Graduate Certificate Antarctic Studies

“To Fe or not to Fe?”

Literature review

Iron fertilization in the Southern Ocean.

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“Give me a half tanker of iron,

and I will give you another ice age.”

John Martin - 1991

Iron Fertilization in the Southern Ocean.

Introduction

As public concern about global warming grows, and the need to reduce greenhouse gas emissions is becoming clear; lawmakers, businesses, the public and investors are being presented with a number of new ideas for how to achieve these goals. Recently one such approach, ‘iron fertilization’ of the oceans - the process of ‘seeding’ some parts of the ocean with the essential micronutrient iron in order to promote plankton growth and thus remove atmospheric carbon (in the form of CO_2) and store it in the oceans - has been promoted in the hope that iron fertilization could go some way to sequester carbon emissions[1]. However, this process raises a number of questions, including its effectiveness as a market-based sequestration system as well as the possible negative effects on the ocean and other environmental systems.

Fertilizers of various forms have become a common means toward improving plant growth. Imagine a fertilizer so powerful it could increase a yield by over 2500%. This is what scientists observed when they ‘fertilized’ a patch of ocean in 1995 with Iron Sulfate as part of the IronEX II experiment. But why would this chemical have had such a profound effect on phytoplankton growth?

Over 20% of the world’s oceans are nutrient rich but iron poor[2], which is the limiting nutrient for phytoplankton growth. By adding sufficient levels of iron to the surface ocean water, a phytoplankton bloom can be induced, and the effect can be quite dramatic. During the 1995 experiment, 450 Kg of iron was spread over a 100 km^2 patch of the ocean, producing a phytoplankton bloom which consumed over 2500 tons of carbon dioxide from the surface ocean waters[3]. Whether iron fertilization has been a viable mechanism controlling climate in the past, and whether it could be useful in the future is a topic of current debate. What is clear from fertilization experiments to date is that they have been effective tools allowing us to question the role of iron in controlling phytoplankton growth, nutrient cycling and the flux of carbon from the atmosphere to the deep sea.

Background

Phytoplankton is a major contributor to the global carbon cycle, accounting for about 40% of the natural consumption of CO_2 by biomass[4]. This tends to suggest that the livelihood of phytoplankton would play an essential role in management of the global carbon cycle. Generally phytoplankton grow, consuming CO_2 through photosynthesis, die, and are broken down by bacteria, returning the nutrients they consumed except for a small fraction of carbon that sinks into the deep oceans or dissolves into the ocean waters and is circulated to the deep oceans.

Iron Hypothesis

Baron Justis von Liebig (1803-1873), the founder of modern organic chemistry, is also recognised as the father of agricultural chemistry. He was the first to determine the exact elements taken up by plants from the air and soil, which enabled him to develop efficient fertilizers. With this understanding, Liebig was the first to realize that the "…growth of a plant is dependent on the amount of food stuff which is presented to it in minimum quantity." This has become known in ecological circles as Liebig's Law of the Minimum[5]. Scientists recognised that iron concentrations would be limited in the oceans due to the high oxygen concentrations and limited natural sources of iron being generally limited to iron laden dust falling out of the atmosphere, rivers and hydrothermal vents in deep ocean ridges[6].

Consideration of iron's importance to phytoplankton growth and photosynthesis dates back to the 1930's when English biologist Joseph Hart speculated that the ocean's great "desolate zones" (areas apparently rich in nutrients, but lacking in plankton activity or other sea life) might simply be iron deficient[7]. Little further scientific discussion of this issue was recorded until the 1980's, when oceanographer John Martin renewed controversy on the topic with his marine water nutrient analyses. His studies indicated it was indeed a scarcity of iron micronutrient that was limiting phytoplankton growth and overall productivity in these "desolate" regions, which came to be called "High Nutrient, Low Chlorophyll" (HNLC) zones[8,9]. HNLC waters primarily exist in the Southern (Antarctic) Ocean and the equatorial Pacific as shown in Figures 1 & 2.

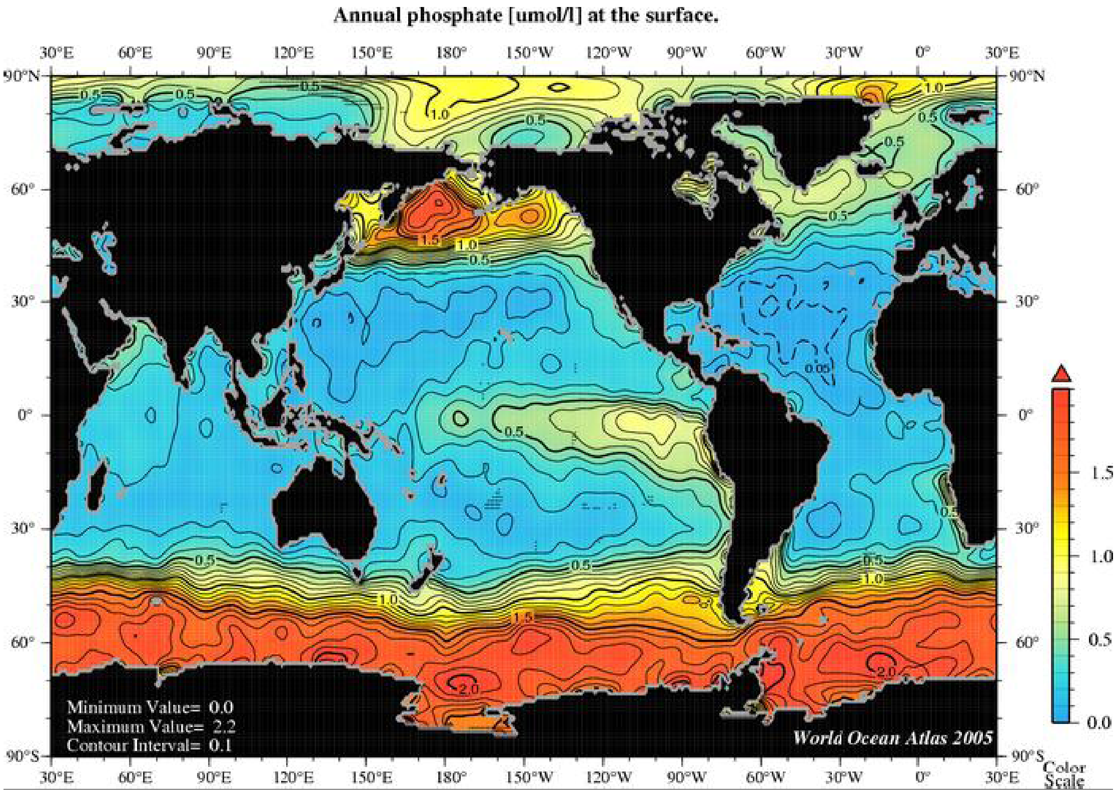

Figure 1: Annual mean phosphate concentration at the ocean surface (umol/kg)[10].

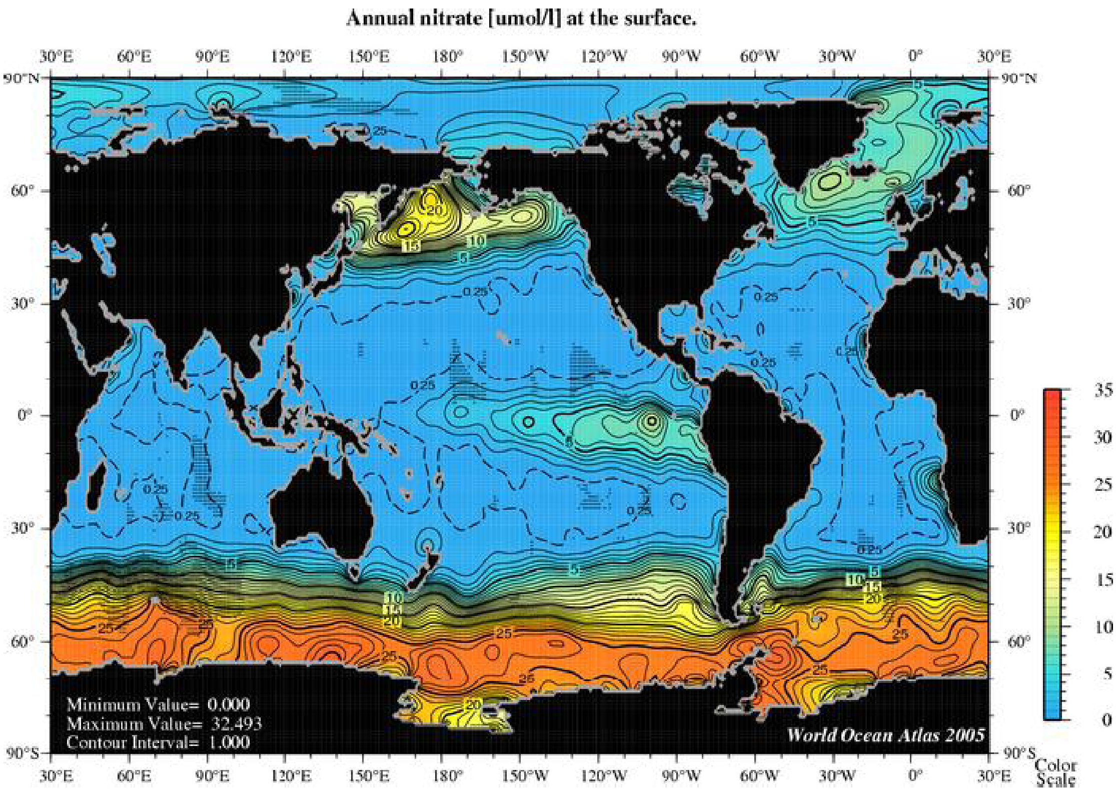

Figure 2: Observed annual mean nitrate concentration at the ocean surface in umol/kg. This image clearly shows the high levels of nitrate in the sub-arctic Pacific, the equatorial Pacific and the Southern Ocean[11].

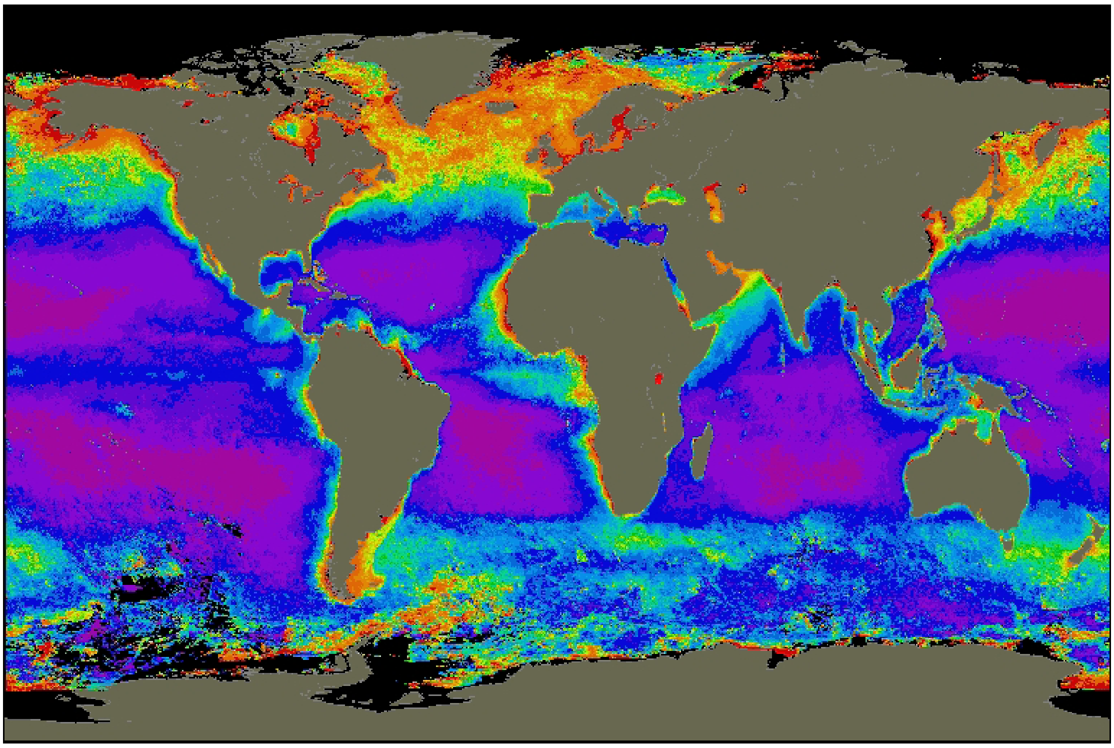

Figure 3: Observed concentrations of chlorophyll in phytoplankton. Purple areas near the equator show low chlorophyll levels; yellow and brown areas indicate increased levels; and red indicates high levels. Low levels of chlorophyll can been seen in the Sub-arctic Pacific, the Equatorial Pacific and the Southern Ocean[12].

Martin's famous 1991 quip at Woods Hole Oceanographic Institution (WHOI), "Give me a half a tanker of iron and I will give you another ice age"[13], drove a decade of research whose findings suggested that iron deficiency was not merely impacting ocean ecosystems, it also offered a key to mitigating climate change as well. Martin hypothesised that increasing phytoplankton photosynthesis could slow or even reverse global warming by sequestering large volumes of CO_2 in the sea. He died before IronEX I, a "proof of concept" research voyage, was successfully carried out near the Galapagos Islands in 1993 by his colleagues at Moss Landing Marine Laboratories[14]. Since then nine other international ocean trials have confirmed the iron fertilization effect:

- IronEX II , 1995
- SOIREE (Southern Ocean Iron Release Experiment), 1999
- EisenEx (Iron Experiment), 2000
- SEEDS (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study), 2001

- SOFeX (Southern Ocean Iron Experiments - North & South), 2002
- SERIES (Subarctic Ecosystem Response to Iron Enrichment Study), 2002
- SEEDS-II, 2004
- EIFEX (European Iron Fertilization Experiment), 2004
- CROZEX (CROZet natural iron bloom and Export experiment), 2005

As described earlier, the first major success in iron fertilization occurred in 1995 with IronEX II. For this experiment, a 10 by 10 Km patch of ocean near the Galapagos Islands was fertilized due to its ideal control characteristics (abundant sunshine, weak currents). This experiment slowly spread 450 Kg of Iron Sulfate into the surface ocean waters for 18 days. A plankton bloom rapidly invoked the entire patch, turning the waters brown with plankton. It was estimated from plankton density samples that the plankton consumed nearly 2500 tons of CO_2, significantly reducing the concentration of CO_2 in the ocean patch from its original value.

However, perhaps the most dramatic support for Martin's hypothesis was seen in the aftermath of the 1991 eruption of Mount Pinatubo in the Philippines. Environmental scientist Andrew Watson analyzed global data from that eruption and calculated that it deposited approximately 40,000 tons of iron dust into the oceans worldwide. This single fertilization event generated an easily observed global decline in atmospheric CO_2 and a parallel pulsed increase in oxygen levels[15].

Natural Ocean Carbon Cycle

The oceans contain about 50 times more CO_2 than the atmosphere and 19 times more than the land biosphere[16]. CO_2 moves between the atmosphere and the ocean by molecular diffusion when there is a difference in the CO_2 gas pressure (pCO_2) between the atmosphere and oceans (e.g. when the atmospheric pCO_2 is higher than the surface ocean, CO_2 diffuses across the air-sea boundary into the seawater). The oceans are able to hold much more carbon than the atmosphere because most of the CO_2 that diffuses into the oceans reacts with the water to form carbonic acid and its dissociation products, bicarbonate and carbonate ions. The conversion of CO_2 gas into nongaseous forms such as carbonic acid and bicarbonate and carbonate ions effectively reduces the CO_2 gas pressure in the water, thereby allowing more diffusion from the atmosphere.

The two basic mechanisms that control the distribution of carbon in the oceans are referred to as the solubility pump and the biological pump.

Solubility Pump:

The solubility pump is driven by two principal factors. First, more than twice as much CO_2 can dissolve into cold polar waters than in the warm equatorial waters. As major ocean currents move waters from the tropics to the poles, they are cooled and can take up more CO_2 from the atmosphere. The high latitude zones are also places where deep waters are formed. As the waters are cooled, they become denser and sink into the ocean's interior, taking with them the CO_2 accumulated at the surface.

Biological Pump:

Another process that moves CO_2 away from the surface ocean is called the biological pump. Growth of marine plants (e.g., phytoplankton) takes CO_2 and other chemicals from sea water to make plant tissue. Plankton that generate calcium or silica carbonate skeletons, such as diatoms, coccolithophores and foraminifera, account for most direct carbon sequestration. Of the carbon-rich biomass generated by natural plankton blooms and fertilization events, half or more is generally consumed by grazing organisms (zooplankton, krill, small fish, etc.) but 20 to 30% sinks below 200 meters into the colder water strata below the thermocline[17]. Much of this fixed carbon continues falling into the abyss as marine snow, but a substantial percentage is redissolved and remineralized. At this depth, however, this carbon is now suspended in deep currents and effectively isolated from the atmosphere for centuries or more. This process of carbon sequestration is effectively shown in Figure 4.

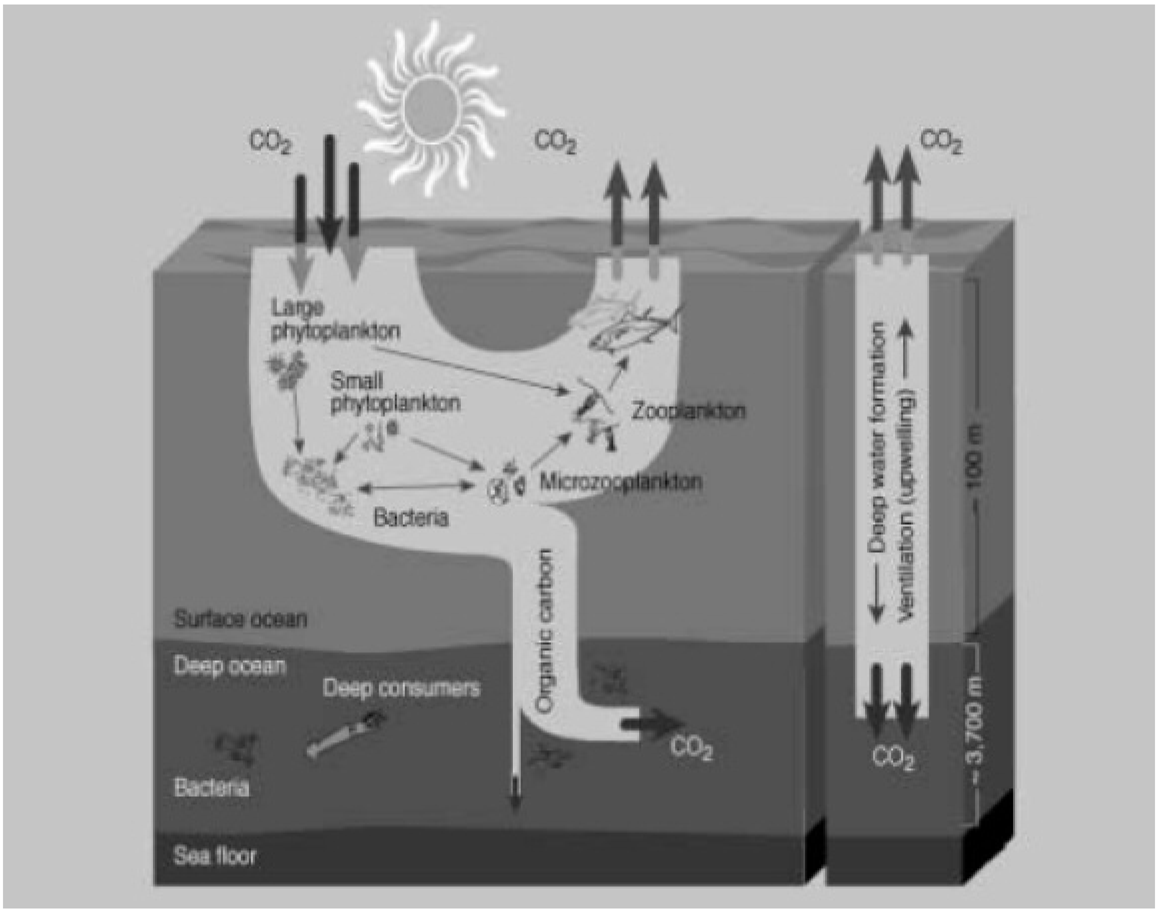

Figure 4: A schematic representation of the biological pump[18].

Implications

ESSE (Earth System Science Education) estimate that if the entire 20% of the world's oceans that are primed for this 'induced' phytoplankton growth (e.g. HNLC zones as described earlier) were fertilized with iron, the results would be reasonably encouraging with ~38 PPM of CO_2 would be reduced from the control scenario by the year 2100[19]. But what good would the reduction of only 38 PPM do towards reducing global warming? In itself perhaps not a great deal, but there is a deeper issue to explore here. With the potential future situation where carbon taxes are implemented globally, there is a great deal to be said for the economic feasibility of various means for carbon removal. Could a country engage in fertilization to count against carbon production within their country? Would this be fair when the cost is borne not so much by the country, but by the ecosystems of the Antarctic, a "commons" resource?

Since the advent of the Kyoto Protocol several countries and the European Union have established carbon offset markets which trade certified emission reduction credits (CER's) and other types of carbon credit instruments internationally. In 2007 CER's sell for approximately €15~20/ton CO_2e and European analysts project these prices will nearly double by 2012[20]. NASA scientists have reported a minimum 6~9% decline in global plankton production since 1980[21] (and other scientists report 10~12% losses[22]), which suggests that a full-scale international plankton restoration program could play a significant role towards increasing the carbon sequestration capacity, which in turn would be worth considerable amounts in carbon offset value.

What effects would resolve from long term fertilization? At present, little is known about the possible reactions to the oceanic ecosystem from this type of activity. From observations there appears to be a correlation between algal blooms and reduction in biodiversity. Similar correlations might exist with phytoplankton. What would happen to the ocean chemistry following large scale fertilization? Quite possibly the added biomass would consume the deep ocean oxygen levels and produce methane as it decayed, a potent greenhouse gas[23]. The added surface matter would also reduce the depth to which sunlight would penetrate, likely upsetting deeper algae growth. There are many other potential issues that would need to be considered before this type of activity should be considered on a large scale, some of which might include:

- Dimythel sulfide and clouds

This issue deals with the release of dimethyl sulfide (DMS) as a by-product of plankton growth. Some plankton species produce DMS, a portion of which enters the atmosphere where it oxidizes to form sulphate aerosols and ultimately clouds. The concern here is that the potential increase in cloud cover may increase the albedo of the planet and lead to a cooling trend in the Earth's temperature.

- Effects on oceanic ecosystems

Depending on the composition and timing of delivery, these iron additions could potentially favour certain species and alter the concerned marine ecosystems. Little is known of the long term effects to the biota in the sea, only some of the short term effects to the plankton have been have been looked at so far. A great deal of research would need to be conducted to determine the potential risks to the world's ocean biodiversity prior to implementation of this type of system.

- Harmful Algal Blooms (HAB)

Some plankton species cause red tides and other toxic phenomena which can have devastating effects. Even though the water is perceived to be too cold to be very favourable to red tide (*K. Brevis),* these Red Tide Blooms have flourished[24]. However, most species of phytoplankton are harmless, and indeed beneficial. Red tides and other harmful algal blooms are considered coastal phenomena, whereas iron stimulated plankton blooms are only completed in deep oceans where iron deficiency is a problem. This is because most coastal waters are replete with iron and adding more has no effect.

- Associated gases

Increased productivity of diatoms (the most common type of phytoplankton) may boost nitrous oxide (N_2O) and methane (CH_4) production, which are both greenhouse gases. Sinking of large phytoplankton blooms into the deep ocean may also reduce oxygen levels.

Conclusion

There are still too many unanswered questions about iron fertilization in the oceans for large-scale implementation to be considered. However, this issue will likely be coming to the forefront in the not-so-distant future as countries become increasingly concerned with cost-benefit analyses for carbon reduction. With our limited understanding of the ocean system, our best course of action for now would be to continue small-scale experimentation and advance our knowledge level concerning the ocean ecological systems, particularly in HNLC zones such as the Southern Ocean.

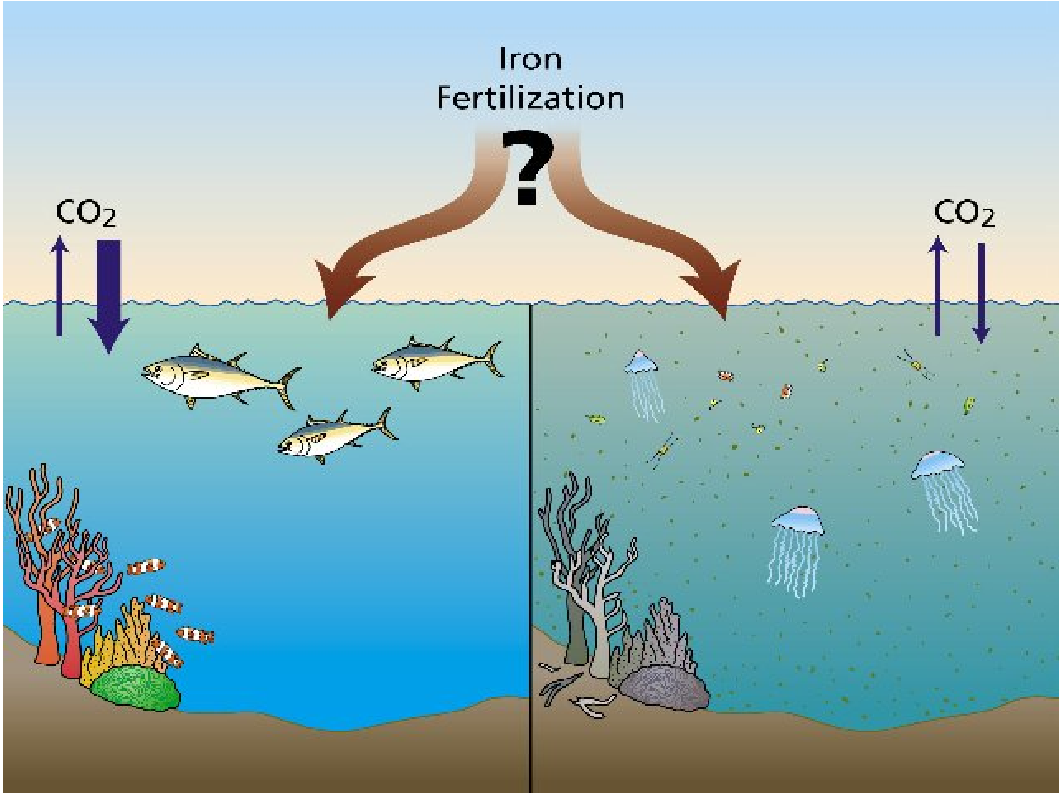

Figure 5: The long-term effects of iron fertilization are still unknown[25].

References

1 Sagarin, R.; Dawson, M.; Karl, D.; Michael, A.; Murray, B.; Orbach, M.; St. Clair, N. (2007). *Iron Fertilization in the Ocean for Climate Mitigation: Legal, Economic, and Environmental Challenges*. Working Paper, Nicolas Institute for Environmental Policy Solutions, Duke University.

2 Coale, K.H.; Johnson, J.S.; Fitzwater, S.E.; Gordon, R.M.; Tanner, S.; Chavez, F.P.; Ferioli, L.; Sakamoto, C.; Rogers, P.; Millero, F.; Steinberg, P.; Nightingale, P.; Cooper, D.; Cochlan. W.P.; Landry, M.R.; Constantinou, J.; Rollwagen, G.; Trasvina, A.; Kudela, R. (1996). A massive phytoplankton bloom induced by an ecosystem scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383: 495-501.

3 ESSE (Earth System Science Education). NASA. *Iron Fertilization*.
Retrieved: 08-12-2007.

4 Ibid[3].

5 Odum, E.P. (1971). *Fundamentals of Ecology*, 3rd Ed. W.B. Saunders Co., Philadelphia, 574 p.

6 Martin, J.H. (1990). Glacial-interglacial CO2 change: The iron hypothesis. *Paleoceanography* 5: 1-13.

7 Weir, J. *On the Shoulders of Giants – John Martin (1935-1993)*. NASA Earth Observatory. Retrieved: 10-12-2007.

8 Martin, J.H. (1991). Iron, Liebig's law and the greenhouse. *Prog. Oceanogr.* 4: 52-55.

9 Ibid[2].

10 Noaa- nesdis- national oceanographic data center.
http://www.nodc.noaa.gov/cgibin/OC5/WOA05F/woa05f.pl.
In: Takougang, E.T. (2007). *Iron fertilization in the ocean and consequences for the global carbon cycle*. African Institute for Mathematical Sciences (AMIS).

11 Ibid[10].

12 Ocean color viewed from space.
http://vathena.arc.nasa.gov/curric/oceans/ocolor/index.html.
In: Takougang, E.T. (2007). *Iron fertilization in the ocean and consequences for the global carbon cycle*. African Institute for Mathematical Sciences (AMIS).

13 WHOI (Woods Hole Oceanographic Institution). *Ocean Iron Fertilization – Why Dump Iron into the Ocean*. Café Thorium. Retrieved: 08-12-2007.

14 Ibid[7].

[15] Watson, A.J. (1997). Volcanic iron, CO_2, ocean productivity and climate. *Nature* 385: 587-588.

[16] Sabine, C.L. *Carbon Dioxide in the Ocean and Atmosphere*. Retrieved: 11-12-2007.
[17] Wikipedia. *Iron Fertilization*. Retrieved: 09-12-2007.

[18] Coale, K. (2001). *Open Ocean Iron fertilization for Scientific Study and Carbon Sequestration*. Moss Landing Laboratories, California.

[19] Ibid[3].

[20] CO_2 Australia Ltd. (2007). *Carbon Update*.

[21] NASA Observatory. *Ocean Plant Life Slows Down and Absorbs less Carbon*. Retrieved: 11-12-07.

[22] BBC news. *Plankton Found to Absorb Less Carbon Dioxide*.
Retrieved: 11-12-07.

[23] Ibid[3].

[24] Ibid[16].

[25] Buesseler, K.O. (1999). Fertilizing the Ocean with Iron. *WHOI (Woods Hole Oceanographic Institution) Annual Report.*