11. Ocean Fertilization

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Part 1: Introduction to the Climate System (4 sessions)
1. Introduction and scope of the lecture
2. The Climate System – Radiation Balance
3. Elements of the Climate System - Greenhouse Gases, Clouds, Aerosol
4. Dynamics of the Climate System - Sensitivity, Predictions

Part 2: Climate Engineering Methods - Solar Radiation Management, SRM
1. SRM – Reflectors in space
2. SRM – Aerosol in the Stratosphere
3. SRM – Cloud Whitening
4. SRM – Anything else

Part 3: Climate Engineering Methods – Carbon Dioxide Removal, CDR
1. Direct CO\textsubscript{2} removal (CDR) from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization
4. Removal of other greenhouse gases

Part 4: CE – Effectiveness, Side Effects (3 sessions)
1. Comparison of Techniques, characterisation of side effects
2. Other parameters than temperature
3. Summary
Literature Ocean Fertilization


Contents of Today's Lecture

- Ocean Fertilization: the Idea
- Which fertilizers?
- Biology and organic carbon in the ocean
- Fertilization Experiments
- Side effects?
- Efficiency in removing CO$_2$ from the Atmosphere
- Model calculations
- Conclusions
Ocean Fertilization – The Idea (1)

Relative (molar) amounts of elements which algae use in building their organic tissue:

Redfield Ratios* of the nutrient elements to carbon, in algal tissues (Although there can be large variations):

Typically:

\[ \text{C : N : P : Fe} = 106 : 16 : 1 : 0.001 \]

(eg, Sarmiento & Gruber 2006).

| Molar masses: | C: 12 | N: 14 | P: 31 |

| Mass ratios: | \( \text{C : N : P : Fe} = 41 : 7.2 : 1 : 0.0018 \) |

\[ \Rightarrow \text{C/Fe} = 22777 \]

Ocean Fertilization – The Idea (2)

There are large areas of the ocean where growth of marine phytoplankton is limited by one or a few nutrients. (and the Redfield-Ratio gives a measure for the limitation)

Ideal for CE are nutrients which are only required in small quantities compared to the amount of biomass (i.e. fixed carbon) which is produced.

So we have to find areas where the growth of marine phytoplankton is limited by a particular nutrient which is only required in small quantities (compared to fixed C)
Ocean (Iron) Fertilization: Enhance CO$_2$-Uptake

Redfield Ratio: $C:N:P:Fe \approx 106:16:1:0.001$ (e.g. Sarmiento&Gruber 2006)

\[
\frac{C}{N} \approx 6.6
\]

\[
\frac{C}{P} = 1
\]

\[
\frac{C}{Fe} \approx 10^5
\]

\[
\approx 2 \cdot 10^4
\]

by mass

John Martin* (1989):

„Give me half a tanker of Iron and I will give you an ice age“

*Oceanographer, presentation at Woods Hole Oceanographic Institution
Enhanced Fe Input to the Oceans by Dust Reduces Atmospheric CO$_2$?

Figure 2. Relationship between Fe and CO$_2$ concentrations from the Vostok ice cores. After Martin (1990b)
Which Fertilizers?

Artificial fertilization techniques:

**Iron** in seawater is mostly in an insoluble form → rapid precipitates out of the surface ocean.
Fertilization experiments: Fe has been added as iron sulphate (FeSO$_4$·7H$_2$O), which is a common agricultural fertilizer and relatively soluble. The iron sulphate is dissolved in acidified seawater, and pumped into the ocean behind a moving vessel. The acidic solution is neutralised rapidly upon mixing with ambient seawater and the iron is transformed chemically into its insoluble form, more rapidly in warmer waters. Commercial fertilization activities might add chemical complexing agents to keep iron in solution for longer.

**Phosphorus** addition experiments have used concentrated phosphoric acid mixed with sodium bicarbonate, or direct addition of anhydrous monosodium phosphate. The solutions are pumped into surface waters behind a moving vessel.

**Nitrogen (nitrate):** addition of urea (NH$_2$)$_2$CO has been commercially-proposed, either as a liquid mixed with phosphate solution and seawater and pumped into the ocean or as spherical grains spread over the ocean surface.
The leverage factor is by far the greatest for iron!

→ Use iron?

Problem: We need ocean areas where all nutrients are more abundant (relative to their Redfield-Ratio) than iron.

→ These areas do exist, but they are not large enough to sequester the full annual anthropogenic CO₂ emission.
## Properties of Fertilizers

<table>
<thead>
<tr>
<th></th>
<th>upwelling and mixing of deep water</th>
<th>atmospheric supply as gas</th>
<th>atmospheric supply as dust</th>
<th>conc. limiting productivity</th>
<th>conc. range in the oceanic euphotic zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>phosphorus</td>
<td>★★★★★</td>
<td>★</td>
<td>★</td>
<td>&lt;0.01 μM</td>
<td>0.005–2.0 μM</td>
</tr>
<tr>
<td>nitrogen</td>
<td>★★★★★</td>
<td>★</td>
<td>★</td>
<td>&lt;0.02 μM</td>
<td>0.002–30.0 μM</td>
</tr>
<tr>
<td>silicon</td>
<td>★★★★★</td>
<td>★</td>
<td>★</td>
<td>0.2 μM</td>
<td>0.05–130 μM</td>
</tr>
<tr>
<td>iron</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>0.2 nM</td>
<td>0.005–1.0 nM</td>
</tr>
<tr>
<td>zinc</td>
<td>★★★★★★</td>
<td>★</td>
<td>★</td>
<td>0.2 nM</td>
<td>0.01–1.0 nM</td>
</tr>
<tr>
<td>carbon (DIC)</td>
<td>★★★★★</td>
<td>★</td>
<td>★</td>
<td>2.0 mM</td>
<td></td>
</tr>
</tbody>
</table>

*From: Lampitt et al. 2008*
Global annual minimum distribution of surface concentrations of nitrate, one of the principal macronutrients limiting primary production (Levitus world ocean atlas 1994).
Distribution of phosphate from S to N in the Pacific (170°W) → near-surface depletion and increase in concentration with depth.
Nitrate at the World Ocean Surface + Fe-Fertilization Experiments

Lampitt et al. 2008
How to Fertilize?

1) Ships: Pump e.g. FeSO$_4$-solution over board (of a tanker)

2) Artificial upwelling: floating pipes have been proposed, incorporating one-way valves that exploit wave energy or oceanic temperature and salinity gradients to bring deeper water to the near-surface. Typical dimensions suggested for the pipes are ~10 m diameter with lengths of 100–300 m or longer. Networks of pipes, either free-floating or tethered to the seafloor, could be distributed across regions with low surface nutrient concentrations.

Wallace et al. 2012
Processes involved in biological production, decomposition and nutrient cycling in the open ocean

Interactive version at: www.whoi.edu/oceanus/viewFlash.do?fileid=30687&id=23452&aid=35609

Bottom line: Only a small fraction of the C drawn into the ocean by plankton blooms makes it into depths where it can no longer exchange with the atmosphere.

Interactive version at: www.whoi.edu/oceanus/viewFlash.do?fileid=30687&id=23452&aid=35609
CO₂ – Uptake in the Ocean: The “Biological Pump”

Schematic of the decrease in downward flux of organic carbon as a function of depth in the water column. This is based on Martin et al. (1987) depicting the values that may be encountered in the temperate North Atlantic Ocean but the general principle is common to other regions. The two factors that determine the shape of the curve are the sinking rate of the particles and their rate of degradation.

From: Lampitt et al. 2008
Fe/C Molar Ratios from a series of Experiments

Boyd et al. 2007
Sites of the 13 iron fertilization experiments (red), two commercial trials using iron (pink) and two phosphate addition studies (white) carried out to date, on map of satellite-based ocean primary production (yellow/green, high; dark blue, low).

Wallace et al. 2012
Sample Experiment (N-E Pacific)

Satellite image of the phytoplankton bloom stimulated by the SERIES iron fertilization experiment in the North East Pacific (circled). Black areas are cloud cover. The red/orange colours south of Alaska and in other coastal areas are natural blooms. This SeaWiFS image was acquired 19 days after initial addition of iron (on 29 July 2002); five days later, the patch was barely visible.

Wallace et al. 2012
How Effective is Ocean Fertilization?

Sketch of processes and inefficiencies involved in C-sequestration by ocean fertilization

**Blue arrows**: intended sequestration pathways

**Red arrows**: pathways reducing efficiency

Wallace et al. 2012
… it is difficult to see how ocean iron fertilization with such a low \( C_{\text{sequestered}}: Fe_{\text{added}} \) export efficiency would easily scale up to solve our larger global C imbalance problems... It would scale up to a region of \( 10^9 \) km\(^2\)—more than an order of magnitude larger than the entire area of the Southern Ocean.

K. O. Buesseler et al., Science 2002 and 2008

Side Effects:

enhanced production of greenhouse gases like DMS, COS, organic halogen species

M. Lawrence, Science, 2001

**CO\(_2\)** Sequestration by Fertilization of Suitable Ocean Areas
How Effective is Ocean Fertilization?

Model-based estimates of the effectiveness of carbon sequestration (cumulative drawdown over 100 yr) for large-scale, iron-based ocean fertilization as a function of year of publication.

Wallace et al. 2012

0.25 GtC/a
How to improve Effectiveness of Ocean Fertilization

Fertilization experiment (1.5 µmol/l of FeSO₄) in the Antarctic circumpolar current (Feb. - March 2004)

→ Diatom dominated bloom
→ about 50% of fixed carbon reached depths >1000m

# Model Calculations on Fe-Fertilization Effects

| Model                        | Approach                                                        | Overall estimate of C sequestered | Maximal estimate of C sequestration rate | Summary                                                                                                                                                                                                 |
|------------------------------|                                                                |                                  |                                        |                                                                                                                                                                                                 |
| Sarmiento and Orr, 1991      | Complete macronutrient depletion due to iron fertilization of HNLC regions | 98–181 Gt C over 100 yrs         | Rates around 1–1.5 Gt yr\(^{-1}\) integrated over a century | Assumes complete macronutrient depletion due to OIF of the entire Southern Ocean and results in a 20% reduction in anthropogenic emissions only if this level of fertilization is maintained for 100 years. |
| Gnanadesikan et al., 2003    | patchy fertilization; includes downstream effects of macronutrient depletion on biological pump | Ultimately, the negative effect on productivity from OIF could be 30x the amount of C exported from OIF | 2–20% sequestration of 2 Gt yr\(^{-1}\) as an initial estimate of global export production | Sequestration (for 100 yr) is a small percentage of annual export production. Overall downstream impacts of OIF may outweigh the carbon sequestration response. |
| Aumont and Bopp, 2006        | Uses models based on OIF experiments to simulate productivity, export production, and ultimately sequestration | 70 Gt C over 100 yrs             | Export production: Initial increase 3.8 Gt yr\(^{-1}\), slows to 1.8 Gt yr\(^{-1}\) Sequestration: 0.3–1 Gt yr\(^{-1}\) | Ultimately, 90% of sequestration comes from the Southern Ocean. Model predicts substantial increases in productivity. Only a fraction of this productivity is ultimately exported, and only a fraction of that is ultimately sequestered. Requires constant summer fertilization. |
| Jin et al., 2008             | Models patch to basin-scale fertilization for one decade; analyzes CO\(_2\) drawdown | 3.4 Gt C over 10 yrs             | N/A                                                                 | The model shows high atmospheric CO\(_2\) uptake efficiency, but low total biological pump efficiency; full fertilization of the entire Pacific HNLC for 10 yrs results in 3.4 Gt of CO\(_2\) drawdown. |
| Zahariev et al., 2008        | Complete relief of iron limitation in the global ocean         | 77 Gt C over 5,300-yr maximum     | 1 Gt yr\(^{-1}\) maximum | Continuous fertilization of the entire Southern Ocean results in about 11% offset of global emissions under the most ideal conditions. |

- CO\(_2\)-drawdown in surface ocean
- Little export to deep sea
- typ. \(\approx\) 1 GtC/year

**Strong et al. 2009**
Side Effects of Ocean Fertilization

- Change in the composition of phytoplankton communities
- Other nutrients are depleted (since there is more plankton growth)
- Marine biochemistry is changed
- Plankton produces gaseous products
  - $\text{CH}_4 \rightarrow$ enhanced greenhouse effect, enhanced trop. $\text{O}_3$
  - $\text{N}_2\text{O} \rightarrow$ enhanced greenhouse effect
  - DMS $\rightarrow$ Trop. particle production (further cooling?, see Wingenter et al. 2007)
  - Halocarbons ($\text{CH}_3\text{Cl}$, $\text{CH}_3\text{Br}$, $\text{CH}_3\text{I}$, etc. $\rightarrow$ $\text{O}_3$-reduction, disturbance of photochemistry)
  - COS $\rightarrow$ Strat. particle formation (further cooling, see „S to the stratosphere“)
- Enhanced biological activity heats the ocean (up to 1.5 W/m$^2$) ?
- Changed surface ocean temperature may change ocean circulation
Summary

- Originally ocean fertilization (OF) was seen as a very effective CE-measure (in principle high leverage of the order of 30000)
- Recent research including the results of several experiments indicate that OF might not be very effective
- Nevertheless, the leverage of OF is large, making it a potentially viable CE-measure
- However suitable ocean areas are limited, probably less than 10 - 15% of the global annual CO$_2$ emission could be removed by OF
- Also, there are side effects, e.g. the production of halogenated species by phytoplankton