PCAS 17 (2014/2015)

Supervised Project Report
(ANTA604)

The Future of Iron Fertilisation Experiments

Hannah Udell

Student ID: 85693423

Word count: 7395 (excluding abstract and references)

Abstract/executive summary

The Iron Hypothesis put forward by J. H. Martin (1990) is behind the development of artificial iron fertilisation as a geoengineering method which could be used to draw down anthropogenic carbon dioxide (CO_2) levels. The Southern Ocean, which is rich in macronutrients but iron limited, is a focus for experiments on iron fertilisation. The past experiments (1999 to 2009) have shown that iron increases phytoplankton bloom productivity, and utilised surface water CO_2, which would promote draw down of atmospheric CO_2. What has not been proven to a climatically relevant extent is the export of carbon to the deep ocean, and over what time scale it could be stored for. These are key components of a CO_2 removal method. Also poorly monitored as a result of increased productivity, were side effects such as ecosystem community structures, local food web impacts or the production of other greenhouse gases such as nitrous oxide (N_2O). Future experiments should be conducted to understand these side effects and increase monitoring and validation of carbon export, if iron fertilisation is to be considered a legitimate method for CO_2 removal.

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Introduction

Current global climate change has been described as a combination of natural and anthropogenic forces. The Intergovernmental Panel on Climate Change (IPCC) have defined climate change as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2013).

One of the main observations in past climate research are the alternating levels of atmospheric carbon dioxide (CO_2) over glacial to interglacial cycles. These are most notable in the Vostok ice core records back 400,000 years (Petit et al., 1999), but also over the last two million years (Sigman & Boyle, 2000). The pacing of this climate change has reflected natural Milankovitch cycles in the Earth's orbit over 100, 42, and 21 thousand year cycles (Sigman & Boyle, 2000). The average levels of atmospheric CO_2 over each glacial to interglacial cycle ranges between 180 and 280 ppm (Petit et al., 1999). With the addition of anthropogenic CO_2 into the atmosphere, the current level is now pushing 400 ppm (Ciais et al., 2013).

In an effort to reduce atmospheric CO_2 levels, geoengineering methods have been put forward for consideration. Geoengineering has been described by the IPCC as methods to deliberately alter the climate system in order to alleviate the impacts of climate change (IPCC, 2013), of which carbon dioxide removal (CDR) is a component. CDR methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere, primarily by increasing natural sinks for carbon with the intent of reducing the atmospheric CO_2 concentration. CDR methods mostly involve the ocean and land systems, including artificial ocean fertilisation, artificial ocean upwelling, and afforestation (IPCC, 2013).

This paper is going to look into one CDR method, artificial ocean fertilisation using iron, with a Southern Ocean focus. This method uses iron to increase productivity of phytoplankton blooms in the oceans where iron is limited, which will subsequently draw down atmospheric CO_2 levels. This paper will briefly introduce the carbon cycle, followed by an introduction to iron. Past artificial and natural iron fertilisation experiments in the Southern Ocean are analysed and the consequences and knowledge gaps will be identified.

The key questions this paper will ask include the effectiveness of the method for increasing ocean productivity, for sequestering CO_2 from the atmosphere, and how much of an impact the side effects will have on local and global ocean waters.

Carbon Cycles

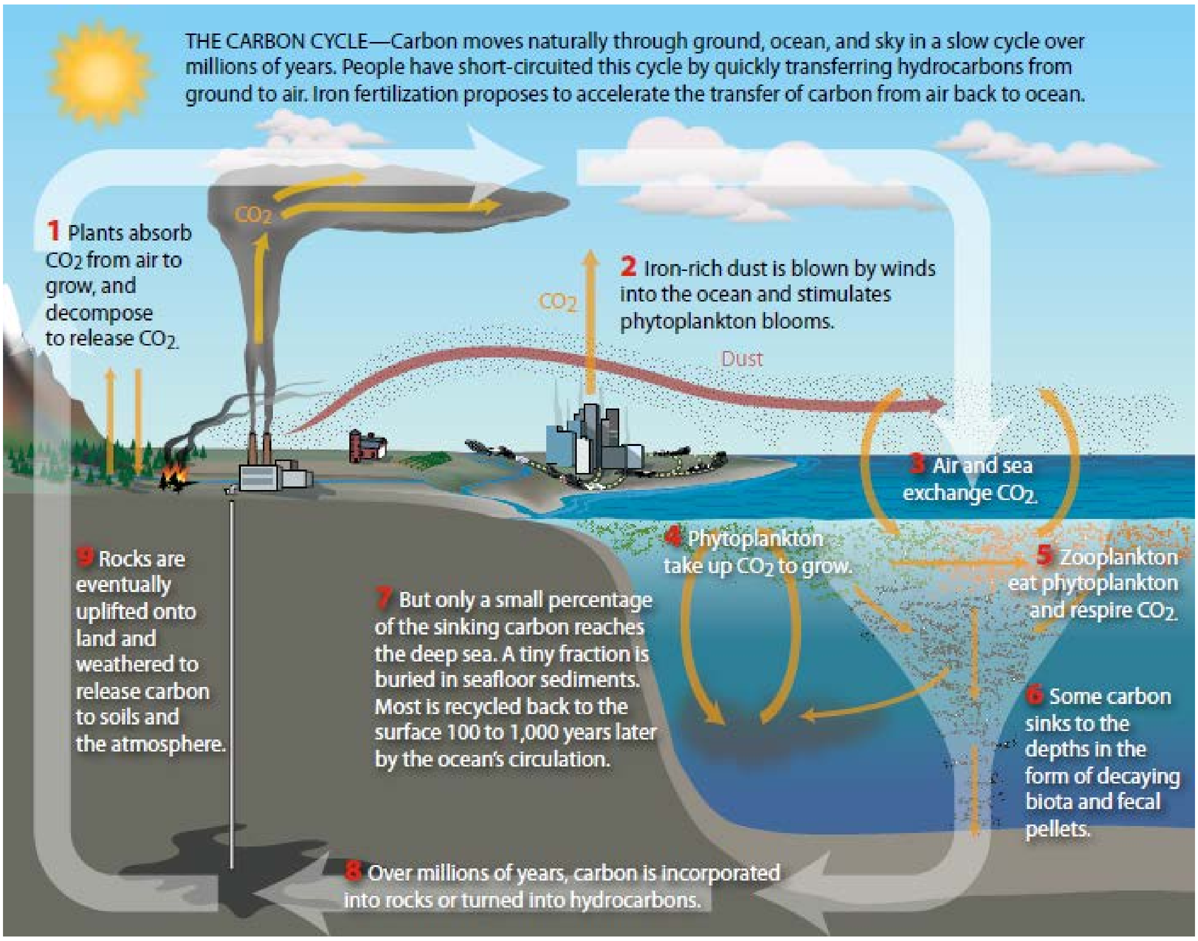
The carbon cycle includes land, air and sea components, which act to regulate the global storage of carbon. Figure 1 shows a simplified cycle of these components. With regards to ocean fertilisation, the oceanic component of the carbon cycle will be discussed here.

Within the ocean, carbon is typically held as Dissolved Inorganic Carbon (DIC) (carbonic acid, bicarbonate and carbonate ions), as well as a smaller pool of Dissolved Organic Carbon (DOC), dominated by marine organisms including phytoplankton (Ciais et al., 2013). The transfer of atmospheric CO_2 into ocean waters is due to difference in partial pressure of CO_2 (pCO_2) between the atmosphere and the surface ocean. These are balanced by gas exchange at the surface ocean. If the ocean had increased pCO_2 in comparison to the atmosphere, then CO_2 would be released from the ocean into the atmosphere to balance the pressure gradient. Balancing CO_2 is a key component of the iron fertilisation methodology.

The oceanic carbon cycle and the influence on pCO_2 is utilised by two key mechanisms outlined below.

The biological pump: This is the process of transporting carbon from the surface ocean to the deep ocean by the primary production of marine phytoplankton, which converts DIC and nutrients into organic matter through photosynthesis, sequestering CO_2. This natural cycle is limited primarily by the availability of light and macronutrients such as phosphate, nitrate and silicic acid, and micronutrients, such as iron (IPCC, 2013). Particles of organic matter (DOC) sink to the deep ocean, usually as faecal pellets, and store the sequestered CO_2 in the deep ocean waters or sediments. Figure 2 shows a model of this process.

The marine carbonate pump: This relates to the process within the biological pump where carbonate ions are incorporated into calcareous shells of microorganisms in the surface ocean. During formation of calcareous shells, two bicarbonate ions split into one carbonate ion and one dissolved CO_2 molecule, which acts to increase pCO_2 in the surface water, promoting release of CO_2 into the atmosphere (Ciais et al., 2013). Subsequent re-mineralisation of shells after sinking, into calcium and carbonate ions, releases the sequestered CO_2 back into the ocean waters.



THE CARBON CYCLE—Carbon moves naturally through ground, ocean, and sky in a slow cycle over millions of years. People have short-circuited this cycle by quickly transferring hydrocarbons from ground to air. Iron fertilization proposes to accelerate the transfer of carbon from air back to ocean.

1 Plants absorb CO_2 from air to grow, and decompose to release CO_2.

2 Iron-rich dust is blown by winds into the ocean and stimulates phytoplankton blooms.

3 Air and sea exchange CO_2.

4 Phytoplankton take up CO_2 to grow.

5 Zooplankton eat phytoplankton and respire CO_2.

6 Some carbon sinks to the depths in the form of decaying biota and fecal pellets.

7 But only a small percentage of the sinking carbon reaches the deep sea. A tiny fraction is buried in seafloor sediments. Most is recycled back to the surface 100 to 1,000 years later by the ocean's circulation.

8 Over millions of years, carbon is incorporated into rocks or turned into hydrocarbons.

9 Rocks are eventually uplifted onto land and weathered to release carbon to soils and the atmosphere.

Figure 1: The carbon cycle showing land, ocean and atmospheric components, from Powell (2008a).

Iron in the Southern Ocean

The Southern Ocean is classed as a high nutrient, low chlorophyll (HNLC) ocean, with some limiting nutrients resulting in low phytoplankton productivity rates (Wadham et al., 2013). It was proposed that iron is the key limiting nutrient on productivity levels as it lowers the rate phytoplankton can uptake major nutrients found in HNLC waters such as nitrogen and phosphorous (J. H. Martin, 1990). Iron is also required for the processes of photosynthesis and respiration.

J. H. Martin (1990) proposed the Iron Hypothesis, where atmospheric dust as a supply of iron during glacial periods, increased phytoplankton productivity in the Southern Ocean. He suggested that iron enhanced the uptake of upwelled major nutrients, as the water was no longer iron limited and this utilised more surface water CO_2. The increased productivity subsequently drew down atmospheric CO_2, resulting in lower glacial CO_2 ppm values. Sigman and Boyle (2000) suggest that up to 25% of the drop in atmospheric CO_2 levels during the last glacial period was linked to iron increased productivity.

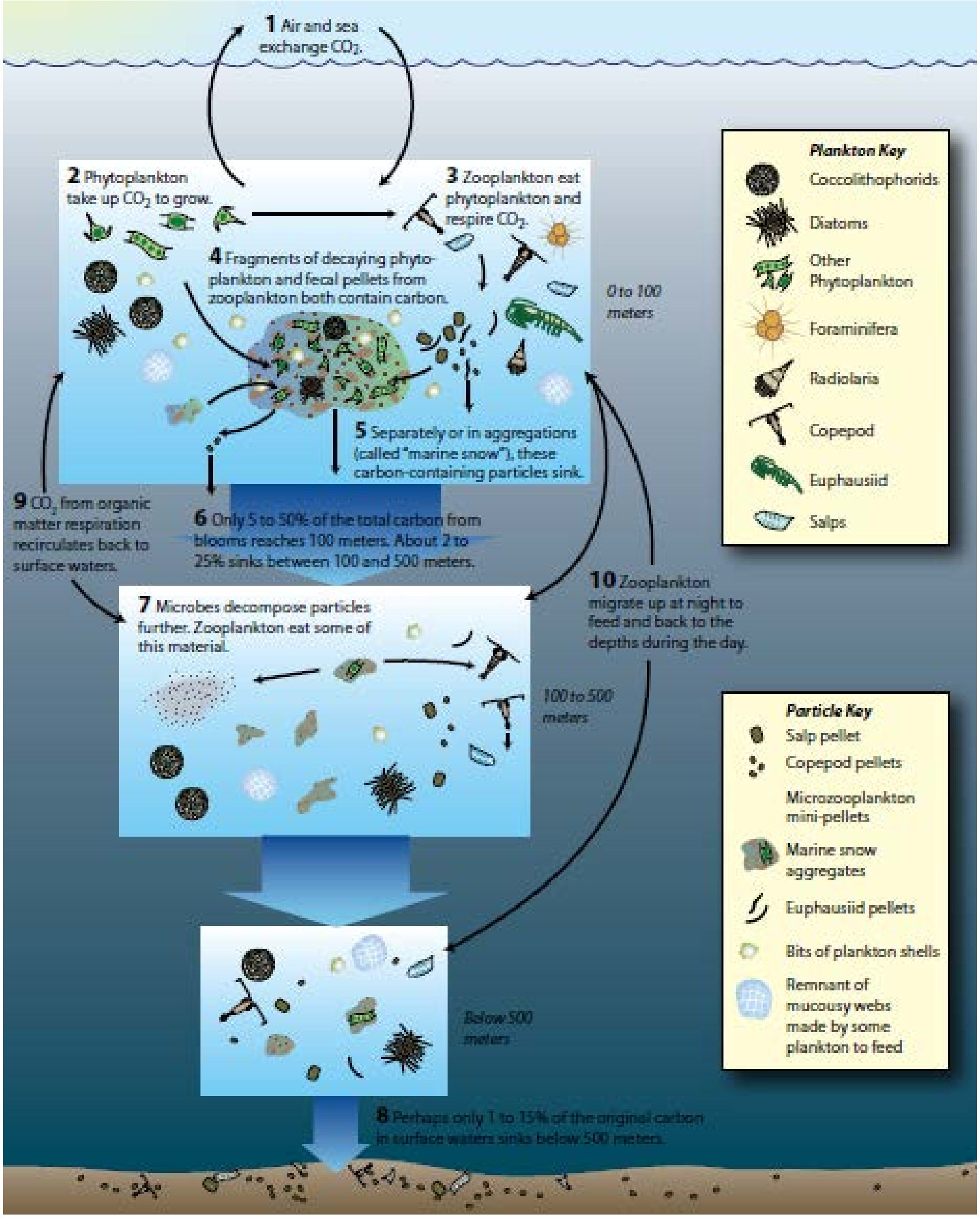


Figure 2: The role of plankton in the biological pump within the carbon cycle, from Powell (2008c).

With regards to the Southern Ocean, naturally available iron which increases productivity is typically sourced in four ways. These were highlighted by J. H. Martin (1990) and remain the most influential. Sediments from neritic environments, on continental shelves, are naturally rich in iron as the bottom sediments can become suspended. J. H. Martin (1990) outlined that neritic environments around Antarctica show higher levels of productivity, especially off islands, in comparison to open waters. Atmospheric dust increases productivity in these open waters further off shore, sourced mainly from the Australian interior and Patagonian desert (Wadley, Jickells, & Heywood, 2014). Another source of iron in Antarctic and Southern Ocean waters is ice rafted debris released from melting glaciers and icebergs. Glacial run off as a source of iron has recently been attributed to a phytoplankton bloom in the Amundsen Sea (Alderkamp et al., 2012). The fourth source, which acts more as iron storage (Wadley et al., 2014) is sea ice, which collects atmospheric dust over the winter and releases these nutrients into spring/summer waters as the sea ice melts (J. H. Martin, 1990).

A recent study on these four iron sources in the Southern Ocean stated that neritic sediments are a significant source of iron, and that icebergs and glacial ice provide hotspots of productivity (Wadley et al., 2014). The model ran by Wadley et al. (2014) showed that during winter, phytoplankton productivity is low, and light limited, but as spring arrives, productivity rapidly increases around islands with neritic sources of iron. To the north of the Antarctic Peninsula, productivity in spring is affected by both neritic iron and iceberg supply (Wadley et al., 2014). The model also highlighted strong phytoplankton blooms in areas of the Antarctic coastline where retreating ice increases available light and allows increased productivity with higher iron levels, also most likely from sediments and icebergs (Wadley et al., 2014).

The model results showed that iron supply in the Southern Ocean was 89% from sediment sources, 11% from iceberg melt, and 0.3% from atmospheric dust (sea ice was modelled as storage only) (Wadley et al., 2014). One interesting result in the model was that the small 0.3% supply of atmospheric dust was 50 times more effective at increasing productivity over the other two methods (Wadley et al., 2014). This led to conclusions that atmospheric dust is able to be immediately utilised in the surface waters by phytoplankton, whereas iron from neritic sediments for example likely gets scavenged in deeper water before it reaches the surface (Wadley et al., 2014). In line with this, iceberg melt sources of iron are very isolated which lowers overall productivity. This paper summarised that it is the inability of the Southern Ocean waters to hold iron in a dissolved state, without the impact of grazing, which limits the supply to the surface waters, even in high source zones such as shallow continental shelf coastal environments (Wadley et al., 2014). This adds to the HNLC classification of the Southern Ocean.

Due to the limitation but high levels of macronutrients, water in the Southern Ocean has been the focus of research into the Iron Hypothesis, as adding iron is highly likely to promote phytoplankton blooms and increase productivity. As proposed in the Iron Hypothesis, the Southern Ocean waters are likely to be able to store increasing amounts of CO_2 from the increased productivity. This concept lies behind the use of artificial ocean fertilisation as a CDR method. Increased productivity and increased sequestration of CO_2 into the deep water would reduce the anthropogenic CO_2 levels through partial pressure balance. The following section outlines some iron fertilisation experiments that have tested the Iron Hypothesis for CO_2 draw down from increased productivity in the Southern Ocean.

Key Iron Fertilisation Experiments

Several artificial iron fertilisation experiments in the Southern Ocean have been undertaken in the past to assess the Iron Hypothesis proposed by J. H. Martin (1990). While natural Southern Ocean iron sources are known (and some experiments have analysed these), the artificial fertilisation experiments aimed to understand the limitations on productivity in HNLC waters. Iron was added into the surface waters, following the effective utilisation observed by atmospheric dust as a source of iron (Wadley et al., 2014). Some of these experiments also attempted to assess carbon export as a result of the increased productivity. Evidence of carbon sequestration and export would be required to move from scientific experiments to use as a CDR method.

Artificial Experiments

SOIREE

The Southern Ocean Iron Release Experiment (SOIREE) was the first experiment in the Southern Ocean to test artificial iron fertilisation. This took place in 1999, south of the Antarctic Polar Front (APF). Over the 13 day experiment, 3.8 tonnes of iron, as acidified $FeSO_4.7H_2O$, was added over a 50 km^2 area in the Australian-Pacific sector of the Southern Ocean. A sulphur hexafluoride (SF_6) tracer was also added to this mix (Boyd & Law, 2001).

This study increased photosynthesis of all algae size ranges, and the diatom dominated bloom lasted for over 40 days, shown in satellite images after the experiment (Boyd & Law, 2001). A 10% draw down of surface water CO_2 was recorded over the 13 days, promoting draw down of atmospheric CO_2 (Boyd & Law, 2001).

Drifting sediment traps at depth collected diatom-rich aggregates, however particulate export from the surface was not observed to have enhanced compared to a control area during the 13 day experiment (Boyd & Law, 2001). However, the end of the bloom was not observed which could have skewed export results. Horizontal dispersion of fertilised waters into surrounding HNLC waters over the 40 day bloom may explain lower sediment deposition rates (Boyd & Law, 2001). Also observed was an increase in dimethyl sulphide (DMS) and nitrous oxide (N_2O) from increased productivity (Boyd & Law, 2001).

EisenEx

This experiment took place in the Atlantic sector of the Southern Ocean in 2000. EisenEx was located within an eddy system, to contain the bloom within a circling system, reducing horizontal dispersion. A total of 2.3 tonnes of iron was released into a 50 km^2 area of ocean for this experiment, along with the tracer SF_6 (Bakker et al., 2005). The experiment lasted for three weeks to record the duration of the resulting diatom bloom.

In comparison to SOIREE, this experiment sequestered four times more surface water CO_2, which was attributed to the eddy motion and strong storms which increased surface water mixing (Bakker et al., 2005). Measurements of carbon export were not collected during this experiment.

SOFeX

This Southern Ocean Iron Experiment took place in 2002, in the Pacific sector of the Southern Ocean. Three ships were used for the two experiments, one north and one south of the Antarctic Polar Front. The primary objective was to compare carbon export in the northern, silica poor waters, against the southern, silica rich waters (Coale et al., 2004). Both the northern (1.7 tonnes iron over 225 km^2) and southern (1.2 tonnes iron over 225 km^2) experiments (with SF_6) yielded increased primary productivity (Coale et al., 2004).

Diatom blooms occurred in both patches, utilising a larger amount of silicate in the silica poor northern experiment (Krishnamurthy, Moore, & Doney, 2008), even though the dominant phytoplankton types in the northern experiment were non-siliceous (Coale et al., 2004). Increased carbon export was only observed as a lowering of surface water pCO_2 (Coale et al., 2004), however the rate was smaller than expected. The low rate of pCO_2 change was linked to both horizontal mixing (Krishnamurthy et al., 2008) and not being able to collect measurements as the end of the diatom bloom was not observed (Buesseler, Andrews, Pike, & Charette, 2004).

EiFEX

The European iron fertilisation experiment was also undertaken in an eddy system in line with the APF over 37 days in 2004. The key aims of this experiment were to assess the ecosystem community response and resulting carbon export (Cavagna et al., 2011).

Iron fertilisation, using 7 tonnes of iron with SF_6 over 150 km^2, prompted an increase in productivity and phytoplankton became dominated by diatoms (Cavagna et al., 2011). Due to mass mortality of some diatom species, carbon export was measured from 150 m water depth, to a depth over 1000 m (Victor Smetacek et al., 2012). This depth is important for long term sequestration of carbon from the atmosphere.

LOHAFEX

Another iron fertilisation experiment, LOHAFEX (*loha* meaning iron in Hindi) was conducted in an eddy in the Atlantic sector of the Southern Ocean in 2009 (P. Martin et al., 2013). Two tonnes of iron, from 10 tonnes of $FeSO_4.7H_2O$, with SF_6, was spread over a 300 km^2 area. A second batch of the same amount of iron was added after 18 days, in the longest artificial iron experiment so far which lasted 39 days (P. Martin et al., 2013). This part of the Southern Ocean was silica limited.

Primary productivity increased during this experiment. Diatoms were found in low concentrations due to silica limitation, while flagellates made up over 90% of the biomass (P. Martin et al., 2013). These flagellates grazed the other plankton and remineralised carbon in the surface waters, likely releasing CO_2 back into the water. There was no evidence of enhanced export during this experiment, and very little sediments collected in sediment traps, likely as a result of increased grazing (P. Martin et al., 2013).

Natural Experiments

KEOPS

This experiment, the KErguelen Ocean and Plateau compared Study, was conducted in 2005. The natural iron fertilisation experiment was conducted as Antarctic and Subantarctic islands show high levels of productivity due to natural iron export from the land and neritic sources (Blain, Quéguiner, & Trull, 2008).

Low levels of dissolved iron were recorded in the top 150 m, but water below 150 m, above the plateau, was enriched in iron. It was suggested that wave activity makes the deeper neritic iron available and also provides macronutrients to the surface water (Blain et al., 2008). Another reason why this area was chosen was due to weak currents around the plateau which increases the residence time of the bloom in the water, for almost the entire season (Blain et al., 2008).

The naturally fertilised bloom was dominated by large diatom species. The surrounding HNLC waters were a combination of nano- and micro-phytoplankton in comparison (Blain et al., 2008). Both grazing flagellates and viral production were observed to regulate productivity in the Kerguelen bloom (Blain et al., 2008).

The bloom was shown to be a deep sink of CO_2 compared to the surrounding waters. Zooplankton grazers were shown to export CO_2 as faecal pellets as the main control on carbon export. This accounted for a flux of carbon from the surface waters, to the plateau at 450m, between 25 and 40% compared to the control area (Blain et al., 2008).

CROZEX

The Crozet Islands and Plateau are located south of the Subantarctic Front within the Antarctic Circumpolar Current. This natural iron fertilisation experiment took place in the 2004-2005 austral summer (Pollard et al., 2009). The natural phytoplankton bloom occurs above deep water so sediment traps were positioned at approximately 100 and 3000 m water depth (Pollard et al., 2009).

The CROZEX study compared naturally fertilised areas with a HNLC zone of water close by. The results of the study found a two to three-fold increase in both productivity and carbon export at 100 m depth, and also a two to three-fold increase in sediments collected at 3000 m compared to the HNLC control area (Pollard et al., 2009).

Summary of Iron Fertilisation Experiments

In all experiments described above, primary productivity was increased (Wadham et al., 2013) and surface water CO_2 was depleted due to photosynthetic fixation (de Baar et al., 2005). This would have resulted in draw down of atmospheric CO_2 due to the air-sea exchange (de Baar et al., 2005). This proves the initial part of the Iron Hypothesis.

Similar methods were used in each experiment, and for artificial experiments, acidified $FeSO_4.7H_2O$ was commonly used as the iron source with SF_6 tracer. Experiments in eddy systems were observed to increase productivity and reduce horizontal dispersion of iron within the well mixed waters.

The timescale of iron fertilisation experiments has been relatively short, with only some of experiments observing the duration of the phytoplankton bloom. For these experiments, cost and logistics would have played a part in the duration. The different spatial and temporal scales in each experiment make comparison of the results difficult. Silica poor waters appeared to utilise less surface water CO_2 compared to silica rich waters. A lack of siliceous diatoms, which incorporate the CO_2 into their tests, would explain this.

Results from SoFex North and LOHAFEX have shown that silica is also a limiting nutrient in fertilisation experiments. The blooms resulting from fertilisation were diatom poor, and therefore less surface water CO_2 was observed to be incorporated (Coale et al., 2004) compared with the other fertilisation experiments with diatom rich blooms (P. Martin et al., 2013). It was then suggested that silica poor water masses, areas of nutrient co-limitation, were not suitable for iron fertilisation experiments in the Southern Ocean (P. Martin et al., 2013).

Export of carbon from surface waters was not commonly assessed. Some experiments only observed a reduction in surface water pCO_2. Some of these measured the export of carbon in sediments traps from the surface water. Both natural experiments, KEOPS and CROZEX, recorded carbon export and even noted a three-fold increase in sediments at 3000 m depth (Pollard et al., 2009). This shows that some experiments proved the second part of the Iron Hypothesis where reducing surface water pCO_2 can sequester atmospheric CO_2.

Naturally occurring iron in ocean waters is thought to be more usable to marine life than the iron artificially added to the oceans (Powell, 2008a) and therefore natural experiments are more likely to enhance surface water CO_2 uptake, as observed in KEOPS and CROZEX, compared to artificial results. Pollard et al. (2009) outlined one key difference between natural and artificial fertilisation, the accumulation of natural iron in water over winter. Pollard et al. (2009) state that the gradual increase in natural fertilisation in spring time as light limitation is slowly reduced, enhances productivity more than sudden fertilisation observed in artificial experiments. KEOPS authors explained that natural iron fertilisation experiments cannot be compared to artificial experiments as the impacts are significantly different on the changes in local ecosystem and the impact on biogeochemical cycles (Boyd et al., 2007).

The impact of grazing plankton species was noted in some of these fertilisation experiments. This could have prevented the sinking of CO_2 and likely released some of the utilised CO_2 back into the surface waters. The impact of grazing on bloom productivity appears to be an unknown component of the experiments. It is likely that grazing species in the local ecosystem regulate the blooms in naturally fertilised experiments, such as KEOPS, where the grazing species were observed to provide the carbon export into the deeper water (Blain et al., 2008). In comparison, the unknown ecosystem changes in artificial experiment areas could have different responses depending on the dominance of grazing species in those areas at the time.

It appears that, while the Iron Hypothesis was proven in the most part, there was little focus on the follow on effects of iron fertilisation on small or large temporal or spatial scales. The need to understand the impact on the local marine ecosystem, release of different greenhouse gases, and other consequential results are important for consideration if iron fertilisation experiments are going to continue, especially at larger scales. It will be very important to understand these consequences if iron fertilisation of the oceans is going to be considered as a CDR method to counter anthropogenic climate change.

Consequences and Knowledge Gaps

From the iron fertilisation experiments summarised above, some key consequences, both positive and negative, can be discussed. Each of these consequences will require further research in their own right, as the majority (especially the negative) are implied or suggested, with no/little conclusive evidence gathered during the experiments. The key consequences of fertilisation experiments are outlined below.

Positive

Productivity of phytoplankton in the surface ocean was shown to increase with iron fertilisation in the HNLC waters of the Southern Ocean, as proposed in the Iron Hypothesis. The whole size range of plankton species appeared to increase productivity and abundance, as well as grazing zooplankton in the area. Multiple experiments recorded lower surface water CO_2 levels as a result of the iron fertilised bloom. It was observed in some experiments and implied in others that through sea-air exchange, atmospheric CO_2 would have been drawn into the oceans and sequestered in deep ocean water as it sank as DOC through the water column. This links to the Iron Hypothesis where increased productivity, due to higher atmospheric dust levels in glacial periods, played a role in lowering atmospheric CO_2 levels (J. H. Martin, 1990).

The SOIREE and EisenEx experiments both showed a 'top hat effect' where the centre of the experiment showed uniform reductions in surface water CO_2, implying that the amount of iron added in this area was enough to overcome iron limitation, and productivity was close to a maximum rate (Bakker et al., 2005). This also showed that the macronutrients nitrate, phosphate and silicate did not become a limiting factor for productivity during these experiments, unless it was already limited (Bakker et al., 2005).

Linked to increased productivity of phytoplankton was the resulting production of DMS, observed in SOIREE and implied in other experiments. DMS acts as a nucleus for encouraging cloud formation. Increased cloud formation helps to reflect radiation from the sun and can act to cool the climate in the local area (Smetacek & Naqvi, 2008). This would enhance the cooling effect in line with the reduced atmospheric CO_2 levels. The amount of DMS which could be produced is unknown, and the size of the experiments could alter this, where larger experiments could produce larger volumes of DMS. We do not yet know this information so further research is required for this to be understood.

It was proposed that increasing the amount of plankton in a bloom would act to increase productivity within the local food web as a larger primary food source was provided by the bloom. No evidence was observed, or longer term monitoring installed, to analyse the effect of the phytoplankton blooms on the local food web during the past experiments. This effect has longer term implications from fertilisation experiments which need to be assessed. However, some in the commercial fishing industry believe that increased iron fertilisation of the ocean waters would increase fish stocks.

Commercial Fishing

A prominent example of this is from patents outlined by an American, Michael Markels. He attempted to patent the idea that by replacing the limiting nutrients such as iron in areas of low fish stocks, the larger food source in the phytoplankton bloom would increase growth and replenish the fish stocks (Markels, 1996). His patent suggested using 250,000 tonnes of iron fertiliser over a 140,000 km^2 area, but made little mention of the environmental impacts of an experiment this large, much larger than any mentioned earlier in this report. An experiment was not conducted.

More recently, in 2012, the Haida Salmon Restoration Corporation (HSRC) undertook a large scale fertilisation experiment in the HNLC waters off British Columbia in the northeastern Pacific Ocean. This experiment however, is under investigation as ocean fertilisation is prohibited under the Canadian Environmental Protection Act. As no scientific papers have been released as a result of this experiment, the HSRC website explained that 100 tonnes of iron sulphate and 20 tonnes of iron oxide were added to a 5,000 km^2 eddy, 300 nautical miles from the coastline (HSRC, 2015). According to the website, the phytoplankton bloom was timed to occur when salmon migrated through the area to provide a larger food source. In 2013 a surge in salmon stocks were recorded. While this cannot be directly linked to the iron fertilisation experiment, the HSRC are actively researching the link between them as a positive result of artificial iron fertilisation (HSRC, 2015). Again, as no papers have been released, any negative side effects of this large phytoplankton bloom are unknown. In any case, these results likely increase commercial interest in ocean fertilisation as a way to increase food availability in our ever growing world.

Negative

While increased productivity was observed in the past experiments, along with surface water CO_2 reductions, the lack of evidence for ongoing ecosystem effects will likely prevent commercial use of the method for fishing, and the lack of evidence for carbon export will likely prevent its utilisation as a CDR method for geoengineering the climate.

The experiments to date have primarily focused on monitoring productivity changes and understanding the limitations on productivity, so carbon export was not primarily monitored. Of the fertilisation experiments discussed in this paper, only two or three resulted in measured carbon export over the control levels, as a result of increased productivity. The lack of evidence for carbon export is a huge limit on the potential use of iron fertilisation as a CDR method.

It should be acknowledged that export of carbon to 100 m depth does not tend to sequester carbon from the atmosphere for a length of time which would impact climate. Sequestration over climatically relevant time periods should sink to depths below the thermocline (P. Martin et al., 2013). The thermocline occurs between 100 and 1000 m as a temperature gradient, lying between the surface ocean and the deep ocean, where mixing of deep and surface waters is prevented (IPCC, 2013). When sequestered CO_2 is unable to mix with the surface, it could be sequestered over century length timescales (Caldeira, 2005). We have little evidence so far that this could result from iron fertilisation experiments. Therefore, it is likely that future experiments will have to focus on the carbon export and sequestration monitoring to prove its worth as a CDR method, although knowledge of this as part of the biological pump would be worth the investigation.

Robinson et al. (2014) ran models to assess sequestration of carbon in the ocean waters over a period of 100 years, linked to IPCC guidelines. Their experiments looked at how much sequestered carbon remained below 1000 and 2000 m water depth, and therefore would be sequestered for 100 years or longer. For 1000 m depth, linked to the depth of the thermocline, the model results showed that 66% of the carbon that had been sequestered was re-exposed to the atmosphere over approximately 37 years (Robinson et al., 2014). A 29% leak of carbon was observed from 2000 m depth. The authors explained that depth criteria should be better understood for longer term storage of CO_2 in the oceans. Gaining a clearer understanding of the depth required for optimal sequestration is key to enhancing experiment potential in the future. This would need to take into account site specific depth levels for each experiment location. More research should be conducted to understand mechanisms behind CO_2 leakage, even from depths greater than 2000 m in the water column, if we are aiming to store excess atmospheric CO_2 at these depths.

None of the experiments monitored the side effects of the phytoplankton blooms on the local biomass or food web, however, changes in dominant diatom species was observed in some experiments due to silica limitation for example. Neither were the effects throughout the water column monitored. The focus seemed only to be the surface water depths. Honjo et al. (2014) explained that, as a result of this, changes through large parts of the biological pump are still unknown and therefore we need to undertake more research into these processes, before increasing the scale of iron enrichment experiments. Their paper states that, while we have knowledge of subsurface biomass, we are limited in knowledge regarding the biological cycle throughout the water column. In the euphotic zone (to approximately 100 m depth), phytoplankton productivity needs to be assessed for the community structure and possible changes, as well as export rates to deeper waters. In the mesopelagic zone (to approximately 1000 m depth), the impact of grazing and remineralisation by zooplankton/prokaryotes needs to be established for their impact on the flux of DOC from surface waters and potential return back again over short time periods. Then, in the bathypelagic zone, typically deeper than 1000 m depth and the largest reservoir of organic carbon, research is required to understand the stability of carbon held in sediments and microorganism assemblages (Honjo et al., 2014). It has also been proposed that an entire bloom collapse, such as observed in EiFEX, would be required to cause significant export of CO_2 from the euphotic zone to deeper waters, which again requires more research (Victor Smetacek et al., 2012). The latest IPCC report states that there is still a low confidence in the effects iron fertilisation (as CDR method) will have on the carbon and biogeochemical cycles in the ocean (Ciais et al., 2013).

Nutrient robbing from increased productivity within HNLC waters could lead to reduced macronutrients in the water mass as it is then transported around the oceans. This may impact productivity in waters downstream from the site of experiments. This was not observed or recorded in the small scale experiments discussed here, apart from utilisation of silica in silica limited experiments. Williamson et al. (2012) stated that this is more likely to occur on large scale experiments which could even lead to a redistribution or decrease in fish stocks, opposing the possible increased fish stocks proposed by Markels (1996). As neither larger experiments, nor monitoring have occurred to date, to understand these suggested implications on a more global scale, further research will be needed.

Ocean anoxia is a component of deep water which could be affected by increased productivity. Oxygen is utilised during decomposition of organic matter as it sinks through the water column (Powell, 2008b) resulting in low oxygen waters harmful to other marine life. This has not been observed in the experiments so far, as no deep water monitoring was in place, but would need to be considered as an important side effect for larger scale fertilisation experiments in the future (Williamson et al., 2012).

One consequence that was observed by some experiments was the release of N_2O, a greenhouse gas with a potential 300 times more than CO_2 (Williamson et al., 2012). A model ran by Jin and Gruber (2003) where iron fertilisation occurred over the entire Southern

Ocean (which is unrealistic) drew down of 60 ppm CO_2 over 100 years. However, they also noted that the reduction of atmospheric CO_2 could be offset by the emissions of N_2O through increased productivity, from a few percent to 100% (Jin & Gruber, 2003). Formation of N_2O in ocean waters utilised oxygen, therefore increasing N_2O production also aligns with decreased oxygen in deeper waters which could harm marine life. The amount of N_2O observed in the earlier small scale experiments was small, but scale could have influenced the levels of N_2O produced. Longer term experiments in the future would need to monitor this more closely.

One other component of the atmospheric system to consider is the ‘rebound effect’. This is defined as the balance in the system when CO_2 is removed from the atmosphere. The partial pressure between the atmosphere and the land/ocean reservoirs becomes reduced, so the land and ocean sinks become less likely to naturally draw down more CO_2 from the atmosphere. This could then prompt release of CO_2 from these reservoirs into the atmosphere to balance the partial pressure of CO_2 (IPCC, 2013). This highlights the likely requirement that, for a CDR method to mitigate atmospheric levels, twice the desired amount of CO_2 should be removed from the atmosphere due to the rebound and release of CO_2 from other natural carbon sinks (Clarke L., 2014).

As with many controversial topics, more negative impacts can be identified here in comparison to the positives, which are typically the reason for the experiments to take place. In this case, it would be wise to increase our research and understanding of these possible impacts, including knowledge of ecosystems within HNLC regions and how they link to global ocean processes, to decide if the positive impacts outweigh the negatives. Only then could iron fertilisation experiments be used commercially, knowing the ecosystem links to food stocks, or as a CDR method with increased carbon export knowledge.

Future Focus of Iron Fertilisation

Natural Environments

Natural sources of iron around Antarctica should be assessed to understand their impact on Antarctic and Southern Ocean waters to natural fertilisation (Boyd & Ellwood, 2010). This is especially key due to the seasonal effect on blooms in this area (Williamson et al., 2012).

The projected future influence of subglacial lake discharge over Antarctic continental shelf environments has the potential to increase productivity due to increased nutrient export into the Southern Ocean (Wadham et al., 2013). This would be in addition to the release of iron, largely deposited as iceberg rafted debris, as well as from melting sea ice (Wadham et al., 2013). Some phytoplankton blooms have recently been linked to freshwater melt from glaciers providing iron to the ocean waters (Alderkamp et al., 2012; Gerringa et al., 2012).

Natural observatories for iron enrichment, such as the Kerguelen plateau are important for future long term research (Blain et al., 2008). Southern Ocean natural and artificial fertilisation experiments should consider the type of environment they occurred in and not extrapolate results to different areas, as bathymetry and water flow/upwelling will be different between coastal, open ocean or gyre experiments (Williamson et al., 2012). Natural environments need to be understood with initial importance to understand the ecosystem community, prior, during and after the natural blooms, and understand the amount of carbon that can be exported as a result, from each different environment. These natural results should be understood to identify optimal conditions before further artificial experiments occur in the Southern Ocean.

Carbon Export

From analysis of the iron fertilisation experiments outlined in this report, it appears that there is no consensus in the amount of primary productivity increase, or carbon export within the surface and deeper waters.

The low rate of carbon export to the deep ocean recorded so far is a major obstacle for future work (Bakker et al., 2005), and experiments could be focussed in areas around deep water formation to enhance the transport of carbon (Bakker et al., 2005). Another focus should also include differentiation of scales of future experiments. For instance, we should aim to discover whether a larger spatial experiment would provide increased productivity and carbon export, in comparison to a similar area but using more iron over a longer period of time. It is likely that larger scale experiments, both spatial and temporal, would be required. This would provide increased data and hopefully a better understanding of carbon export as a focus for these larger scale experiments. Increased logistical capabilities would be required for these experiments to go ahead. Perhaps a multi-ship, multinational approach could be taken. A larger experiment would need to consider the ‘top hat’ effect observed in earlier experiments and ensure that optimal fertilisation occurred over the entire area in the experiment. Some have even suggested that fertilisation would need to occur over at least one century, in a large area of the ocean, for iron fertilisation to be able to significantly reduce atmospheric CO_2 levels (Ciais et al., 2013).

Research into the flux of carbon, and validation of this, is required if iron fertilisation is to be discussed further as a CDR method (Lampitt et al., 2008). More research is required to understand the amount of carbon that can be exported and how long for. This would involve comparisons to other HNLC areas which are not being fertilised to show the difference gained by artificial fertilisation. Long term monitoring, after long term experiments may also be required to assess the long term impacts on ecosystems for example, which could offset the 'good' gained by carbon export. Future work required for this is more thorough analysis of export for validation that the exported carbon will be sequestered for a long period of time.

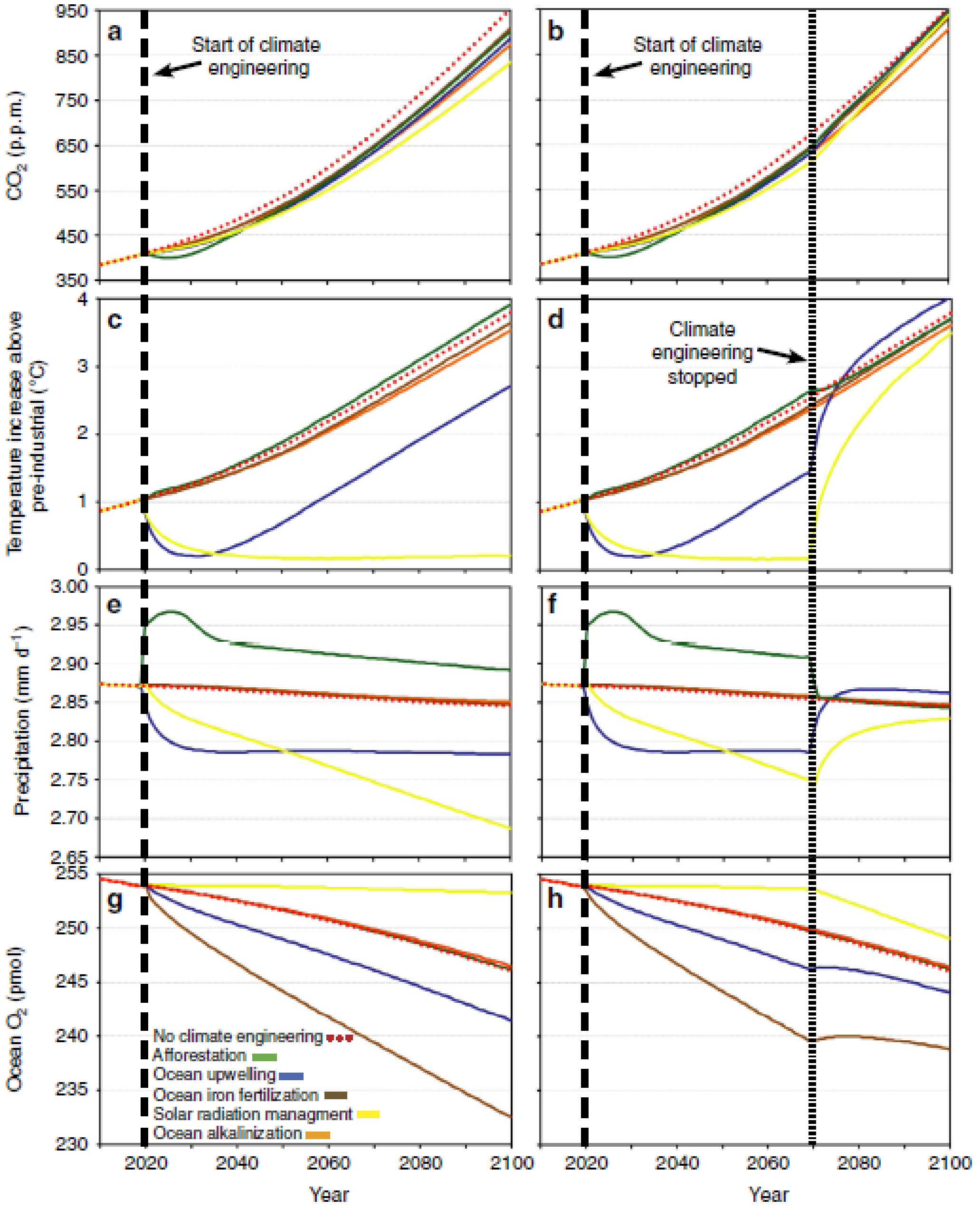


Figure 3: Modelled results of five climate engineering methods on four global atmospheric properties with continued geoengineering until 2100 in a, c, e and g. Results with geoengineering stopped after 50 years are shown in b, d, f and h (Keller, Feng, & Oschlies, 2014).

Use as a CDR Method

The use of iron fertilisation as a mitigation technique should remain classed as within a research phase of investigation, due to the unconfirmed impacts on the ecosystem and ocean systems such as ocean acidification, decreased downstream productivity, and increased N_2O for example.

A recent study on climate engineering methods used an Earth system model to compare the effectiveness and side effects of geoengineering methods including afforestation, artificial ocean upwelling, artificial ocean fertilisation, ocean alkalinisation and solar radiation management (Keller et al., 2014). Four atmospheric properties were assessed in this model, including CO_2 levels (Figure 3). The model ran two scenarios, one where geoengineering ran continuously until 2100 (Figure 3 a, c, e, g) and one where geoengineering stopped after 50 years, in 2070 (Figure 3 b, d, f, h). This model found that, for each type of geoengineering method, while atmospheric CO_2 was reduced by 2100 with continuous use, it was only a small reduction (Keller et al., 2014). In the scenario where geoengineering stops by 2070, the four atmospheric properties appeared to rapidly revert to their original trajectory had no climate interference occurred, especially for atmospheric CO_2 (Keller et al., 2014).

The authors of this paper summarised that the modelled results for each geoengineering methods appeared either ineffective at limiting warming, or had too severe side effects from the methods themselves for them to be utilised (Keller et al., 2014). The authors state that, due to these results, geoengineering should be utilised only as a compliment to other mitigation strategies if we continue to produce emissions at our current and projected rates (Keller et al., 2014).

The ‘London Convention/London Protocol (LC/LP) on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter’ only allows the use of ocean fertilisation for legitimate scientific research. Annex 6, “the assessment framework for scientific research involving ocean fertilisation” was adopted on 14 October 2010 (LC/LP, 2010). This outlines a process of initial assessments, an in-depth environmental assessment to cover all aspects of the experiment, followed by a requirement for monitoring results to be published, before approval on a case by case basis is obtained. The framework also stipulates that no economic interests should influence the activity, and that no economic or financial gains should come from the results of the activity (LC/LP, 2010). This likely puts a halt on the commercial use of iron fertilisation, but does not necessarily limit its use as a CDR method. What is taken into account on review of proposals is the size and impacts of each experiment. Investigators need to show how they will prevent ecological side effects occurring as a result of their proposed experiment. This mitigation will likely affect the size limit, time scale and amount of iron to be added to the ocean in the future, which will hinder the collection of results if larger scale experiments are required for use as a CDR method.

Conclusion and Recommendations

Past natural and artificial fertilisation experiments have shown that iron is a limiting nutrient in HNLC waters such as the Southern Ocean. In all experiments in the Southern Ocean mentioned in this paper, a phytoplankton bloom was developed, productivity increased, and surface water pCO_2 was reduced. This shows the effectiveness of iron fertilisation at increasing productivity. This also credits the Iron Hypothesis for increased productivity resulting in the eventual draw down of atmospheric CO_2 into the ocean during glacial periods, lowering atmospheric CO_2 levels.

With regards to iron fertilisation experiments being used as an effective method to promote carbon draw down into the deep ocean waters, through sequestration and carbon export, the results of the experiments undertaken so far leave this largely unknown. Some experiments did not measure carbon export, and those that did measure export, did not have the capability to monitor the effects of remineralisation for example which could release the CO_2 back into the surface waters. To overcome this, it is recommended that research should be increased into the grazing potential in phytoplankton blooms, the impact of remineralisation throughout the water column, and the depth criteria for optimal sequestration.

Alongside this, research into the side effects of fertilisation experiments is required to understand the follow on effects from increased productivity, both positive and negative. This is hugely important as most of the impacts discussed here are suggested with no conclusive evidence obtained during the past fertilisation experiments.

In spite of this need to conduct more research, likely over larger scales, to gain a better understanding of the whole process, future experiments are likely to be limited by regulations such as the London Convention/London Protocol on the size of the experiments and possible economic implications of them. This will prevent the use of iron fertilisation in the commercial fishing industry.

This regulation, and low levels of confidence in the current experiments outlined by the IPCC, means that the use of iron fertilisation as a CDR method is also unlikely, at least for a time. It is recommended that iron fertilisation experiments initially continue only for legitimate scientific reasons, to help understand ecosystems in HNLC environments and how they link on a more global oceanic scale. Naturally fertilised blooms would be ideal for this. In these experiments, the main focus would be on the side effects which so far have not been well monitored or understood. The second key focus would be the further analysis and monitoring of carbon export, and therefore validation of carbon sequestration, although mainly for its role within the biological cycle. Only when all side effects can be analysed and carbon export on climatically relevant scales can be validated, would iron fertilisation be considered as a legitimate CDR method.

Acknowledgments

I would like to thank the tutors and staff from Gateway Antarctica, University of Canterbury for their help during this course. I would also like to thank my family and friends for helping me focus while working on this report.

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