Improving the Efficiency of the Ocean’s Biological Carbon Pump

David M. Karl
University of Hawaii
and friends
Stabilization Wedges

Current path = “ramp”

16 GtC/y

Eight “wedges”

Interim Goal

R. Socolow, 28 Nov 2007
Exploring Ocean Iron Fertilization: the scientific, economic, legal and political basis

Symposium held at Woods Hole Oceanographic Institution
26-27 September 2007
K. Buesseler, S. Doney, H. Kite-Powell, co-organizers
http://www.whoi.edu/page.do?pid=14618

Oceanus article by Hugh Powell
http://www.whoi.edu/oceanus

“Moving ahead with uncertainty”
ACKNOWLEDGEMENTS

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OUTLINE

• Station ALOHA *(Mauna Loa of the Sea)*
• Ocean’s Biological Carbon Pump
• Ocean Fertilization: Design, Implementation and Outcomes *(expected and unexpected)*
• The Future
Data availability: http://hahana.soest.hawaii.edu

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Sea surface $p\text{CO}_2$ and pH at Station ALOHA

- Sea $p\text{CO}_2$ based on DIC & TAlk
- Wet air $p\text{CO}_2$ based on MLO data
- pH based on DIC & TAlk
- pH based on direct measurement

$p\text{CO}_2$ (µatm)

89 91 93 95 97 99 01 03 05
Seasonal and long-term dynamics of the upper ocean carbon cycle at Station ALOHA near Hawaii

Charles D. Keeling
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Holger Brix
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Keeling et al. 2004, Global Biogeochemical Cycles, vol. 18
OCEAN’S BIO-C PUMP

• How is it *structured*?
• How does it *function*?
• What determines its *efficiency*?
• How is it linked to *ocean C sequestration*?
the Ocean's Carbon Pump

Biological

CO₂

Physical

CO₂

Particulate

Dissolved

sea

air

inorganic

gut flux

organic

inorganic

cooling

upwelling

depth ocean circulation

CaCO₃

organic carbon

CaCO₃

sediment
Model calculations show that Biological Pump is necessary to explain field data.
The "Biological Pump"

Combined biological processes which transfer organic matter and associated elements to depth
- pathway for rapid $C$ sequestration

Quickly remove $C$ from surface ocean & atm.
- turn off bio pump and 200 ppmv increase atm. $CO_2$
Adapted from Legendre and Le Fèvre (1989)
How do we get from the marine food web to a global assessment of CO$_2$ flux to a mitigation policy???

With great difficulty!
OCEAN NUTRITION OPTIONS FOR (POSSIBLE) C SEQUESTRATION

• *Fe fertilization of HNLC*
• Fe or Fe/P fertilization of LNLC
• P fertilization in P-stressed regions
• *Artificial upwelling in open ocean*
CASE STUDY 1:

Fe fertilization

- Site is critical (HNLC)
- Export is key
ON THE SHOULDERS OF GIANTS

John Martin (1935-1993)
by John Weter

A little over ten years ago at a lecture at the Woods Hole Oceanographic Institution, oceanographer John Martin stood up and said in his best Dr. Strangelove accent, “Give me a half tanker of iron, and I will give you an ice age.”

These inflammatory words centered around a theory known as the iron hypothesis. Martin professed that by sprinkling a relatively small amount of iron into certain areas of the ocean, known as high-nutrient, low-chlorophyll zones (HNLCs), one could create large blooms of those unicellular aquatic plants commonly known as algae. If enough of these HNLC zones were fertilized with iron, he believed the growth in algae could take in so much carbon from the atmosphere that they could reverse the greenhouse effect and cool the Earth.

"Give me a half tanker of iron, and I will give you an ice age."

On the Shoulders of Giants
John Martin
Personal life
An ocean full of metal
The Iron Hypothesis
Following the vision
References

More Giants
Svante Arrhenius
Wilhelm Bjerkenes
Rachel Carson
Benjamin Franklin
Robert Goddard
Samuel Langley
Results from small scale bottle experiments in HNLC region

K. Johnson
Whole-Ecosystem Experiments

Replication Versus Realism: The Need for Ecosystem-Scale Experiments

David W. Schindler*

• Compared results of bottle experiments and mesocosms with whole lake observations
• Small scale studies give highly reproducible but spurious results (no realism!)
• All problems pale to scale (time and space)
11 mesoscale Fe experiments in > 10 years

Boyd et al. (2007)
TWO KEY REVIEWS

Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment

Hein J. W. de Baar,1,2 Philip W. Boyd,3 Kenneth H. Coule,4 Michael R. Landry,5 Atsushi Tsuda,6 Philipp Assmey,7 Dorothee C. E. Bakker,8 Yann Bozec,1 Richard T. Barber,1 Mark A. Brzezinski,10 Ken O. Buesseler,11 Marie Boyé,12,12 Peter L. Crook,1,13 Frank Garvais,7 Maxim Y. Gorbonov,14 Paul J. Harrison,15 William T. Hiscock,16 Patrick Laan,1 Christiane Lancelot,17 Cliff S. Law,18 Maurice Levasseur,19 Adrian Marchetti,20 Frank J. Millero,21 Jun Nishioka,21 Yukihiro Nojiri,22 Tim van Oijen,7 Ulf Riebesell,23 Micha J. A. Rijkenberg,1,2 Hiroaki Saito,23 Shigenobu Takeda,24 Klaas R. Timmermans,1 Marcel J. W. Veldhuis,1 Anya M. Waite,25 and Chi-Shing Wong26

Received 16 July 2004; revised 8 May 2005; accepted 14 July 2005; published 28 September 2005.


Boyd et al. (2007) Science 315
de Baar et al. (2005) JGR 110
Objective:
Promote nutrient utilization in the surface layer and remove carbon

CO₂ + Nutrients → Organic Matter

CO₂ + Nutrients ← Organic Matter

Primary production

upwelling and mixing

sinking particles

Decomposition

Bottom

Organic C
Intended consequences of large-scale fertilization

- Increased deep ocean concentrations of CO₂, N and P
- Decreased deep ocean concentrations of O₂
- Decreased surface layer concentrations and ratios of N, P and Si
Secondary effects must be quantified

\[ \text{N}_2\text{O} \quad \text{Nitrous oxide} \]
- Greenhouse gas
- \(300\times\text{CO}_2\)

- \(\text{CO}_2\)
- \(\text{NH}_4\)
- \(\text{NO}_3^-\)
- \(\text{N}_2\)

\(\text{N}_2\text{O}\) from phytoplankton bloom

- Organic N
- \(\text{NH}_4\)
- \(\text{NO}_3^-\)

\(\text{N}_2\text{O}\) from microbial nitrification

\(\text{N}_2\text{O}\) from microbial denitrification

\(\text{N}\) remineralization
A.C. REDFIELD (1958)

“The inadequacy of experiments in marine biology”

- Ecosystem manipulation/perturbation experiments are essential
- Complex systems must be thoroughly described and well understood before relevant experiments can be conducted
Iron is added with $\text{SF}_6$ as inert tracer for dilution
SF6 coloured/ sigma-t lines

Depth (m)

Time (hr)

Log SF6

Behrenfeld et al. (1996)

Iron fertilization in the equatorial Pacific

P. Boyd
Common findings in mesoscale iron experiments

Virtually all experiments resulted in blooms

A similar experimental design was used in all studies

P. Boyd
A wide range in bloom signatures

De Baar et al. (2005) / P. Boyd
“Iron fertilization is not a silver bullet …
let’s look at it on our portfolio for mitigation
… uncertainty shouldn’t preclude research”

Margaret Leinen, Climos

“There is a limited amount of money and time …
the worst possible thing would be to invest in
something that doesn’t work and has big impacts
that we don’t anticipate”

Lisa Speer, Natural Resources Defense Council

H. Powell, Oceanus article, Nov 2007
SUMMARY:  
**HNLC Fe Fertilization**

- Add Fe → Bloom
- Unresolved issues
  - C:Fe stoichiometry
  - C export ??
  - Unexpected ecosystem consequences (CH₄, N₂O production)
  - Patch-to-system scaling considerations
CASE STUDY 2: Artificial Upwelling

- Site is critical (C-N-P)
- Community succession is key
- C-N-P Stoichiometry is key
Ocean pipes could help the Earth to cure itself

SIR — We propose a way to stimulate the Earth’s capacity to cure itself, as an emergency treatment for the pathology of global warming.

Immediate retort from the science community… essentially “What are you smoking in those pipes?”

The issue has to do with the CNP ratio of upwelled water relative to particle export

Nothing’s as fundamental as elemental!!

Geo-engineering might cause, not cure, problems

SIR — James E. Lovelock and Chris G. Rapley, in their Correspondence ‘Ocean pipes could help the Earth to cure itself’ (Nature 449, 403; 2007) propose a variant on some well-publicized schemes to remove carbon dioxide from the atmosphere, by fertilizing the surface waters of the ocean (see also Nature doi:10.1038/news070924-8; 2007). All such schemes suffer from a major problem, because simply enhancing the growth of phytoplankton is not enough. It is the sinking flux of particulate organic carbon into the deep ocean — and ideally into the sediments (usually a small fraction of the total primary production) — that must be enhanced for sequestration to be effective.

J. Shepherd et al. 2007
Bloom creation –
wave driven ocean upwelling pumps

- Transfer nutrients by “sea elevator”
- Remove C by bio-pump
- Net result depends on ocean chemistry, microbial community structure and luck
STA. ALOHA (1988-2007)

C:P

\[(\text{DIC} - X_{\text{DIC}})/(\text{TDP} - X_{\text{TDP}})\]

N:P

\[(\text{TDN} - X_{\text{TDN}})/(\text{TDP} - X_{\text{TDP}})\]

DEPTH (m)

N2 Fixers

N2 Fixers
Water from ~300 m DIC:P = 150 N:P < 16

“Redfield” bloom and export with residual DIC and P

Selects for phototrophic N₂ fixing microbes

Non-Redfield “echo” bloom and export

STA. ALOHA UPWELLING HYPOTHESIS

STEP 1

STEP 2

STEP 3

106C:16N:1P

325C:50N:1P

N₂/CO₂
SUMMARY: ARTIFICIAL UPWELLING

- Deep-water nutrient loading of LNLC regions → Bloom
- Plankton community succession leads to N\textsubscript{2} fixation if upwelled N:P is lower than Redfield Ratio
- C sequestration trajectory and efficiency may be more predictable than in Fe fertilization experiments
“We are just at the threshold of our knowledge of the oceans… this knowledge is more than a curiosity, our very survival may hinge on it.”

John F. Kennedy
Science – Society Connections

- **CO₂ emissions and abatement**
  - Carbon credits
  - Standard/cost of living

- **Biogeochemical cycles**
  - Biological pumps
  - Biodiversity

- **Field observations**
  - Ecosystem experiments
  - Sensor design

- **Predictions of greenhouse gas-induced climate change**
  - Models

- **Controls on carbon sequestration**
  - Data

- **Methods and model development and training**

- **Societal concern and policy issues**
  - Taxpayers and politicians

- **Interdisciplinary ocean science**
  - Scientists

- **Data collection and hypothesis generation**
Is ocean fertilization a viable “stabilization wedge” option?

• Scientific jury is still out
• Ecology always trumps economics and policy
• Environmental impacts not well constrained
• Import of export

“Moving ahead with uncertainty”
An Ethics Code for Ocean Carbon Experiments

By Eli Kintisch
ScienceNOW Daily News
10 October 2007

Scientists and entrepreneurs alike are abuzz over iron fertilization, a controversial technique that uses iron-seeded plankton to sequester atmospheric carbon for centuries deep underwater. Now, a San Francisco-based climate startup called Climos has proposed a code of conduct to address contentious aspects of how experiments are conducted.
BEST PRACTICES & CODE OF CONDUCT

• Permits (notwithstanding ambiguity of need)
• Environmental assessments
• Avoid marine protected areas
• Transparency, peer review / published, collaboration

http://www.climos.com
Manoa Climate Change Commission

- Established Feb 2007
- Lorenz Magaard, Chair

Task Force Global Climate Change Solutions Act of 2007

- Maurice Kaya / Laurence Lau, co-Chairs
- Lorenz Magaard and Makena Coffman, members
“It is the microbes that will have the last word”

Louis Pasteur