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Critical Literature Review
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Iron Fertilisation in the Southern Ocean

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Abstract:

The Southern Ocean (below 60°S) surrounds Antarctica. This ocean is known as a high-nutrient low-chlorophyll (HNLC) environment where there is an excess of macronutrients but little primary productivity (Wadley, Jickells, & Heywood, 2014). This is due to the deficit of iron in this region as iron is a limiting micronutrient in phytoplankton growth (Nicol et al., 2010). There have been many studies that have examined this area and experimented by injecting iron into the waters. These identified that artificial fertilisation significantly increases biological productivity (Joos, Sarmlento, & Siegenthaler, 1991; Nishioka et al., 2005; Oschlies, Koeve, Rickels, & Rehdanz, 2010; Williamson et al., 2012; Martin et al., 2013). This leads to an increase in the sequestration of atmospheric CO_2 as the phytoplankton utilise the dissolved carbon in the ocean water during their enhanced photosynthetic rates. These artificial fertilisation experiments have been considered as a long-term method to reduce the anthropogenic atmospheric carbon, however, based on the current literature, the risks of damaging the surrounding environment (ocean acidification, anoxic waters, nutrient deficit, and greenhouse gas emission) exceed the potential benefits. To be able to consider artificial ocean iron fertilisation as a method for carbon sequestration there must be much more comprehensive research done about the consequences and the risks to the environment.

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1. Introduction:

Iron has been established as a limiting nutrient in the Southern Ocean that surrounds Antarctica. The overall deficiency of iron in this ocean has been found to limit the primary productivity of phytoplankton, which in turn impacts the wider ecosystem (Xavier & Peck, 2015). There is an abundance research into the process of artificially fertilising the Southern Ocean with iron to increase the primary productivity. This can result in reduction of atmospheric carbon dioxide (CO_2) through sequestration. However, there are other consequences that can result from this process, and which have to be considered when preparing to fertilise the ocean.

This paper will review and synthesise current literature that discusses iron in the Southern Ocean and ocean iron fertilisation (OIF). The importance of iron in the Southern Ocean and its contribution to primary productivity and CO_2 sequestration will be examined. The natural sources of iron will then be covered, and their relative importance to the Southern Ocean iron content. Previous OIF experiments will be discussed. Finally, the future of iron in the Southern Ocean will be considered and the question of whether long-term OIF should be employed in this region will be answered with regards to the overall environment now and into the future.

2. Importance of iron in the Southern Ocean:

Iron regulates biological productivity in the marine ecosystem due to its role as an essential micronutrient that is required for the photosynthesis of phytoplankton. Iron contributes to the electron transfer processes during photosynthesis and adenosine triphosphate production (Nicol et al., 2010). This means that the iron deficiency in the Southern Ocean limits phytoplankton growth despite the surplus of macronutrients, such as nitrogen and phosphorous (Tabliabue, Bopp, & Aumont, 2009; Bertram, 2010; Williamson et al., 2012).

Phytoplankton are vital components of the food chain as Antarctic krill consume them, and larger organisms, such as baleen whales, in turn eat the krill (Nicol et al., 2010). Therefore, this limited growth in phytoplankton could result in changes in the structure of the marine food web and the diminution of some species. It has been suggested that if iron were added to an area in the Southern Ocean it would result in increased biological productivity.

In addition to the importance of iron to the biology of the Southern Ocean, it also plays a crucial role in the atmosphere-ocean CO_2 exchange (Wingenter et al., 2004). Due to the unbalanced partial pressure of CO_2 between the atmosphere and the ocean, the ocean absorbs some of the atmospheric CO_2. This CO_2 then dissolves and becomes biologically available for use by phytoplankton during photosynthesis. The CO_2 is stored in the phytoplankton biomass and is exported to the deep ocean once the organism dies. When iron is added to this process, the increased productivity results in an increased biological uptake of CO_2 from the seawater during photosynthesis (Joos et al., 1991; Bertram, 2010). This reduces the amount of dissolved CO_2 in the shallow seawater, which increases the difference between the atmospheric and oceanic partial pressures. This leads to an increased draw down of CO_2 into the ocean and subsequent export into the deep ocean (Joos et al., 1991). If artificial OIF was implemented over a long time period, it is believed that the carbon sequestration would contribute to the offset of anthropogenic carbon emissions, which may have global ramifications (Oschlies et al., 2010).

3. Natural iron sources:

Despite the apparent lack of any iron in the Southern Ocean, there are many sources that provide iron to this region. The significant size of the Southern Ocean, however, means that the amount of iron that is deposited in the ocean is not sufficient to allow the phytoplankton to reach their full biological potential.

3.1 Sedimentary source

One of the dominant sources of iron in the Southern Ocean is sediment-derived iron (Tabliabue et al., 2009; Borrione, Aumont, Nielsdóttir, & Schlitzer, 2014; Wadley et al., 2014). This type of iron enters the Southern Ocean in two ways: through sediments from the continental shelves, and from glaciers and icebergs. (Wadley et al., 2014). Sedimentary iron that originates from the continental margins is incorporated into the water column and increases productivity, which produces phytoplankton blooms in the ocean surrounding the continental shelf (Charette et al., 2007). Sedimentary iron that enters the water column below the euphotic zone can be transported upwards through vertical mixing and utilised by the phytoplankton once it reaches sufficiently sunlit waters (Charette et al., 2007). The depth of iron entry is important when considering the availability of iron however, as iron that is injected into deep water may be scavenged before it reaches the euphotic zone (Wadley et al., 2014). This suggests that the sedimentary source of iron is more concentrated in shallower water, such as the Antarctic Peninsula (Wadley et al., 2014). Tabliabue et al. (2009) found that this source of iron is one of the most important in the overall Southern Ocean, and plays a vital role in total carbon export. The shelves surrounding New Zealand and Australia, Patagonia, and Antarctica are significant contributors of sedimentary iron for the Southern Ocean. In the case of Antarctica, the shelf is the primary source of iron as the ocean surrounding the continent is too far away from other landmasses to receive other sources of iron, such as atmospheric (Tabliabue et al., 2009).

Sedimentary iron sources are also found in ice coming off the Antarctic continent, such as glaciers and icebergs (Wadley et al., 2014). As glaciers move along the bedrock of continental Antarctica they pick up iron-rich sediments, which then become entrained within the ice. Sediment can also be incorporated into a glacier through airborne dust that is deposited onto the glacier surface. When icebergs form at the Antarctic margins this iron-rich sediment enters the Southern Ocean. This injection of sedimentary iron significantly increases the primary productivity around the icebergs and the glacial ice shelves. It has been hypothesised that with increased global warming and subsequent melting of the Antarctic ice shelves, the iceberg flux will increase and introduce more iron to the ocean, therefore increasing the primary productivity and CO_2 sequestration, thus creating a negative feedback loop. However, this increase is unlikely to have a significant impact on global warming, as the sediment flux is too small (Wadley et al., 2014).

3.2 Atmospheric source

Another source of iron in the Southern Ocean is through atmospheric transportation, where aeolian processes pick up iron-rich dust from continental interiors and deposit it into the oceans. This is another significant source of iron for the Southern Ocean, however not as considerable as the sedimentary iron (Tabliabue et al., 2009; Wadley et al., 2014). The Patagonian desert and the interior of Australia in particular are important sources for aeolian dust (Wadley et al., 2014). Areas of ocean that are adjacent to such sources have increased biological productivity as a result of this significant iron flux, and can even result in a surplus of dust (Tabliabue et al., 2009). This high iron flux increases the total carbon export in these regions. Due to the considerable size of the Southern Ocean, however, iron supply to the ocean is low outside of areas adjacent to aeolian dust sources (Wadley et al., 2014). It is possible that with climate change, the atmospheric iron flux could increase, which would lead to an amplified draw down of CO_2, which has been observed in the records of past glacial cycles (Wadley et al., 2014).

3.3 Fluvial source

Iron derived from the sediment carried by the glacial runoff streams of Antarctica also plays an important role in the natural fertilisation of the Southern Ocean, though it is not as large as the contributions of aeolian and sedimentary iron sources (Lyons et al., 2015). This source of iron creates localised areas of increased primary productivity near the Antarctic coast. The iron originates from the chemical weathering of the stream channel itself, or the deposition of aeolian sediment onto the glacier surface that is then incorporated into the glacial melt. Lyons et al. (2015) hypothesise that with climate warming glacier melt will increase, the ice-free areas will increase, and more iron-rich sediments will be picked up by the streams and deposited into the Southern Ocean.

3.4 Biological source

While this is not a primary source of iron, the biological processes that recycle iron also play an important role in the natural fertilisation of the Southern Ocean (Nicol et al., 2010). During phytoplankton blooms, Antarctic krill consume the primary producers, incorporating the iron into their own biomass. Baleen whales then eat the krill, further concentrating the iron into their bodies, and eventually defecating, which recycles the iron back into the ocean water (Nicol et al., 2010). Due to the significant concentration of iron in the faeces (145.9 +/- 133.7 mg kg^{-1}), which is approximately ten million times that of the Southern Ocean seawater, the defecation of baleen whales could act as a fertiliser for the iron deficient Antarctic waters when released back into the ocean mixing layer. Nicol et al. (2010) hypothesises that before the exploitation of whales the larger populations of the whales and krill would have stored and recycled greater quantities of iron in the ocean, therefore enhancing primary productivity. This would have created a positive feedback loop where the larger whale population would have recycled greater amounts of iron and fertilising larger areas, increasing the productivity of phytoplankton and therefore krill. This suggests that allowing the whale population to recover from the historic exploitation may increase the productivity of the Southern Ocean (Nicol et al., 2010).

3.5 Rock weathering source

The final noteworthy source of iron in the Southern Ocean is through the weathering of rocks on the Antarctic continent (Dold et al., 2013). Sulphide minerals, such as pyrite (which contains iron), in the exposed bedrock of Antarctica can undergo weathering in the form of oxidation by cold-climate microbes. This oxidation releases iron, sulphur, and other heavy metals, and brings them to an aqueous phase, reducing the pH and generating acid. This is known as acid rock drainage (ARD). This ARD then is transported as groundwater and as runoff in glacial streams and deposited into the sea (Dold et al., 2013). This is an efficient process that effectively transports dissolved iron into the Southern Ocean, allowing the phytoplankton to utilise it and increase their productivity near the islands and continent, although it is difficult to determine the amount of dissolved iron that reaches the open ocean.

4. Ocean iron fertilisation experiments:

Since iron has been identified as a limiting nutrient in the Southern Ocean biological productivity and as an important component in atmospheric carbon sequestration, series' of artificial ocean fertilisation experiments have been undertaken in the Southern Ocean in an attempt to quantify the effect that iron has. This process can be done through the direct introduction of external soluble iron (ferrous sulphate) from a ship (Williamson et al, 2012).

One of the most well-known OIF experiments is LOHAFEX. This study was conducted during between January and March 2009 in the Atlantic sector of the Southern Ocean. The experiment involved the dissolution of 2t of iron into the seawater across an area of 300km^2 (Martin et al., 2013). The iron was injected into the middle of an eddy, which kept the iron from spreading outside of the study area. During the 39 day study period Martin et al. (2013) found that the chlorophyll content and primary productivity doubled, however, based on the data gathered, there was no significant increase in the export of carbon in this area. It is believed that this is due to the silica deficiency in the Southern Ocean, which limits diatom blooms (Quéguiner, 2013). It has been suggested through other experiments (EIFEX, CROZEX, KEOPS, SOFeX) that iron fertilisation in silica-rich waters can enhance diatom blooms, leading to significant carbon export into deeper waters (Martin et al., 2013).

The November 2000 EisenEx iron fertilisation experiment pre-dated LOHAFEX and produced different results than the later study. This experiment was conducted in a mesoscale eddy within the Polar Frontal Zone of the Southern Ocean. Much like LOHAFEX, dissolved iron was added to the eddy, however this study only used an area of 50km^2 (Nishioka et al., 2005). Over the course of the 23-day experiment a gradual increase of the chlorophyll content was observed, with the maximum level being four to five times greater than the base level in that are of the Southern Ocean, demonstrating the significant biological response (Nishioka et al., 2005). Storm events were found to cause a significant decrease in the iron concentration through mixing, which may have resulted in less of an increase than would otherwise occur during fertilisation.

Based on past studies it has been found that artificial OIF in the Southern Ocean leads to an increase in biological productivity in the upper layers of ocean, and may lead to reductions in CO_2 in these waters. This leads to the enhanced draw down of atmospheric CO_2, though the degree at which this occurred differed in the various experiments. It has been suggested that these are the result of differences in the amount of iron added, the status of the phytoplankton prior to fertilisation, the depth of the mixed layer, the time that the fertilised waters remain at the atmosphere-ocean interface (Williamson et al., 2012). The success of these experiments has lead to debates about the viability of this process as a method to reduce atmospheric CO_2 and offset anthropogenic carbon emissions.

5. Discussion:

Although previous artificial OIF experiments have yielded overall positive results with regards to productivity and carbon sequestration, there are still many other aspects of the process that need to be considered, such as the unforeseen consequences of large-scale, long-term artificial OIF in the Southern Ocean. One possible side effect of long-term OIF is ocean acidification as a result of the increased sequestration of CO_2. This is especially pronounced in the deeper waters of the Southern Ocean where the CO_2 is stored. Modelling has found that the stored carbon remineralises and releases CO_2, therefore increasing the acidity of the surrounding ocean water (Bertram, 2010; Oschlies et al., 2010; Williamson et al., 2012). This has a significant impact on the organisms that live in this environment as the acidified water limits their ability to develop carbonate shells (Oschlies et al., 2010; Williamson et al., 2012). Another consequence that OIF could have on the Southern Ocean is the downstream reduction of nutrients. With fertilisation and an increase in primary productivity more macronutrients are trapped within the fertilisation area and are unable to be exported elsewhere, resulting in a nutrient deficit in other regions. This could have adverse effects on the biological activity in these areas (Bertram, 2010; Güssow, Proelss, Oschlies, Rehanz, & Rickels, 2010; Oschlies et al., 2010; Morris & Charette, 2013). With the increase of productivity with large-scale fertilisation, the biomass in these areas also increases. As this increased biomass decomposes the biochemical process consumes oxygen, decreasing the oxygen levels of the ocean water and leading to anoxic environments where life is difficult to sustain (Bertram, 2010; Güssow et al., 2010; Williamson et al., 2012). OIF has also been found to enhance the emission of greenhouse gases from the ocean waters (Wingenter et al., 2004; Bertram, 2010; Güssow et al., 2010; Oschlies et al., 2010; Williamson et al., 2012). These greenhouses gases are associated with bacterial activity and a low availability of dissolved oxygen. This combination can result in the amplified production of gases such as nitrous oxide and methane, both of which are more forceful than CO_2, which means that they could offset the carbon sequestration that resulted from the large-scale ocean fertilisation (Bertram, 2010). Another gas that is produced during this process is dimethyl sulphide (DMS). Once this gas is released into the atmosphere it enhances the formation of particles that encourage cloud formation. Over a long timescale and large area of fertilisation, this enhanced emission of DMS could cause a increase in albedo through cloud formation. This would result in increased reflectivity of solar radiation and cooling (Wingenter et al., 2004; Williamson et al., 2012). While this may seem like a positive result of ocean fertilisation, the enhanced production of DMS could have unforeseen global atmospheric ramifications.

As previously mentioned, OIF can have significant beneficial impacts on the primary productivity of the Southern Ocean, as well as enhance the atmospheric carbon sequestration. Other positive outcomes from a long-term OIF operation is the increase in fishery yields, and the increased nutrient levels in other areas of the ocean where the nutrient-rich waters (originating from the decomposing biomass of the fertilised phytoplankton) upwell elsewhere and enhance the productivity of these remote regions (Williamson et al, 2012).

As anthropogenic CO_2 emission rates and global warming increases, it is becoming more urgent to find ways to offset carbon emissions and slow down climate warming. One of these ways is believed to be the large-scale fertilisation of the Southern

Ocean. However, this may not be as effective as previously believed and the consequences of this process may outweigh the benefits. Based on current research, the continued sequestration of CO_2 is not guaranteed during OIF as CO_2 can be released back into the atmosphere as the surface ocean mixes and advects (Bertram, 2010; Martin et al., 2013). In addition to this, the fertilisation process must be continuous otherwise the system may be returned to its original, unfertilised state (Joos et al., 1991). This suggests that Southern Ocean iron fertilisation may not be a viable long-term carbon sequestration option. As global warming continues, many of the natural iron sources found in the Southern Ocean will be enhanced (such as icebergs, ARD, and aeolian sources), which may mean that artificial OIF will not be required as the planet attempts to re-equilibrate its temperature naturally through negative feedback loops.

To conclude, based on the current literature and overall state of knowledge, large-scale and long-term artificial OIF projects should not be emplaced, as there is not enough understanding about the unintended, long-term consequences of this process and it may exacerbate the issue rather than reducing it. Much more research into this topic is needed to fully understand the ramifications that may occur.

6. Conclusion:

The Southern Ocean surrounding Antarctica is iron-deficient, which results in limited phytoplankton blooms and biological productivity. While there are many sources of iron into the Southern Ocean, including aeolian-transported dust, sediment-derived iron, icebergs, fluvial, biological, and rock weathering, the huge area of the ocean means that the overall iron concentration is too low to support high primary productivity. This has led to artificial fertilisation experiments in the Southern Ocean, which demonstrate a significant increase in biological activity when iron is deposited. This results in an enhanced draw down of atmospheric CO_2 and subsequent export of the carbon into the deep ocean. However, the consequences for employing this process as a long-term method for sequestering carbon currently outweigh the benefits, based on current knowledge and literature. This may change in the future if CO_2 emissions continue on their current trend, and the need for carbon sequestration may eventually exceed the risks to the environment. There needs to be more research done on the repercussions that OIF could have on the environment before considering it in the future.

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