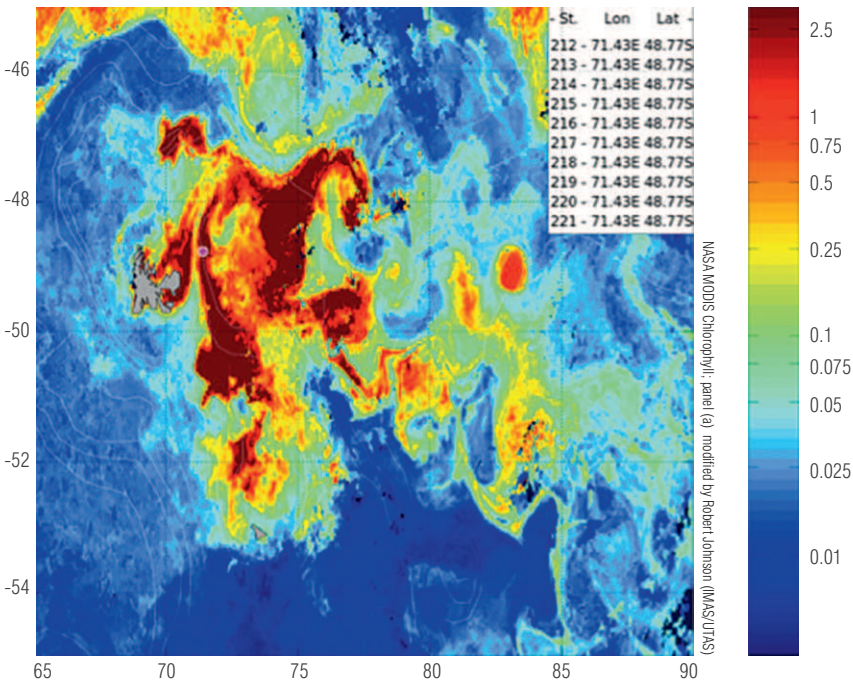


FIGURE 9(b): Ocean colour image of complex structure of the phytoplankton bloom over the Kerguelen plateau as studied during the KEOPS-2 program on November 11, 2011. The grey surface at 49°S, 70°E is Kerguelen Island. Colour scale: Chlorophyll concentration ($\mu\text{g L}^{-1}$)

FURTHER READING

Reports and reviews

- Boyd PW (2008a) Ranking geo-engineering schemes. *Nature Geoscience* 1, 722-4
- (2009) Secretariat of the Convention on Biological Diversity. Scientific Synthesis of the Impacts of Ocean Fertilisation on Marine Biodiversity. Montreal, Technical Series No. 45, 53 pages, <http://www.cbd.int/doc/publications/cbd-ts-45-en.pdf>
- Enhanced Carbon Storage in the Ocean (ECOR) (2011) Enhanced Carbon Storage in the Ocean working group, http://www.oceanicresources.org/wp-content/uploads/2012/03/ECOR_WG_Report_4.6_clean.pdf
- Flannery T. (2015). *Atmosphere of Hope: Searching for Solutions to the Climate Crisis*. : Text Publishing, 272pp, ISBN 9781925240191
- Intergovernmental Panel on Climate Change (IPCC) (2012) Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.-K. Plattner, S. Schlömer, G. Hansen, M. Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 99 pp.
- Lampitt et al. (2008) Ocean fertilisation: a potential means of geoengineering? *Phil Trans Roy Soc A*, 366 (1882), 3919-45
- Markels et al. (2011) Enhanced carbon storage in the ocean. Report of Engineering Committee for Oceanic Resources (ECOR), version 4.6. Online at www.oceanicresources.org/wp-content/uploads/2012/03/ECOR_WG_Report_4.6_clean.pdf
- National Oceanic and Atmospheric Administration (NOAA) (2010) Ocean Fertilisation: the potential of ocean fertilisation for climate change mitigation. Report to Congress. Requested on page 636 of House Report 111-366 accompanying the fiscal year 2010. Consolidated Appropriations Act (PL 111-117), http://www.gc.noaa.gov/documents/2010_climate_fert_rept_Congress_final.pdf
- National Research Council (2015). *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: The National Academies Press, ISBN 978-0-309-30529-7, 140pp.
- Royal Society (2009) *Geoengineering the climate: science, governance and uncertainty*. RS Policy Document 10/09, London, 82 pp., ISBN: 978-0-85403-773-5
- Vaughan, N. E., and T. M. Lenton (2011). A review of climate geoengineering proposals. *Climatic Change*, 109(3-4), 745-790.
- Wallace D.W.R., Law C.S., Boyd P.W., Collos Y., Croot P., Denman K., Lam P.J., Riebesell U., Takeda S., Williamson P. (2010). *Ocean Fertilisation. A Scientific Summary for Policy Makers*. IOC/JUNESCO, Paris (IOC/BRO/2010/2). <http://unesdoc.unesco.org/images/0019/001906/190674e.pdf>
- Williamson et al. (2012) Ocean fertilisation for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection*, Volume 90, Issue 6, November 2012, Pages 475-488, doi:10.1016/j.psep.2012.10.007
- Bowie et al. (2015). Iron budgets for three distinct biogeochemical sites around the Kerguelen Archipelago (Southern Ocean) during the natural fertilisation study, KEOPS-2. *Biogeosciences* 12 (14), 4421-4445
- Boyd et al. (2000) A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* 407, 695 - 702
- Boyd et al. (2005) FeCycle: Attempting an iron biogeochemical budget from a mesoscale SF6 tracer experiment in unperturbed low iron waters. *Global Biogeochem. Cycles*, 19, GB4S20, doi:10.1029/2005GB002494
- Boyd, P.W., and T. W. Trull (2007), Understanding the export of marine biogenic particles: is there consensus?, *Progress in Oceanography*, 4, 276-312, doi:10.1016/j.pocean.2006.10.1007.
- Boyd et al. (2007) Mesoscale iron enrichment experiments 1993-2005: synthesis and future directions. *Science* 315, 612-617, <http://dx.doi.org/10.1126/science.1131669>
- Boyd PW (2008b) Implications of large-scale iron fertilisation of the oceans - introduction and synthesis. *Mar. Ecol. Prog. Ser.* 364, 213-218, <http://dx.doi.org/10.3354/meps07541>
- Boyd et al. (2012) A new database to explore the findings from large-scale ocean iron enrichment experiments. *Oceanography* 25(4):64-71, <http://dx.doi.org/10.5670/oceanog.2012.104>
- Buesseler KO, Doney SC, Karl DM, Boyd PW and others (2008). Ocean iron fertilisation - moving forward in a sea of uncertainty. *Science* 319:162
- Charette, M. A., S. T. Gille, R. J. Sanders, and M. Zhou (2013), Southern Ocean natural iron fertilisation, *Deep-Sea Research Part II*(90), 1-3.
- Cullen JJ and Boyd PW (2008) Predicting and verifying the intended and unintended consequences of large-scale ocean iron fertilisation. *Marine Ecology Progress Series*, 364, 295-301, <http://dx.doi.org/10.3354/meps07551>
- Cao L and Caldeira K (2010) Can ocean iron fertilisation mitigate ocean acidification? *Climatic Change* 99, 303-11
- de Baar et al. (2005). Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature* 373, 412 - 415; doi:10.1038/373412a0
- de Baar et al. (2005) Synthesis of iron fertilisation experiments: from the iron age in the age of enlightenment. *J. Geophys. Res.* 110, <http://dx.doi.org/10.1029/2004JC002601>, C09S16
- de Baar et al. (2008) Efficiency of carbon removal per added iron in ocean iron fertilisation. *Marine Ecology Progress Series*, 364, 269-82
- Glibert et al. (2008) Ocean urea fertilisation for carbon credits poses high ecological risks. *Marine Pollution Bulletin* 56, 1049-56
- Gnanadesikan, A., J. L. Sarmiento, and R. D. Slater (2003), Effects of patchy ocean fertilisation on atmospheric carbon dioxide and biological production, *Global Biogeochemical Cycles*, 17(2), 1050-.
- The Guardian (2012). World's biggest geoengineering experiment 'violates' UN rules. Martin Lukacs, [theguardian.com](http://www.theguardian.com/environment/2012/oct/15/pacific-iron-fertilisation-geoengineering), Monday 15 October 2012, <http://www.theguardian.com/environment/2012/oct/15/pacific-iron-fertilisation-geoengineering>
- Güssow, K., A. Proelss, A. Oschlies, K. Rehdanz, and W. Ricketts (2010), Ocean iron fertilisation: Why further research is needed, *Marine Policy*, 34(5), 911-918.
- Harrison, D P (2013) A method for estimating the cost to sequester carbon dioxide by delivering iron to the ocean. *International Journal of Global Warming*, 5, issue 3, 231-254.
- Jickells T.D., An Z.S., Andersen K.K., Baker A.R., Bergametti G., Brooks N. et al. (2005). Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* 308, 67-71.
- Jones, ISF (2014) The Cost of Carbon Management using Ocean Nourishment *International Journal of Climate Change Strategies and Management*, 6, 391-400.
- Judd B., Harrison D.P., Jones I.S. (2008). Engineering ocean nourishment, *Proceedings of the World Congress on Engineering Vol II*, London, U.K. ISBN:978-988-17012-3-7.
- Karl D.M., Letelier R.M. (2008). Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascape. *Marine Ecology Progress Series* 364, 257-268, doi:10.3354/meps07547.
- Lannuzel et al. (2015). Iron biogeochemistry in Antarctic pack ice during SIPEX-2. *Deep-Sea Research II*, doi:10.1016/j.dsr2.2014.12.003.

- Law CS, Ling RD (2001). Nitrous oxide flux and response to increased iron availability in the Antarctic Circumpolar Current. *Deep Sea Research Part II: Topical Studies in Oceanography*, Volume 48, Issues 11–12, 2001, Pages 2509–2527
- Lawrence, M. W. (2014). Efficiency of carbon sequestration by added reactive nitrogen in ocean fertilisation. *International Journal of Global Warming*, 6(1), 15–33.
- Le Quéré et al. (2015). Global carbon budget 2014. *Earth Syst. Sci. Data*, 7, 47–85. 10.5194/essd-7-47-2015.
- Lovelock J.E., Rapley C.G. (2007). Ocean pipes could help the Earth cure itself. *Nature* 449, 781, <http://dx.doi.org/10.1038/449403a>
- Markels, M. Jr., Barber R.T. (2001). Sequestration of carbon dioxide by ocean fertilisation. Paper presented at the 1st National Conference on Carbon Sequestration, National Energy and Technology Laboratory, Washington, DC, May 14–17, 2001.
- Martin et al. (2013). Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX. *Global Biogeochem. Cycles*, 27, 871–881, doi:10.1002/gbc.20077.
- Matear R.J., Elliot B. (2004) Enhancement of oceanic uptake of anthropogenic CO₂ by macronutrient fertilisation. *J Geophysical Research* 109 (C04001) doi: 10.10129/2000JC000321
- Matear R., Lenton A. (2015). Earth system modelling: Restoration of the oceans. *Nature Climate Change*, doi:10.1038/nclimate2737
- Mathesius S., Hofmann M., Caldeira K., Schellnhuber H.J. (2015). Long-term response of oceans to CO₂ removal from the atmosphere. *Nature Climate Change*, doi:10.1038/nclimate2729.
- Morris, P.J., and M. A. Charette (2013). A synthesis of upper ocean carbon and dissolved iron budgets for Southern Ocean natural iron fertilisation studies. *Deep Sea Research Part II: Topical Studies in Oceanography*, 90, 147–157.
- Oschlies et al. (2010a) Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters* 37, L04701, doi:10.1029/2009GL041961
- Oschlies et al. (2010b) Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilisation. *Biogeosciences* 7, 4017–4035, <http://dx.doi.org/10.5194/bg-7-4017-2010>.
- Pollard et al. (2009) The Crozet Natural Iron Bloom and Export Experiment (CROZEX). *Deep Sea Research Part II: Topical Studies in Oceanography*, Volume 54, Issues 18–20, September–October 2007, Pages 1905–1914, doi: 10.1016/j.dsr2.2007.07.023
- Pollard et al. (2009) Southern Ocean deep-water carbon export enhanced by natural iron fertilisation. *Nature Vol 457 | 29 January 2009 |* doi:10.1038/nature07716
- Raiswell, R., Benning, L.G., Tranter, M. and Tulaczyk, S. (2008) Bioavailable iron in the Southern Ocean: the significance of the iceberg conveyor belt. *Geochemical Transactions*, 9, doi: 10.1186/1467-4866-9-7.
- Sarmiento, J. L., and C. Le Quéré (1996). Oceanic carbon dioxide uptake in a model of century-scale global warming. *Science*, 274, 1346–1350.
- Schiermeier Q. (2003). Climate change: The oresmen. *Nature* 421, 109–110, doi:10.1038/421109a
- Secretariat of the Convention on Biological Diversity, U. (2009). Scientific Synthesis of the Impacts of Ocean Fertilisation on Marine Biodiversity Rep., 53 pp, Montreal, CA.
- Silver et al. (2010) Toxic diatoms and domoic acid in natural and iron enriched waters of the oceanic Pacific. *Proceedings of the National Academy of Sciences* vol. 107 no. 48, 20762–20767, doi: 10.1073/pnas.1006968107
- Smetacek V and Naqvi W.A. (2008). The next generation of iron fertilisation experiments in the Southern Ocean. *Phil. Trans. R. Soc. A* vol. 366 no. 1882, 3947–3967. Doi: 10.1098/rsta.2008.0144
- Smetacek et al (2012) Deep carbon export from a Southern Ocean iron-fertilised diatom bloom. *Nature* 4787, 313–319. Doi:10.1038/nature11229
- Strutton P (2012). Mixing iron into the north Pacific stirs geo-engineering controversy. *The Conversation*, 8 November 2012. <http://theconversation.com/mixing-iron-into-the-north-pacific-stirs-geo-engineering-controversy-10490>
- Tollefson J (2012) Ocean-fertilisation project off Canada sparks furore. *Nature*, 490, 458–459
- Trull, T., S. R. Rintoul, M. Hadfield, and E. R. Abraham (2001). Circulation and seasonal evolution of polar waters south of Australia: Implications for iron fertilisation of the Southern Ocean. *Deep-Sea Research Part II-Topical Studies in Oceanography*, 48(11–12), 2439–2466.
- Trull et al. (2015) Chemometric perspectives on plankton community responses to natural iron fertilisation over and downstream of the Kerguelen Plateau in the Southern Ocean. *Biogeosciences* 12, 1029–1056, 10.5194/bg-12-1029-2015, 2015.
- Volk, T., Hoffert, M. I. (1985): Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO₂ changes, in: *The Carbon Cycle and Atmospheric CO₂: Natural Variations Archaean to Present*, 32 ed., edited by: Sundquist, E., and Broecker, W. S., Geophys. Monogr., AGU, Washington, D. C., 99–110.
- Watson et al. (2008) Designing the next generation of ocean iron fertilisation experiments. *Mar. Ecol. Progr. Ser.* 364, 303–309, <http://dx.doi.org/10.3354/meps07552>
- White, A., K. Björkman, E. Grabowski, R. Letelier, S. Poulos, B. Watkins, and D. Karl (2010). An Open Ocean Trial of Controlled Upwelling Using Wave Pump Technology. *Journal of Atmospheric and Oceanic Technology*, 27(2), 385–396.
- Wolff et al. (2011) The Effects of Natural Iron Fertilisation on Deep-Sea Ecology: The Crozet Plateau, Southern Indian Ocean. *PLoS ONE* 6(6): e20697. Doi:10.1371/journal.pone.0020697
- Xiu P, Thomas A.C., Chai F. (2014). Satellite bio-optical and altimeter comparisons of phytoplankton blooms induced by natural and artificial iron addition in the Gulf of Alaska. *Remote Sensing of Environment* 145, 38–46
- Zhou M., Zhu Y., Dorland R.D., Measures C.I. (2010). Dynamics of the current system in the southern Drake Passage. *Deep Sea Res. I*, 57, 1039–1048.

Policy and governance

- Bertram C (2010) Ocean iron fertilisation in the context of the Kyoto protocol and the post-Kyoto process. *Energy Policy* 38, 1130–1139, <http://dx.doi.org/10.1016/j.enpol.2009.10.065>
- Blackstock JJ and Long JCS (2010). The politics of geoengineering. *Science* 327 (5965), 527
- Freestone D and Rayfuse R (2008) Ocean iron fertilisation and international law. *Mar. Ecol. Progr. Ser.* 364, 227–233, <http://dx.doi.org/10.3354/meps07543>
- Ginzky H, Frost R. (2014). Marine Geo-Engineering: Legally Binding Regulation under the London Protocol. *Carbon and Climate Law Review* 8(2), 82–96.
- Gussow et al. (2010) Ocean iron fertilisation: Why further research is needed. *Marine Policy* 34, 911–918. doi:10.1016/j.marpol.2010.01.015
- International Maritime Organization (2013). Marine geoengineering including ocean fertilisation to be regulated under amendments to international treaty. 35th Consultative Meeting of Contracting Parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention) 8th meeting of Contracting Parties to the 1996 Protocol thereto (London Protocol). <http://www.imo.org/MediaCentre/PressBriefings/Pages/45-marine-geoengineering.aspx>
- Leinen M (2008) Building relationships between scientists and business in ocean iron fertilisation. *Marine Ecology Progress Series*, 364, 251–6
- Mayo-Ramsay J (2010) Environmental, legal and social implications of ocean urea fertilisation: Sulu sea example. *Marine Policy* 34, 831–35
- Scott K (2013) 'International Law in the Anthropocene: Responding to the Geoengineering Challenge' 34 *Michigan Journal of International Law* 309, 322.
- Strong AL (2009) Ocean fertilisation. *Science, policy and commerce. Oceanography*, 22, 236–261

Commercial interests

- Atmocean Inc (wave-driven ocean upwelling system) www.atmocean.com
- Ocean Nourishment Corporation Pty Ltd (macronutrient additions to enhance fish stocks and carbon sinks) www.oceannourishment.com
- Climos (potential application of ocean iron fertilisation) www.climos.com
- Planktos (seeding the ocean to capture carbon) www.planktos.com; recently funded by the Haida Salmon Restoration Corporation to fertilise the North Pacific Ocean off Canada <http://science.haidasalmon.net>



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