Lecture „Climate Engineering“

11. Ocean Fertilization

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Lecture Program of „Climate Engineering

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_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

Boyd P.W. et al. (2007), Mesoscale Iron Enrichment Experiments 1993-2005: Synthesis and Future Directions, Science 315, 612.

Feng E.Y., Koeve W., Keller D.P., and Oschlies A. (2017), Model-Based Assessment of the CO_2 Sequestration Potential of Coastal Ocean Alkalinization, Earth's Future 5, 1252–1266, https://doi.org/10.1002/2017EF000659

Gnanadesikan A. and Marinov I. (2008), Export is not enough: nutrient cycling and carbon sequestration. Marine Ecology Progress Series, 364, 289-94.

Güssow K., Proelss A., Oschlies A., Rehdanz K. & Rickels W. (2010), Ocean iron fertilization: Why further research is needed. Marine Policy 34, 911-918.

Lampitt R.S. and 11 others (2008), Ocean fertilization: A potential means of geoengineering?, Phil. Trans. Roy. Soc. A, 366 (1882) 3919-3945.

Secretariat of the Convention on Biological Diversity (2009), Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity. Montreal, Tech. Ser. No. 45, 53pp.

Smetacek V., Klaas C., Strass V.H., Assmy P., Montresor M., Cisewski B., Savoye N., Webb A., d'Ovidio F., Arrieta J.M., Bathmann U., Bellerby R., Berg G.M., Croot P, Gonzalez S., Henjes J., Herndl G.J., Hoffmann L.J., Leach H., Losch M., Mills M.M., Neill C., Peeken I., Röttgers R., Sachs O., Sauter E., Schmidt M.M., Schwarz J, Terbrüggen A. & Wolf-Gladrow D. (2012), Deep carbon export from a Southern Ocean iron-fertilized diatom bloom, Nature 487, 313-319.

Strong A.L., Cullen J.J. & Chisholm S.W. (2009). Ocean fertilization. Science, policy and commerce. Oceanography 22, 236-61.

Wallace D. et al. (2011). Ocean fertilization: A Scientific Summary for Policymakers Intergovernmental Oceanographic Commission.

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:

C : N : P : Fe = 106 : 16 : 1 : 0.001
(eg, Sarmiento & Gruber 2006).

Molar masses: C: 12

N: 14

P: 31

Mass ratios:

C : N : P : Fe = 41 : 7.2 : 1 : 0.0018

→C/Fe = 22777

*Redfield, Alfred C. in *James Johnstone Memorial Volume* (ed. R. J. Daniel) 177–192 (Univ. Press of Liverpool, 1934).

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)

Compare: Liebig's Law of the Minimum

Stating that growth (of plants) is controlled not by the total amount of resources available, but by the scarcest resource (limiting factor).

Ocean (Iron) Fertilization: Enhance CO_2-Uptake

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

$$\frac{C}{N} \approx 6.6$$

$$\frac{C}{P} = 1$$

$$\frac{C}{Fe} \approx 10^5$$

$$\approx 2 \cdot 10^4$$

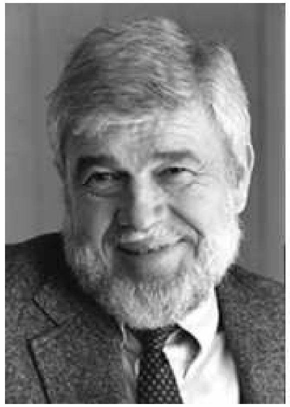
bymass

Martin, J. H. and Fitzwater, S. E. (1988) Iron-deficiency limits phytoplankton growth in the Northeast Pacific Subarctic. *Nature* 331, 341-343

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?

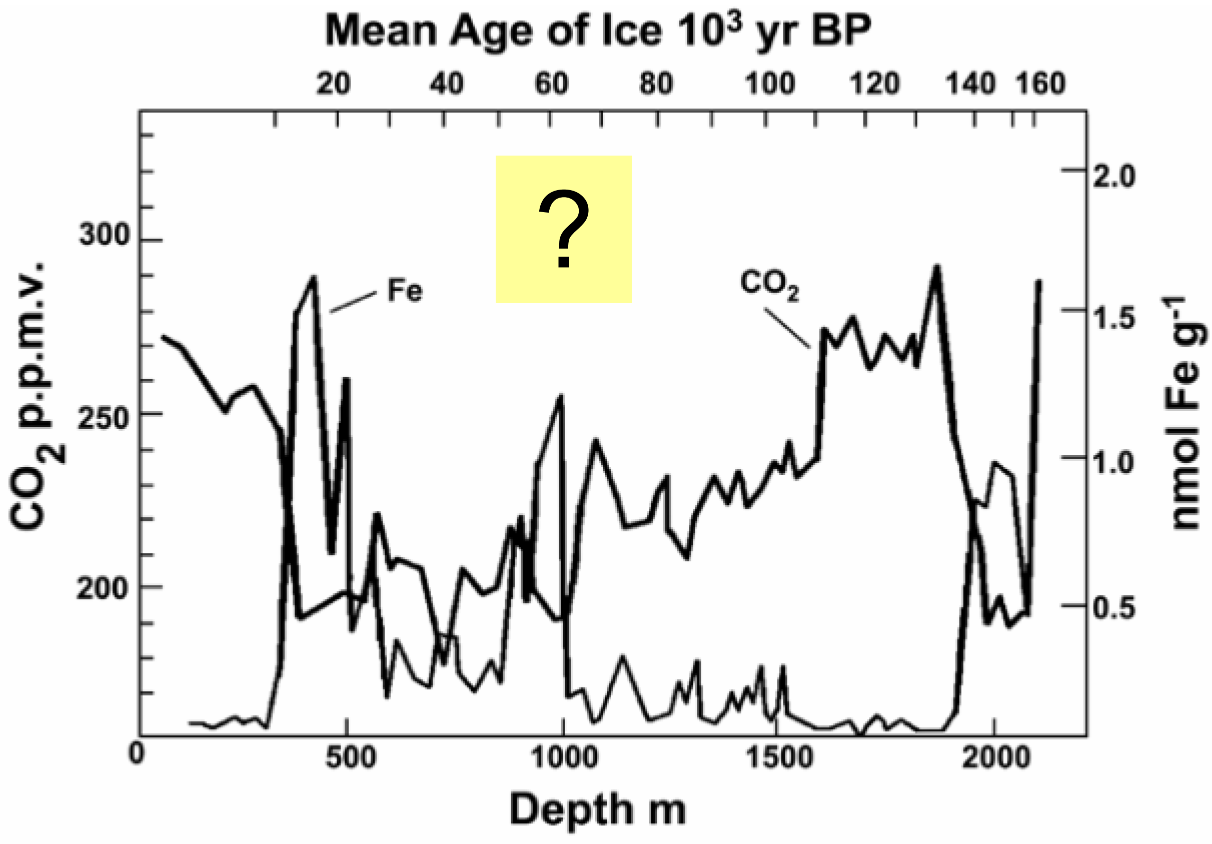


Figure 2. Relationship between Fe and CO_2 concentrations from the Vostok ice cores. *After Martin (1990b)*

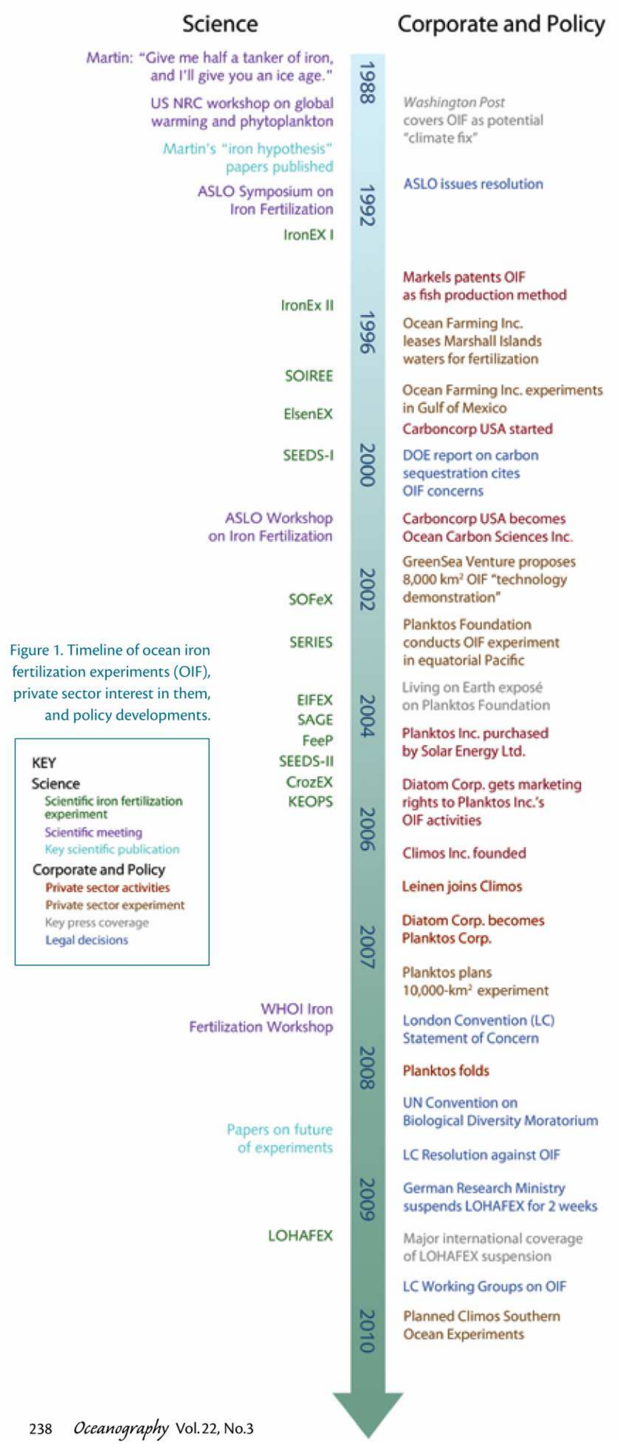


Figure 1. Timeline of ocean iron fertilization experiments (OIF), private sector interest in them, and policy developments.

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 ($FeSO_4 \cdot 7H_2O$), 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 $(NH_2)_2CO$ 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.

Leverage Ratio of Different Fertilizers

Fertilizer X	Mass Ratio C/X	Mass Ratio CO_2/X	Mass Ratio CO_2/Y
N	5.7	21	$CO_2/NaNO_3$ 3.5
P	41	150	CO_2/Na_3PO_4 28
Fe	22800	83500	$CO_2/FeSO_4$ 30700

The leverage factor is by far the greatest for iron!

→ Use iron?

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

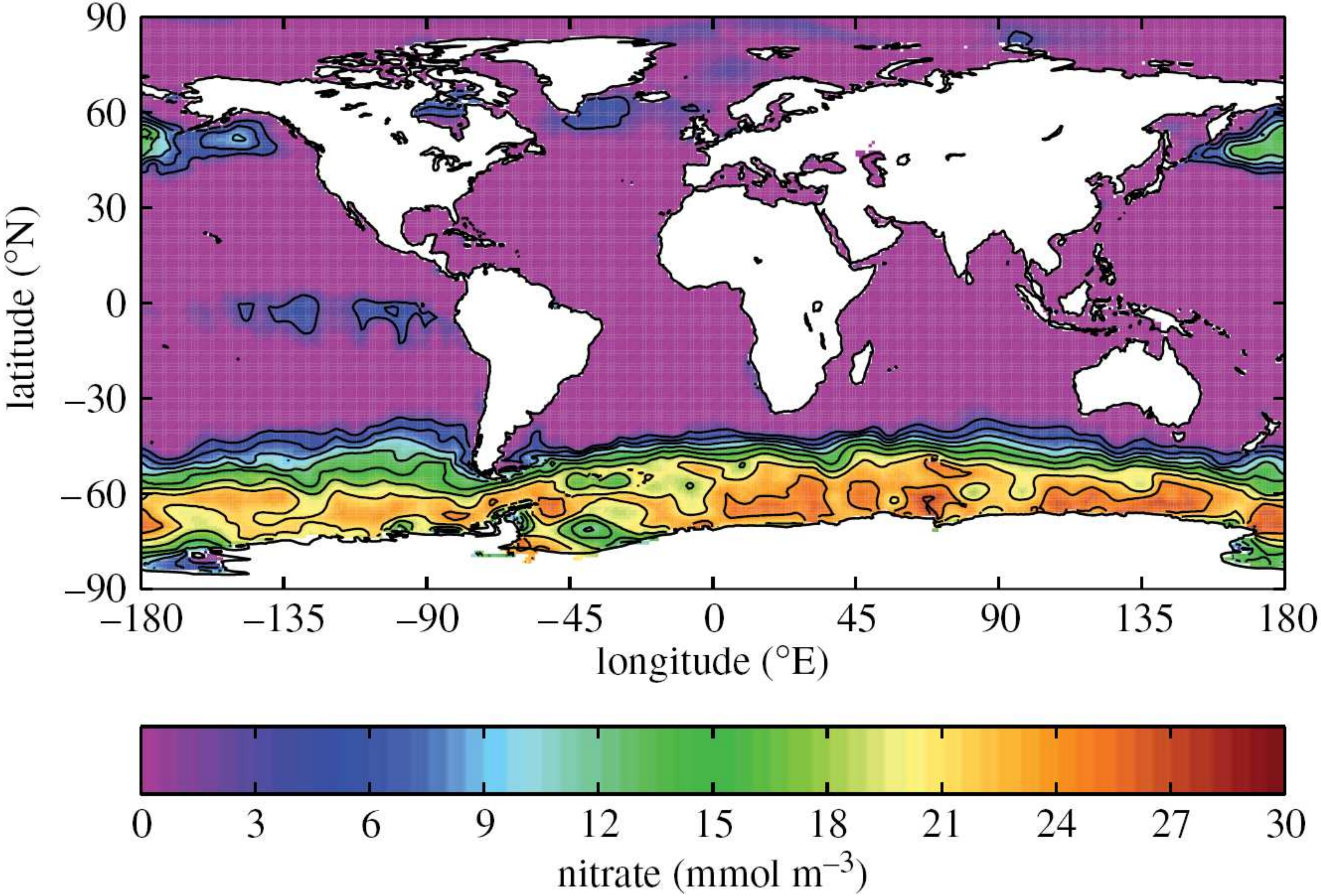
→ These areas do exist, but they are not large enough to sequester the full annual antropogenic CO_2 emission.

Properties of Fertilizers

	upwelling and mixing of deep water	atmospheric supply as gas	atmospheric supply as dust	conc. limiting productivity	conc. range in the oceanic euphotic zone
phosphorus	♦♦♦♦		♦	<0.01 µM	0.005–2.0 µM
nitrogen	♦♦♦	♦	♦	<0.02 µM	0.002–30.0 µM
silicon	♦♦♦♦		♦	0.2 µM	0.05–130 µM
iron	♦♦♦		♦♦	0.2 nM	0.005–1.0 nM
zinc	♦♦♦♦♦				0.01–1.0 nM
carbon (DIC)	♦♦♦♦	♦			2.0 mM

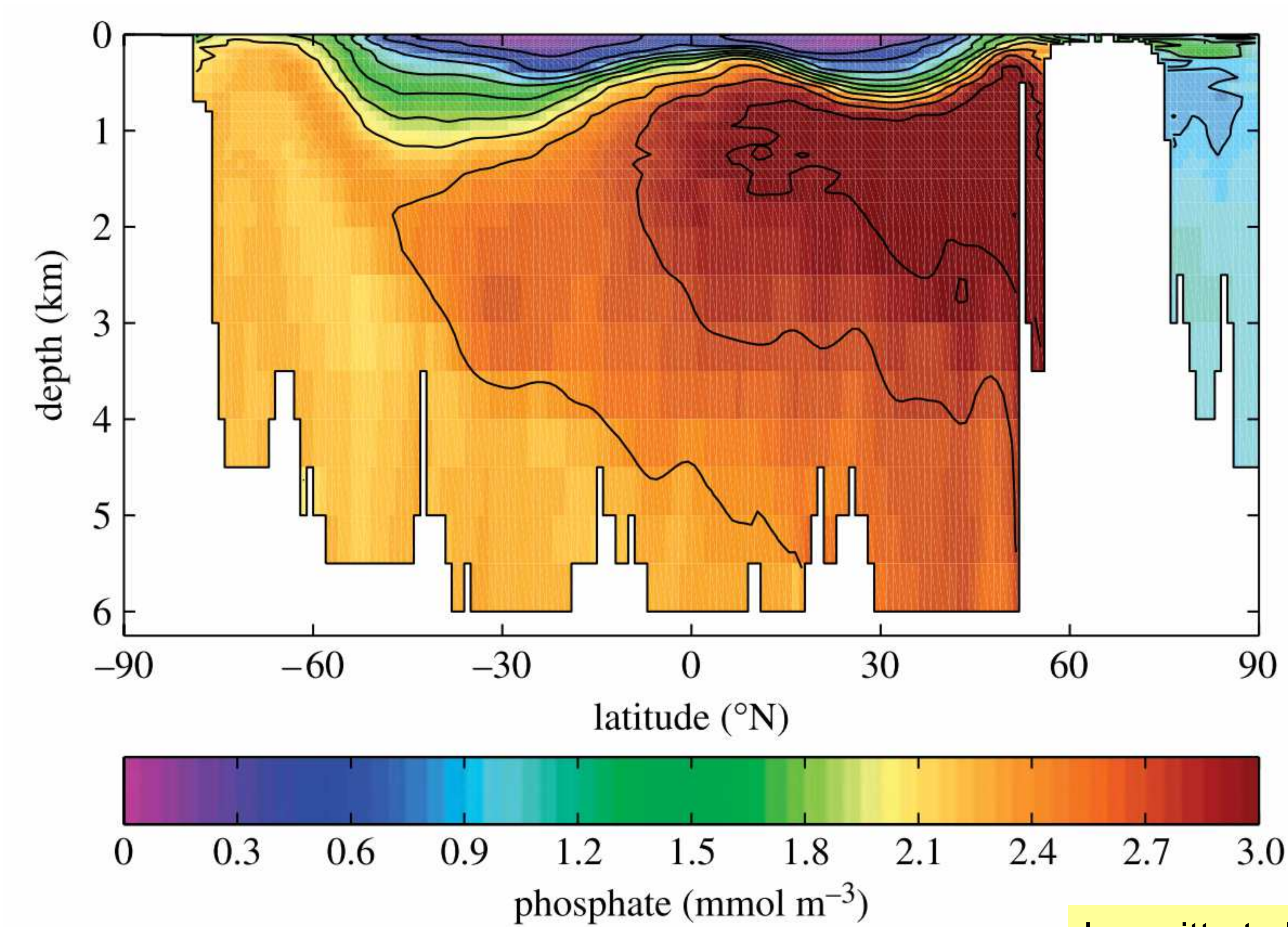
From: Lampitt et al. 2008

Nitrate at the World Ocean Surface



Global annual minimum distribution of surface concentrations of nitrate, one of the principal macronutrients limiting primary production (Levitus world ocean atlas 1994).

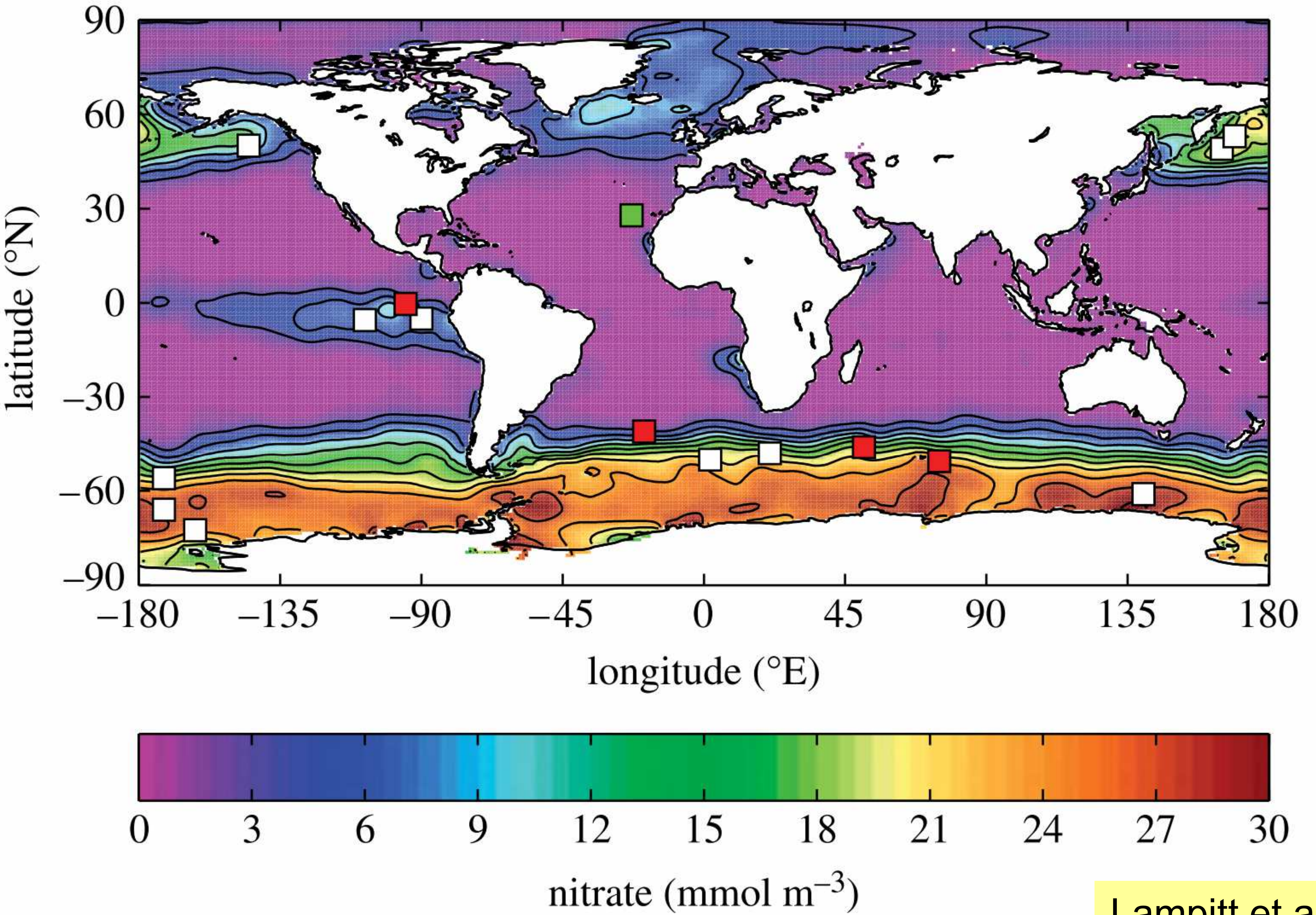
PO_4^{3-} N-S-Distribution in the Atlantic



Lampitt et al. 2008

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

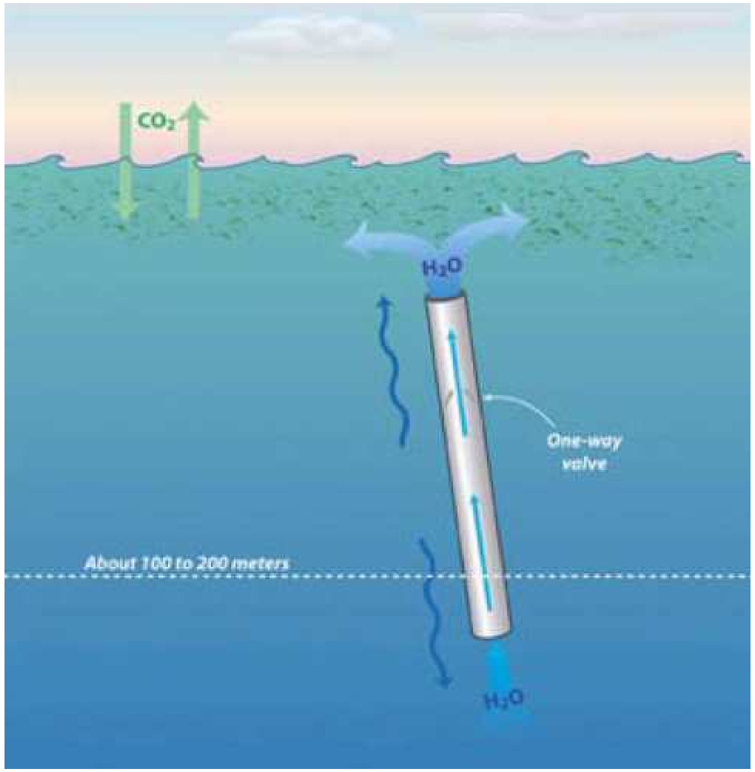


Lampitt et al. 2008

How to Fertilize?

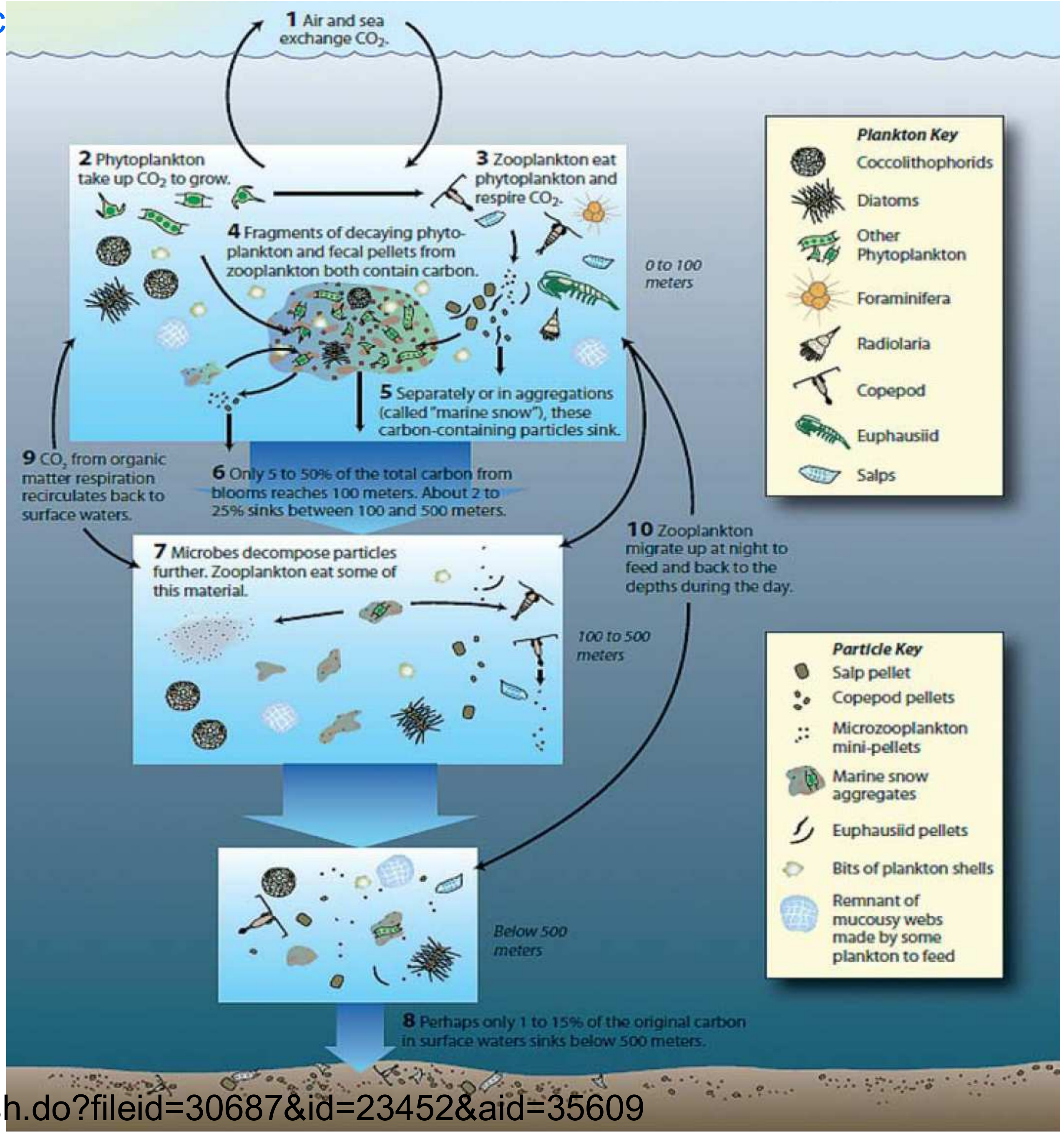
1) Ships: Pump e.g. $FeSO_4$-solution over board (of a tanker)

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

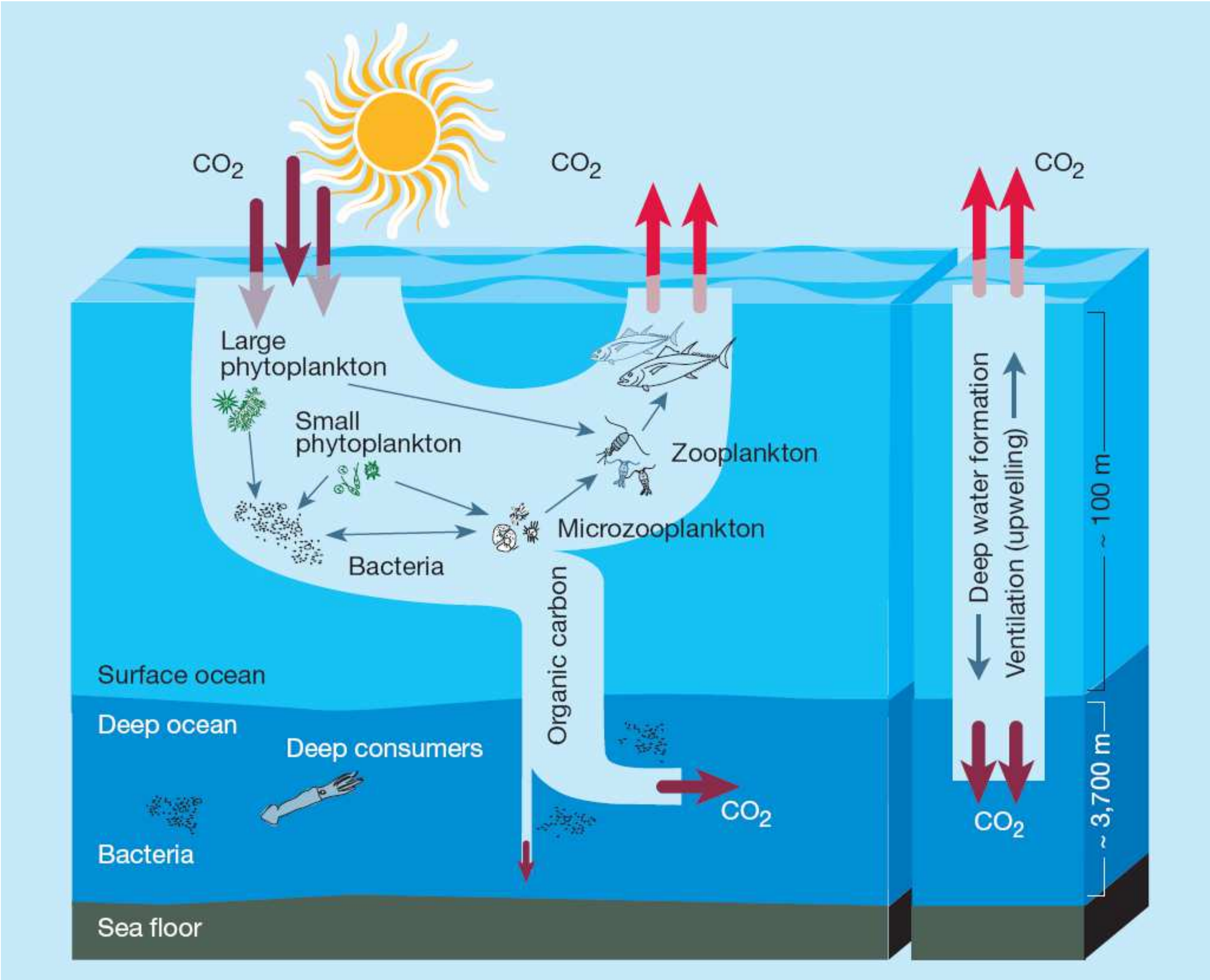
Processes involved in biological production, decomposition and nutrient c



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

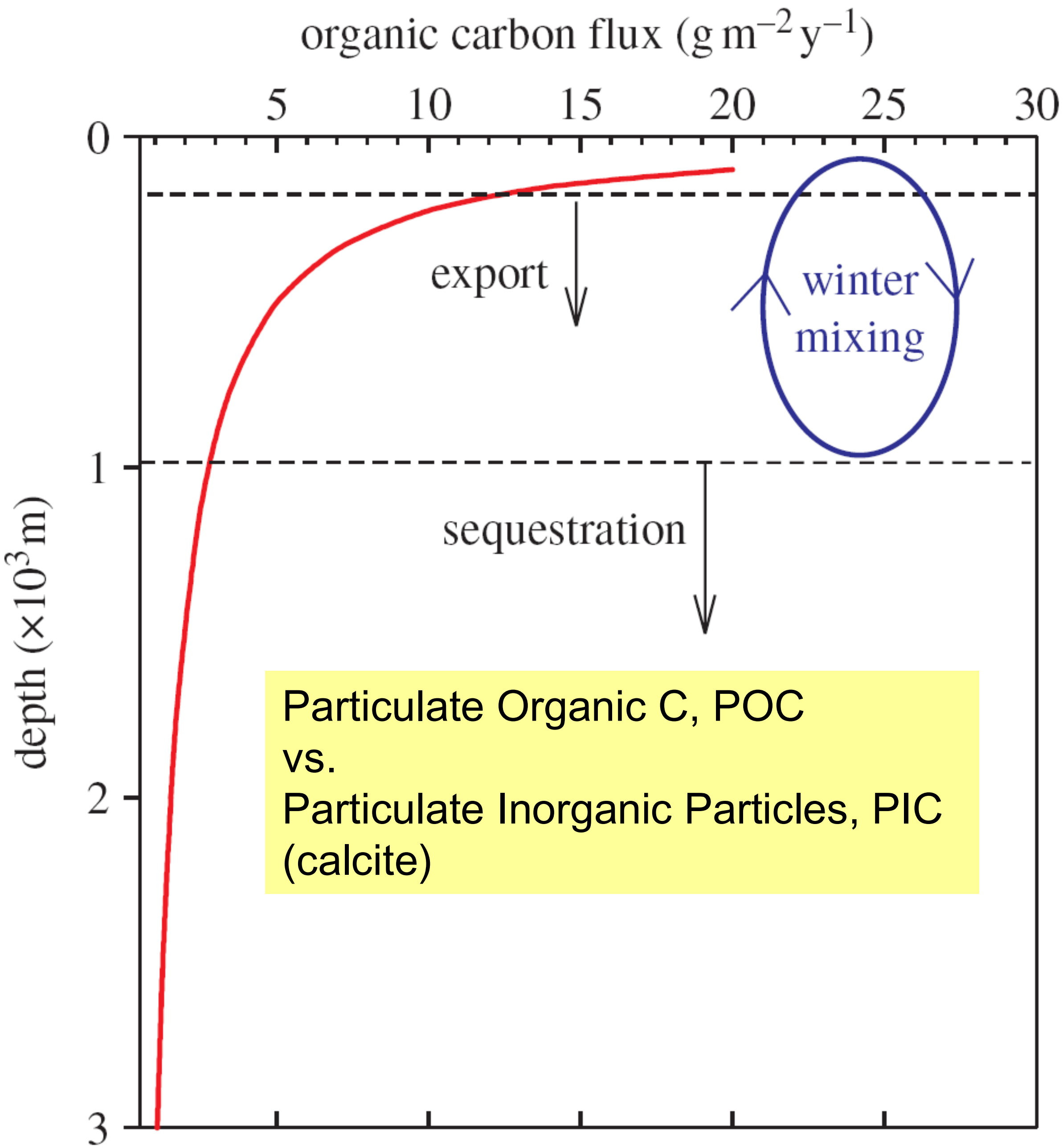
CO_2 – Uptake in the Ocean: The “Biological Pump”



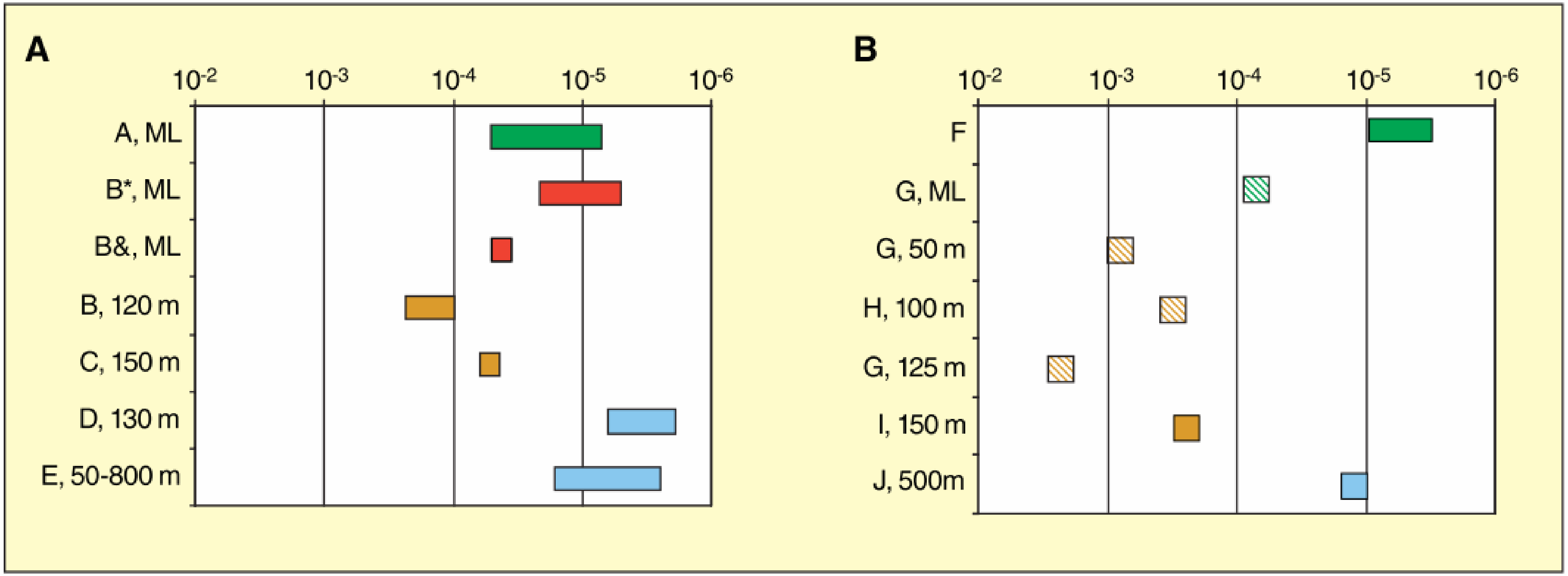
S.W. Chisholm, Nature **407**, (2000)

Vertical C-Flux in the Ocean

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

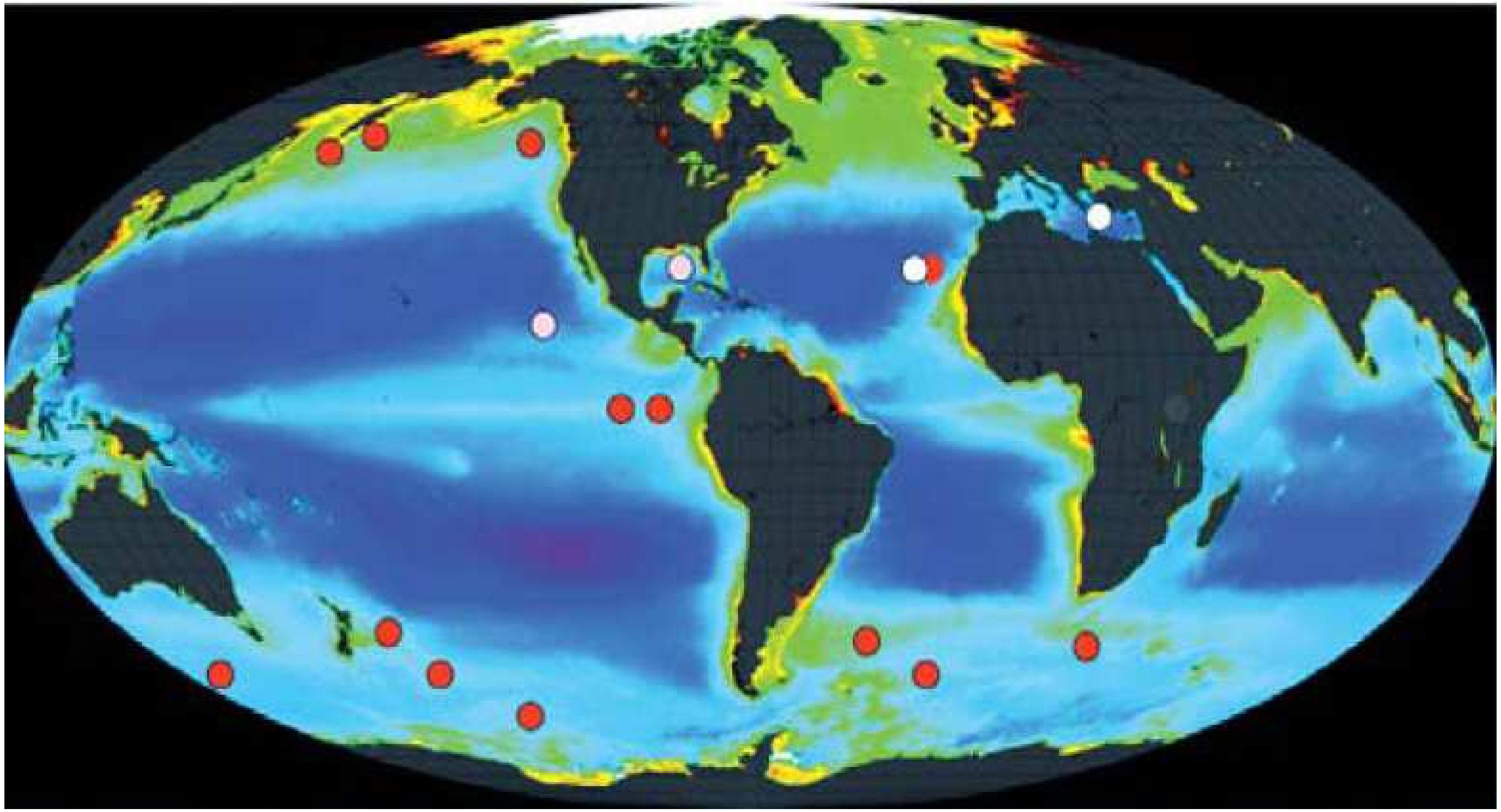


Fe/C Molar Ratios from a series of Experiments



Boyd et al. 2007

Sites of Fertilization Experiments

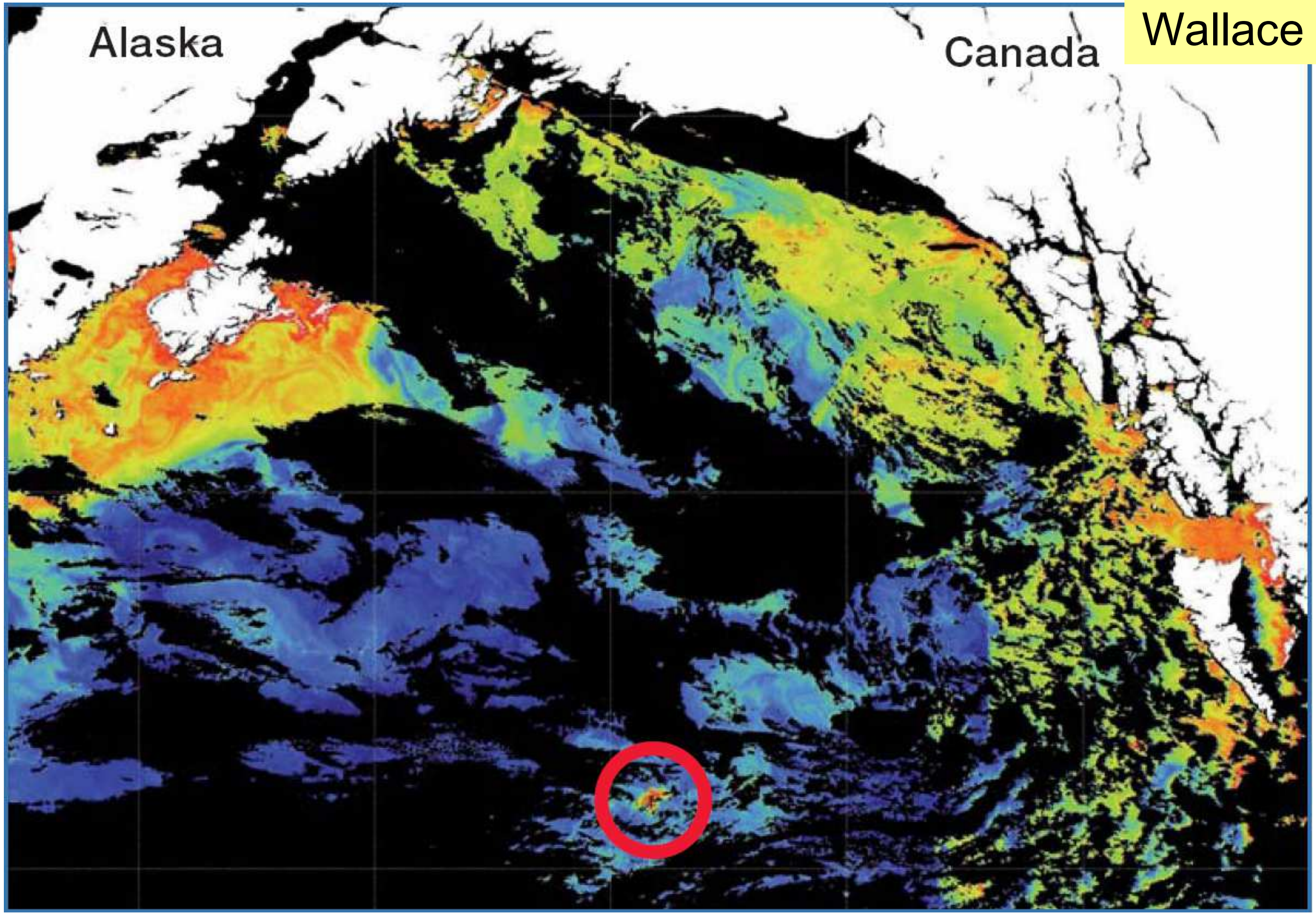


Sites of the 13 iron fertilization experiments (red), two commercial trials using iron (pink) and two phosphate addition studies (white) carried out to date, on map of satellite-based ocean primary production (yellow/green, high; dark blue, low).

Wallace et al. 2012

Sample Experiment (N-E Pacific)

Wallace et al. 2012



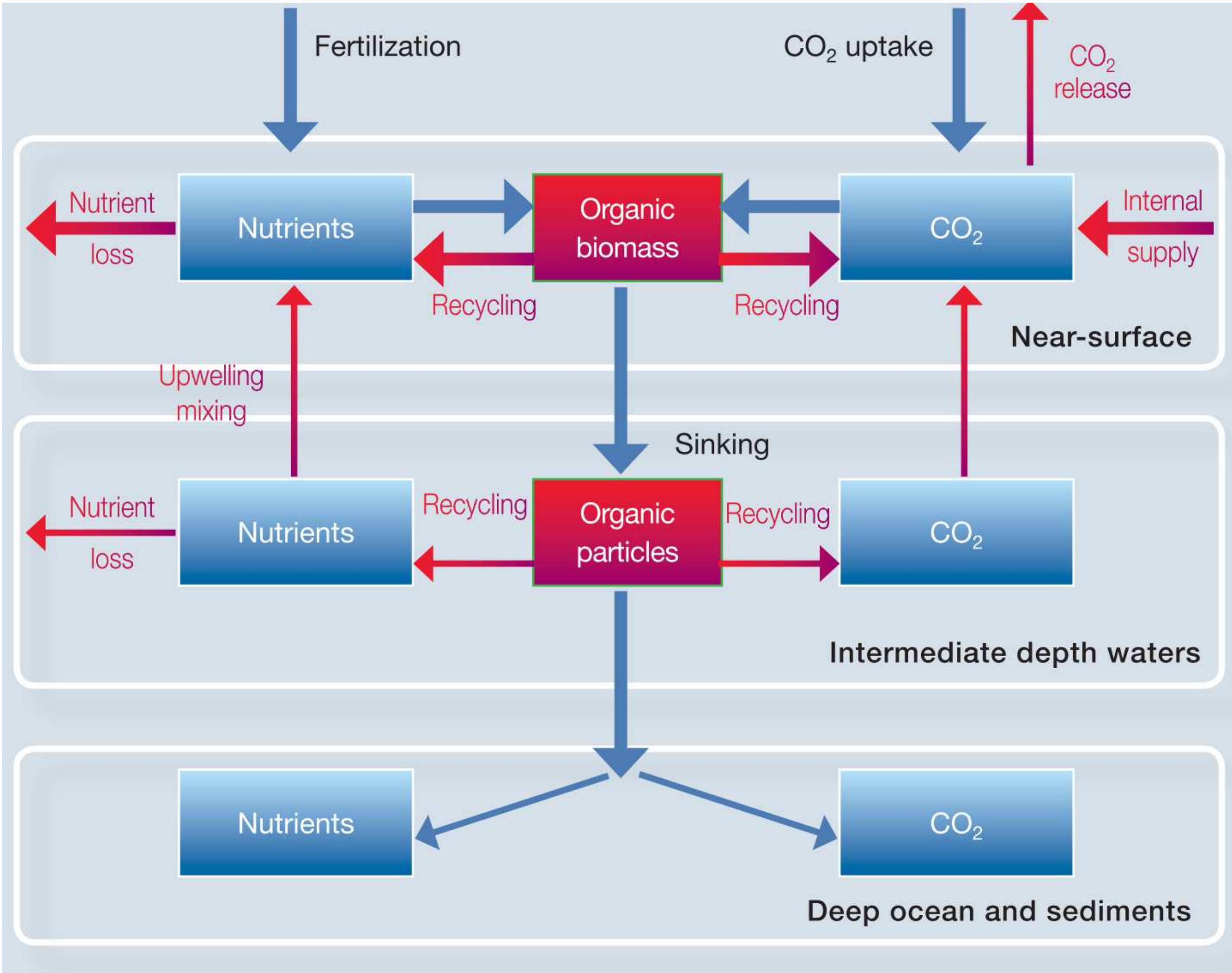
Satellite image of the phytoplankton bloom stimulated by the SERIES iron fertilization experiment in the North East Pacific (circled). Black areas are cloud cover. The red/orange colours south of Alaska and in other coastal areas are natural blooms. This SeaWiFS image was acquired 19 days after initial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

How Effective is Ocean Fertilization?

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

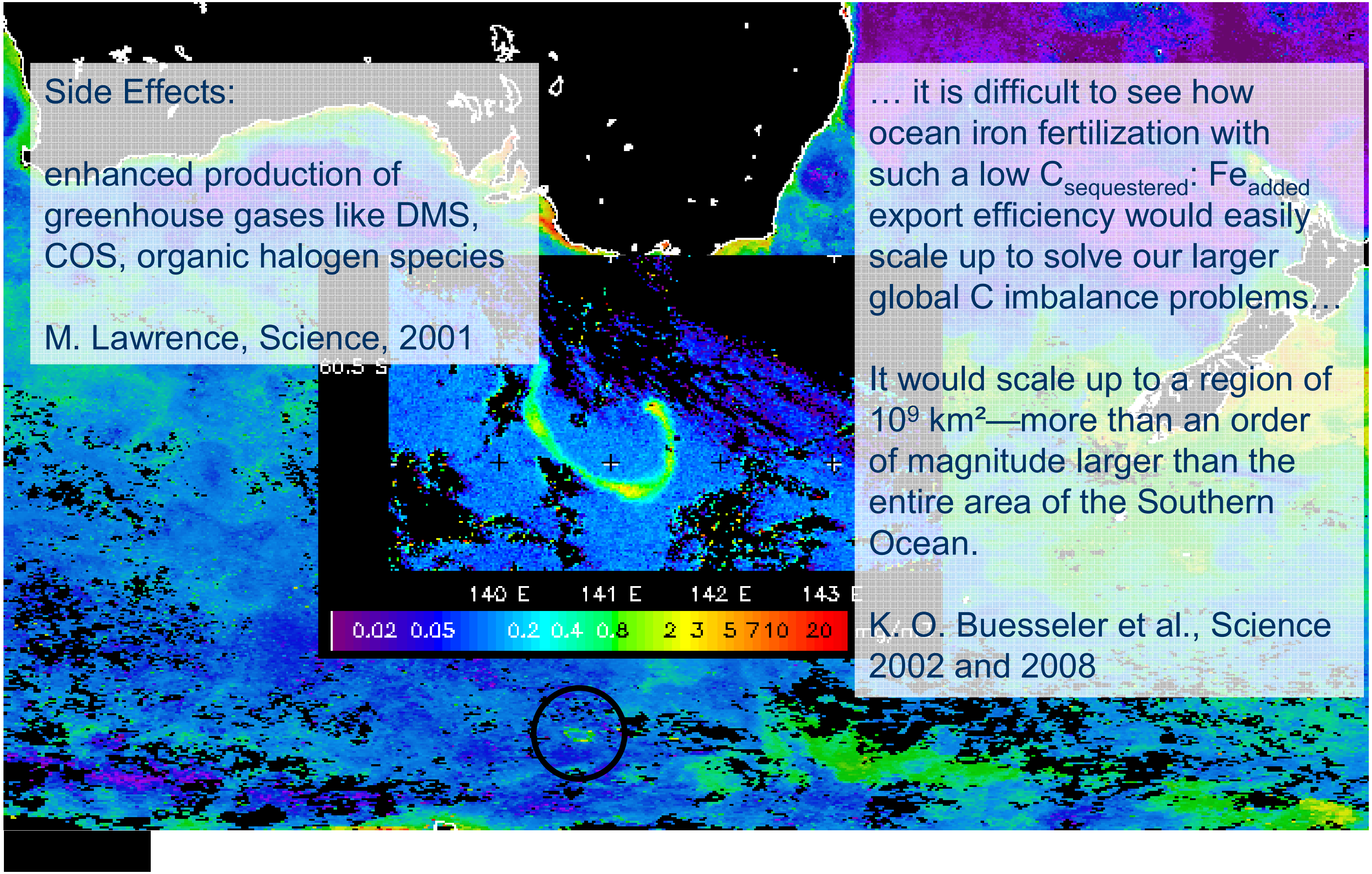
Blue arrows: intended sequestration pathways

Red arrows: pathways reducing efficiency



Wallace et al. 2012

CO_2 Sequestration by Fertilization of Suitable Ocean Areas



Side Effects:

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

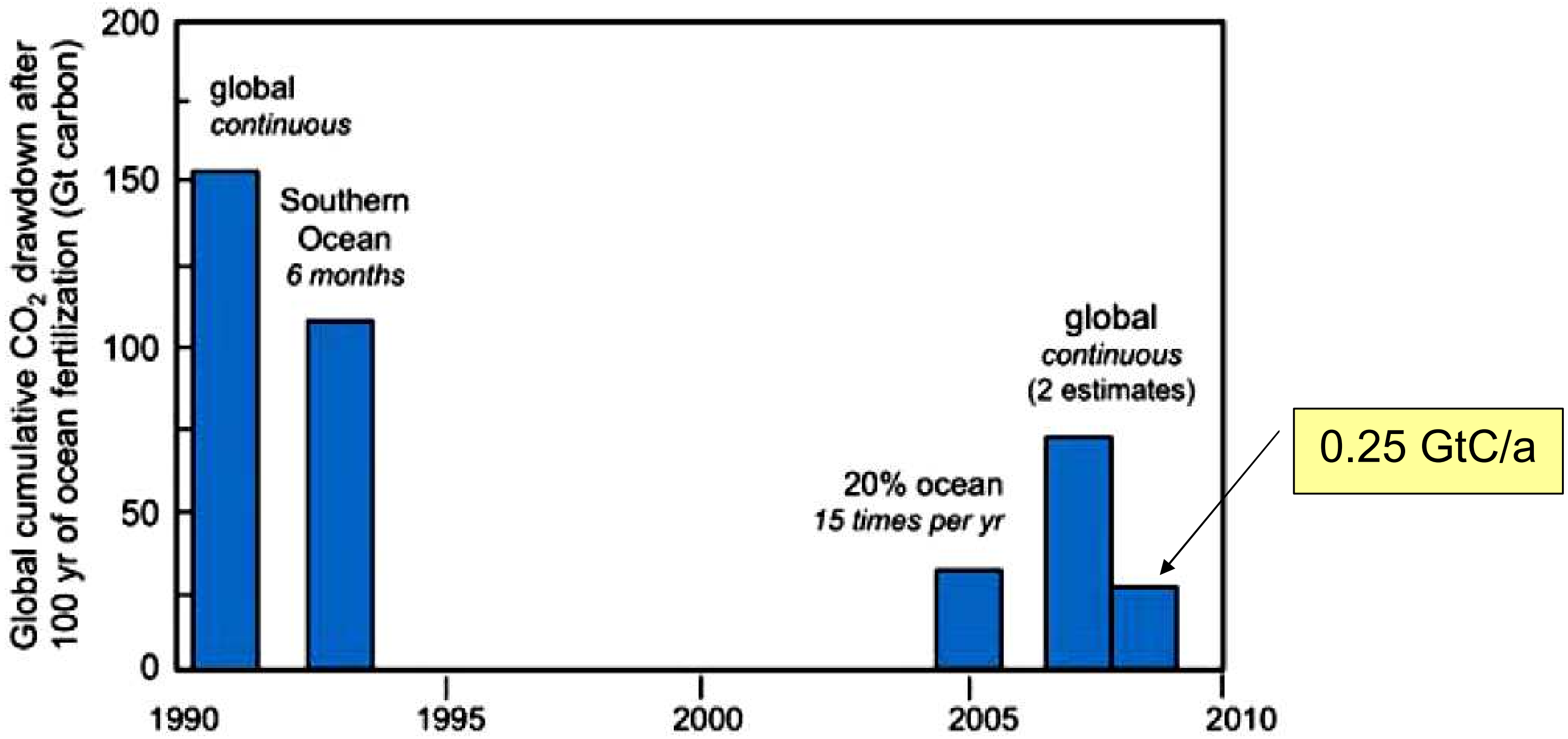
M. Lawrence, Science, 2001

… it is difficult to see how ocean iron fertilization with such a low $C_{sequestered}$: Fe_{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 km²—more than an order of magnitude larger than the entire area of the Southern Ocean.

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

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

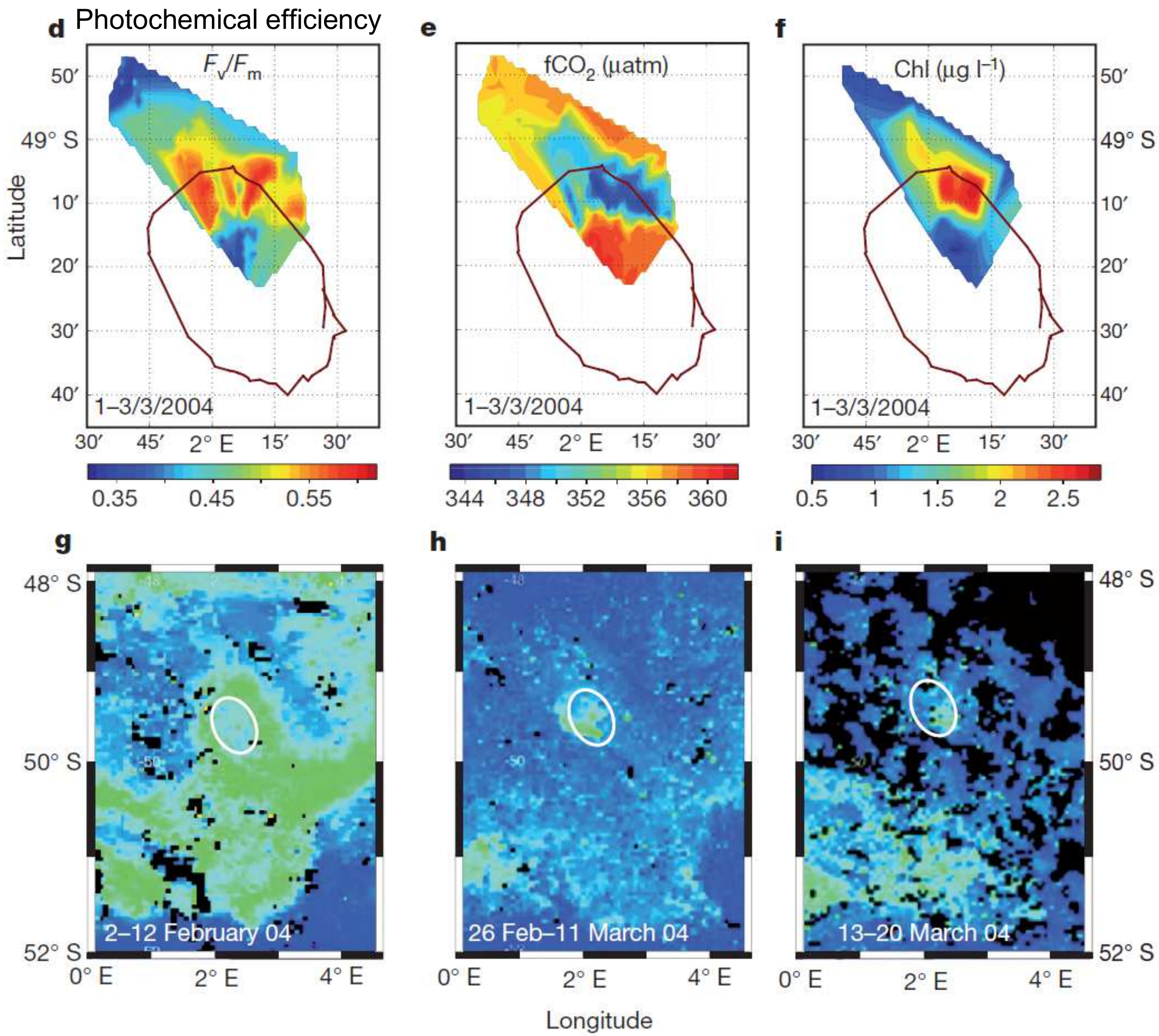
How to improve Effectiveness of Ocean Fertilization

European Iron Fertilization Experiment (EIFEX)

Fertilization experiment (1.5 µmol/l of $FeSO_4$) in the Antarctic circumpolar current (Feb. - March 2004

→ Diatom dominated bloom

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



Smetacek et al. (2012), Deep carbon export from a Southern Ocean iron-fertilized diatom bloom, Nature 487, 313-319.

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. <≈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
  - CH_4 → enhanced greenhouse effect, enhanced trop. O_3
  - N_2O → enhanced greenhouse effect
  - DMS → Trop. particle production (further cooling?, see Wingenter et al. 2007)
  - Halocarbons (CH_3Cl, CH_3Br, CH_3I, etc. → O_3-reduction, disturbance of photochemistry)
  - COS → 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