Kiel **Policy Brief**

Ocean Iron Fertilization: An Option for Mitigating Climate Change?

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No. 3 | March 2009

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1. Introduction

The world is very likely to experience a range of adverse climate change impacts in the coming decades and ocean iron fertilization is discussed as one measure to contribute to the mitigation of these impacts. Ocean iron fertilization aims at stimulating phytoplankton growth in certain parts of the ocean, thus enhancing oceanic CO_2 uptake and reducing atmospheric CO_2 concentrations. But its utilization is currently highly debated and its mitigation potential is not yet explored well enough.

Lately, ocean iron fertilization has received increased attention when the German Government – concerned about potential harmful environmental side effects – tried to stop a new ship-based experiment in the Southern Antarctic Ocean that aims to find out more about the impacts of ocean iron fertilization. In response to this, independent scientific and legal reviews were carried out, affirming that the experiment would neither violate environmental standards nor international laws.

The controversy about the utilization of ocean iron fertilization is based on the fact that its effects, including intended and unintended ones, are not yet fully understood. Still, there are vital commercial interests that favour this method in order to sequester CO_2, generate carbon offsets and sell these offsets on carbon markets. As of today, selling carbon offsets generated through iron fertilization projects would only be possible on voluntary carbon markets and these carbon offsets could not be used for compliance with the Kyoto Protocol. However, continually increasing CO_2 emissions to the atmosphere could raise the pressure to include further sinks into a Post-Kyoto agreement. So, given the commercial interests that foster employing ocean iron fertilization on larger scales, it is necessary to investigate its potential as a mitigation option as well as regulatory issues connected to its utilization.

2. Scientific Background

The idea to fertilize the ocean with iron dates back to 1990, when John Martin first published the so-called Iron Hypothesis, suggesting that iron could be the limiting factor for photosynthesis in some parts of the ocean, where the concentration of macronutrients is high but where the concentration of chlorophyll is low (*Martin 1990*). This is the case e.g. for large parts of the Southern Ocean. Adding iron to the surface water in these ocean regions increases the amount of CO_2 used for photosynthesis and stored in the resulting biomass. Phytoplankton will take up CO_2 that is dissolved in the seawater and convert it to particulate organic carbon (POC), part of which will then sink from the surface to the deep ocean or even to the ocean ground. This process is called the biological pump, leading to increasing CO_2 concentrations in the ocean's interior and decreasing CO_2 concentrations in the ocean's upper layer. Eventually, the carbon exported to the deep ocean will reach the surface again. Nevertheless, the carbon could circle in the deep ocean for decades to centuries, which could qualify as sequestering CO_2 (*Denman 2008*).

However, not all the carbon taken up by phytoplankton will be sequestered in the deep ocean. Instead, a large fraction of it will get back to the atmosphere within short time scales due to remineralization or the respiration and excretion of the higher animals that eat phytoplankton. More than 50 % of the POC is already remineralized during the first 100 meters of sinking. Further on, only about 2 to 25 % of the carbon reaches a depth of 100 to 500 meters and only 1 to 15 % of the carbon sinks below 500 meters (*Powell 2008a*). Consequently, carbon sequestration is less than export and it depends on the depth that will be deep enough to keep the carbon away from the surface ocean, e.g. for a hundred years. Moreover, this depth varies and depends on several factors such as ocean currents, temperature, weather conditions, lateral patch dilution and grazing activity. In addition to carbon export and sequestration, it also has to be investigated how much carbon iron fertilization will actually draw down from the atmosphere into the ocean in order to assess its potential to mitigate atmospheric CO_2 concentrations (*De Baar et al. 2005 and 2008*).

3. Quantitative Potential of Ocean Iron Fertilization

Different types of studies, including ship-based experiments, modeling studies and the observation of natural fertilization events, have made unequivocally clear that iron addition leads to enhanced photosynthetic activity. But the extent of carbon export and sequestration is hard to measure and the observed results vary greatly. During the twelve patch fertilization experiments carried out so far, observed export efficiencies to a depth of 100m ranged from zero to 650 mol carbon (C) per mol iron (Fe) up to 6,648 mol C per mol Fe (*De Baar et al. 2008*).[1] Export efficiencies to a depth of 250 m would be roughly half of these amounts and even less for depths below 500 m. Model simulations suggest that the cumulative sequestration potential of patch fertilization could be at most some ten million tons of carbon for a hundred years. In contrast, recent model simulations suggest a cumulative potential of 26 to 70 GtC for large-scale ocean iron fertilization that would deplete all macronutrients in the global ocean for the same time horizon (*Denman 2008*).

Compared to other sequestration options, this is a relatively small amount. The total long-term potential of terrestrial carbon sequestration, for example, amounts to approximately 200 GtC. In addition, several 100 GtC could be stored in geological formations and up to 10,000 GtC could be stored in saline aquifers (*Huesemann 2008*). Moreover, one has to recall the scope of anthropogenic CO_2 emissions which amounted to 7.8 GtC in 2005 and could well reach 3 to 37 GtC by the year 2100. Cumulated CO_2 emissions until the year 2100 might reach 770 to 2,540 GtC (*IPCC 2007*). Consequently, no single mitigation strategy alone has the potential to guarantee a stabilization of atmospheric CO_2 concentrations. But large-scale ocean iron fertili-

[1] This implies that one ton of iron added to the water could remove between zero and more than 1,400 tons of carbon from the surface ocean to a depth of a hundred meters.

zation could contribute a significant share to a portfolio of mitigation options aiming for stringent stabilization targets. Patch fertilization on the other hand, which is probably more realistic and feasible, would only have a relatively small impact. Still, future research may explore ways to enhance sequestration efficiencies and thus the quantitative potential of ocean iron fertilization. What is more, compared to existing climate targets laid down in the Kyoto Protocol, which sum up to a joint reduction effort of at most 0.25 GtC, the potential of ocean iron fertilization would be significant.

4. Side Effects of Ocean Iron Fertilization

Besides its positive potential to sequester CO_2, ocean iron fertilization might also bring about a couple of adverse and unintended side effects. For example, ocean iron fertilization could influence food web dynamics because phytoplankton is at the bottom of the food chain. This could have positive effects, e.g. on overfished fish stocks, but it could also cause the development of toxic algal blooms. Moreover, the remineralization of the sinking organic matter could lead to anoxia in the subsurface ocean due to large-scale ocean iron fertilization. Indirect side effects of ocean iron fertilization could also include nutrient depletion and lower primary productivity downstream of the fertilization site, an enhanced production of the forceful greenhouse gases nitrous oxide (N_2O) and methane (CH_4) or increased ocean acidity. But when considering the possible adverse side effects of ocean iron fertilization, one also has to keep in mind that these effects are scale and time dependent. No harmful negative effects have been observed during the past patch fertilization experiments. Still, such effects might occur if iron fertilization activities are scaled up (*Denman 2008*, *Powell 2008b*).

5. Costs of Ocean Iron Fertilization

Early estimates for the costs of ocean iron fertilization were very low so that it appeared to be quite a cheap way to reduce atmospheric CO_2 concentrations. For example, *Markels and Barber (2001)* estimated a price of 1.1 to 2.2 USD per tCO_2 sequestered. With less optimistic and more realistic assumptions regarding the sequestration efficiency of ocean iron fertilization, costs are more likely to be between 7.45 and 74.50 USD per tCO_2 sequestered (*Boyd 2008*). Still, these cost estimates are based on the sequestration efficiency ratios observed during the patch fertilization experiments, which in turn are quite uncertain and vary over one order of magnitude. Consequently, also the *IPCC (2007)* points out that there are no reliable cost estimates available for ocean iron fertilization as a mitigation option.

Moreover, the few cost estimates that are available only include the direct costs of the fertilization activity and ignore costs such as those for potential negative downstream effects, e.g. on fisheries. In addition, the costs for monitoring and verification as well as the costs for unintended side effects are not included. Considering generating carbon offsets, deductions would occur if there was an outgassing of other greenhouse gases such as N_2O or CH_4, which would counteract the initial CO_2 sequestration and bring about further costs. All these additional cost factors imply that cost estimates just based on efficiency ratios will probably underestimate true costs. And as it is hard to predict and measure the possible side effects of ocean iron fertilization, the related costs are even harder to be estimated (*Boyd 2008*).

A comparative assessment of iron fertilization with regard to other mitigation options would also need to include the ratio of estimated costs to arising risks. *Boyd (2008)* classifies ocean iron fertilization as a medium-risk, medium-cost mitigation strategy, stating that other strategies with lower risks may have lower costs as well. In addition to this, the potential profitability of ocean iron fertilization could be assessed by considering the market price for CO_2 emission allowances, e.g. within the EU Emission Trading Scheme (ETS). Throughout the first three quarters of 2008, the price for an EU allowance covering the emission of one ton of CO_2 was between 20 and 30 Euros, which could make ocean iron fertilization profitable given the possibility to sell carbon offsets on this market. Recently, the CO_2 price has dropped to below 10 Euros, which would imply a lower profitability of iron fertilization activities.

6. Regulatory Aspects connected to Ocean Iron Fertilization

One of the most crucial factors influencing the regulation of ocean iron fertilization is that it would predominantly take place on the high seas, where no national jurisdiction applies. Thus, no private property rights are assigned for the use of ocean iron fertilization on the high seas and it could in principal be carried out there by everybody and to an arbitrary extent. One consequence of this is that the possibility to generate carbon credits through iron fertilization activities could be considered to represent an open access resource. A profit incentive would be present for firms engaging in iron fertilization activities if there was the possibility to sell the resulting carbon credits on large carbon markets such as the EU ETS or to use them for compliance with the Kyoto Protocol. Though this is not the case as of today, it could possibly lead to a future non-efficient over use of ocean iron fertilization in an open access setting. Thus, a strict regulation of iron fertilization activities, employing taxes or volume restrictions, would be desirable, not only from an ecological but also from an economic point of view.

Another consequence of the location of iron fertilization activities refers to their legal status, falling under the jurisdiction of international law. As of today, ocean iron fertilization falls into a legal grey area and is neither bindingly prohibited nor regulated (*Freestone and Rayfuse 2008*). However, the Parties to the London Convention (LC)[2] and the London Protocol (LP) consider ocean iron fertilization to be contrary to the aims of the Conventions due to its potential adverse side effects, which could harm the marine environment or marine living resources. Consequently, these activities could be banned under international maritime law. In a non-binding resolution put forward under the umbrella of the International Maritime Organization (IMO) in October 2008, the Parties therefore state that ocean iron fertilization should not be carried out except for careful scientific research, which in turn should be subject to member state permis-

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[2] “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter”.

sion (*IMO 2008*). This underlines that there is a vital need to establish an internationally agreed legal framework including permitting requirements, quality standards and liability regulations for ocean iron fertilization. Moreover, it will have to be clarified how to link international agreements like the Kyoto Protocol or a successor agreement and the LC/LP (*Freestone and Rayfuse 2008*). Permission should be mandatory for all ocean iron fertilization activities, and it could be granted by member states or by an international organization made responsible for it.

So far, carbon credits generated through iron fertilization activities could only be sold in the relatively small segment of voluntary carbon markets. Still, as long as the legal status of ocean iron fertilization is not clearly defined and CO_2 emissions keep growing with an increasing momentum, company interests in selling carbon offsets generated through iron fertilization projects are likely to remain strong. Consequently, strict regulations would be needed if these offsets were to be integrated into a Post-Kyoto agreement or regulated carbon markets in the future. So it is briefly discussed in the following how the Kyoto regulations for afforestation and reforestation within the CDM framework,[3] which play a major role on regulated but also on voluntary carbon markets, could be applied to iron fertilization activities.

Basic requirements within the CDM framework include that projects have to bring about a benefit for the host country's sustainable development and that they have to be approved of by the host Party. Neither would be possible for iron fertilization activities because they would take place on the high seas and far from any country. Another basic issue applying to afforestation and reforestation projects under the CDM is the definition of a project site boundary, which is central to calculating the net anthropogenic greenhouse gas removals by sinks attributable to a project. But it would be very difficult to determine a certain bounded project area in advance of an iron fertilization project due to the rapid dilution and dispersion of the fertilized ocean patch, which moreover depends on local ocean currents.

The demonstration of additionality, showing that a project would not have happened without the CDM, is another important concept within the CDM framework. But it is not likely to be problematic in connection with iron fertilization activities, provided that there are no competing usages for the chosen ocean sites. This is because ocean iron fertilization would only be profitable given the possibility to create and sell carbon credits (*Leinen 2008*). Moreover, ocean iron fertilization does not represent a common practice and the only alternative to fertilizing the ocean with iron would be not to use a specific ocean site at all, so that iron fertilization activities could be considered to be additional per se.

The most problematic issue in connection with creating carbon credits through iron fertilization projects is likely to be the difficult measurement, monitoring and verification. These issues are complicated by the fact that side effects that have to be taken into account could affect the ocean on a global scale and would maybe not occur until in a few decades. A combined

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3 The Clean Development Mechanism (CDM) within the Kyoto framework allows Annex 1 countries to carry out emission reduction or removal projects in Non-Annex 1 countries for compliance with their own emission reduction targets. For detailed information on the regulation of afforestation and reforestation activities within the CDM framework see *UNFCCC 2005*.

approach, using models in addition to experimental observations, could help in this respect, but there still remains considerable uncertainty connected to the adequacy and use of such models (*Watson et al. 2008*). Reporting in order to create transparency with regard to iron fertilization would therefore be necessary too, not only covering monitoring and verification but also regarding possible environmental impacts.

Another issue, which has to be kept in mind, is that the carbon storage induced by ocean iron fertilization might not be permanent. A reversal of greenhouse gas removals would be possible due to an outgassing of CO_2 or an enhanced production of N_2O and CH_4. This non-permanent storage could be accounted for by issuing temporary or long-term credits as under the CDM. But this approach will only be appropriate if net greenhouse gas removals attributable to the iron fertilization project always remain positive. Otherwise, nobody would be held responsible for emissions occurring after the end of the project's crediting period, which would make further liability regulations necessary.

A last aspect arising from the CDM framework is the possibility of leakage. First, iron fertilization activities would have to take into account CO_2 emissions generated by the use of vessels and aircrafts in connection with the project activity. Moreover, the upwelling of CO_2 remote from the project site, decreased carbon export downstream of the project site or an increased production of N_2O and CH_4 have to be considered (*Leinen 2008*). Market leakage effects with regard to iron ore markets do not seem relevant for patch fertilization but might become important should ocean iron fertilization be carried out on large scales.

7. Conclusion

It has been made unequivocally clear by the Fourth Assessment Report of the IPCC that human-induced greenhouse gas emissions are contributing to climatic changes which are very likely to bring about negative effects for humankind. This is why new ways to mitigate climate change impacts are searched for and iron fertilization has been suggested as one. Yet, international negotiations concerning climate change mitigation are slow and difficult, and the political willingness to combat climate change seems less strong now that the financial crisis is affecting the global economy. Against this background, it does not seem probable that oceanic sink enhancement activities like ocean iron fertilization are to be included into a new climate agreement in the near future taking into account the high regulatory and monetary effort that would be needed for such an inclusion.

Moreover, it has been shown in this paper that especially the quantitative potential of ocean iron fertilization seems to be rather limited. Estimates for the cumulative quantitative potential of patch fertilization amount to some ten million tons of carbon for a hundred years. In contrast, large-scale iron fertilization could reach a cumulative potential of 26 to 70 GtC for the same time horizon and thus significantly contribute to reaching stringent global climate targets. However, large-scale ocean iron fertilization does not seem realistic at present, e.g. due to logistic constraints.

Furthermore, there are large uncertainties connected to the potential negative side effects of ocean iron fertilization, including unforeseeable changes of food webs and ecosystems, impacts on fisheries, an increased production of nitrous oxide or methane as well as oxygen depletion and ocean acidification. In addition to this, iron fertilization seems to be more costly than has initially been hoped, and the uncertainties about its costs remain high due to the uncertainties that are also connected to its efficiency. Consequently, it might well be the case that other options to mitigate climate change are cheaper and/or connected to fewer risks.

The substantial uncertainties connected to ocean iron fertilization and its effectiveness have given rise to substantial public resistance against its use, and also the scientific community is convinced that it would at present be premature to carry out iron fertilization commercially (*Buesseler et al. 2008*). In opposition to this, a few companies hope to be able to sell carbon credits generated through iron fertilization projects, but even they admit the need for further research (*Leinen 2008*). Consequently, the future has to show if iron fertilization will one day be better understood and work more efficiently, so that it could be used as a real mitigation option. But this still requires more scientific research, which might be slowly scaled up.

If ocean iron fertilization will one day be used to mitigate climate change by enhancing the oceanic CO_2 uptake, carbon offsets generated by these projects might be sold on global carbon markets. But there are several regulatory issues which will have to be addressed before this should be made possibly. The current legal status of ocean iron fertilization and the open access issue underline that international permitting requirements and liability regulations for these activities are necessary. Furthermore, the CDM regulations could not be easily applied to ocean iron fertilization due to the particularities of the latter.

In this context, it also has to be kept in mind that iron fertilization does not constitute a technology which will be easily controlled. It takes place in the changing surroundings of marine ecosystems, and its effects crucially depend on biogeochemical, physical and ecological interrelations, which are not easy to understand and beyond human control. Interference with these ecosystems might bring about unintended effects not even thought about so far, which would also be a point favouring other mitigation or sequestration options.

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