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# Feasibility of ocean fertilization and its impact on future atmospheric $CO_2$ levels

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[1] Iron fertilization of macronutrient-rich but biologically unproductive ocean waters has been proposed for sequestering anthropogenic carbon dioxide ($CO_2$). The first carbon export measurements in the Southern Ocean (SO) during the recent SO-Iron Experiment (SOFeX) yielded ~900 t C exported per 1.26 t Fe added. This allows the first realistic, data-based feasibility assessment of large-scale iron fertilization and corresponding future atmospheric $CO_2$ prognosis. Using various carbon cycle models, we find that if 20% of the world's surface ocean were fertilized 15 times per year until year 2100, it would reduce atmospheric $CO_2$ by $\lesssim$15 ppmv at an expected level of ~700 ppmv for business-as-usual scenarios. Thus, based on the SOFeX results and currently available technology, large−scale oceanic iron fertilization appears not a feasible strategy to sequester anthropogenic $CO_2$. **Citation:** Zeebe, R. E., and D. Archer (2005), Feasibility of ocean fertilization and its impact on future atmospheric $CO_2$ levels, *Geophys. Res. Lett.*, *32*, L09703, doi:10.1029/2005GL022449.

## 1. Introduction

[2] In most parts of the world's surface ocean, phytoplankton effectively utilizes macronutrients such as phosphorus (P) and nitrogen (N) and converts inorganic carbon (C) into biomass. Roughly 25% of this biomass sinks out of the surface and is remineralized primarily in the upper 1000 m of the ocean [e.g., *Martin et al.*, 1987]. This process leads to vertical gradients in e.g. P, N, and C and is referred to as the biological soft tissue pump. However, in about 20% of the surface ocean, macronutrients go largely unutilized and low biomass and chlorophyll concentrations are observed. These areas are termed high-nitrate, low-chlorophyll (HNLC) areas and comprise large parts of the Southern Ocean, the equatorial Pacific and part of the North Pacific. The late John Martin proposed that a lack of micronutrients such as iron is responsible for this phenomenon [*Martin*, 1990] and over the past decade, his 'iron-hypothesis' has been impressively confirmed [*Martin et al.*, 1994; *Boyd et al.*, 2000, 2004; *Coale et al.*, 2004].

[3] The prospect of potentially increased carbon drawdown by an iron-stimulated biological pump has led to proposals for purposeful large-scale ocean fertilization as a means of sequestering anthropogenically produced $CO_2$, see www.planktos.com and *Markels* [2002]. Indeed, recent reports [*Schiermeier*, 2004] on scientific small-scale iron enrichment studies [*Bishop et al.*, 2004] may be interpreted as if purposeful fertilization were a viable strategy. However, the principal questions regarding fertilization proposals to be addressed first are (i) whether iron-stimulated phytoplankton growth also leads to significant vertical carbon export from the surface ocean [*Boyd et al.*, 2004; *Buesseler et al.*, 2004] and if so (ii) is it potentially of global relevance, and (iii) is it technologically feasible. Before concluding on iron fertilization efficacy, precise data on carbon export is required that is fed into global carbon cycle models in order to quantitatively evaluate the feasibility of this proposal and its potential for future atmospheric $CO_2$ levels. (Other fundamental questions such as biogeochemical secondary effects are discussed elsewhere [e.g., *Fuhrman and Capone*, 1991].)

[4] The first data on Southern Ocean carbon export during the iron enrichment experiment SOFeX have now been obtained [*Buesseler et al.*, 2004] which enables us for the first time to realistically assess the feasibility of iron fertilization to sequester carbon and forecast its impact on future atmospheric $CO_2$. We initially focus on the addition of an iron fertilizer applied by large commercial vessels, e.g., chemical tankers, for which the SOFeX results will serve as the base case, alternative options are discussed later. In order to evaluate the feasibility of large-scale iron fertilization and to study the assessment sensitivity, a set of equations is developed first which is then used to calculate requirements for a desired annual carbon export from the high-latitude surface ocean. This carbon export is, however, not equal to sequestration as will be subsequently demonstrated by our carbon modeling study. Sensitivity parameters will be varied over a wide range. The so calculated spectrum of scenarios should be indicative for the effects of large-scale fertilization, even if the actual parameters of large-scale fertilization would differ from those of SOFeX by an order of magnitude.

## 2. Feasibility

[5] The feasibility assessment parameters are: Total number of ships required to deliver the load of iron ($N_s$) and the ocean surface area that needs to be fertilized ($A_C$). $N_s$ is given by the required iron load divided by the cargo tank capacity ($T_s$) of an individual ship. The required iron load is the desired C export, $F_C$, divided by the ratio of C export:Fe added in an individual patch ($r_{C:Fe}$), see Table 1. The base

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**Table 1.** Parameters of Feasibility Assessment

| Variable | Symbol | Value | Unit |
|---|---|---|---|
| Desired C export[a] | $F_C$ | 1, 5, 10 | Pg C $y^{-1}$ |
| C export:Fe added (base)[b] | $r_{C:Fe,0}$ | 714 | t $t^{-1}$ |
| C export:Fe added | $r_{C:Fe}$ | varies | t $t^{-1}$ |
| C export per area (base)[b] | $F_{A_0}$ | 0.9 | g $m^{-2}$ |
| C export per area | $F_A$ | varies | g $m^{-2}$ |
| HNLC area | $A_H$ | $0.72 \times 10^{14}$ | $m^2$ |
| Number of ships | $N_s$ | varies | – |
| Ship capacity | $T_s$ | varies | t |

[a] Note that this export is not equal to sequestration.

[b] SOFeX [*Buesseler et al.*, 2004].

case patch, index 0, refers to the measured values during SOFeX. Mathematically,

$$N_s = \frac{F_C}{r_{C:Fe} \cdot T_s \cdot \frac{56}{152}} \tag{1}$$

where $\frac{56}{152}$ is the ratio of the molar weight of Fe to $FeSO_4$ (the fertilizer used during SOFeX, alternative fertilizers may change this number).

[6] While the so calculated fleet should be capable for merely shipping the iron, it also needs to be spread over a large surface ocean area in order to induce large-scale phytoplankton blooms. If the iron is released over small areas producing high surface concentrations, iron minerals precipitate and sink unutilized into the deep ocean. We take this into account by considering the ratio of the area ($A_C$) to be fertilized per year for the desired carbon export to the total HNLC area ($A_H$):

$$f = \frac{A_C}{A_H} \,. \tag{2}$$

This is the fertilization frequency, i.e. how often the total HNLC area needs to be fertilized per year. The required area, $A_C$, is given by $A_p$, the individual patch area, times the ratio of total desired export to export in this patch ($A_C = A_p \cdot F_C/F_p$). With $F_p = A_p \cdot F_A$, where $F_A$ is export per unit area (Table 1), equation (2) becomes:

$$f = \frac{F_C/F_A}{A_H} \,. \tag{3}$$

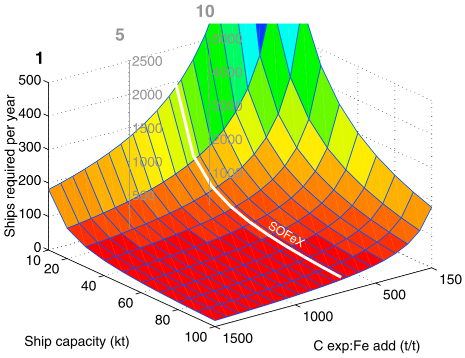

**Figure 1.** Number of ships required per year to deliver the iron to the ocean ($N_s$) for a given carbon export as a function of the ship's cargo tank capacity ($T_s$) and the ratio C export:Fe added ($r_{C:Fe}$). The different z-axes labeled 1, 5, and 10 refer to a desired carbon export of $F_C$ = 1, 5, and 10 Pg C $y^{-1}$, respectively. The white line indicates $r_{C:Fe}$ as measured during SOFeX ($r_{C:Fe,0}$). Note that $N_s$ only satisfies shipping requirements but not area coverage and that C-export is not equal to sequestration.

[7] Results for $N_s$ at a desired carbon export of $F_C$ = 1, 5, and 10 Pg C $y^{-1}$ as a function of the C export:Fe added-ratio and the ship capacity are shown in Figure 1. Capacities of large chemical tankers are in the range 10–50 kt, while super oil tankers can carry up to 100 kt or more. Our results show that for large cargo capacities ($\geq$20 kt) and $r_{C:Fe}$ equal to or larger than $r_{C:Fe,0}$ = 714 t $t^{-1}$ (SOFeX), less than 200 ships are required to simply carry the iron required for a desired carbon export of 1 Pg C $y^{-1}$. If the desired carbon export is 5 and 10 Pg C $y^{-1}$, this number increases to 1,000 and 2,000, respectively.

[8] Figure 2 shows the corresponding fertilization frequency ($f$) required for the same $F_C$ values as a function of the carbon export per unit area. For $F_{A_0}$ = 0.9 g $m^{-2}$ (SOFeX) and $F_C$ = 1 Pg C $y^{-1}$, the total HNLC area (~20% of surface ocean) needs to be fertilized 15 times per year. This is equivalent to an annual area coverage of about twice Earth's surface. $f$ increases to 77 and 154 times per year for $F_C$ = 5 and 10 Pg C $y^{-1}$, respectively. (Note however that there is a limit to $f$ which is reached when the fertilized areas become marconutrient-depleted, see below). In order to reduce the required fertilized area to 50% of the HNLC regions per year, the export efficiency would have to increase by a factor of 27, 140, and 277 over that of SOFeX if 1, 5, and 10 Pg C are to be exported per year, respectively.

[9] It is emphasized that the desired carbon export flux as used above is not equal to carbon sequestration. One reason lies in another legacy of the late John Martin: The so-called Martin curve of remineralization of organic carbon in the ocean's interior [*Martin et al.*, 1987]. Carbon exported from

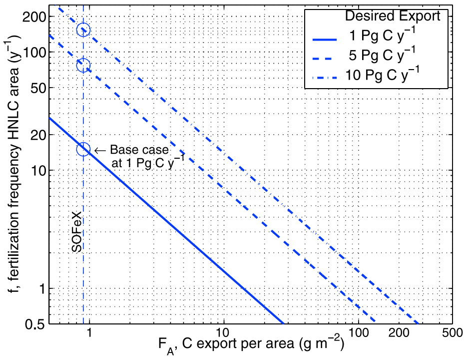

**Figure 2.** Fertilization frequency ($f$) of HNLC area per year for a desired carbon export of $F_C$ = 1, 5, and 10 Pg C $y^{-1}$, respectively. Note that both axes are logarithmic. The base case refers to measured values of $F_A$ during SOFeX which requires, for example, $f$ = 15 for a desired C export of 1 Pg C $y^{-1}$. Fertilizing the HNLC area 15 × per year is equivalent to an annual area coverage of about twice Earth's surface. Note also that there is a limit to $f$ which is reached when the fertilized areas become marconutrient-depleted (see text).

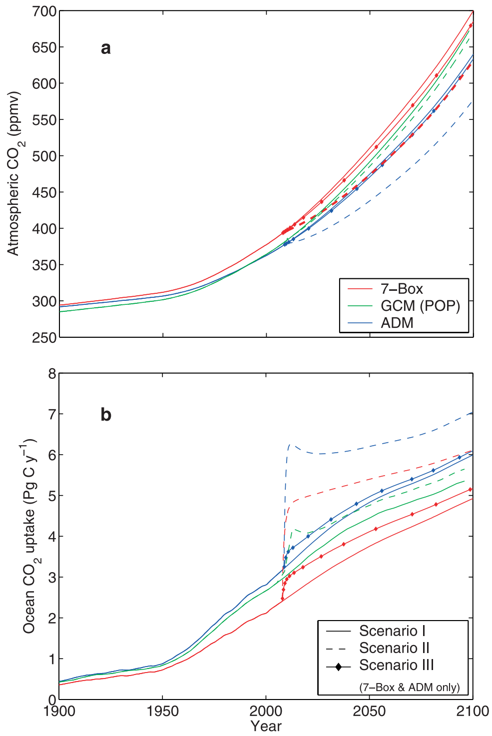

**Figure 3.** (a) Model calculated atmospheric $CO_2$ and (b) oceanic uptake of anthropogenic $CO_2$. Scenario I (solid lines): No fertilization. Scenario II (dashed): High-latitude nutrient depletion by 50%. Scenario III (dot-dashed): Export increased by 1 Pg C $y^{-1}$ (ADM and box model only!). The GCM results were obtained with the Parallel Ocean Program (POP) model, run on a coarse-resolution global grid (100 by 116 gridpoints in longitude and latitude, and 25 depths) using NCEP reanalysis bulk heat fluxes, Gent-McWilliams eddy parameterization [*Gent and McWilliams*, 1990], and carbon cycle following OCMIP protocols [*Orr*, 1999]. The model was spun up for 3000 years under specified $pCO_2$, after which $pCO_2$ was allowed to vary in response to ocean surface forcing and anthropogenic input.

the surface layer is rapidly decomposed back into $CO_2$ while sinking to the deep ocean. In the open ocean, about 50% of the sinking particles are remineralized within the first 150 m of settling. The released $CO_2$ is rapidly mixed within the surface layer and the net effect of sequestration for this carbon portion is zero. Another reason is that physical mixing and water mass transport strongly influence the carbon distribution in the ocean. Thus, in order to assess the potential of iron-stimulated carbon export for net $CO_2$ sequestration, remineralization, ocean mixing, and circulation have to be considered [*Peng and Broecker*, 1991; *Joos et al.*, 1991; *Sarmiento and Orr*, 1991].

## 3. Carbon Cycle Modeling

[10] We employed three different ocean carbon cycle models to prognosticate future atmospheric $CO_2$ levels due to macronutrient depletion as a result of potential iron fertilization. We focused on the Southern Ocean which is by far the most important HNLC region for potential $CO_2$ sequestration because of its tight connection to the large volume of water in the deep ocean. This is not the case for the equatorial and North Pacific [*Sarmiento and Orr*, 1991]. We used an advection-diffusion model (ADM) with a high-latitude surface box [*Siegenthaler and Joos*, 1992; R. E. Zeebe, Simple ocean carbon cycle models: New insights into evaluating glacial $CO_2$ scenarios and predictions of anthropogenic $CO_2$ uptake by the ocean, submitted to *Global Biogeochemical Cycles*, 2005] a seven-box model [*Toggweiler*, 1999], and a General Circulation Model (GCM) (see caption Figure 3). While ADMs and GCMs have been employed for similar purposes before [*Joos et al.*, 1991; *Sarmiento and Orr*, 1991] including IPCC's future projections [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001], the box model has not. Despite the limitations of the box model regarding the considered time scale it is instructive to include it because of its large high-latitude sensitivity [*Archer et al.*, 2003]. This permits the investigation of the response to iron-induced nutrient depletion in the Southern Ocean in models reacting differently to high-latitude forcing.

[11] The models were run from years 1750 to 2100, starting at an atmospheric $CO_2$ concentration of 280 ppmv (271 ppmv in the GCM). For the period 1750 to 2000, $CO_2$ emissions due to fossil fuel burning and land-use changes (G. Marland et al., Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, http://cdiac.esd.ornl.gov/ftp/ndp030/global00.ems, 2003; R. A. Houghton, Woods Hole Research Center, http://cdiac.ornl.gov/ftp/db1009/inputs/deforest.all, 1995) were used to force the models, while the business as usual scenario IS92a was employed for the period 2000 to 2100 [*IPCC*, 2001]. Carbon uptake by the terrestrial biosphere was not modeled here but set to a constant value because its precise value is irrelevant to the outcome of the current study. Atmospheric $CO_2$ concentrations and ocean carbon uptake were calculated in the models using routines summarized by *Zeebe and Wolf-Gladrow* [2001] for three different scenarios (Figure 3). Scenario I: No changes in biological pump. II: Starting in year 2010, particle export in 'high-latitude area' is increased, depleting macronutrients by ~50% until year 2100 (high-latitude area in ADM: high-latitude box, box model: polar box, GCM: south of $-55°$ latitude). III (ADM and box model only): Same as II but particle export is increased by 1 Pg C $y^{-1}$.

[12] The ADM shows a higher oceanic $CO_2$ uptake than the box model and the GCM (Scenario I, Figure 3) which leads to lower atmospheric $CO_2$ in the ADM. Nevertheless, calculated atmospheric $CO_2$ concentrations and ocean uptake of all three models are well within the range of published results [*IPCC*, 2001]. The calculated differences between Scenario II and I for the ADM and the box model are similar, forecasting an atmospheric $CO_2$ reduction by 64 and 69 ppmv and increased carbon uptake by 1.1 and 1.2 Pg C $y^{-1}$ in year 2100 for Scenario II vs. I, respectively. These numbers are likely an overestimate since these models are high-latitude sensitive. In addition, reduction of carbon uptake due to nutrient depletion elsewhere was not considered [*Sarmiento and Orr*, 1991] and the high-latitude surface boxes in which nutrient depletion was simulated have a depth of 250 m in the two models, while observed nutrient depletion is usually

confined to the upper 50 to 100 m [*Martin et al.*, 1994; *Boyd et al.*, 2000; *Coale et al.*, 2004]. The GCM, which is less high-latitude sensitive, only predicts a difference of 11 ppmv and increased carbon uptake by 0.3 Pg C $y^{-1}$ in year 2100 between Scenario II and I.

[13] The calculated difference in atmospheric $CO_2$ and ocean uptake in year 2100 between Scenario III and I are $-7$ and $-15$ ppmv and 0.10 and 0.25 Pg C $y^{-1}$ for the ADM and the box model, respectively. These numbers represent net carbon sequestration estimates and not carbon export from the surface layer! Scenario III was not simulated in the GCM since the effect of Scenario II was already very small.

## 4. Discussion and Conclusion

[14] The results demonstrate that sequestration is less than about 10–25% of the export that may be achieved by fertilization, that is 0.1–0.25 Pg C $y^{-1}$ for an export of 1 Pg C $y^{-1}$ in the ADM and box model and even less in the GCM. For comparison, annual global $CO_2$ emissions by humans are currently $\sim$6.6 Pg C $y^{-1}$ and are expected to increase to $\sim$20 Pg C $y^{-1}$ in year 2100. The sequestration of 1 Pg C $y^{-1}$ (Scenario II) requires an increase of high-latitude carbon export by 4.8 and 10.1 Pg C $y^{-1}$ in the box model and ADM, respectively. Thus, if the desired sequestration from fertilization is 1 Pg C $y^{-1}$, the required export calculated in the different models is about 5–10 times this value or even larger (GCM). The consequences for our feasibility assessment regarding the required number of ships and the fertilization frequency for the ADM and box model-scenarios have been calculated and included in Figures 1 and 2, labeled '5' and '10'.

[15] Given the SOFeX outcome, the results obtained in our assessment show that it should be possible to merely ship the required iron for a desired carbon export of, say 1 Pg C $y^{-1}$. Less than 200 ships are required with a cargo tank capacity larger than 20 kt (Figure 1). However, given the current technology it appears impossible to cover the required annual fertilization area of 15 times the total HNLC regions, equivalent to about twice Earth's surface (Figure 2). Moreover, annual fertilization in the Southern Ocean would have to be accomplished in far less than 12 months because of darkness during part of the year. If the carbon export per $m^2$ in purposeful fertilizations could be increased by a factor of 27 over that of SOFeX, 50% of the HNLC areas need to be fertilized per year. This still appears an extremely challenging if not impossible technological task. Commercial proposals claim to achieve a fertilized patch area of $1.3 \times 10^{10}$ $m^2$ with a single chemical tanker [*Markels and Barber*, 2001]. This area equates to $\sim$0.02% of the HNLC regions. In other words, about 5,500 chemical tankers would be required to cover the total HNLC area.

[16] Finally, even if a considerable carbon export could be accomplished by fertilization, the effective carbon sequestration of that is only $\sim$10–25% (ADM and box model) or much less (GCM), as shown by our carbon cycle modeling study. For a desired carbon sequestration of 1 Pg C $y^{-1}$ in the Southern Ocean, an additional export of at least 5–10 Pg C $y^{-1}$ would be required. Given the SOFeX results, this would translate into 1,000 to 2,000 vessels (capacity $\geq$20 kt) or more for shipping the iron and a fertilization frequency of $f$ = 77 and 154 times per year. Besides the fact that such values of $f$ appear unrealistic, the fertilized areas would also become macronutrient-depleted (in the box model and ADM at $F_C \simeq 8$ and 20 Pg C y, respectively). In order to reduce the frequency to once every 2 years, the carbon export per unit area would have to be increased by a factor of 140 and 277 over that of SOFeX (Figure 2).

[17] Given these numbers, it is difficult to see how iron fertilization can be successful using the strategy examined above or alternative options. It has been suggested to distribute iron via commercial ships that use the major ship lanes across the world's ocean (www.planktos.com). Although this would increase the number of potentially usable ships, each ship would only carry a tiny fraction of the load of a chemical tanker. In addition, major ship lanes cover only small parts of the HNLC regions. Systematic area coverage will not be achieved and the most important HNLC region for carbon sequestration, the Southern Ocean [*Sarmiento and Orr*, 1991], will be left out completely. Iron fertilization via aircrafts would require a number of large cargo aircrafts (payload $\sim$100 t) equal to 200 times the number of chemical tankers (capacity 20 kt) for merely shipping the iron. The problem of area coverage remains the same.

[18] We conclude that based on the SOFeX results and currently available technology, oceanic large-scale iron fertilization not appears a feasible strategy to remove anthropogenic $CO_2$ from the atmosphere. Understanding the role of iron in marine biogeochemical cycles is and should remain a top priority in basic ocean research. Small-scale iron addition experiments including carbon export measurements to investigate iron-carbon cycle feedbacks are crucial [cf. *Chisholm et al.*, 2001], potentially also for the glacial $CO_2$ problem or longer time scales [*Ridgwell*, 2003; *Zeebe and Westbroek*, 2003]. However, decisions whether to further commercial ocean fertilization proposals instead of reducing anthropogenic $CO_2$ emissions will have to take the results presented here into account.

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