

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

A RESEARCH STRATEGY FOR OCEAN CARBON DIOXIDE REMOVAL AND SEQUESTRATION

We will start at 12 pm EST

**Workshop Series Part 4: Nutrient Fertilization &
Artificial Upwelling and Downwelling
February 25, 2021**

Virtual Logistics

- Keep mics and cameras on while speaking and while participating in a panel.
- Committee members and panelists, please use the raise hand function or submit questions through the chat
- If you are watching the webinar, submit questions or comment through Q&A
- Presentations and recording will be posted on our project website: <https://www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration>
- Questions or information about the study, contact Kelly Oskvig, koskvig@nas.edu

Background

- NASEM Consensus Study
- Sponsored by the ClimateWorks Foundation
- Exploring 6 Ocean-based CDR Strategies:
 - Identify the most urgent unanswered scientific and technical questions needed to: assess the benefits, risks, and sustainable scale potential CDR approaches
 - Define the essential components of a research and development program and specific steps that would be required to answer these questions;
 - Estimate the costs and potential environmental impacts of such a research and development program to the extent possible in the timeframe of the study.
 - Recommend ways to implement such a research and development program that could be used by public or private organizations.

Workshop Series

- **January 19, 2021** - Part 1: Setting the Stage
- **January 27, 2021** - Part 2: Technological and Natural Approaches to Ocean Alkalinity Enhancement and CO₂ removal
- **February 2, 2021** - Part 3: Ecosystem Recovery and Seaweed Cultivation
- **February 25, 2021** - Part 4: Nutrient Fertilization and Artificial Upwelling and Downwelling

The Committee

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Ken Buesseler

Jane Flegal

Debora Iglesias-Rodriguez

Kate Moran

Andreas Oschlies

Phil Renforth

Joe Roman

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University of Virginia

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William and Flora Hewlett Foundation

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Ocean Networks Canada

GEOMAR

Heriot-Watt University

University of Vermont

UC Los Angeles

UC Santa Barbara

Columbia Law School

University of Hawai'i

Agenda

12:00pm	Welcome
12:05pm	Nutrient Fertilization: Opportunities and Challenges
1:30pm	BREAK
1:45pm	Artificial Upwelling and Downwelling: Opportunities and Challenges
3:15pm	BREAK
3:30pm	Overarching Challenges and Opportunities
4:30pm	Adjourn

Nutrient Fertilization: Challenges and Opportunities

Keynote (30 minutes):

Philip Boyd

Institute of Marine and Antarctic Studies, University of Tasmania, Australia

OUTLINE

Introduction – macro versus micro-nutrient fertilisation

Ocean Iron Fertilisation (OIF) – what is the state-of-the-art?

The importance of foresighting in developing an R&D Agenda for OIF

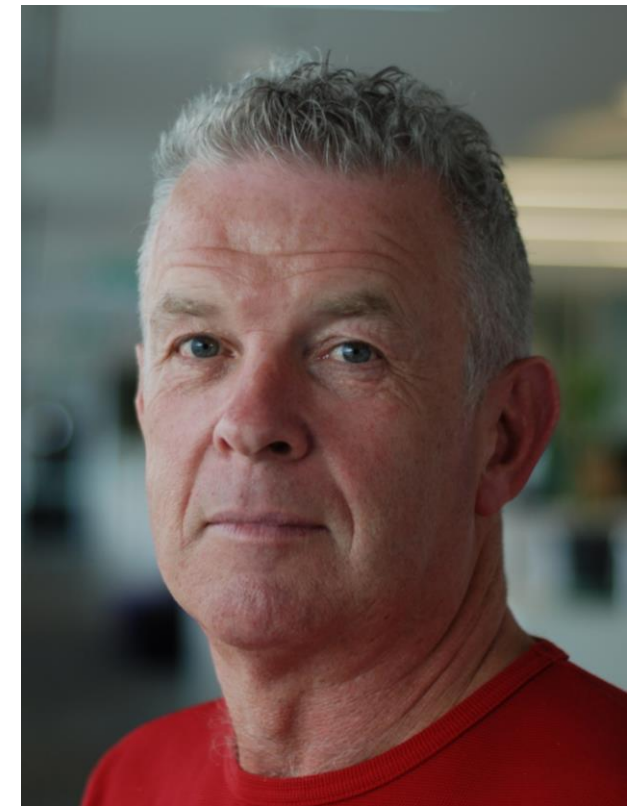
Working backwards - Knowledge gaps

Full Implementation & Deployment

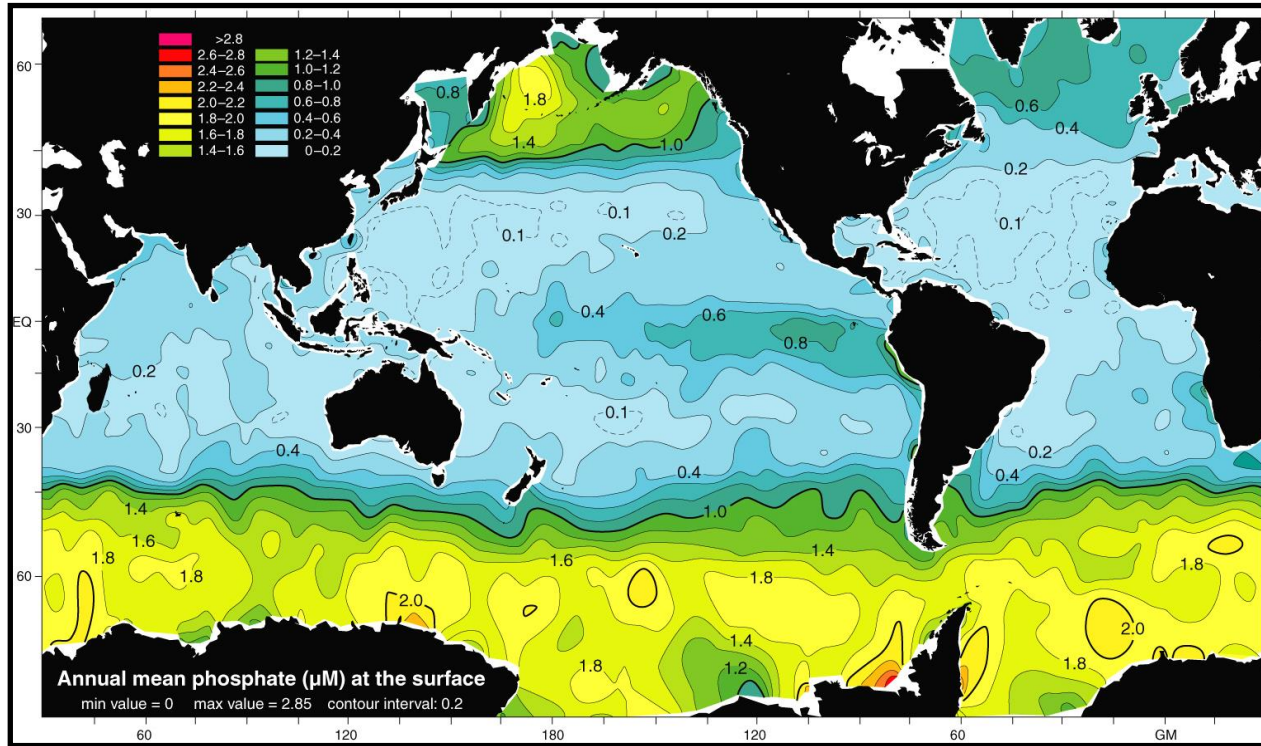
Nested Pilot Studies

New Research Targets

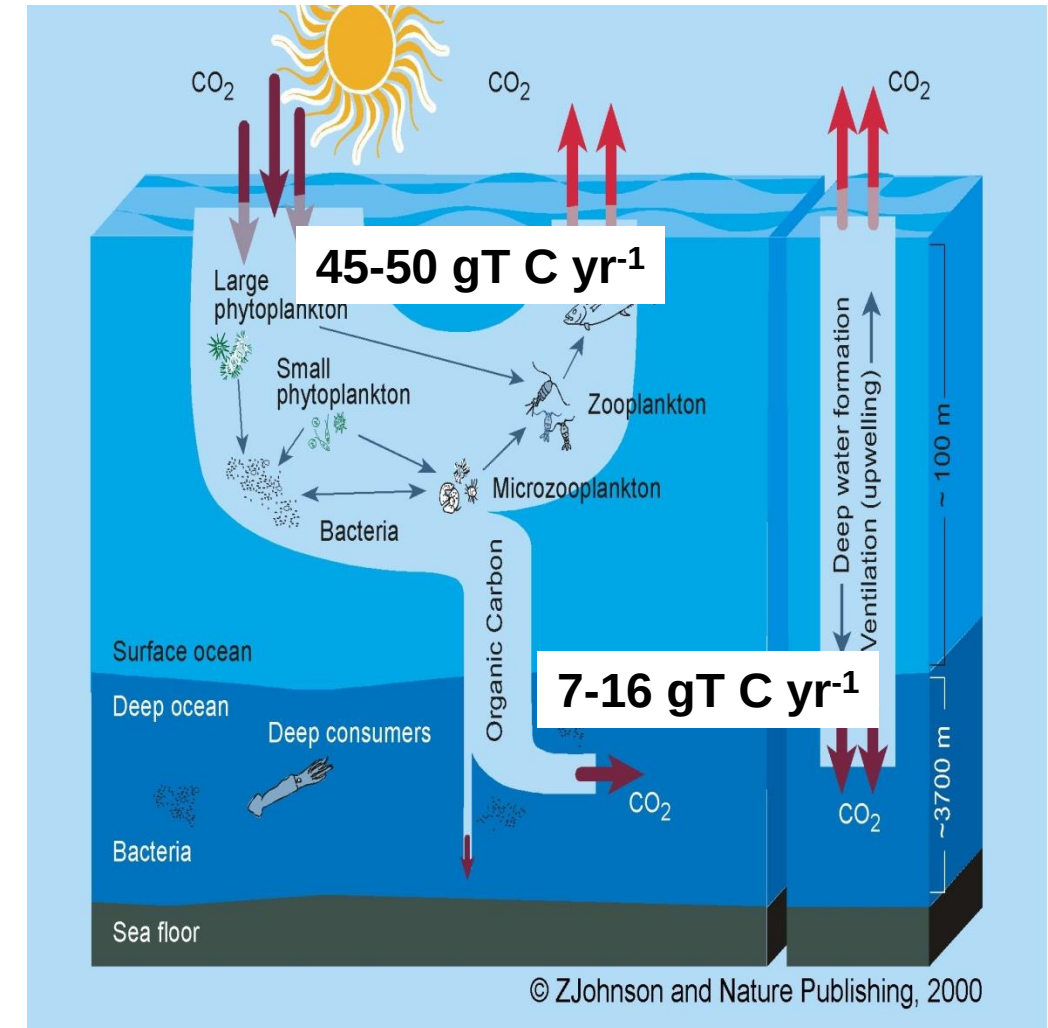
Opportunities & Challenges



How does nutrient fertilization lead to Carbon Dioxide Removal?

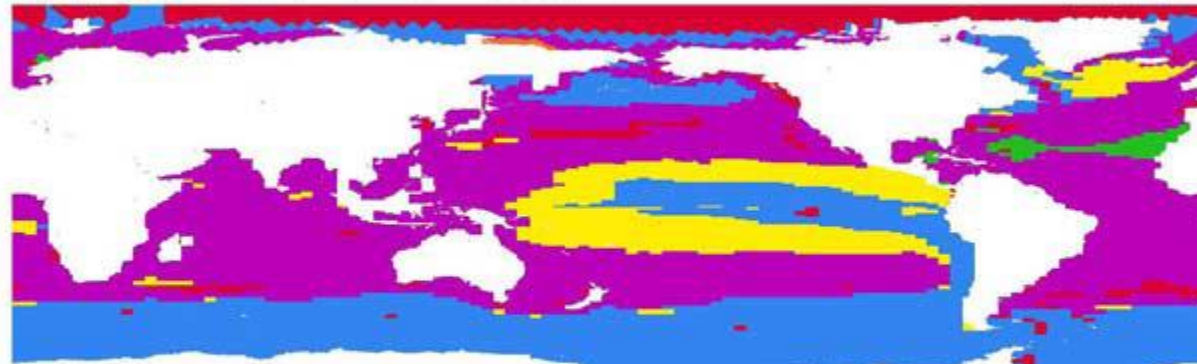


Courtesy of NODC



Nutrient limitation patterns

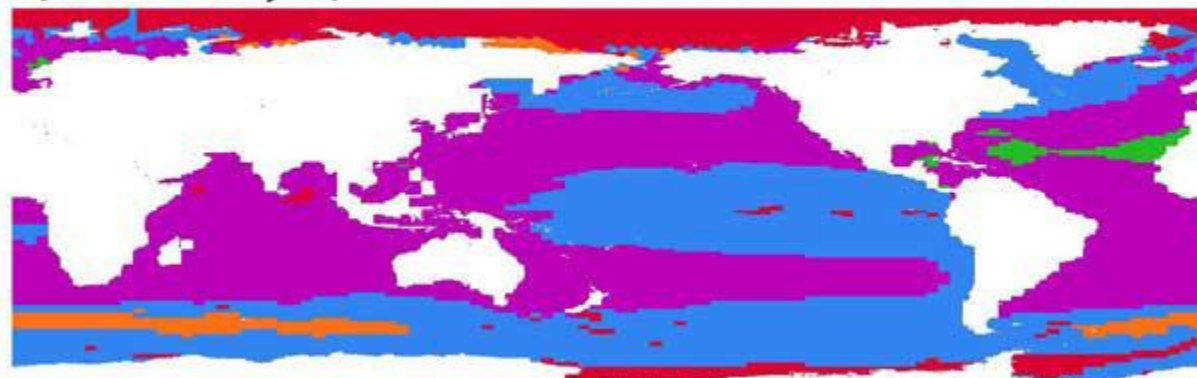
A) Diatom Growth Limitation



Nitrogen 55.73%, Iron 27.67%, Silica 12.54%, Phosphorus 1.405%
Light 2.645%, Replete 0.000%

■ Nitrogen ■ Iron ■ Phosphorus ■ Silicon
■ Light ■ Temperature ■ Replete

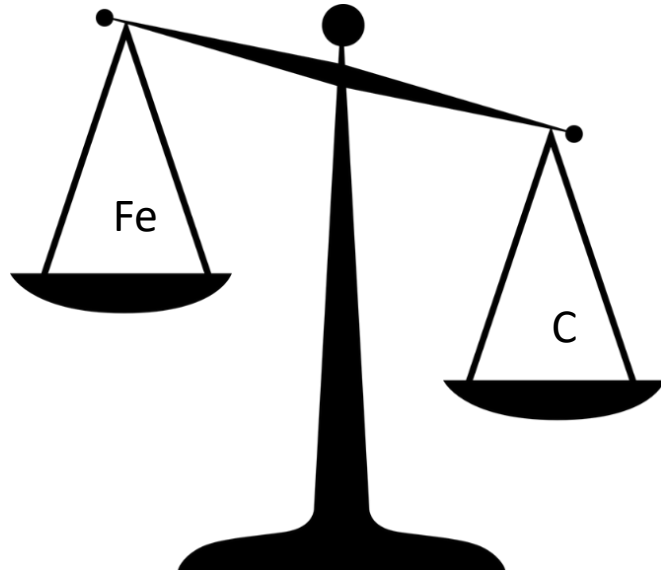
B) Small Phytoplankton Growth Limitation



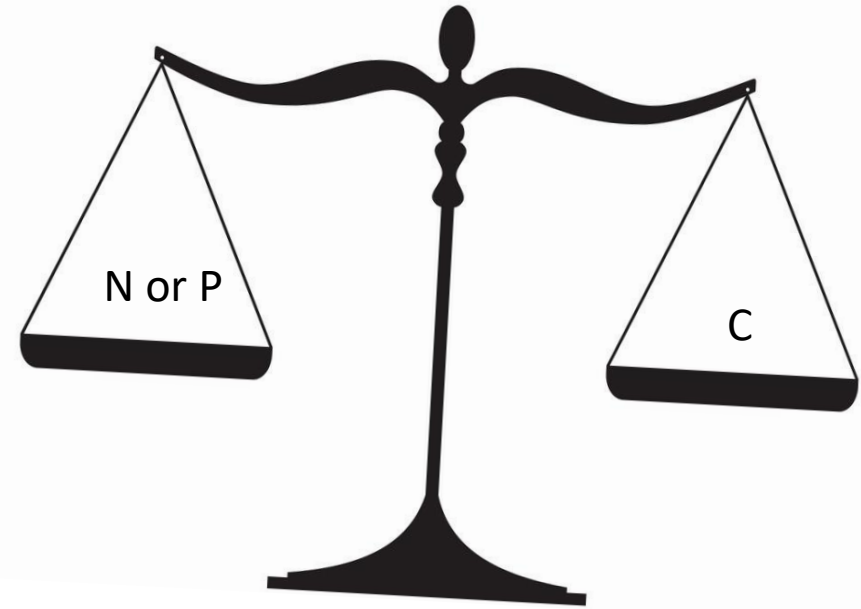
Nitrogen 55.88%, Iron 36.34%, Phosphorus 1.426%
Light 3.788, Replete 2.556%

(Moore et al., 2004).

Introduction Macro- versus micro-nutrient fertilisation



$10^5:1$



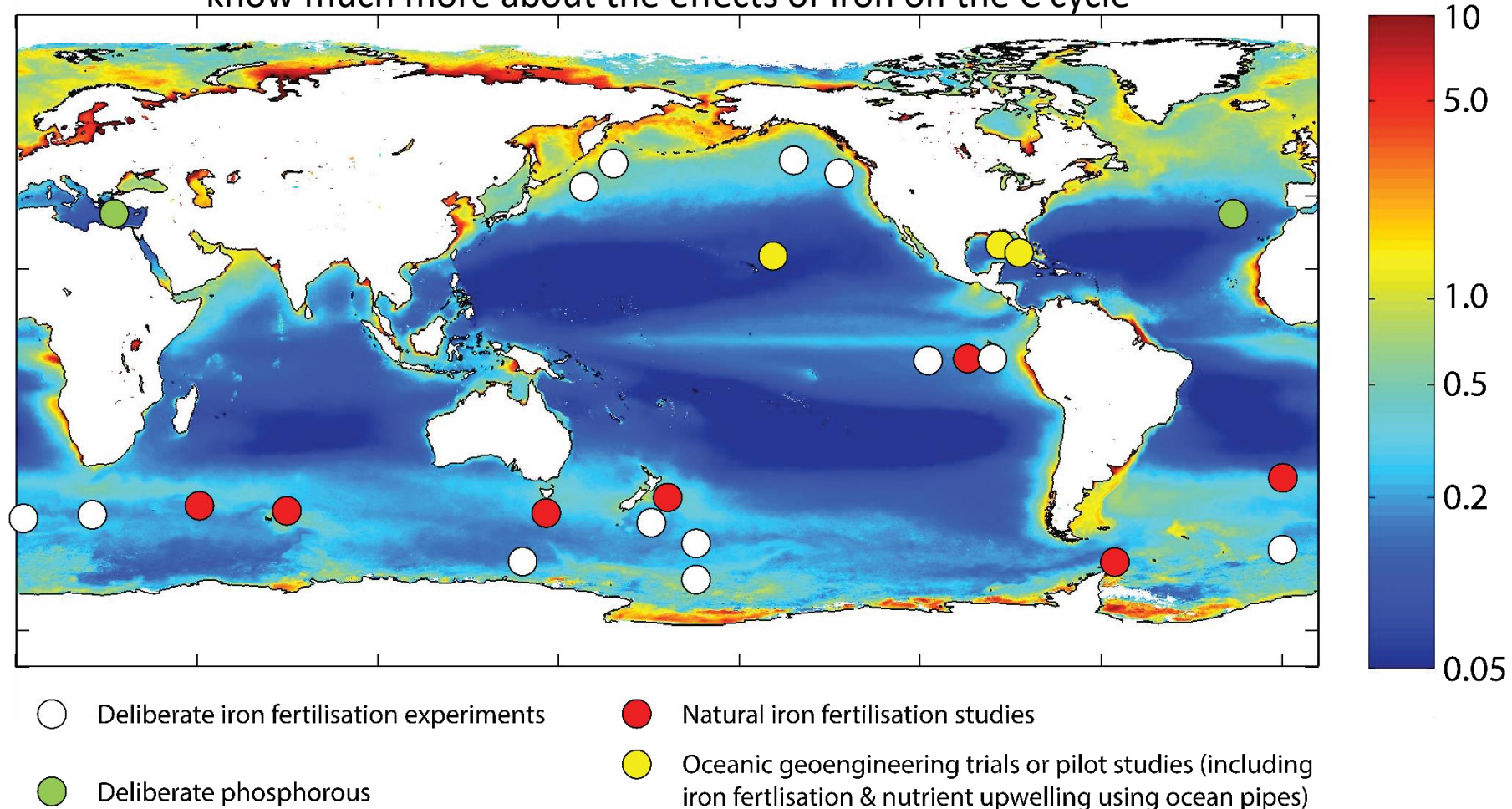
106:16:1

Based on stoichiometry, Iron yields a much bigger C footprint than the macronutrients

“Give me a tanker of iron, and I’ll give you an Ice Age.”

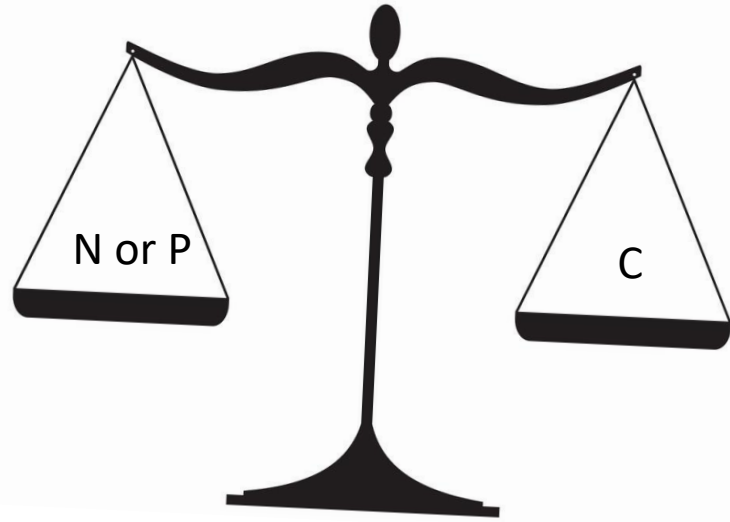


Introduction - from mesoscale fertilisation experiments we know much more about the effects of iron on the C cycle



There have been two mesoscale phosphorus enrichment experiments in waters considered to be phosphorus-limited, in the Eastern Mediterranean and the subtropical North Atlantic. Contrary to expectations, **neither study showed any significant increase in either primary production or chlorophyll concentrations.**

MACRONUTRIENT FERTILISATION



Many of the issues and challenges are similar to that facing OIF

OIF is the best understood of the marine climate invention approaches
And for that reason will be the focus of this presentation

References

Ocean Nourishment Corporation: What we do, <http://www.oceannourishment.com/what-we-do> (Accessed 6 October 2020)

R. J. Matear and B. Elliott, J. Geophys. Res., 2004, 109, C04001.

D. P. Harrison, Environ. Res. Lett., 2017, 12, 035001.

M. W. Lawrence, Int. J. Global Warming, 2014, 6, 15.

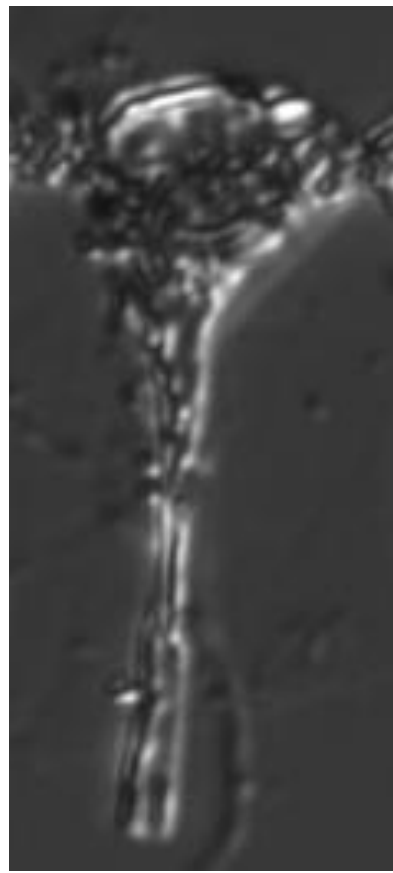
Williamson, P., P. W. Boyd, D. P. Harrison, N. Reynard and A. Mashayek
(in review) Biologically-based negative emissions in the open ocean and coastal seas. Royal Society of Chemistry.

OIF has been well studied relative to other CDR ocean methods

Developing a test-bed for
robust research governance of
geoengineering: the
contribution of ocean iron
biogeochemistry

Boyd and Bressac
(2016) Phil. Trans. R. Soc. A.
374, 20150299

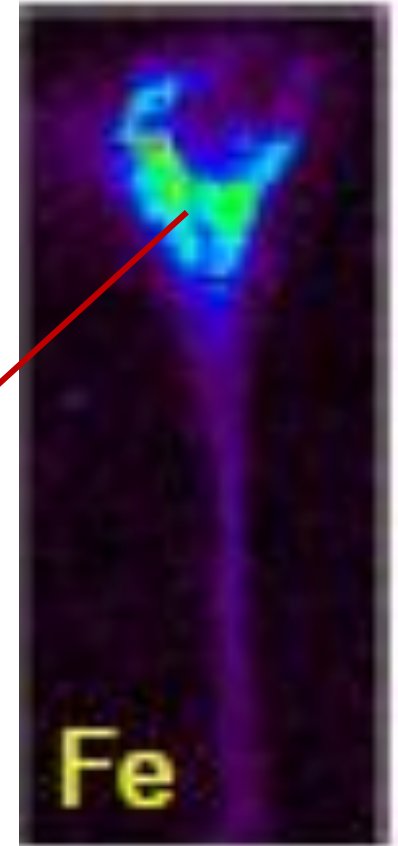
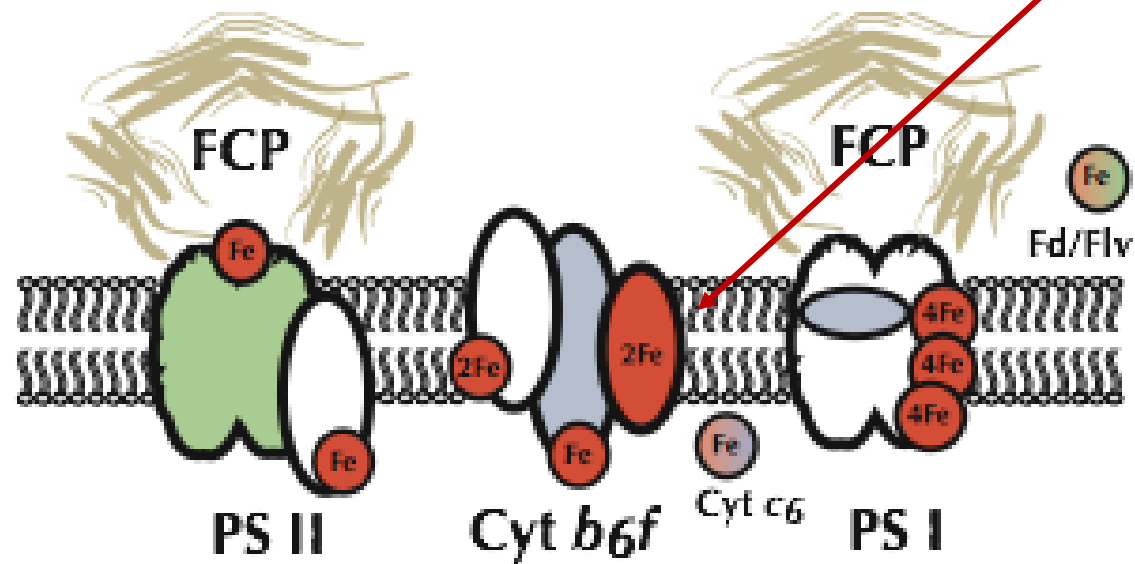
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
synthesis		40		3			4	28,56		
experiments				88						
modelling		90			42					59
'pilots'										
policy					98					
legislation			8					9		
outreach							11			



10 microns

OIF - WHAT IS THE STATE OF THE ART?

A trace element of pivotal importance for phytoplankton growth and productivity



The Photosynthetic apparatus – the cell's engine room

A Gradualist approach to iron enrichment research

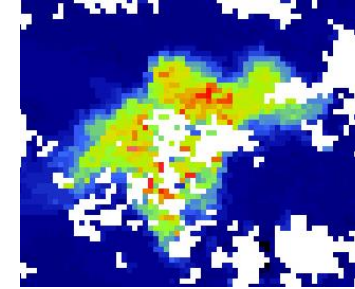
Lab – contained



Field - contained



Field - uncontained



Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic

John H. Martin & Steve E. Fitzwater

Moss Landing Marine Laboratories, Moss Landing, California 95039, USA

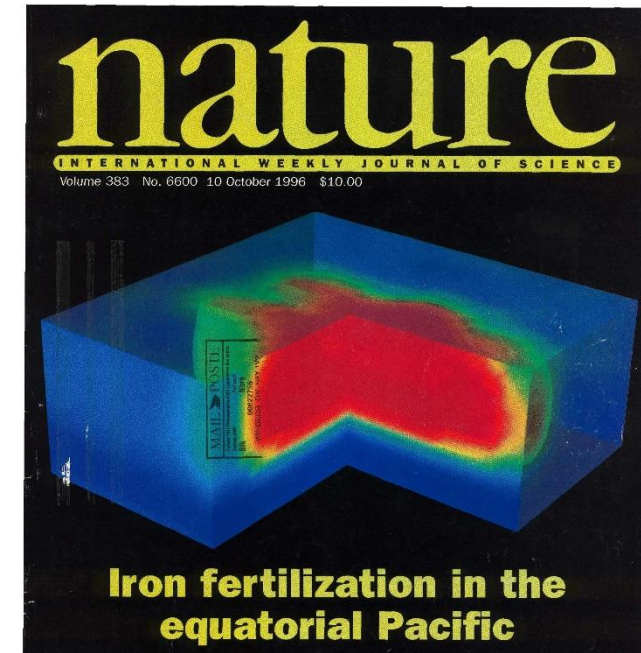
An interesting oceanographic problem concerns the excess major plant nutrients (PO_4 , NO_3 , SiO_2) occurring in offshore surface waters of the Antarctic¹⁻³ and north-east Pacific subarctic Oceans⁴. In a previous study⁵, we presented indirect evidence suggesting that inadequate Fe input was responsible for this limitation of growth; recently we had the opportunity to seek direct evidence for this hypothesis in the north-east Pacific subarctic. We report here that the addition of nmol amounts of dissolved iron resulted in the nearly complete utilization of excess NO_3 , whereas in the controls—without added Fe—only 25% of the available NO_3 was used. We also observed that the amounts of chlorophyll in the phytoplankton increased in proportion to the Fe added. We conclude that Fe deficiency is limiting phytoplankton growth in these major-nutrient-rich waters.

1988

Change in the concentrations of iron in different size fractions during a phytoplankton bloom in controlled ecosystem enclosures

Jun Nishioka^{a,*}, Shigenobu Takeda^a, C.S. Wong^b

1996



1996 to 2008

State-of-the-Art – Fundamental knowledge

Understanding how iron regulates many ocean processes

- **DIRECT**
- **Photosynthesis**
- **Growth rate, NPP**
- **Nutrient uptake (Si:N)**
- **Species composition**
- **Exudation - DOC**
- **Bacterial processes**
- **Biogenic gases**
- **Grazer physiology**
- ***INDIRECT***
- ***S, C, N, Si biogeochemistry***
- ***Export flux***
- ***Gas release and drawdown***
- ***Foodweb structure***
- ***Zooplankton growth & reproduction***
- ***Faunistic shifts***

Synthesis of the fundamental knowledge

Lab – contained



Field - contained



Field

Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic

John H. Martin & Steve E. Fitzwater

Moss Landing Marine Laboratories, Moss Landing, California 95039, USA

An interesting oceanographic problem concerns the availability of plant nutrients (PO_4 , NO_3 , SiO_2) occurring in the waters of the Antarctic¹⁻³ and north-east Pacific subarctic. In a previous study⁴, we presented indirect evidence that inadequate Fe input was responsible for this limitation to growth; recently we had the opportunity to seek direct support for this hypothesis in the north-east Pacific subarctic. We found here that the addition of nmol amounts of dissolved iron led to the nearly complete utilization of excess NO_3 , whereas controls—without added Fe—only 25% of the available NO_3 was used. We also observed that the amounts of chlorophyll in phytoplankton increased in proportion to the Fe added. We conclude that Fe deficiency is limiting phytoplankton growth in these major-nutrient-rich waters.

1988

Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions

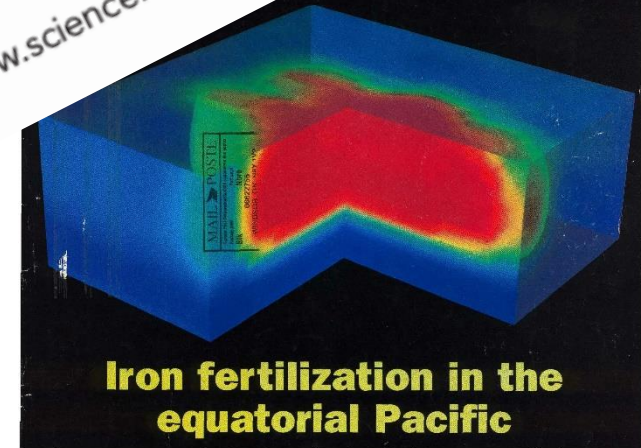
P. W. Boyd,^{1*} T. Jickells,² C. S. Law,³ S. Blain,⁴ E. A. Boyle,⁵ K. O. Buesseler,⁶ K. H. Coale,⁷ J. J. Cullen,⁸ H. J. W. de Baar,⁹ M. Follows,⁵ M. Harvey,³ C. Lancelot,¹⁰ M. Levasseur,¹¹ N. P. J. Owens,¹² R. Pollard,¹³ R. B. Rivkin,¹⁴ J. Sarmiento,¹⁵ V. Schoemann,¹⁰ V. Smetacek,¹⁶ S. Takeda,¹⁷ A. Tsuda,¹⁸ S. Turner,² A. J. Watson²

2 FEBRUARY 2007

VOL 315

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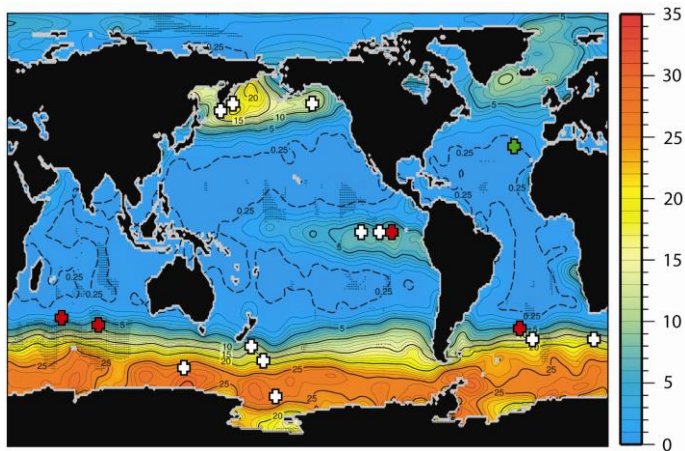
www.sciencemag.org



Iron fertilization in the equatorial Pacific

1996

1996 to 2008



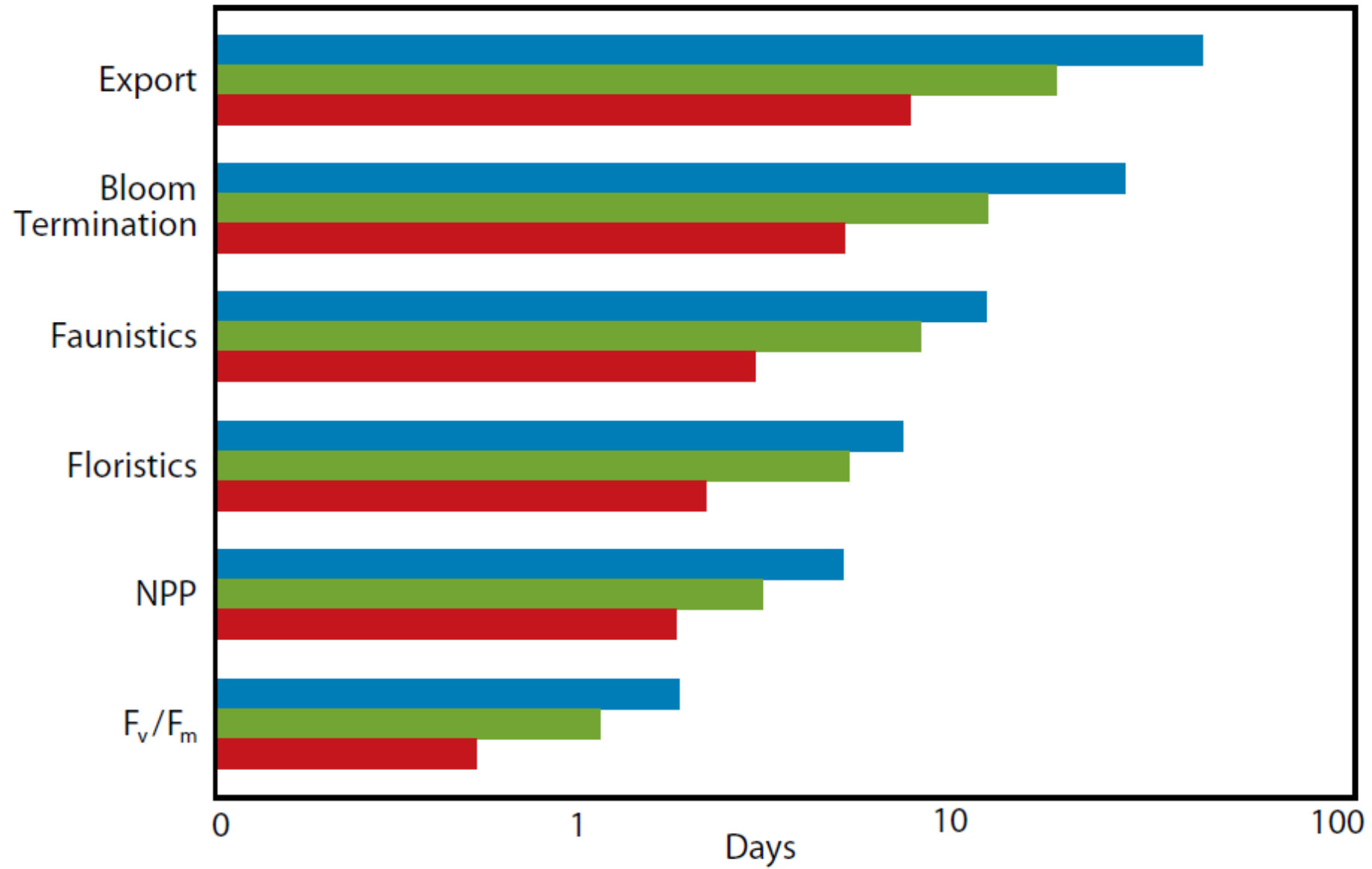
A relational database is available at BCO-DMO

Boyd et al. (2012)

The datasets from the 12 OIF's have been archived

Table 1. The iron enrichment experiments in the SCOR WG 131 data compilation effort are listed along with the FeeP and LOHAFEX projects. References to the experiments are in the text.

Experiment	Voyage Duration	Data Stored	Database	Location
IronEx I	Oct–Nov/1993	Some data	BCO-DMO	5°S, 90°W
IronEx II	May–Jun/1995	Most data	BCO-DMO	4°S, 107°W
SOIREE	Jan–Mar/1999	Most data	BCO-DMO	61°S, 140°E
EisenEx	Oct–Dec/2000	Most data	PANGAEA	48°S, 21°E
SEEDS I	Jun–Aug/2001	Most data	BCO-DMO	48.5°N, 164.5°E
SOFEX-N	Jan–Mar/2002	Most data	BCO-DMO	55°S, 172°W
SOFEX-S	Jan–Mar/2002	Most data	BCO-DMO	66°S, 172°W
SERIES	Jun–Aug/2002	Most data	BCO-DMO	51°N, 144.5°W
EIFEX	Jan–Mar/2004	Many data	PANGAEA	50°S, 2°E
SAGE	Mar–Apr/2004	Most data	BCO-DMO	46.5°S, 172°E
FeeP	Apr–May/2004	Some data	BODC	27.6°N, 22.4°W
SEEDS II	Jul–Aug/2004	Most data	BCO-DMO	48°N, 166°E
LOHAFEX	Feb–Mar/2009	Some data	PANGAEA	48°S, 15°W

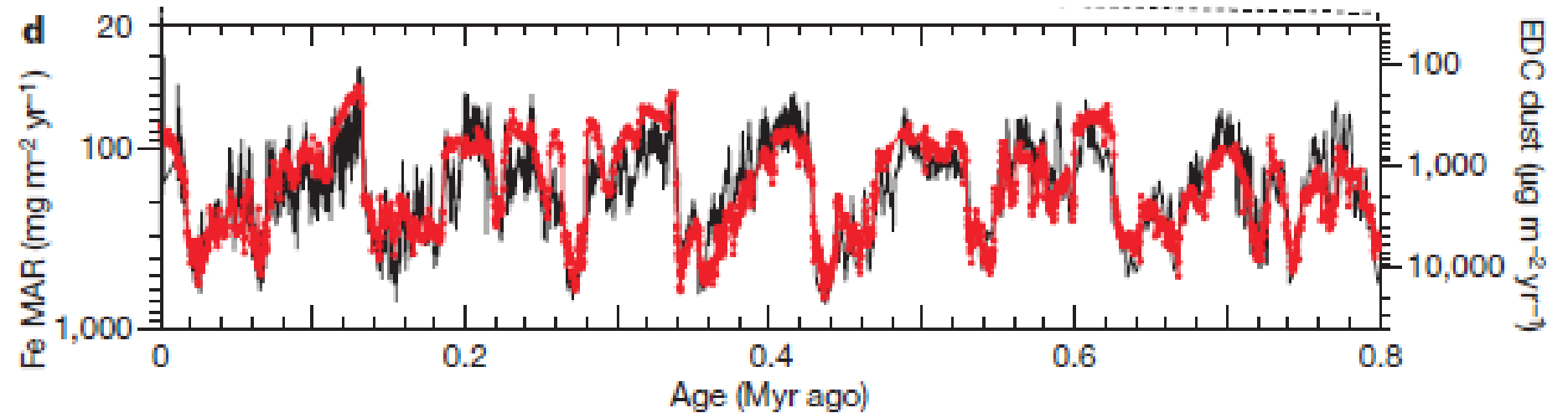


Boyd et al. (2012)

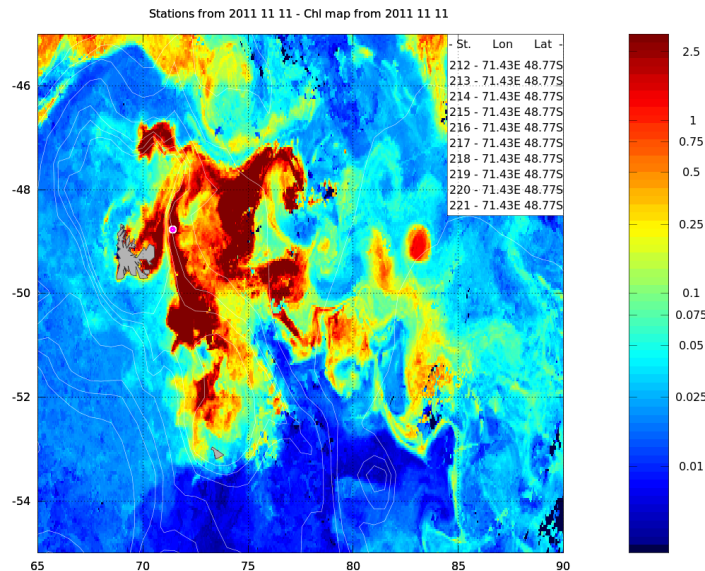
Figure 3. A summary of the timescales of biological responses (log time scale, 0 denotes iron release), from photosynthetic to biogeochemical, following purposeful mesoscale iron enrichment. F_v/F_m is phytoplankton photosynthetic competence; NPP denotes

Southern Ocean dust-climate coupling over the past four million years

Alfredo Martínez-García^{1,2,3}, Antoni Rosell-Melé^{3,4,5}, Samuel L. Jaccard¹, Walter Geibert^{6,7}, Daniel M. Sigman⁸ & Gerald H. Haug^{1,2}



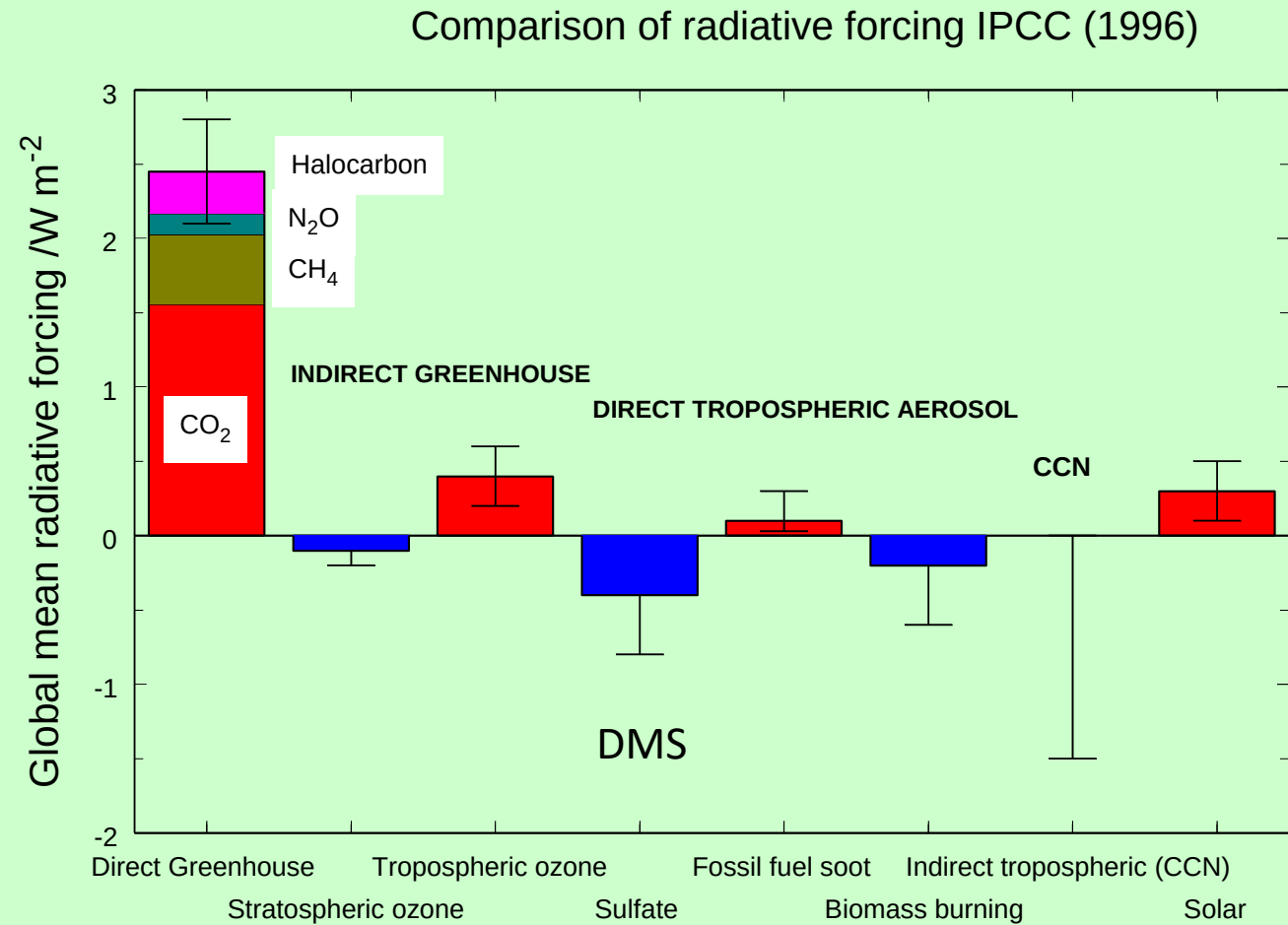
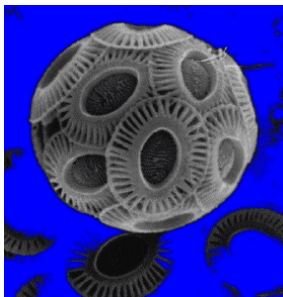
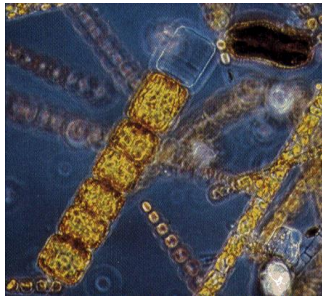
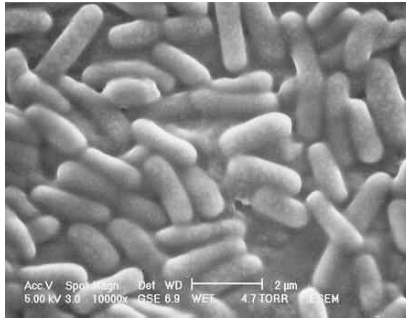
OIF HAS NATURAL
ANALOGUES – IN THE PAST
& PRESENT



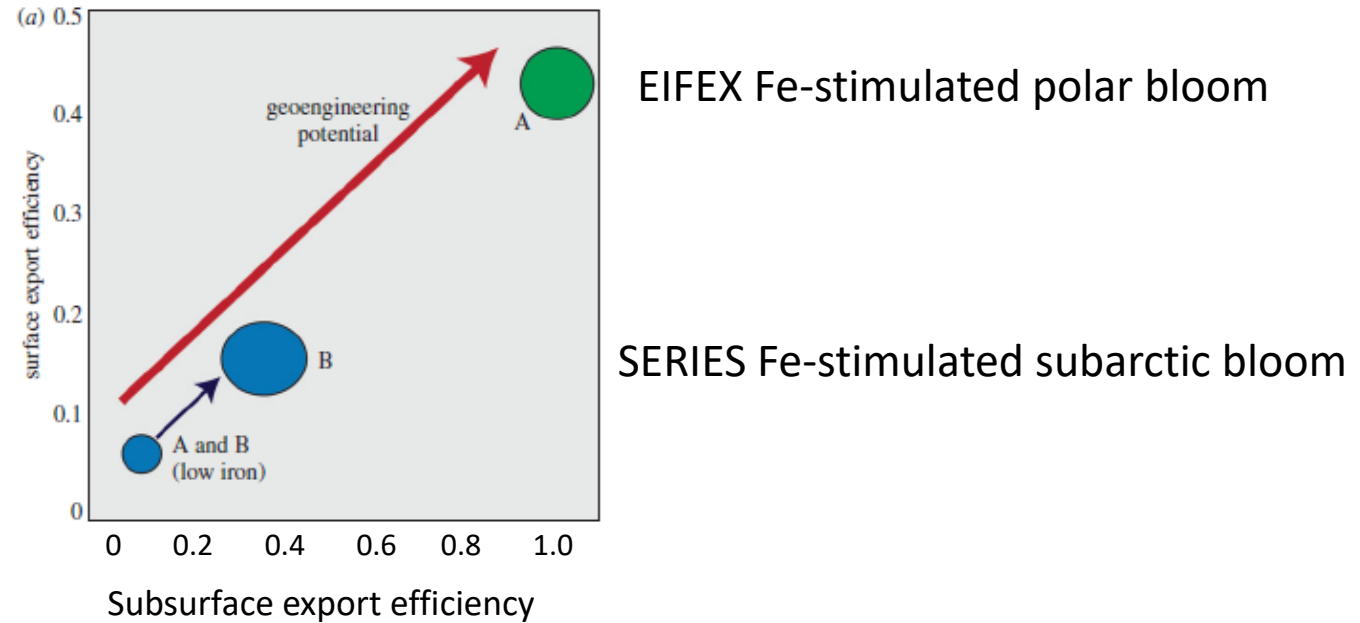
Large-scale changes in deposition i.e. most of the Southern Ocean suggests a CO₂ drawdown of < 40 ppm from subantarctic iron fertilization

OIF and climate

OIF is not just a carbon story – its outcome will be driven by the cumulative change in radiative forcing



State of the art – Location, Location, location



There were also major regional differences in CO₂ drawdown, DMSP/DMS dynamics, production of CH₄ and N₂O subsurface, and foodweb effects.

State-of-the-art - surprises in need of corroboration

Are mesoscale perturbation experiments in polar waters prone to physical artefacts? Evidence from algal aggregation modelling studies

Philip W. Boyd,¹ George A. Jackson,² and Anya M. Waite³

Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas

Charles G. Trick^{a,1}, Brian D. Bill^{b,c}, William P. Cochlan^b, Mark L. Wells^d, Vera L. Trainer^c, and Lisa D. Pickell^d

Efficiency of carbon removal per added iron in ocean iron fertilization

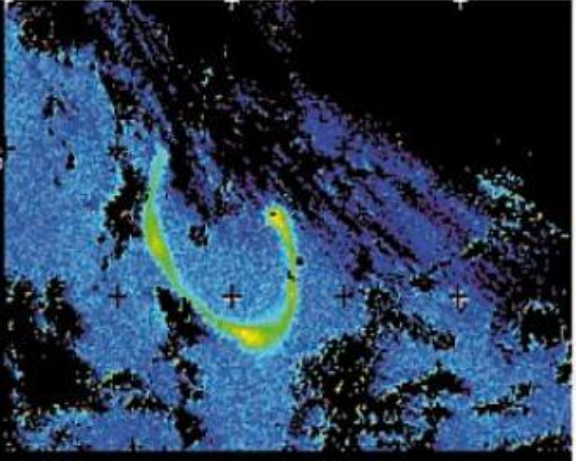
Hein J. W. de Baar^{1,2,*}, Loes J. A. Gerringa², Patrick Laan², Klaas R. Timmermans²

Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions

C. S. Law^{*}

Predicting and verifying the intended and unintended consequences of large-scale ocean iron fertilization

John J. Cullen^{1,*}, Philip W. Boyd²



State-of-the-art

The 100 - 1000 km² mesoscale OIF experiment is an imperfect tool

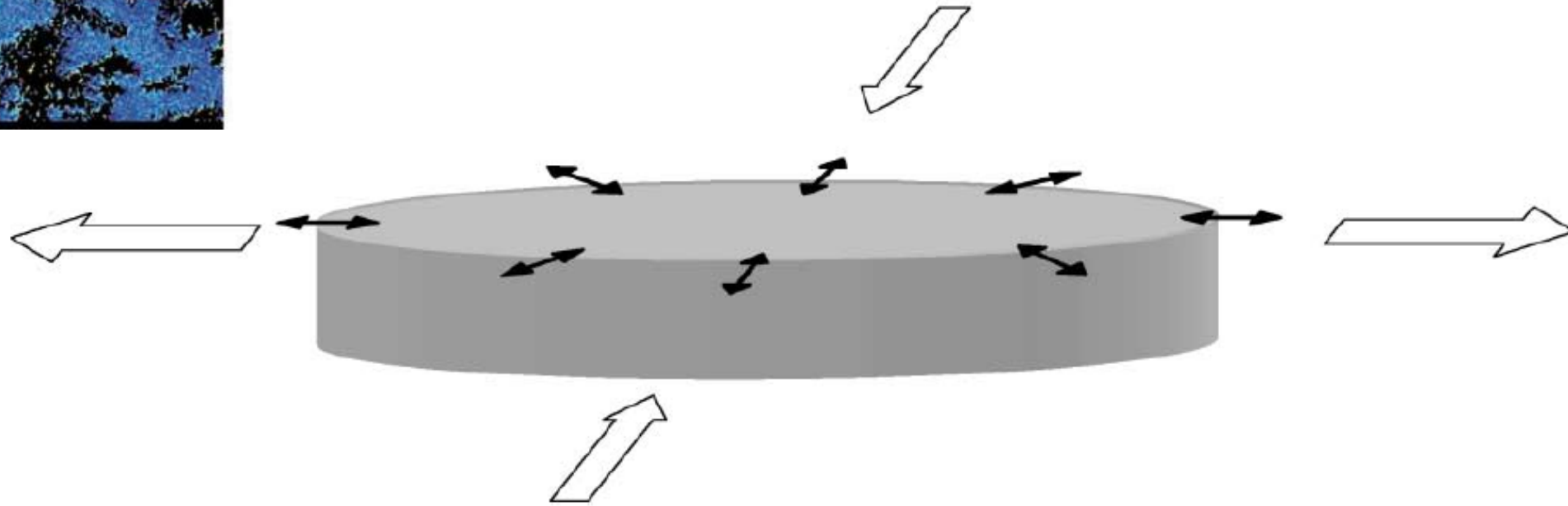
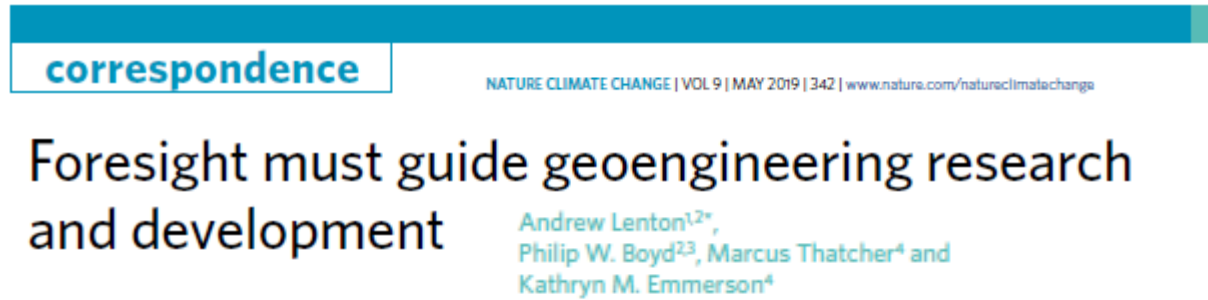


Fig. 2. A schematic of the putative SOIREE ‘chemostat’—the exchange between the iron-fertilised waters of the SOIREE patch and the surrounding HNLC waters during the experiment. Solid black arrows denote diffusion of water to and from the water masses at the periphery of the patch, while the large open arrows represent the effect of strain in the horizontal currents stretching the patch. The area of the fertilised patch increased from 50 to ~ 250 km² by day 13, and was > 1000 km² by day 40 (see Abraham et al. (2000) for more details). Figure courtesy of Edward Abraham.

Issues to consider for the development of a R&D agenda to progress ocean-based CDR approaches

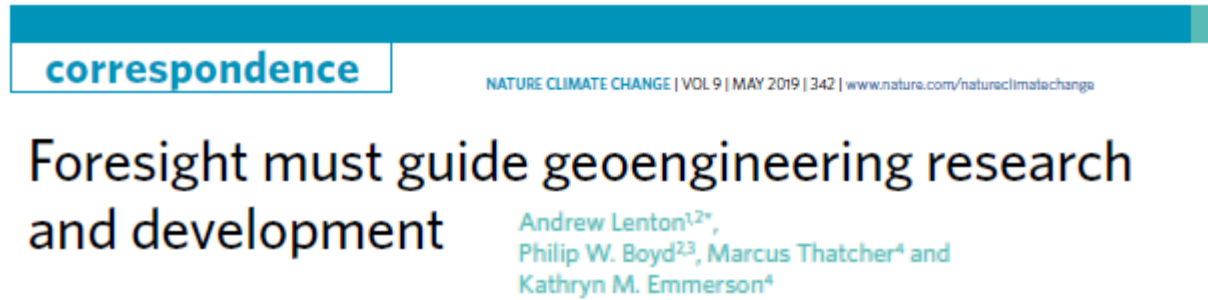


“It is essential to first elucidate the longer-term goals and then identify the trajectory towards a full implementation.”

“This trajectory must be formulated around the scientific and engineering questions relevant for any geoengineering technique at each stage of its development.”

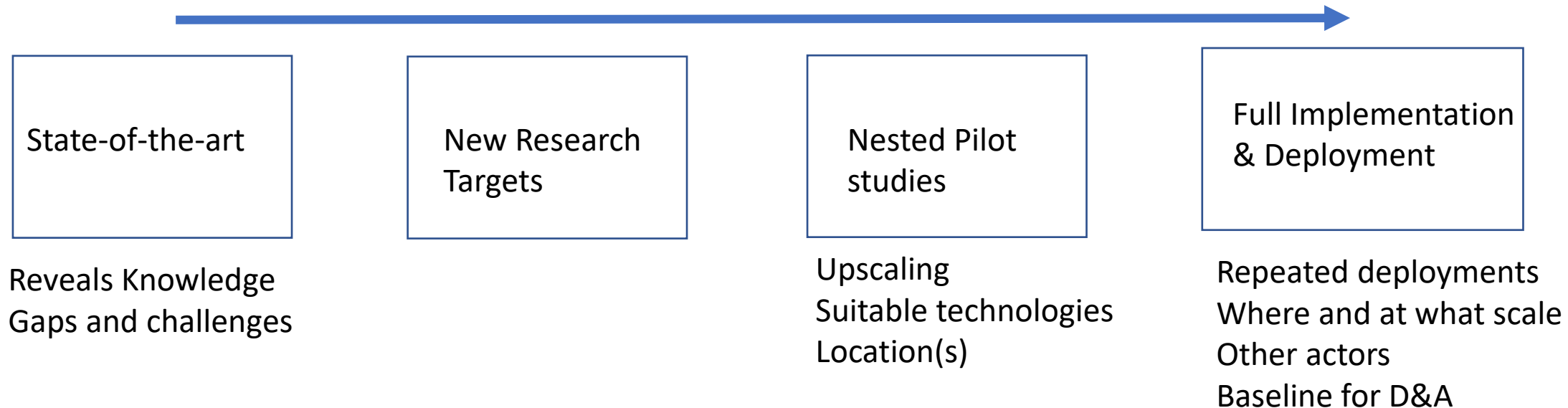


Issues to consider for the development of a R&D agenda to progress ocean-based CDR approaches

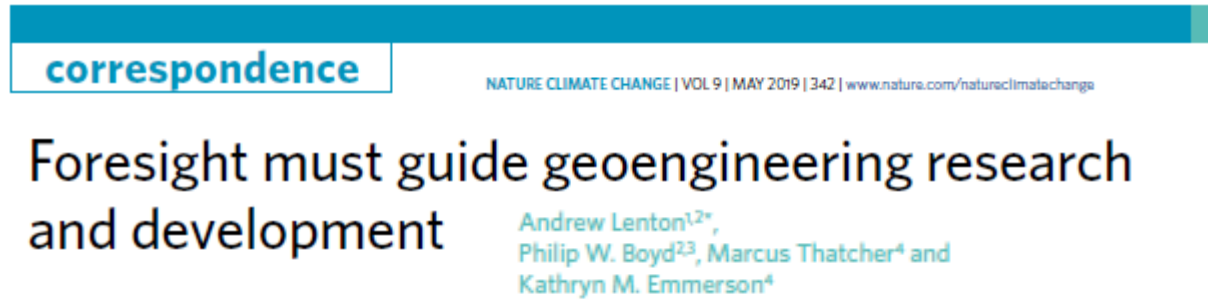


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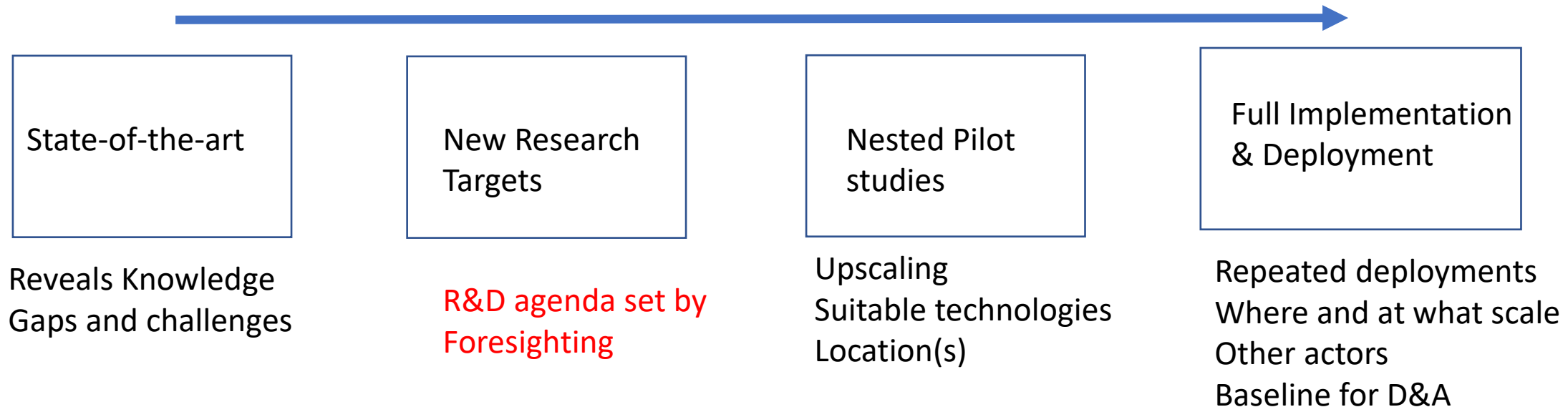


Issues to consider for the development of a R&D agenda to progress ocean-based CDR approaches



“It is essential to first elucidate the longer-term goals and then identify the trajectory towards a full implementation.”

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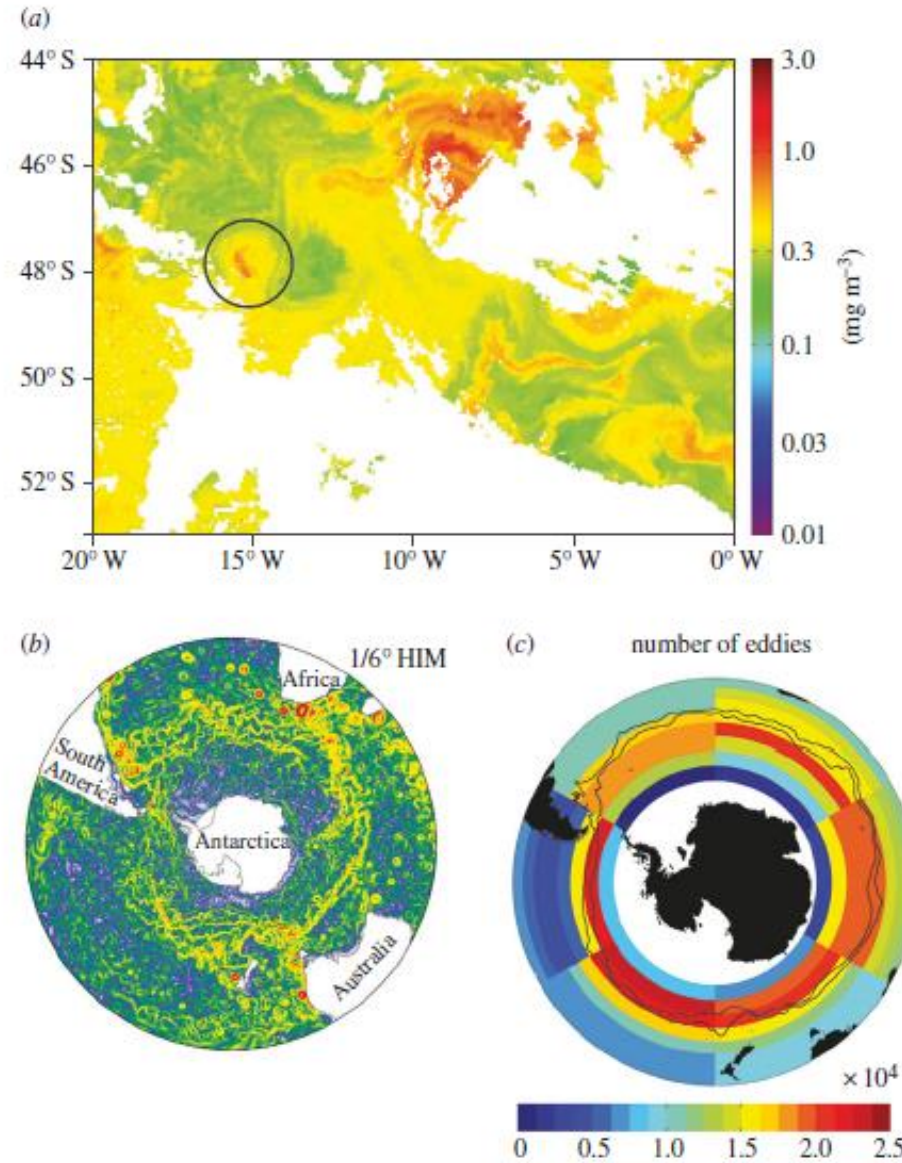


Full Implementation & Deployment

Repeated deployments
Of OIF over multiple years

Working backwards - Knowledge gaps

Proving “Additionality” *sensu* Kyoto Protocol



Boyd & Bressac
(2016)

Full Implementation & Deployment

Working backwards - Knowledge gaps

Where and at what scale?

Circulation

Depth of permanent pycnocline

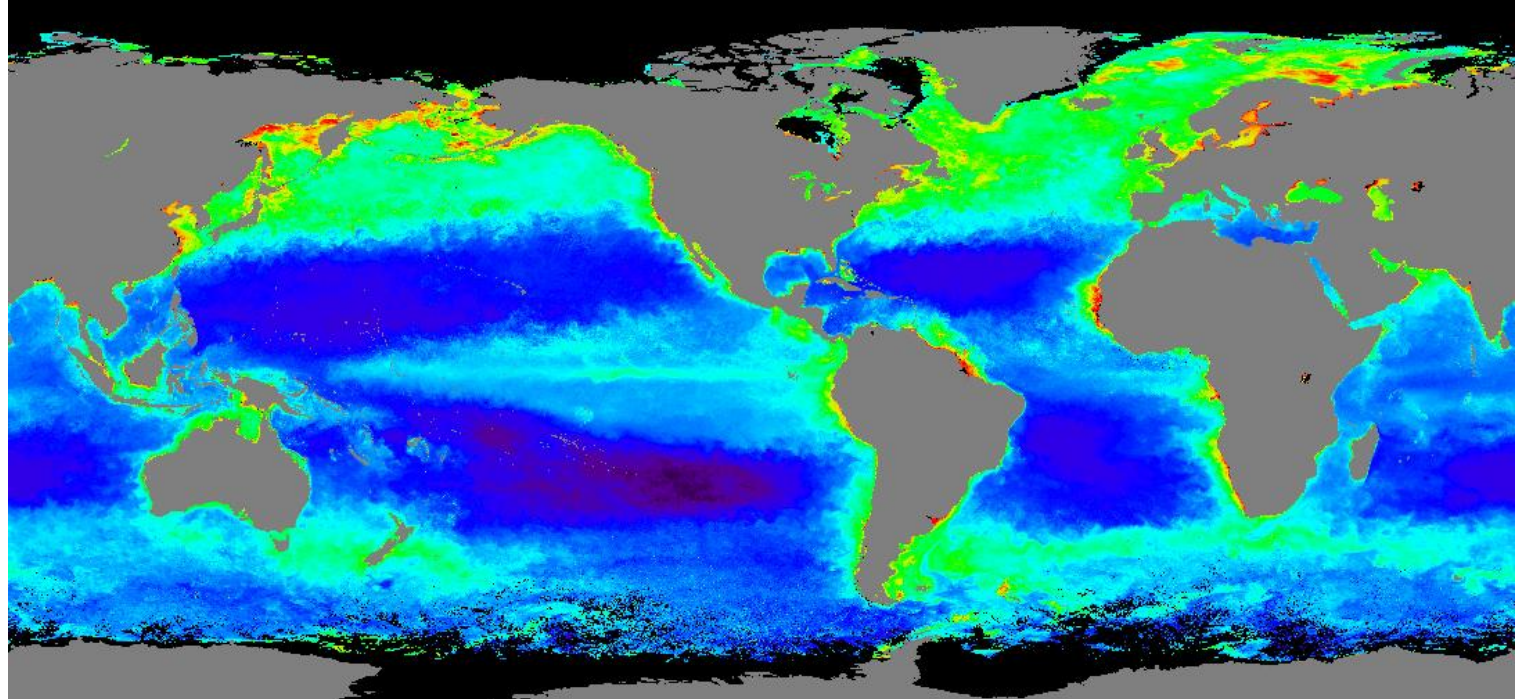
Air/sea equilibration timescales

Resident Fauna

Degree of Anthropogenic change

Ocean temperature

Depth/bathymetry



Full Implementation
& Deployment

Working backwards - Knowledge gaps

Other actors

Its unlikely that only one
Climate intervention will be deployed
In the ocean

There are also likely to be
Concurrent feedbacks, variability, altered
emissions (hysteresis)
That need to be dissected out

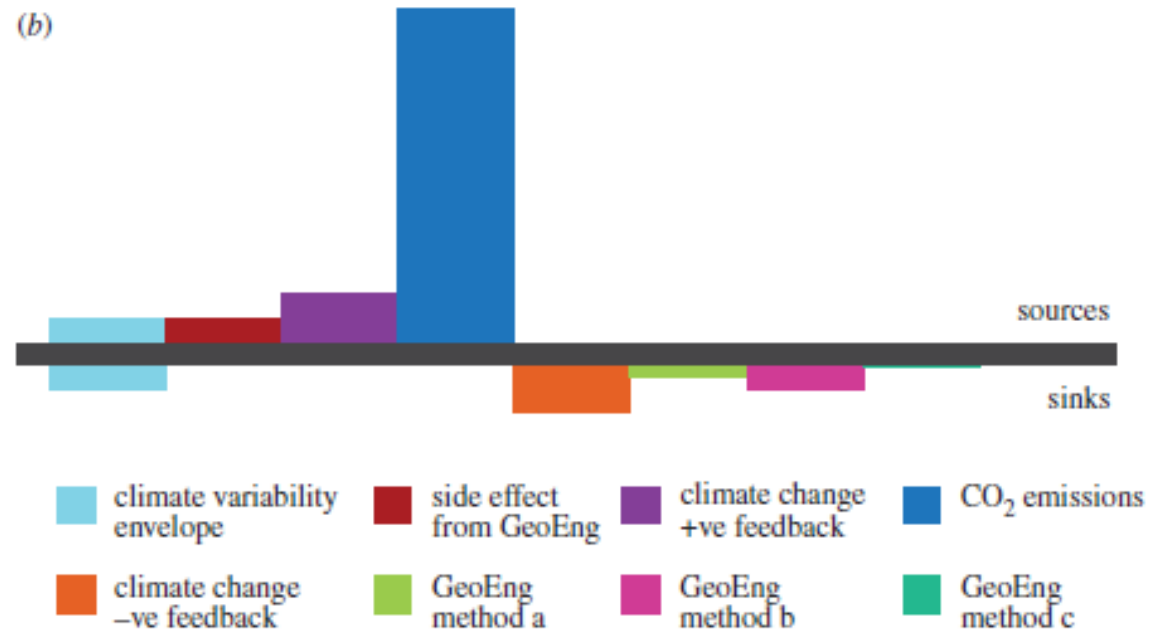


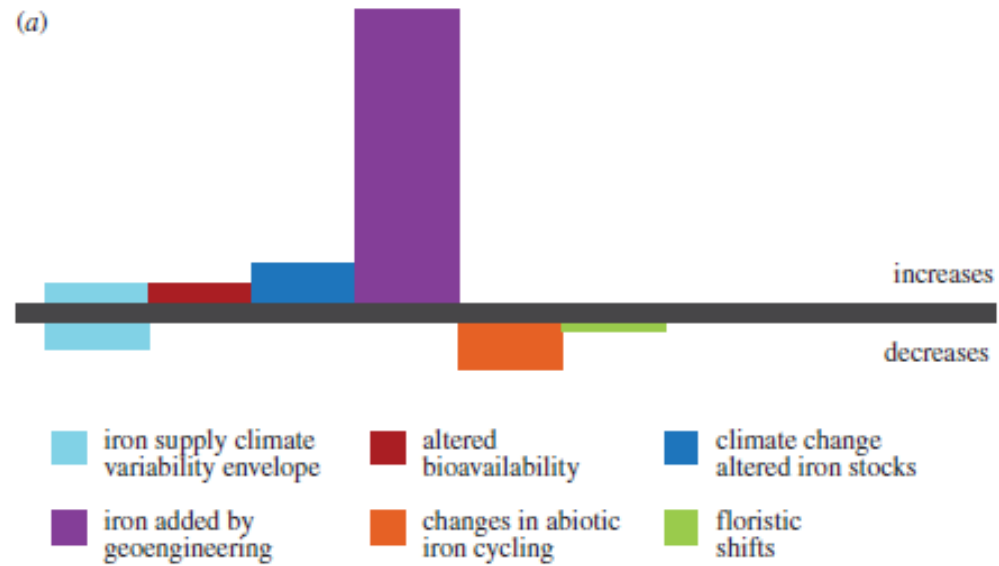
Figure 5. A major challenge for all ocean geoengineering approaches, including iron fertilization, is the detection and attribution of carbon sequestration, and any side-effects on the ocean system. Panel (a) illustrates this challenge using hypothetical changes in iron stocks and/or bioavailability that will likely be mediated by natural variability (such as El Nino

Full Implementation
& Deployment

Working backwards - Knowledge gaps

Baseline for D&A

Anthropogenic alteration of Fe biogeochemistry



Boyd & Bressac (2016)

Full Implementation & Deployment

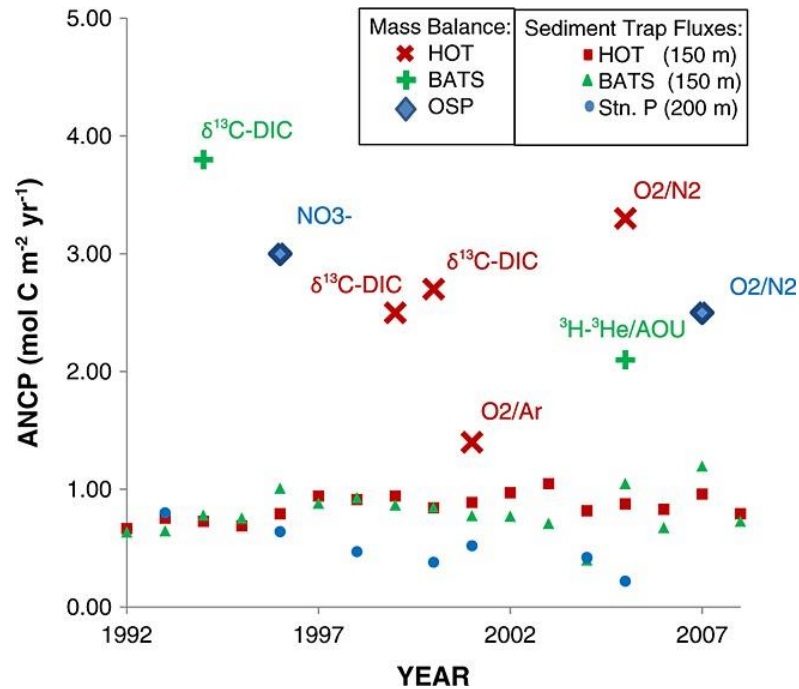
Working backwards - Knowledge gaps

Baseline for D&A
We still do not have
a baseline for C sequestration
In the modern ocean!!

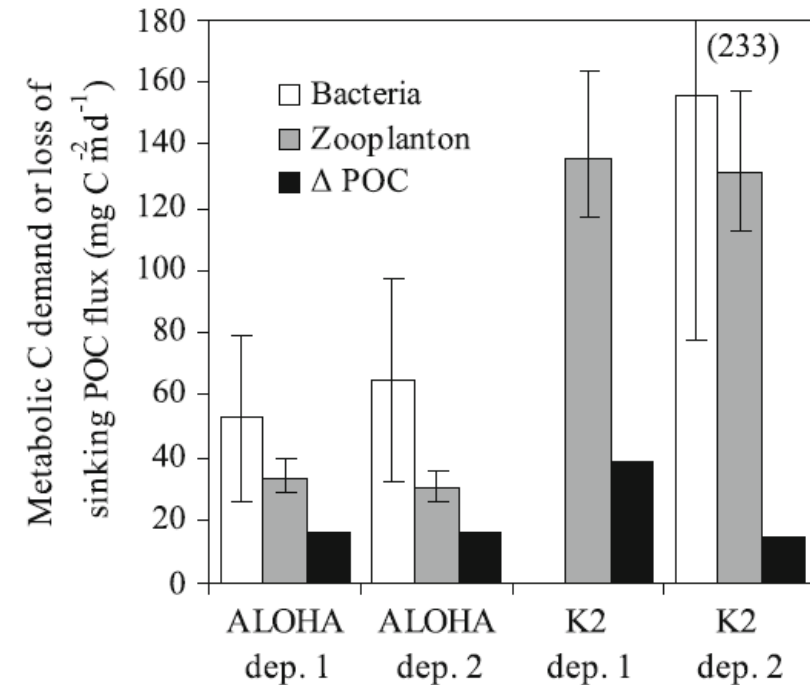
Conspicuous imbalances between POC downward export and export fluxes
derived from geochemical tracers OR the C demand from mesopelagic biota

Assessing the apparent imbalance between geochemical and biochemical indicators of meso- and bathypelagic biological activity: What the @\$#! is wrong with present calculations of carbon budgets?

Adrian B. Burd^{a,*}, Dennis A. Hansell^b, Deborah K. Steinberg^c, Thomas R. Anderson^d, Javier Arístegui^e,



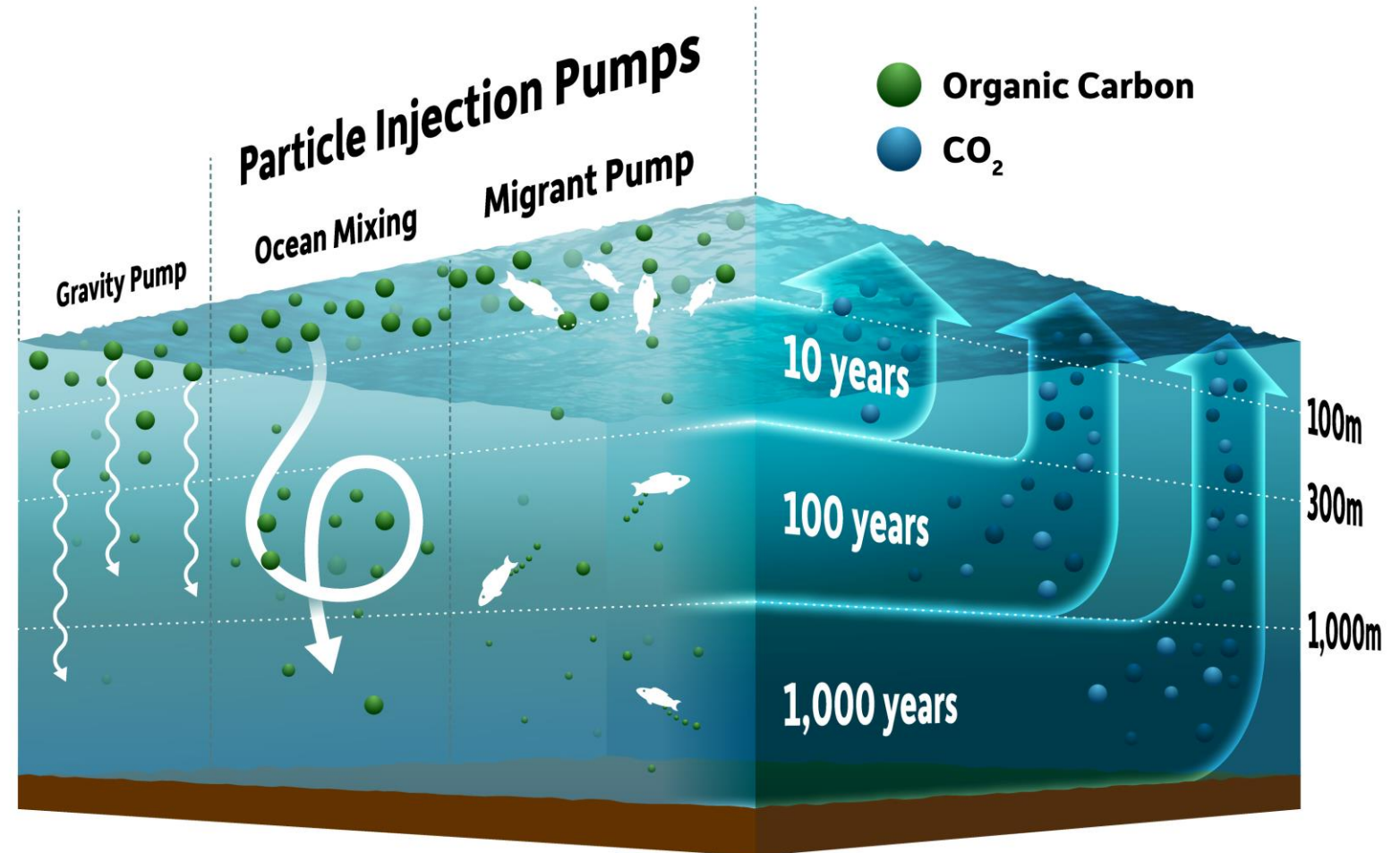
Annual net community production and the biological carbon flux in the ocean (Emerson et al., 2014)



Full Implementation & Deployment

Working backwards - Knowledge gaps

Baseline for D&A
Multi-faceted ways to
Sequester C in the modern ocean



Multi-faceted particle pumps drive carbon sequestration in the ocean

Philip W. Boyd^{1*}, Hervé Claustre^{2,6}, Marina Levy^{3,6}, David A. Siegel^{4,6} & Thomas Weber^{5,6}

Boyd et al. (2019)

Figure courtesy of Tom Weber

Upscaling – we need a different method than the 1000 km² SF₆ labelled OIF patch for next gen pilot studies

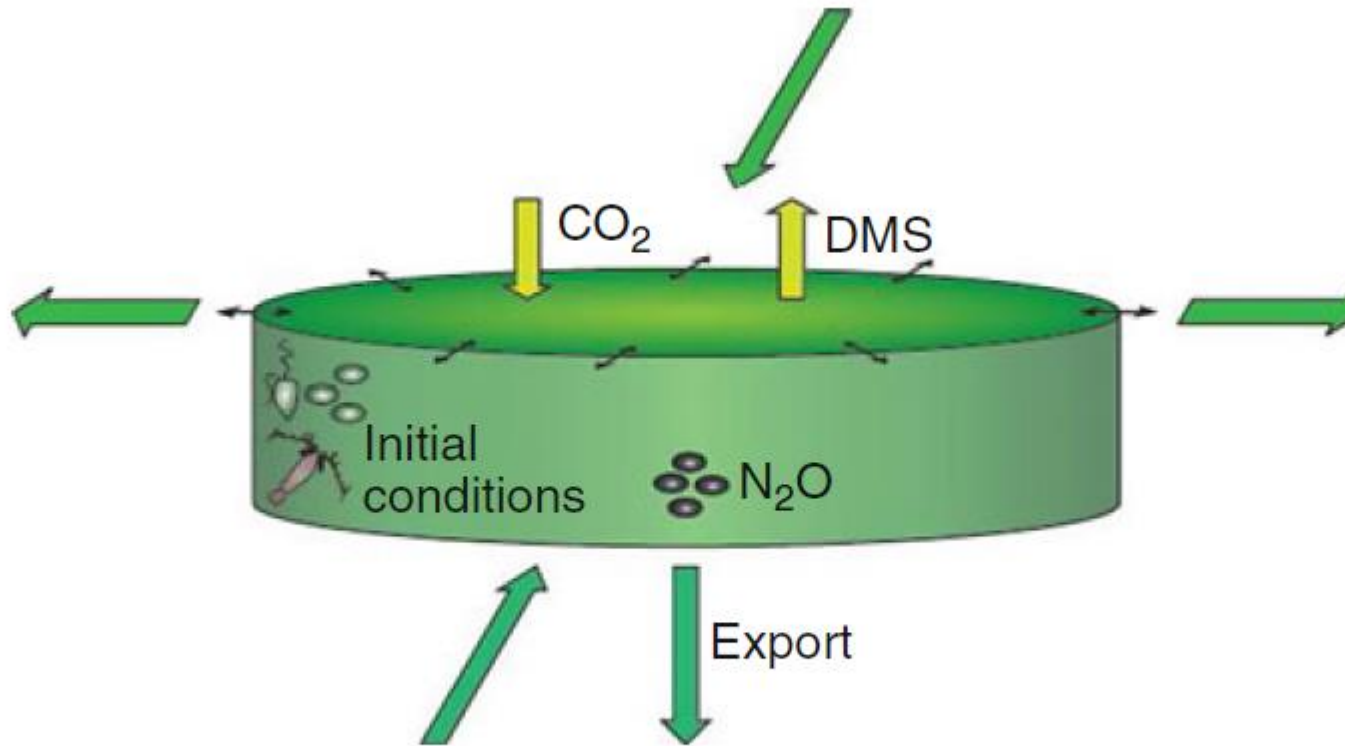


Fig. 5.5 A schematic of the interactions between the iron-enriched patch of upper ocean and the surrounding HNLC waters redrawn after Boyd and Law [31]. Solid *black arrows* denote diffusion

Nested Pilot
studies

Working backwards - Knowledge gaps

Upscaling – what about a 10000 km² OIF patch for next gen pilot studies?

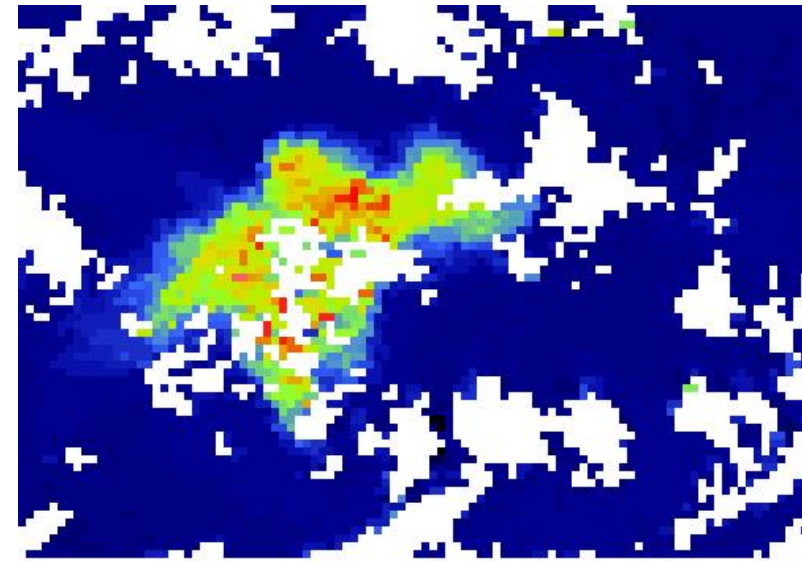
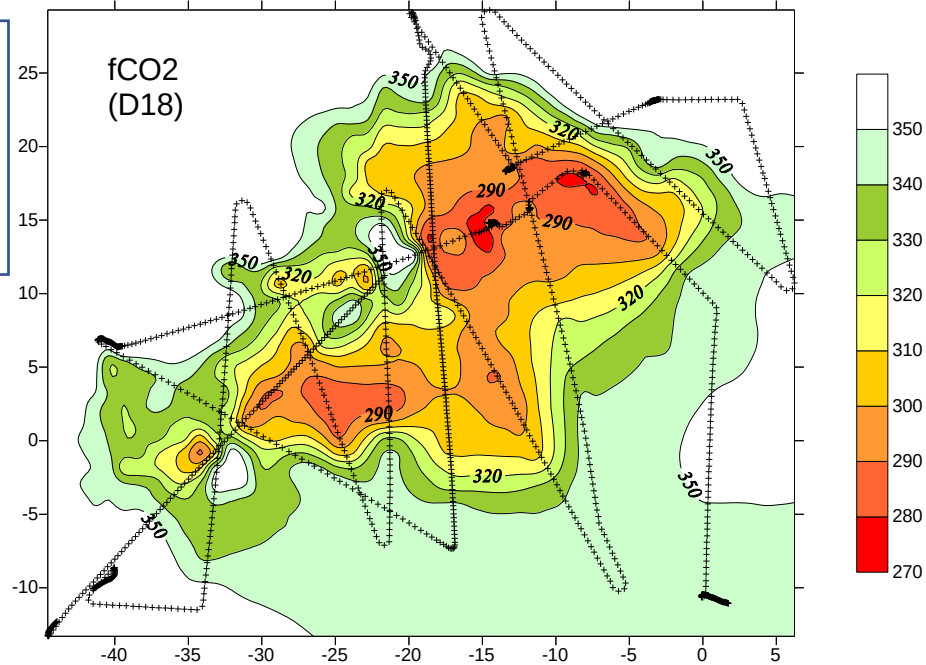
Designing the next generation of ocean iron fertilization experiments

Andrew J. Watson^{1,*}, Philip W. Boyd², Suzanne M. Turner¹, Timothy D. Jickells¹,
Peter S. Liss¹

MEPS 2008

“Our present understanding suggests that any carbon sequestration will occur as the net result of changes in the air–sea flux integrated over millions km₂ and many years, and can only realistically be assessed by modelling.”

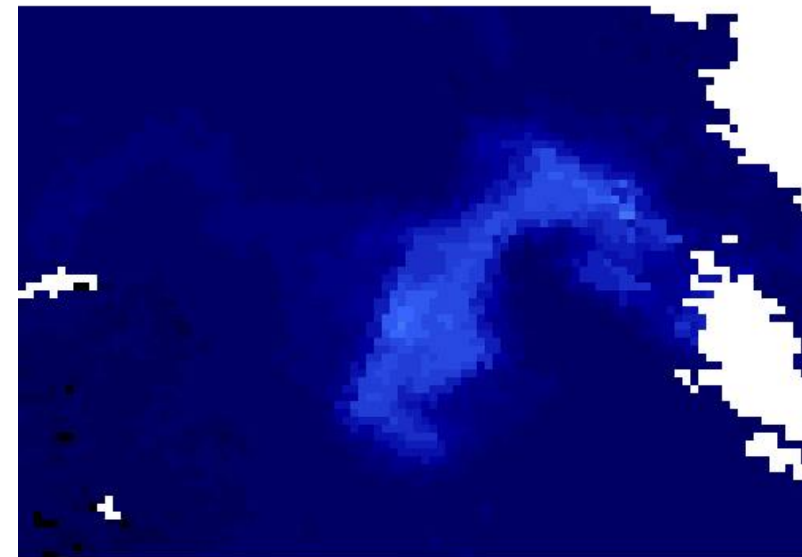
Nested Pilot studies



SERIES experiment (NE subarctic Pacific)

Concurrent ship survey maps of CO₂ drawdown by the Blooming phytoplankton, which match the shape of the bloom as observed from SeaWiFS satellite images

No ships were present for re-equilibration of the upper ocean
The **often neglected key step** in C sequestration



Algal carbon (mg)

Boyd et al. (2004)

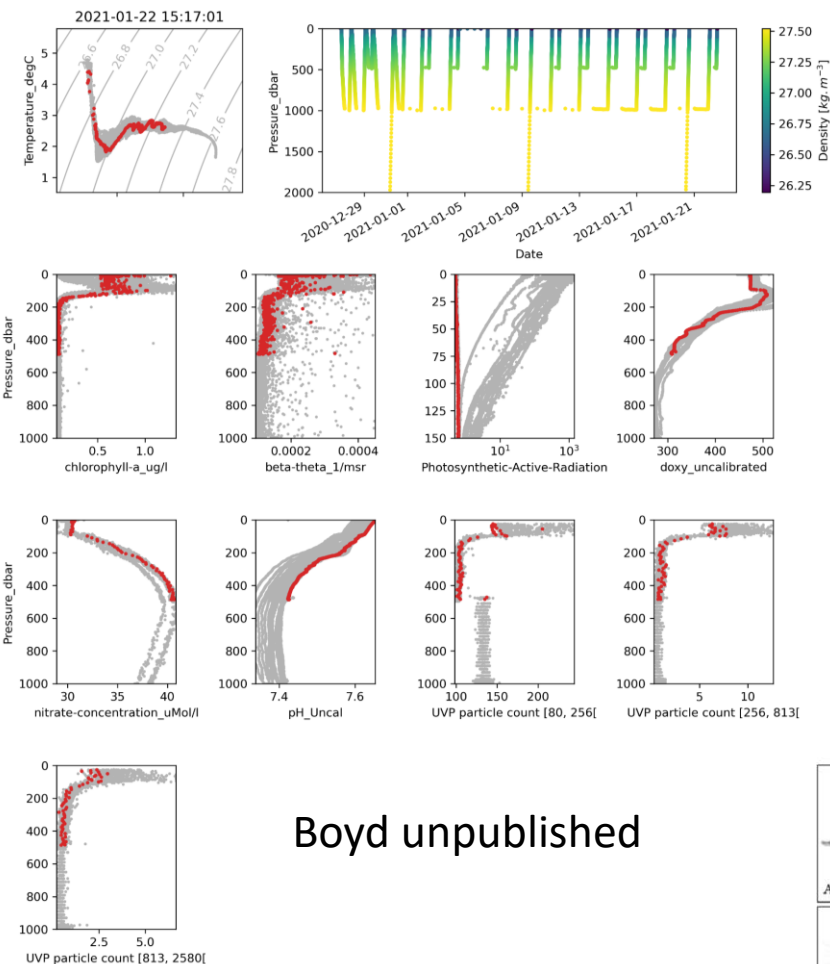
Nested Pilot studies

Working backwards - Knowledge gaps

Suitable technologies

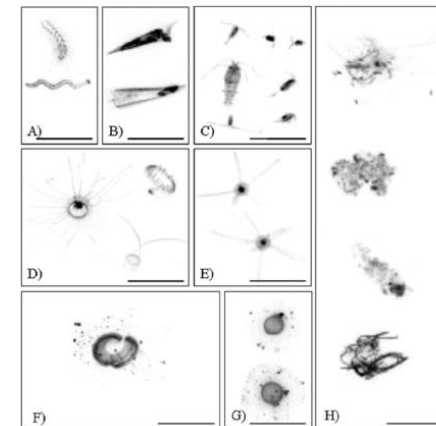


New BGC-ARGO floats
With UVP6 deployed
Jan 2021
In S. Ocean



Boyd unpublished

Claustre unpublished



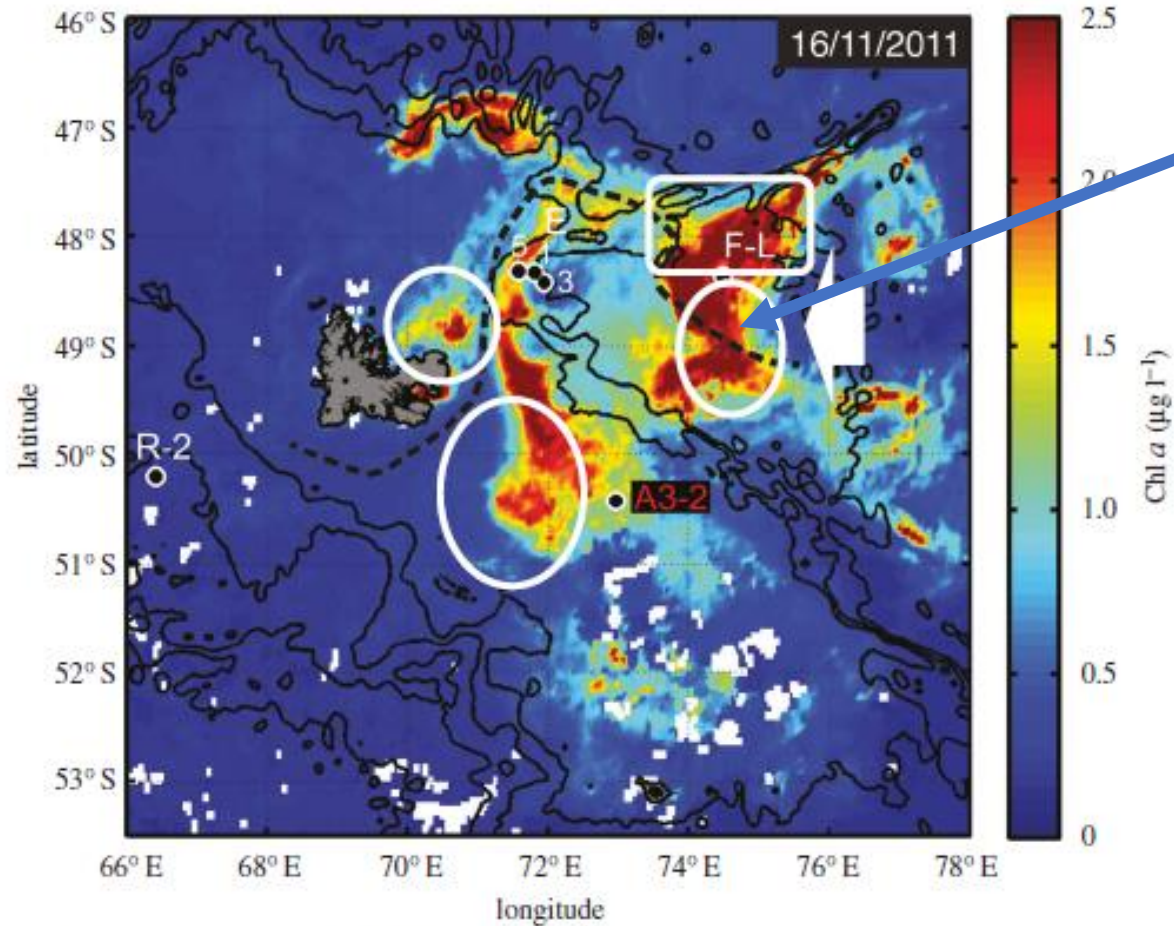
Nested Pilot studies

Location(s)
Different Iron supply rates
In a natural setting

Have we optimised the
iron supply rate?

Is simply adding more Fe better?

Working backwards - Knowledge gaps



Highest POC export
In region with modest
But sustained Fe supply

Figure 3. An ocean colour image from MODIS from mid-November 2011 highlights four distinct iron-fuelled surface chlorophyll features (vertical coloured scale bar in $\text{mg chlorophyll m}^{-3}$) that were sampled during the KEOPS II GEOTRACES process study [82]. The highest measured downward POC export was in a region with sustained but moderate iron supply (open circle to the left of horizontal arrow). Other regions sampled, clockwise (open symbols) from top left are Kerguelen coastal waters; Polar Front plume; recirculating feature and the plateau (redrawn from [84]).

Boyd & Bressac (2016)
From Trull et al. (2014)

New Research
Targets

Working backwards - Knowledge gaps

R&D agenda set by
Foresighting

The importance of line-of-sight from modelling



correspondence

Foresight must guide geoengineering research
and development Lenton et al. (2019)

“As part of this foresighting, there is a strong requirement for (scale- and process appropriate) modelling studies to develop these trajectories from research towards implementation.”

“Critically, this development must precede field experimentation to enable exploration of the wide array of issues around what a pilot study might reveal.”

“To inform the development of realistic trajectories, fit-for-purpose modelling simulations must also look well beyond a pilot study, so as to uncover the characteristics of the subsequent suite of more advanced and upscaled experiments with respect to efficacy, side-effects, and detection and attribution.”

New Research Targets

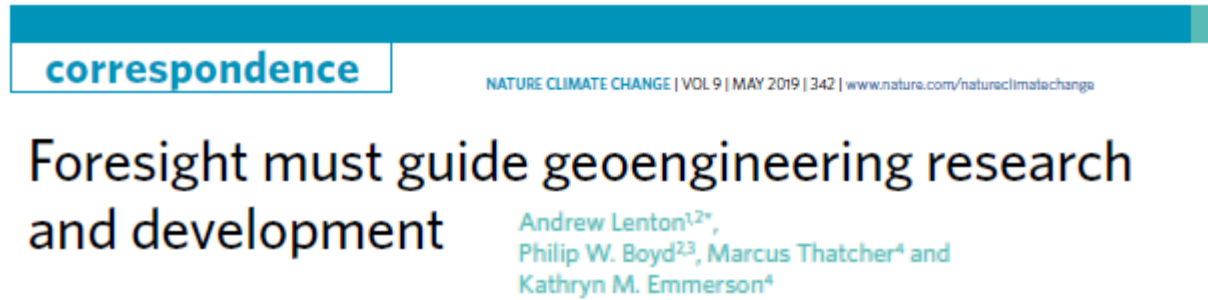
Fundamental
Knowledge gaps
That need to be merged with
foresighting

Table 1. Major uncertainties in the effects of deliberate ocean iron fertilization

Process	Issue	Finding	Comments
Carbon sequestration efficiency	Carbon fixation in surface water	Variable ^a	Latitude, mixed layer depths + light co-limitation
	Carbon export	None/little/significant ^b	Limited duration of studies
	Depth of carbon export	Poorly constrained	
	Duration of carbon sequestration	Unknown	Unanswerable by observations alone
	Fraction fixed from atmosphere	Poorly known	Likely unanswerable by observations alone
Influence on dissolved oxygen	Formation of subsurface O ₂ minima	Poorly known ^c	Potentially harmful, depth dependent
Production of other climate-active gases	Methane & nitrous oxide	No effect/possible enhancement ^{d,e,f}	Significant warming potential
	Dimethylsulphide	No change/ increase ^b	Some evidence that enhancement is transient
	Biogenic halocarbons	Reduction/no change/ increase ^g	Pertinent to atmospheric oxidation chemistry & particle formation
	Biogenic hydrocarbons, including alkyl nitrates	No change/increase ^{e,g}	Pertinent to atmospheric oxidation chemistry & particle formation
Effects on ecosystems and biogeochemistry	Phytoplankton species shifts	Mainly towards diatoms ^b	Are shifts transient?
	Mesozooplankton stocks	No change/increase ^b	Localised increases within Fe patch due to arrested vertical migration: duration of study & longer reproductive cycles
	Higher trophic levels	Unknown	Limited duration of studies. Possibility of enhanced secondary and higher-level production ^j
	Macronutrient uptake	Small to significant ^b	Mixed layer depths + light co-limitation
	Reduction of nutrient transport	Important in upwelling regions ^b	Supply flows to other areas cut off, e.g. sub-tropical gyres
	Nutrient remineralization	May affect global distributions	At present only evident from modelling studies ⁱ
^a de Baar et al. (2005); ^b Boyd et al. (2007); ^c Natural O ₂ minima: e.g. Arabian Sea & east subtropical Pacific, anthropogenic minima: e.g. Gulf of Mexico eutrophication; ^d Law & Ling (2001); ^e Wingenter et al. (2004); ^f Walter et al. (2005); ^g Liss et al. (2005); ^h Cooper et al. (1996); ⁱ Gnanadesikan et al. (2003); ^j Tsuda et al. 2006			

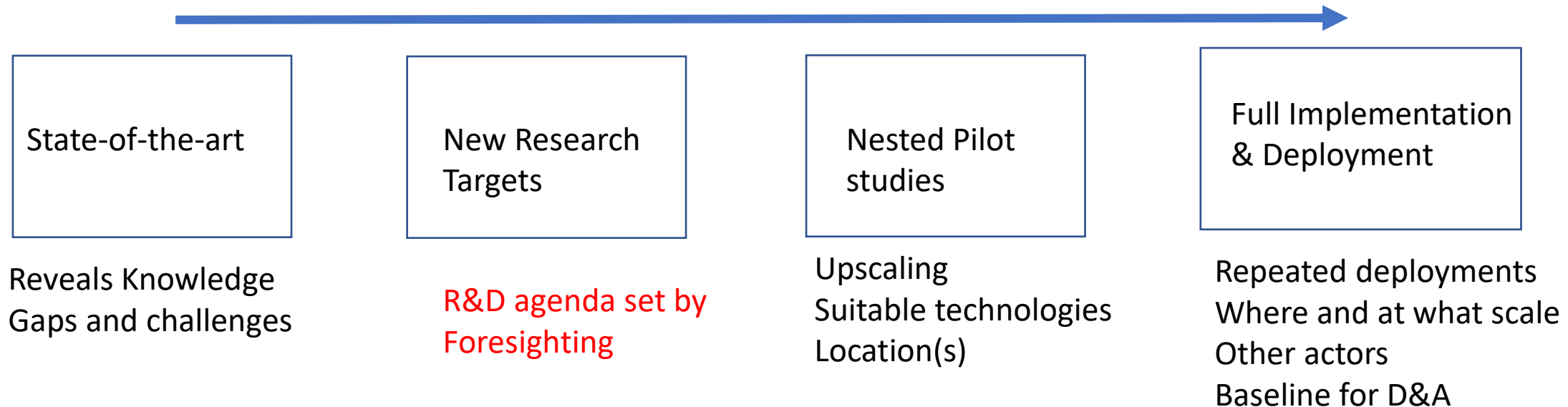
Watson et al.
(2008)

Issues to consider for the development of a R&D agenda to progress ocean-based CDR approaches



“It is essential to first elucidate the longer-term goals and then identify the trajectory towards a full implementation.”

“This trajectory must be formulated around the scientific and engineering questions relevant for any geoengineering technique at each stage of its development.”



Challenges and Opportunities

Vol. 364: 213–218, 2008 doi: 10.3354/meps07541		MARINE ECOLOGY PROGRESS SERIES Mar Ecol Prog Ser		Published July 29	
THEME SECTION					
Implications of large-scale iron fertilization of the oceans					
<i>Idea:</i> Howard Browman, Philip W. Boyd <i>Coordination:</i> Philip W. Boyd					
CONTENTS					
Boyd PW Introduction and synthesis.....213–218		de Baar HJW, Gerringa LJA, Laan P, Timmermans KR Efficiency of carbon removal per added iron in ocean iron fertilization.....269–282			
Denman KL Climate change, ocean processes and ocean iron fertilization.....219–225		Law CS Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions.....283–288			
Freestone D, Rayfuse R Ocean iron fertilization and international law.....227–233		Gnanadesikan A, Marinov I Export is not enough: nutrient cycling and carbon sequestration.....289–294			
Orbach MK Cultural context of ocean fertilization.....235–242		Cullen JJ, Boyd PW Predicting and verifying the intended and unintended consequences of large-scale ocean iron fertilization.....295–301			
Huesemann MH Ocean fertilization and other climate change mitigation strategies: an overview.....243–250		Watson AJ, Boyd PW, Turner SM, Jickells TD, Liss PS Designing the next generation of ocean iron fertilization experiments.....303–309			
Leinen M Building relationships between scientists and business in ocean iron fertilization.....251–256					
Karl DM, Letelier RM Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes.....257–268					

For a range of reasons, OIF is the best studied marine climate Intervention approach

This holds for field experiments, modelling, governance etc.

OIF also gets used of an example of the problems with marine Climate interventions – but that’s likely because it has been Under more scrutiny.

The development of a CDR R&D Agenda should include OIF As it will serve as a lens to look in depth at other CDR methods

Also recall that out understanding of OIF – despite being underpinned by a large body of research – was insufficient To provide a robust scientific assessment during the development of the GESAMP WG41 Report.

Ecological impacts of nutrient fertilization, from community structure to HABs to fisheries

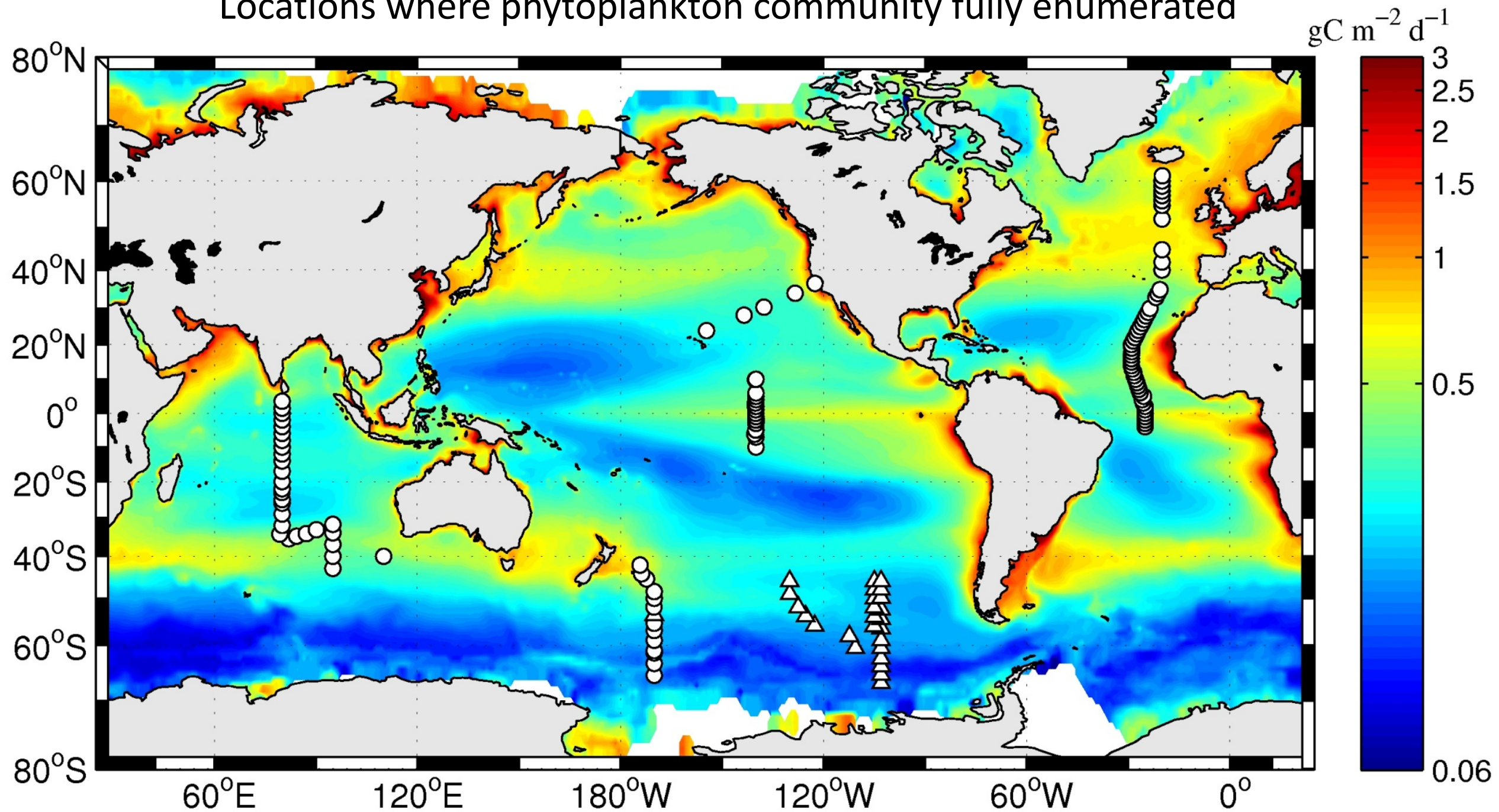
Francisco Chavez
Monterey Bay Aquarium Research Institute



Outline (and Conclusions)

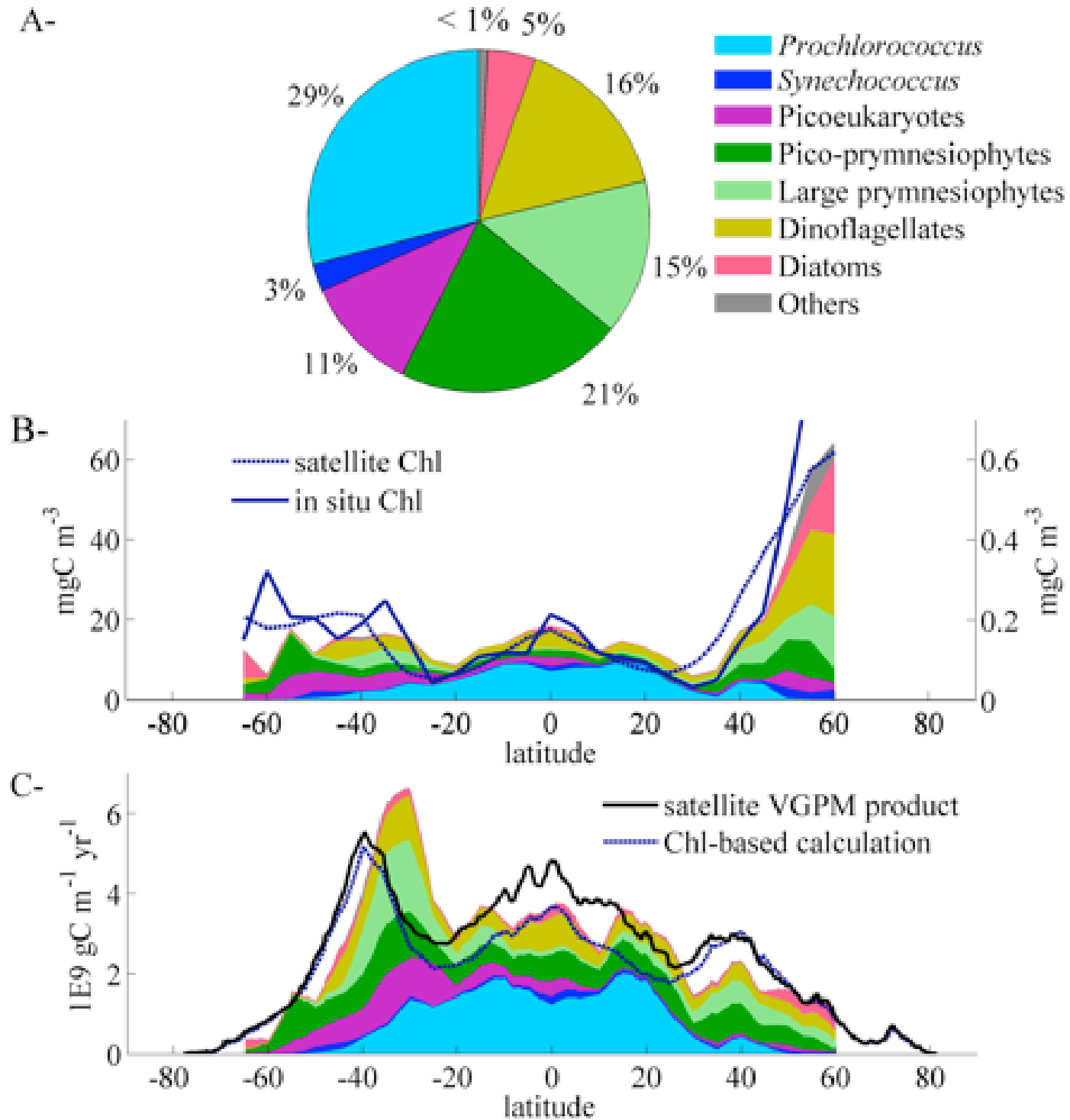
- Current understanding on ecological impacts limited to results from a few short term fertilization experiments
- Ecological impacts (and CDR) are location/season dependent.
- Ecological impacts are linked to the initial food web
- Clear relationships between biomass/productivity and fisheries yield
- Trophic transfer enhanced when habitats are compressed
- Oxygen minimum zones may be good target regions
- The next set of experiments will capitalize on new and emerging technologies

Locations where phytoplankton community fully enumerated

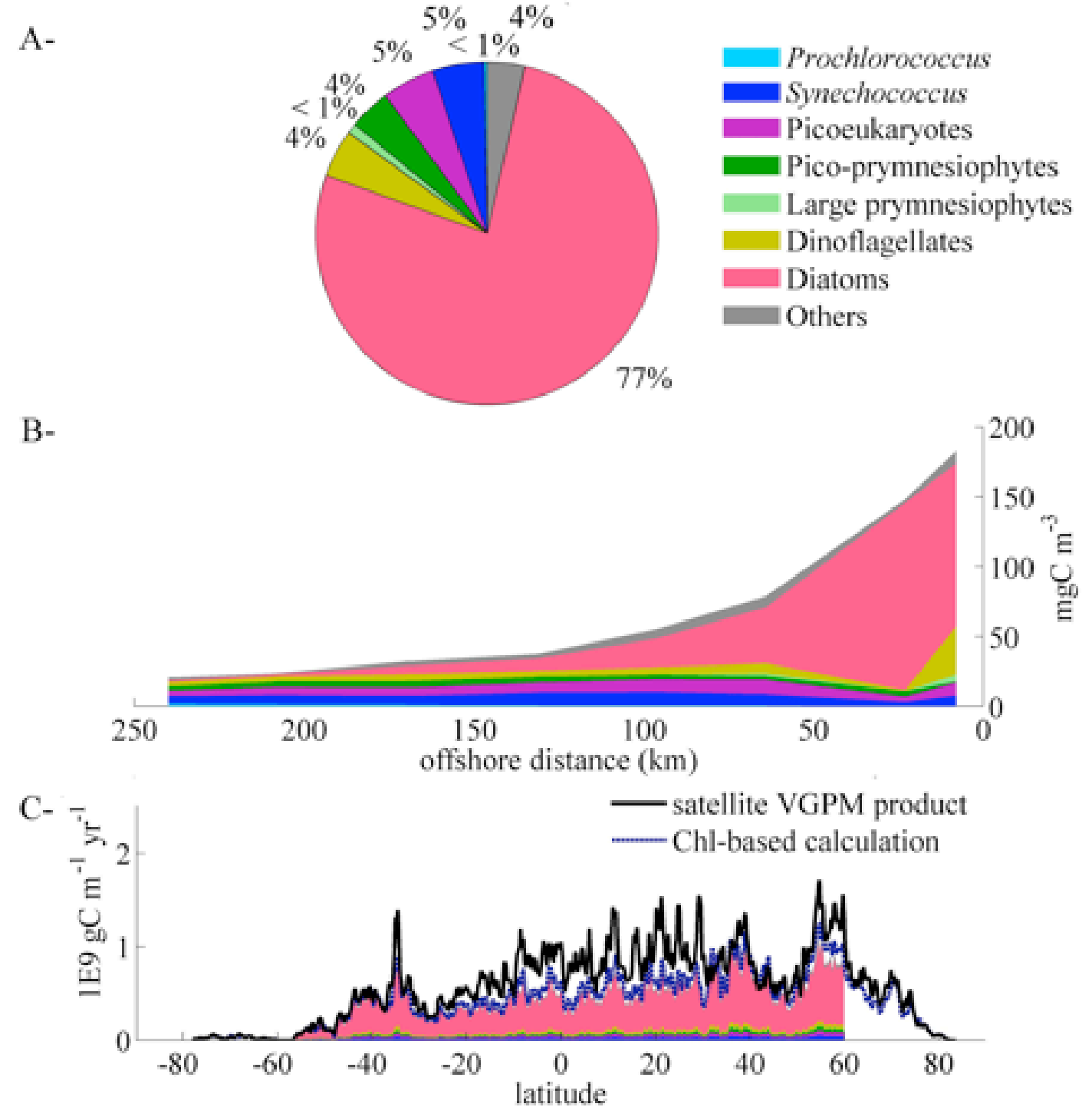


Diatoms are the phytoplankton to be the first responders to fertilization

Open Ocean (mostly pennate diatoms)

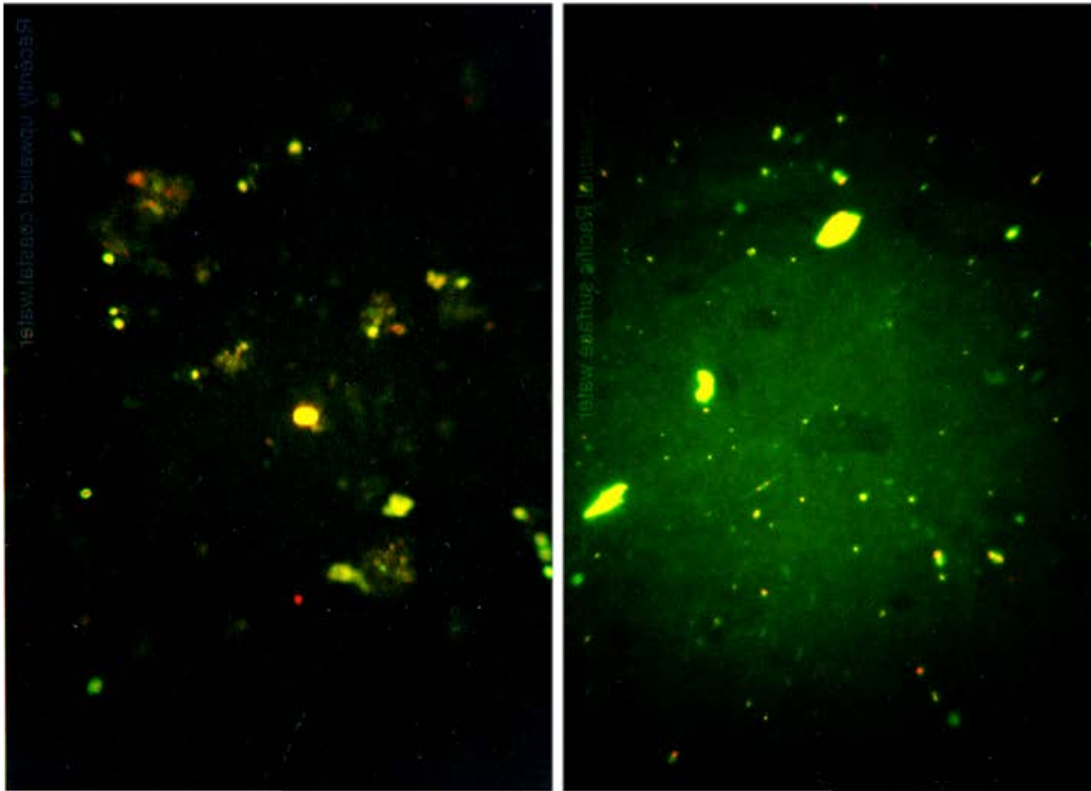


Coast (mostly centric diatoms)

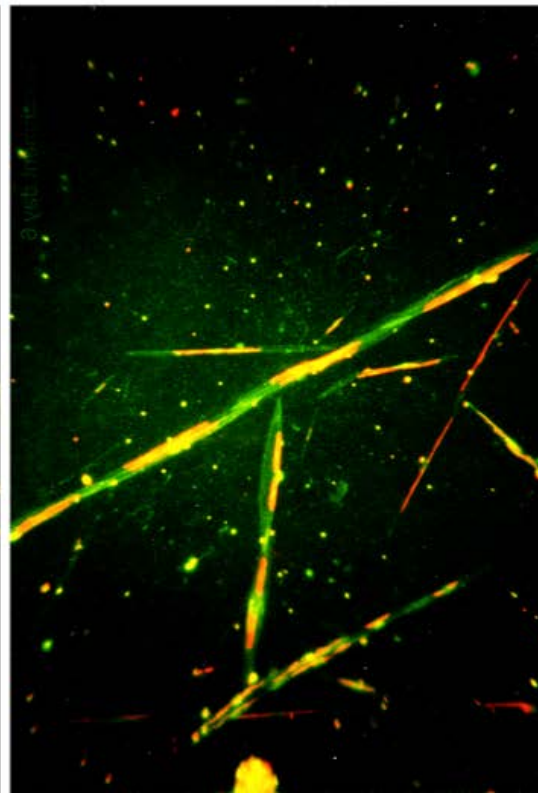


Diatoms are key

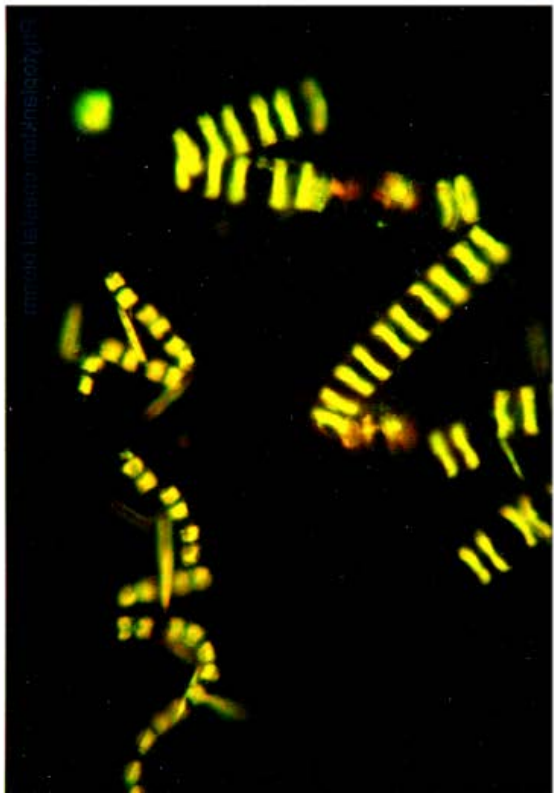
Coastal
Upwelling
center



Open
Ocean
Equator

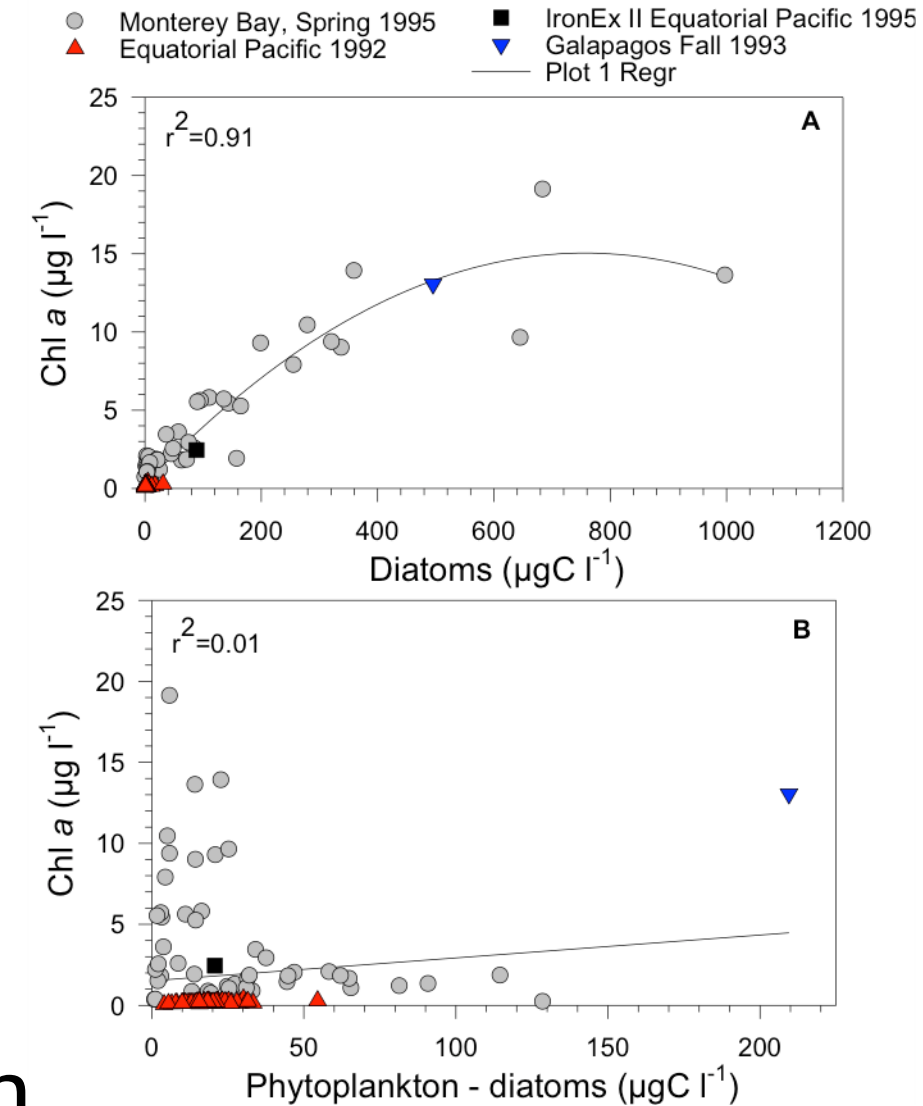


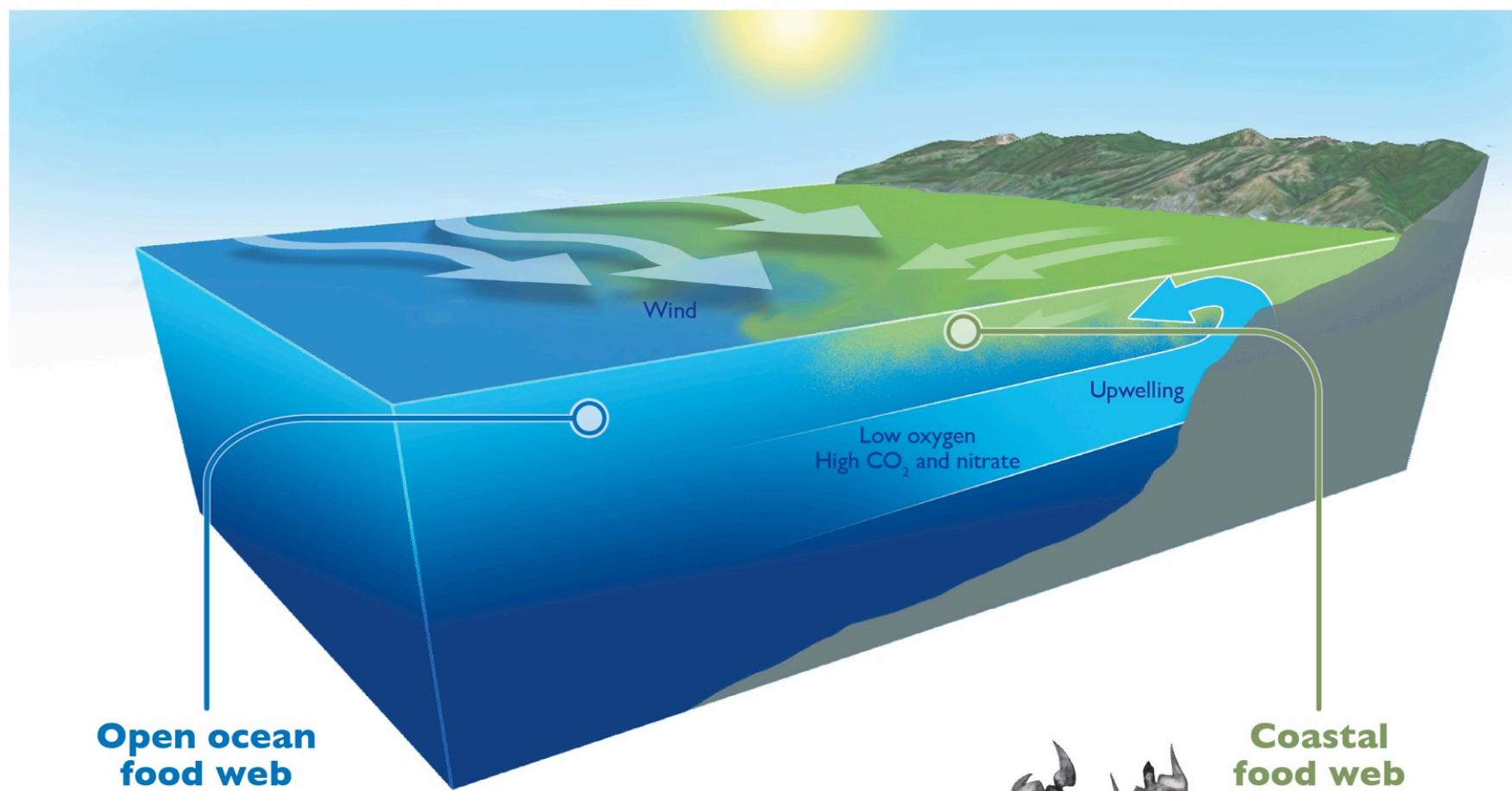
A few days
after
(centrics)



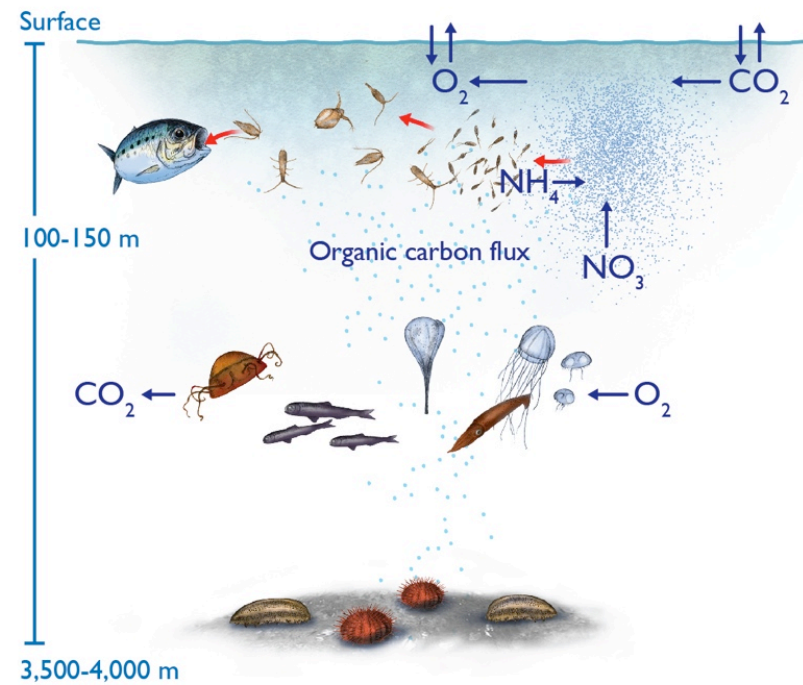
Iron
Fertilization
(pennates)

Pseudo-nitzschia, domoic
acid, Silver et al. 2010

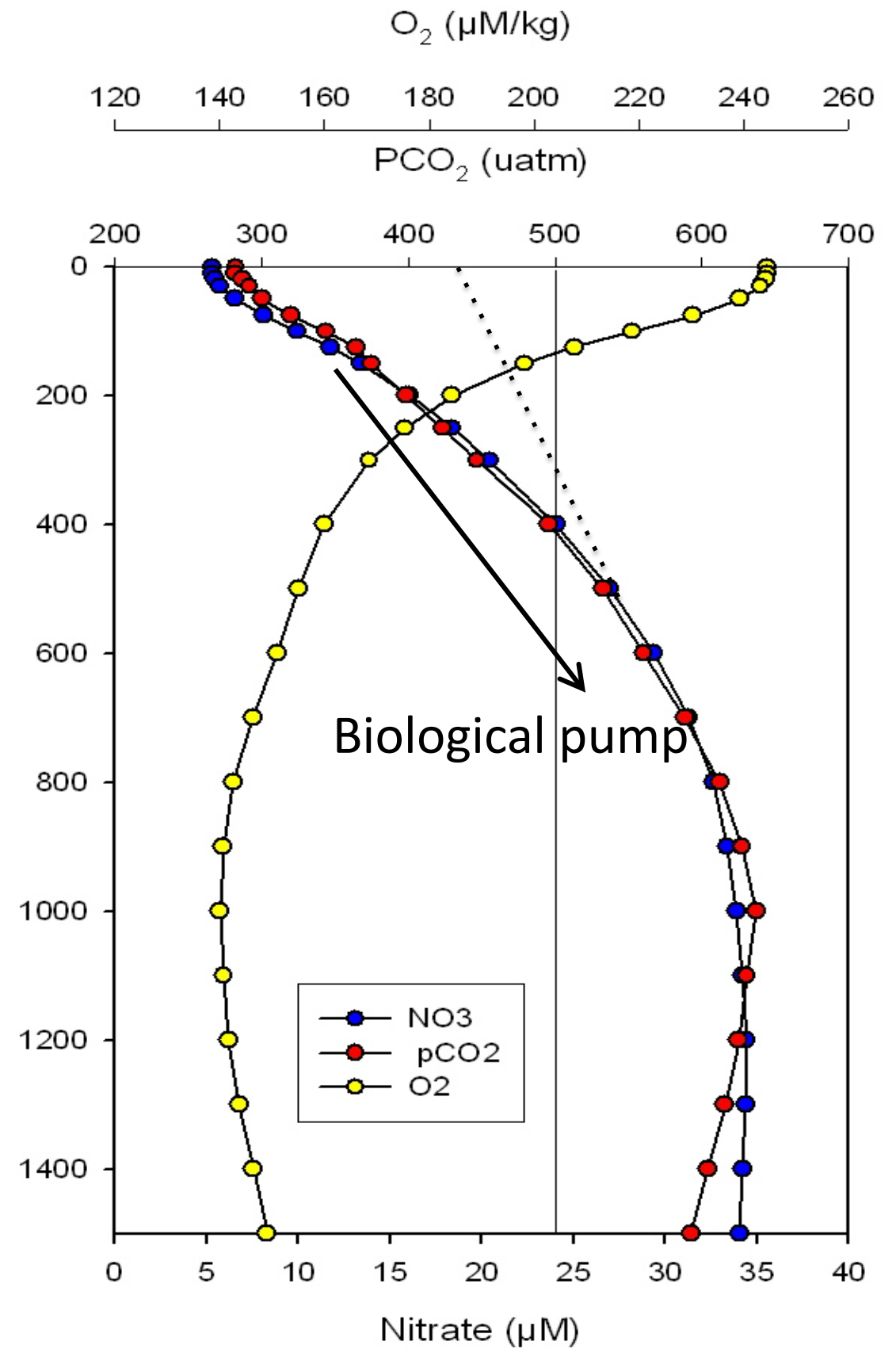
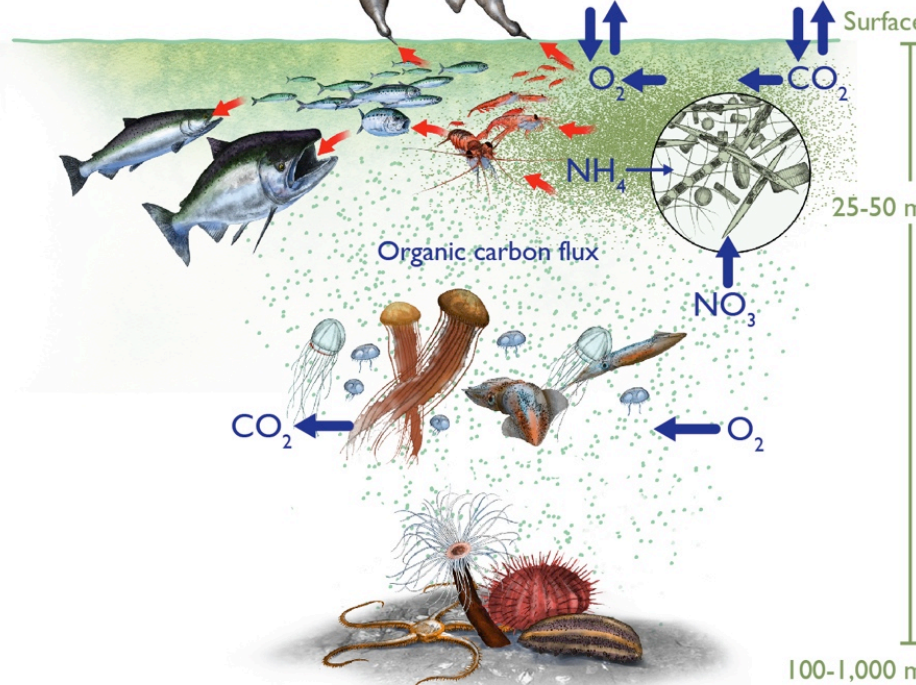




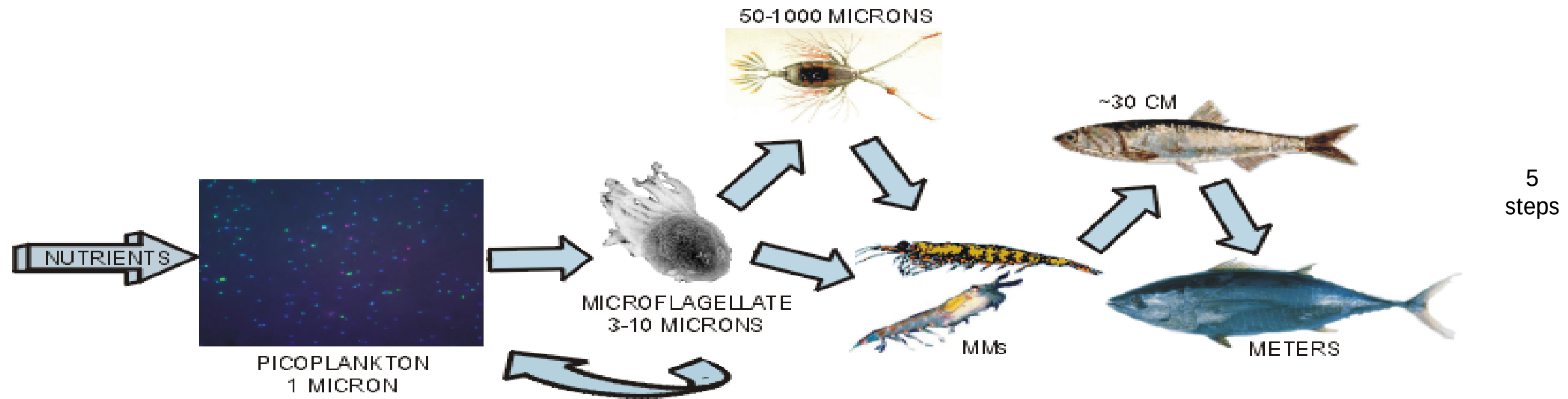
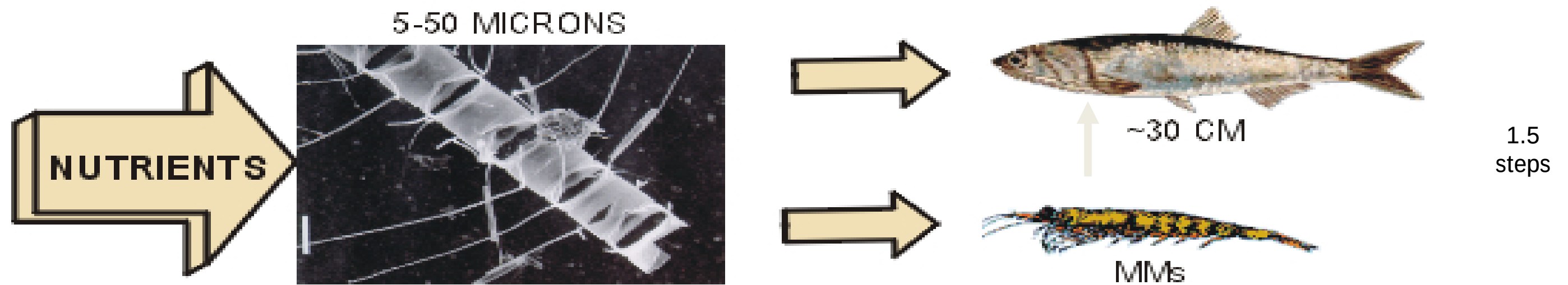
Open ocean food web



Coastal food web



Coastal upwelling



Open Ocean

(after Ryther 1969)

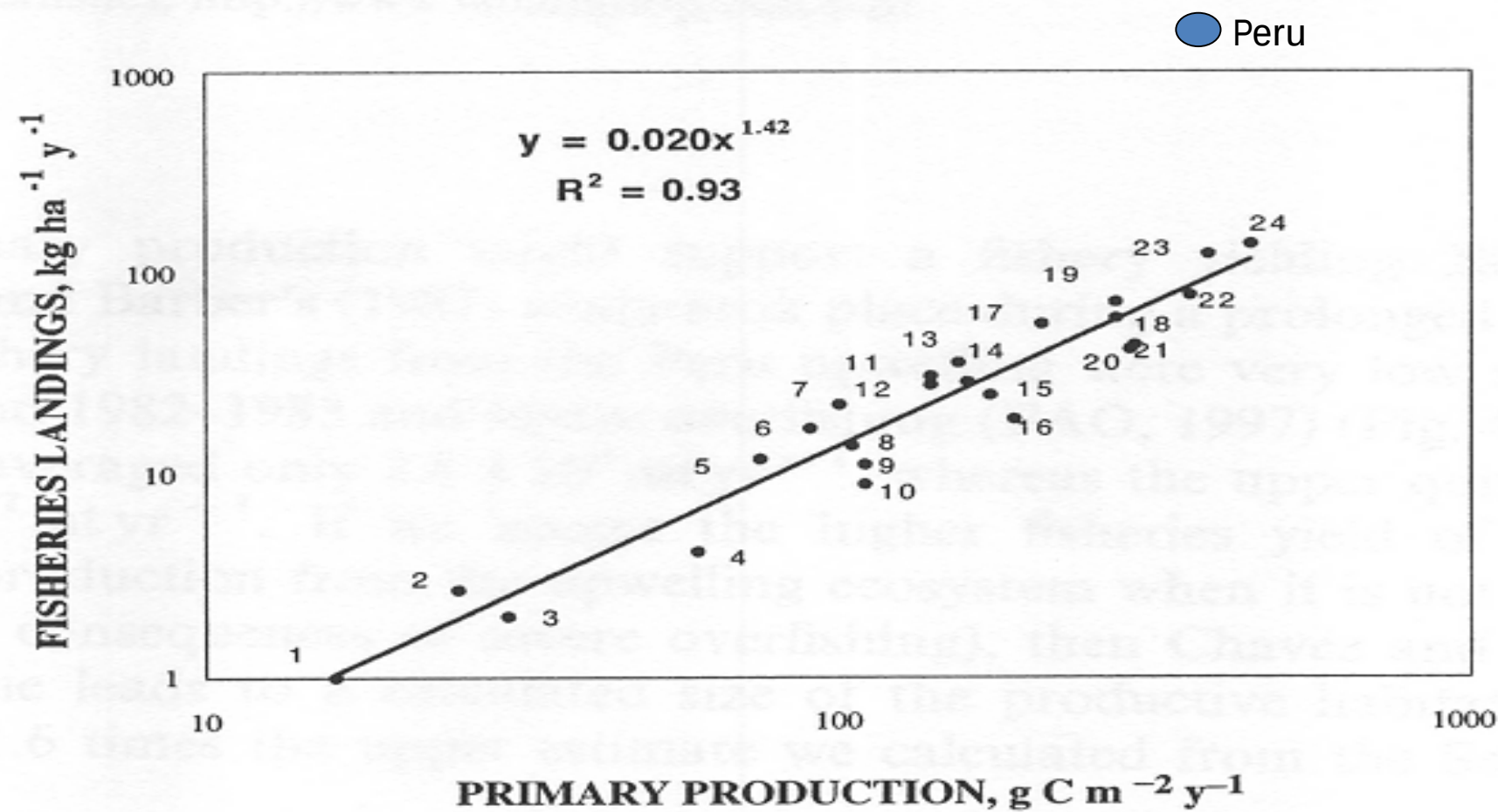
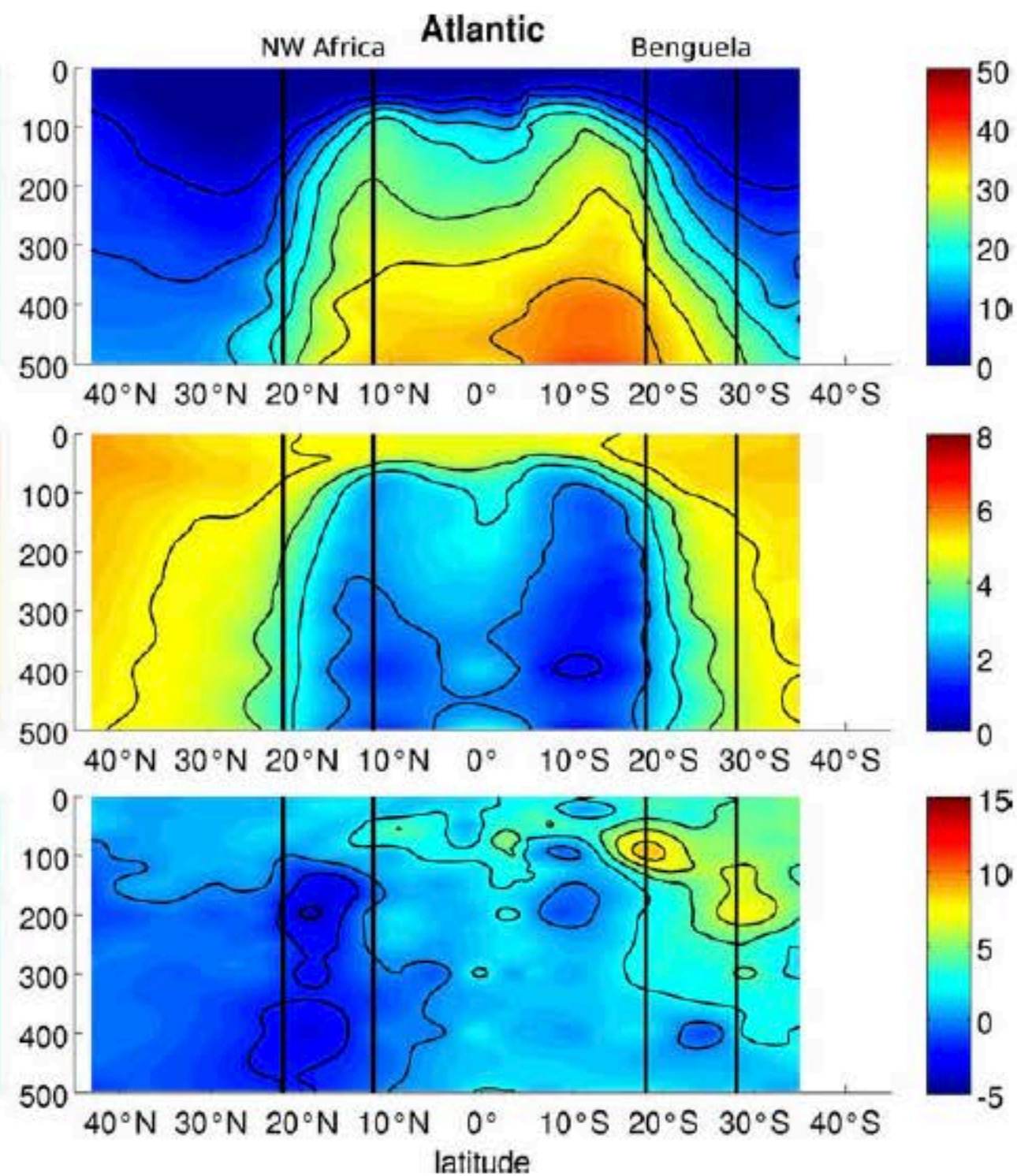
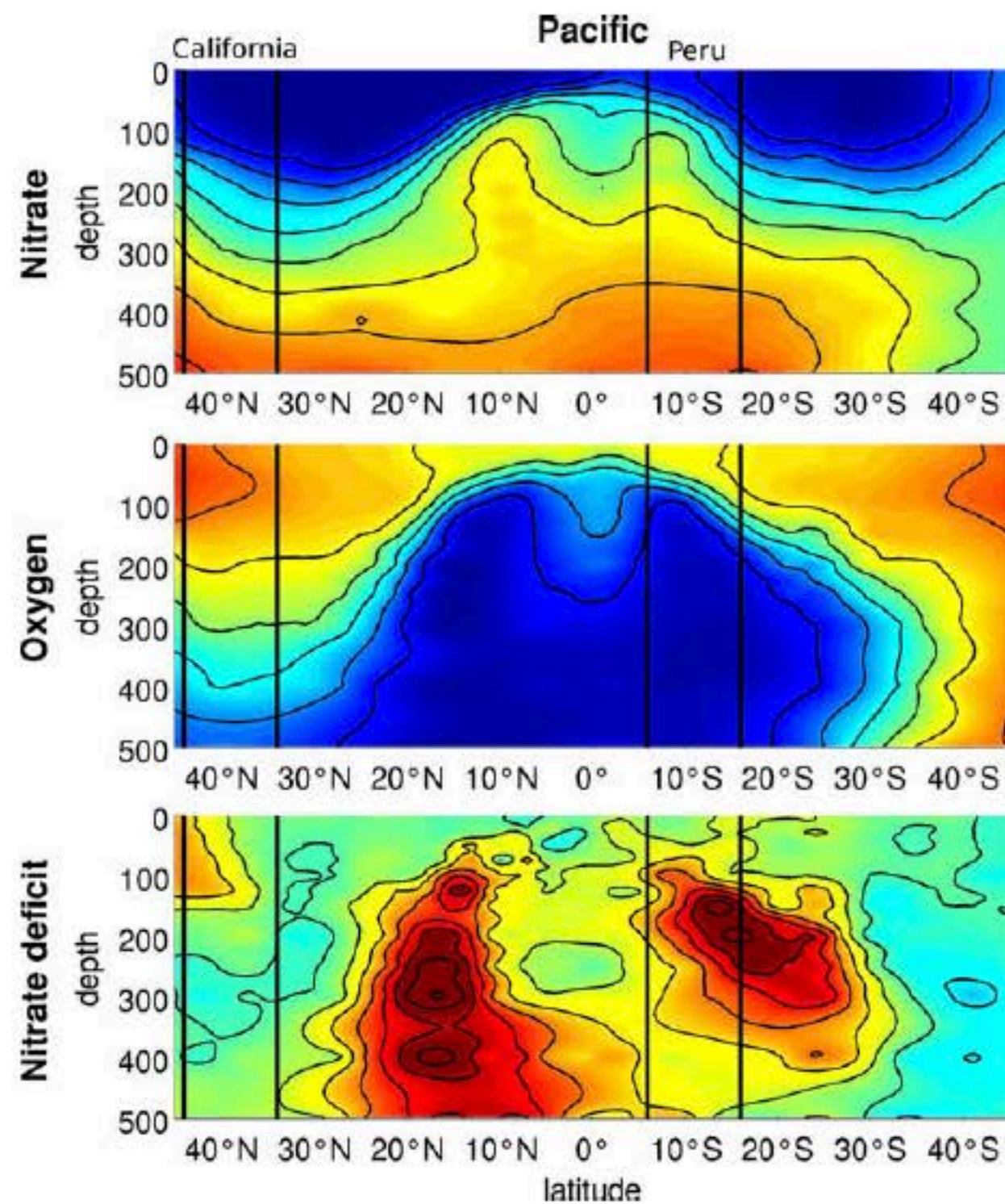
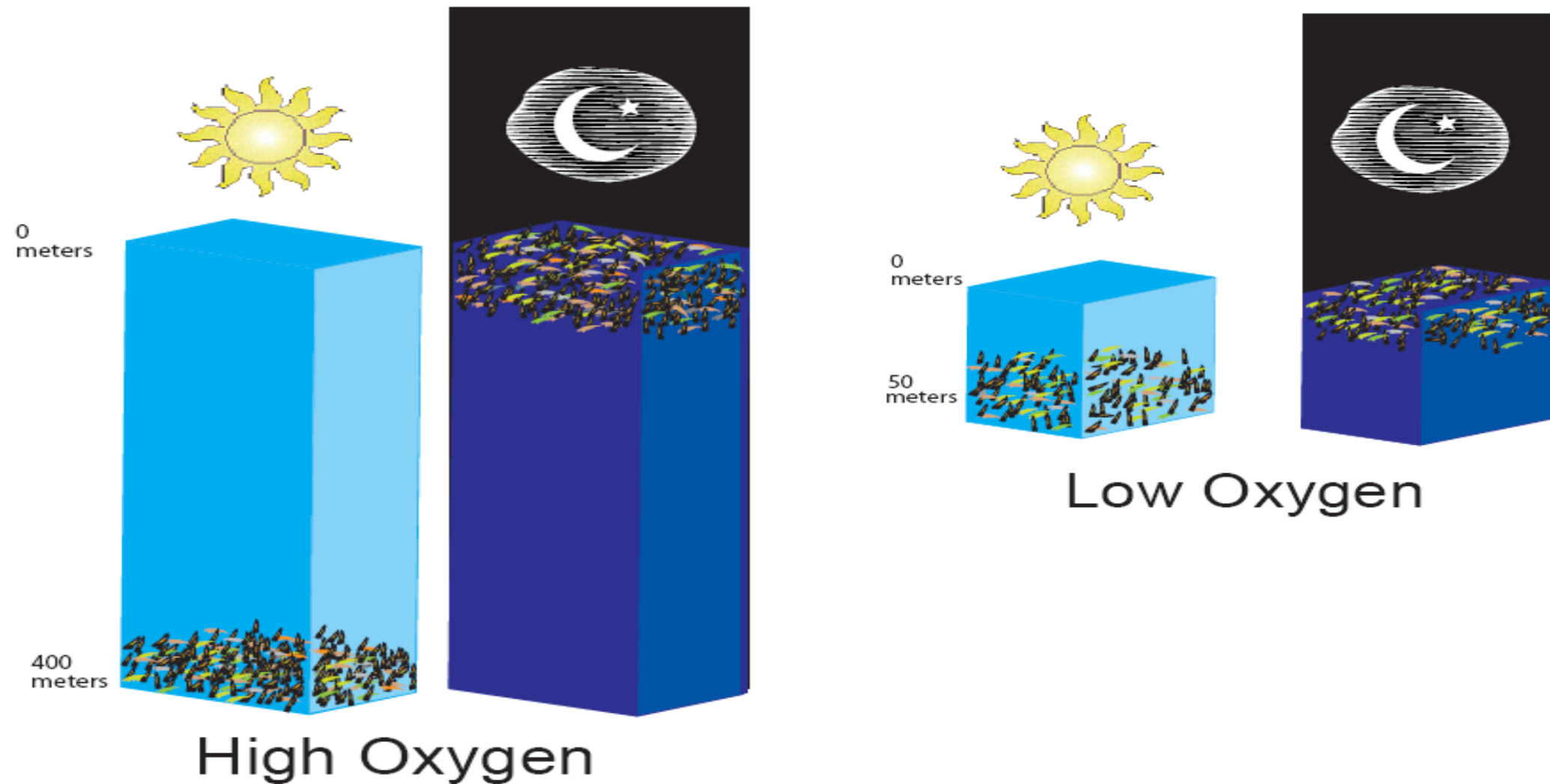


Fig. 3. The annual landings of fish and the primary production (^{14}C uptake) of phytoplankton in a wide variety of marine ecosystems. Measurements are often not contemporaneous. The regression analysis was performed on untransformed data. Systems include: (1) Southeast Mediterranean (postAswan dam construction) (2) Bay of Bothnia (3) Open Gulf of Mexico–Caribbean (4) Sea of Okhotsk (5) Open Mediterranean (6) Adriatic Sea (7) Scotian Shelf (8) Sea of Japan (9) Bothnian Sea (10) Black Sea (11) Gulf of Finland (12) Gulf of Riga (13) English Channel (14) Baltic Sea proper (15) Corpus Christi Bay (16) Gardiners and Peconic Bays (17) North Sea (18) Gulf of Thailand (19) Mid Atlantic Shelf, US (20) Gulf of Maine (21) New England Shelf (22) Apalachicola Bay (23) Georges Bank (24) Great South Bay. Data sources in Nixon (1982) and Nixon et al. (1986). The relationship is discussed more fully in Nixon (1988)

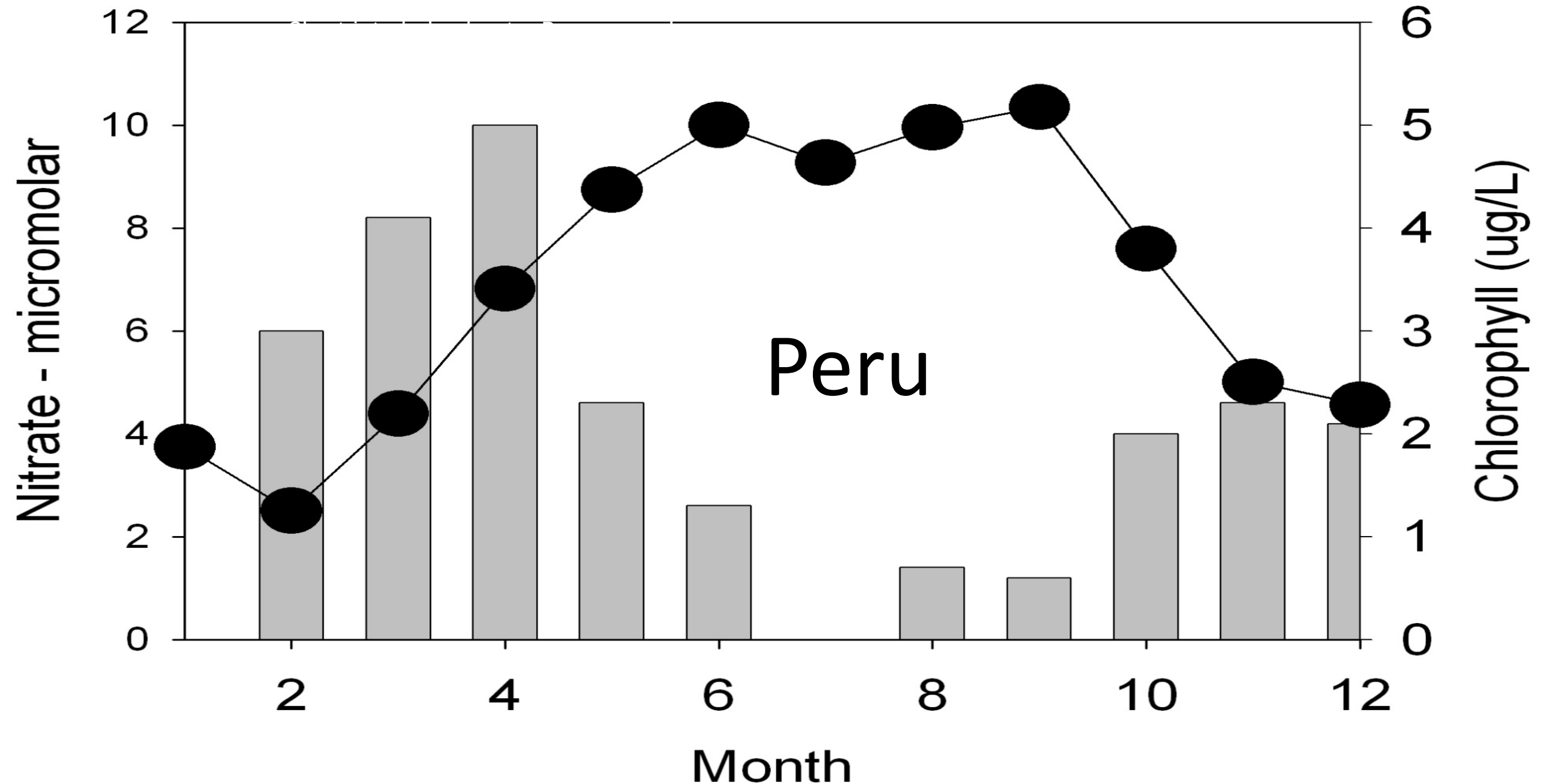


Habitat compression – why Peru produces more fish than any other region in the world?



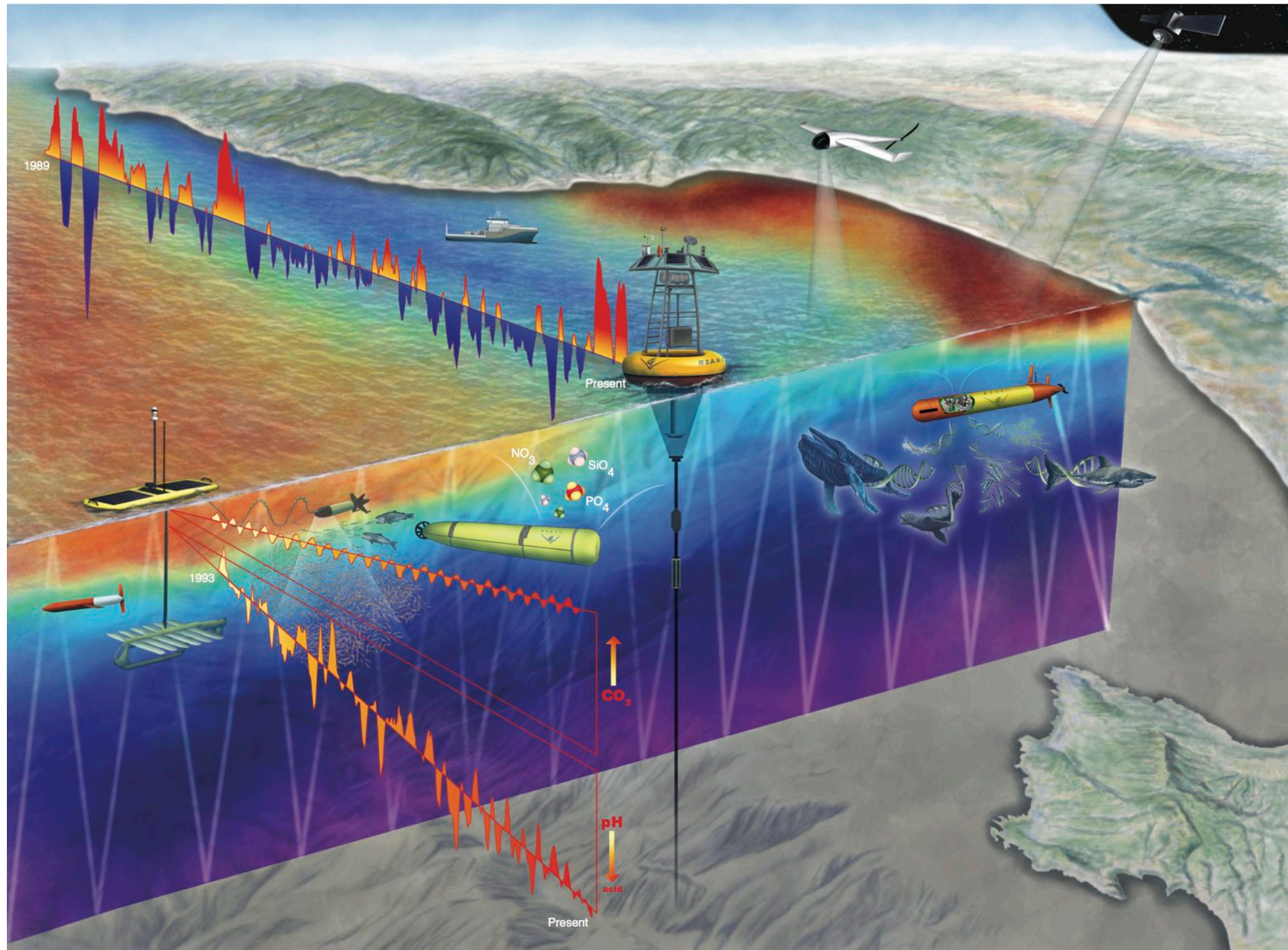
Predators care more about concentration than productivity
Are OMZ's good targets for fertilization experiments?

Seasonally upwelling (fertilization) and productivity can be out of phase



Especially important at high latitudes

The future: a new set of tools (and models) for ocean observing



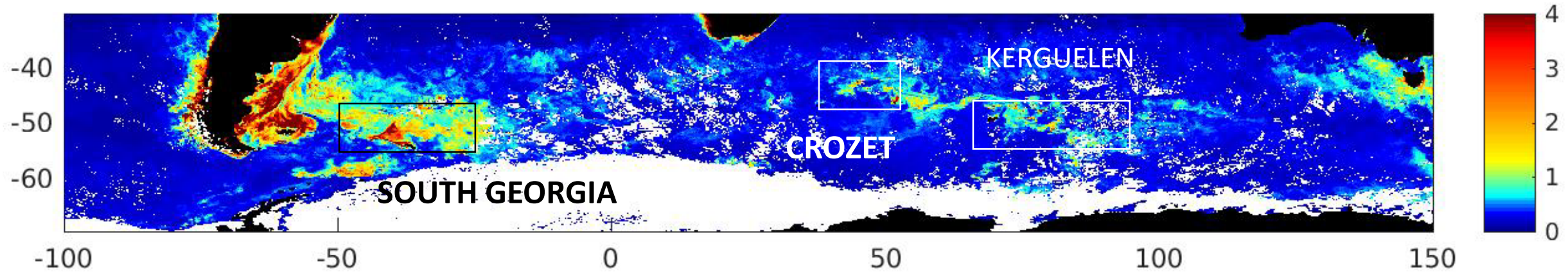
Conclusions

- Current understanding on ecological impacts is limited to results from a few short term experiments
- Ecological impacts (and CDR) are location dependent.
- Ecological impacts are linked to the initial food web
- Clear relationships between biomass/productivity and fisheries yield
- Trophic transfer enhanced when habitats are compressed
- Oxygen minimum zones may be good target regions
- The next set of experiments will capitalize on new and emerging technologies

Artificial nutrient fertilisation as a potential CDR strategy

Stephanie Henson
s.henson@noc.ac.uk

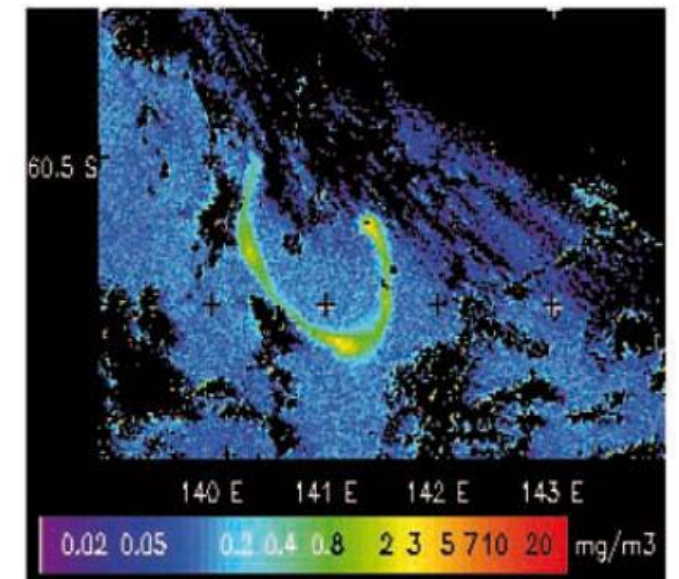
Natural & artificial iron fertilisation



Natural fertilisation occurs downstream of islands in the iron-limited Southern Ocean.

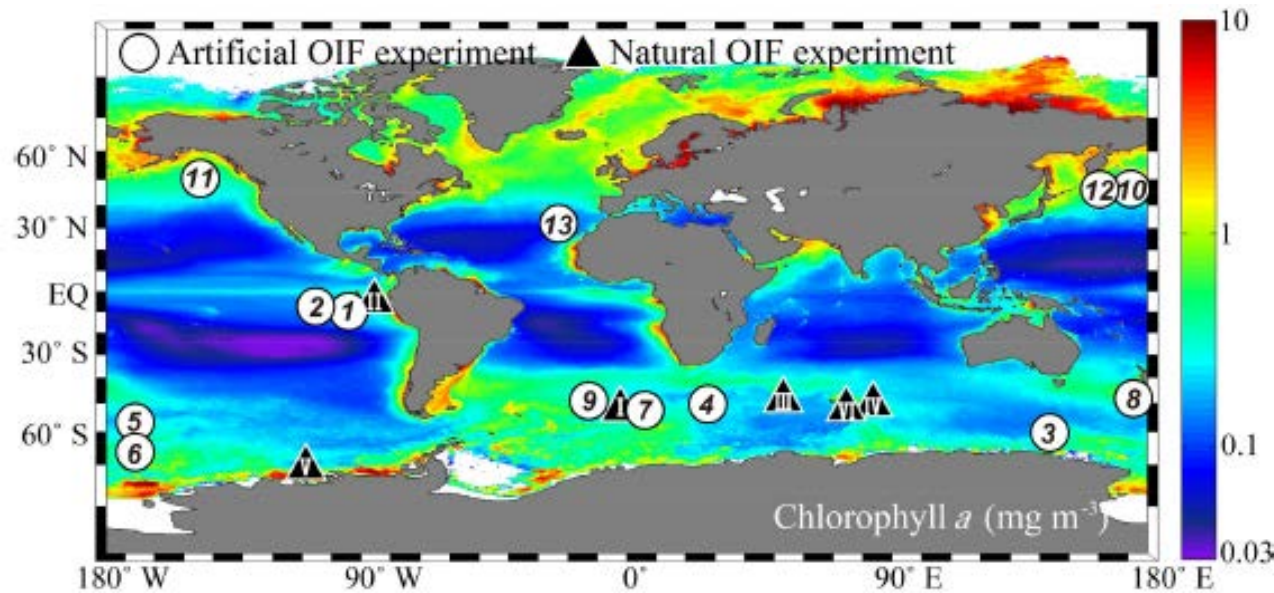
Artificial fertilisation experiments mimic the “island effect”.

Although iron fertilisation stimulates primary production, does it result in enhanced carbon sequestration?



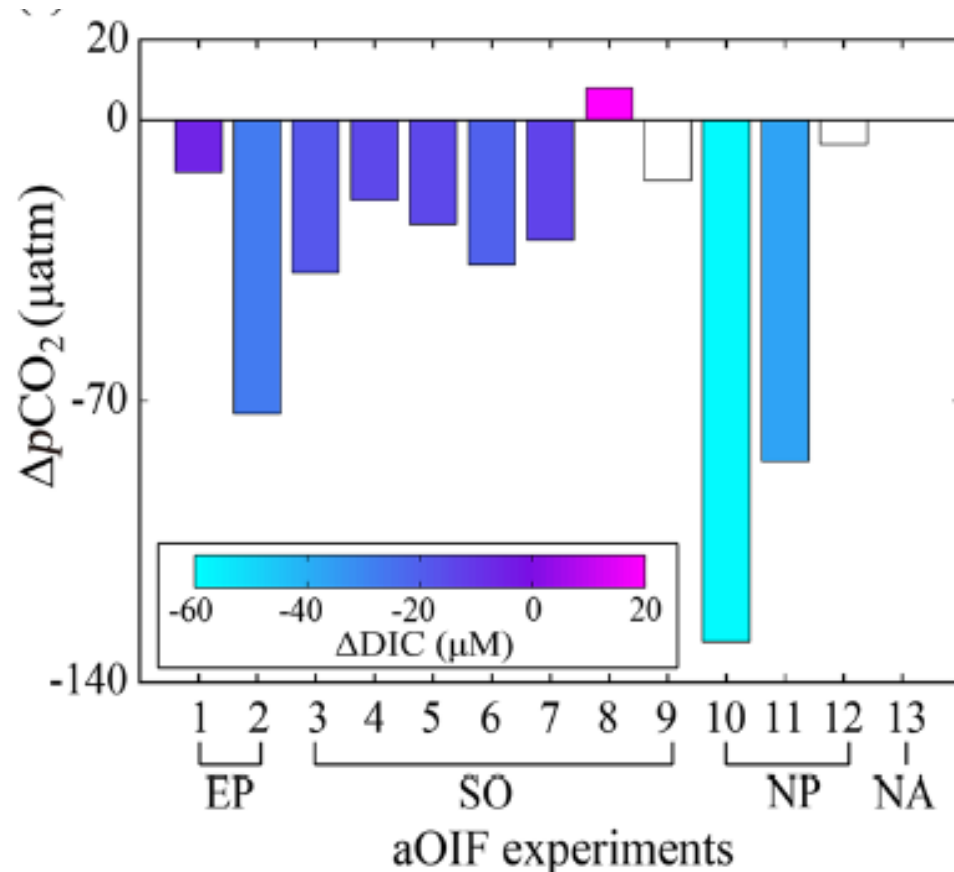
Artificial iron fertilisation

- 13 artificial fertilisation experiments have been performed to date
- They demonstrated that primary production can be significantly enhanced by the artificial addition of iron
- However, only 1 of 13 experiments showed any significant change in the amount of carbon reaching below 1000 m depth [Yoon et al., 2018]



Sequestration efficiency

- Key metric for fertilisation as a climate change mitigation effort is not CO₂ drawdown



Compilation of air-sea CO₂ difference before vs after artificial iron fertilisation

Yoon et al. (2018)

Sequestration efficiency

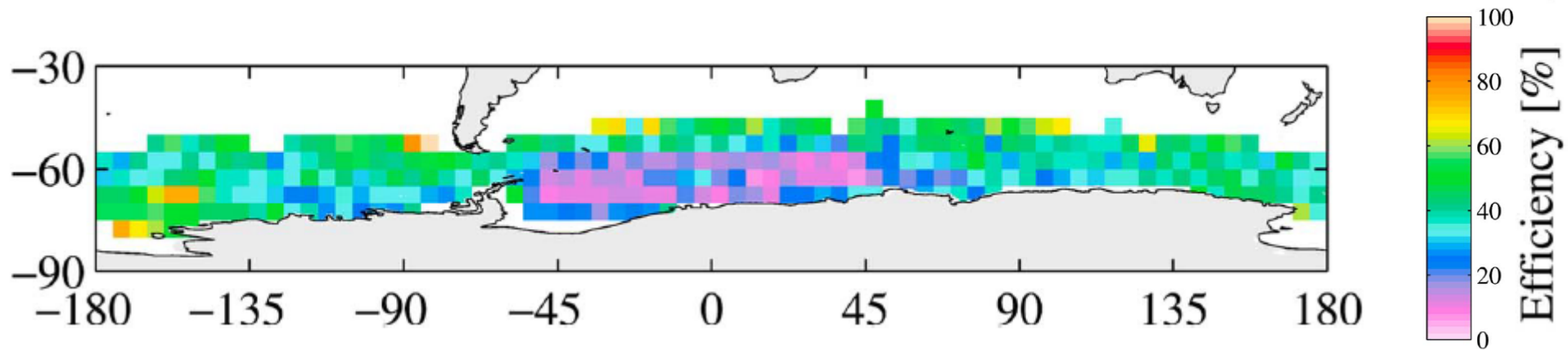
- Effectiveness of iron fertilization depends on C fixed reaching at least ~ 1000 m depth
- Can be defined by the “sequestration ratio” (C sequestered:Fe added)
- Kerguelen: **70,000 – 668,000** mol mol⁻¹ [Blain et al., 2007]
- Crozet: **8,600** mol mol⁻¹ [Pollard et al. 2009]
- Artificial iron fertilisation: **4,300** mol mol⁻¹, again noting that only 1 experiment demonstrated an increase in deep C flux [Yoon et al., 2018]

Sequestration efficiency

- Artificial iron fertilisation results in far lower sequestration efficiency than natural iron fertilisation. Why?
- Slow and continuous input of iron during natural fertilisation. Local ecosystem “primed” for iron input.
- Artificial fertilisation with large amounts of iron within a short period leads to the loss of ~ 80–95% of the added iron [Blain et al. 2009]
- Possibly, local ecosystem is unable to respond to sudden, “unexpected” input of iron

Timescales of sequestration

- Model analysis of water mass trajectories over a 100 year simulation
- For a sequestration depth of 1000 m, 66% of the carbon was re-exposed to the atmosphere in 100 years (average 37.8 years) [Robinson et al. 2014]



In situ experiments are inconclusive. What do models say?

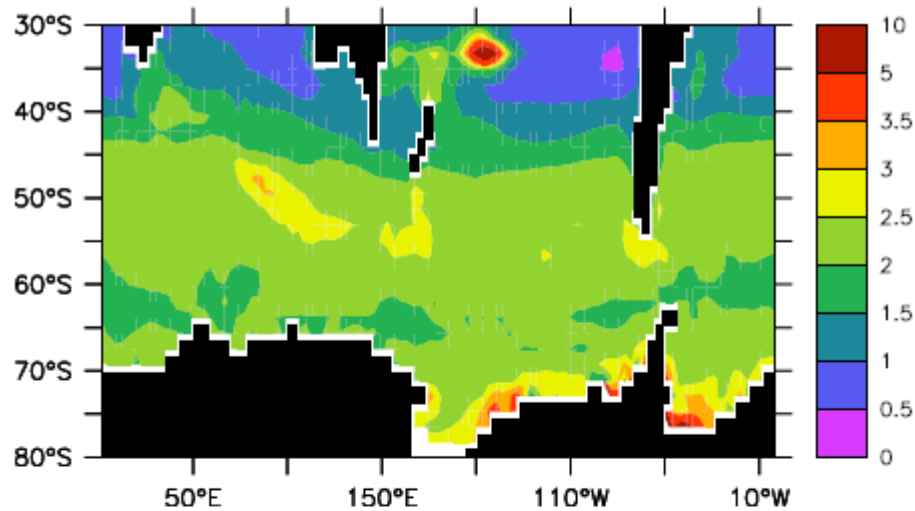


Fig. 1. Ratio of the particulate carbon export across $z=125$ m simulated by the fertilization experiment in year 2011 (first year of fertilization) and the control experiment in the same year.

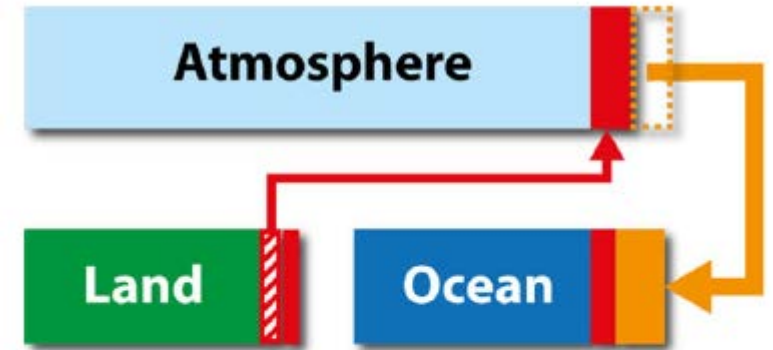
Oschlies et al. 2010
Biogeosciences; Keller et al.,
2014, Nat Comms

Carbon export enhanced 2x with
*continuous simultaneous application of
iron to entire Southern Ocean*

- Increase is largest in first year of fertilisation, but less thereafter
- Because macronutrient limitation kicks in and previously sequestered C returns to the surface

Earth system feedbacks of fertilisation

- Fertilization-induced atmospheric CO₂ drawdown is initially opposed by a net loss of carbon from land
- But subsequently countered by decreasing fertilisation-induced sequestration efficiency and increased terrestrial uptake
- Carbonate counter pump may also reduce fertilisation-induced C sequestration [Salter et al., 2014]



Keller et al., 2018

Macronutrient fertilisation

- Macronutrient fertilisation (e.g., nitrate) has also been proposed
- Up to 15% of annual global CO₂ emissions could theoretically be offset [Harrison, 2017]
- If continuous, simultaneous fertilisation of all N+P limited regions
- Also more expensive than iron fertilisation, because of the much greater quantities of nutrients required [Williamson and Turley, 2012]

Summary

- Low sequestration efficiency of additional C fixed by nutrient fertilisation, plus ocean circulation, limits the potential for long term storage of CO₂
- Comments from IPCC SROCC on ocean fertilisation as a CDR:
 - Meagre efficiency, widespread impacts on ecosystems, short-lived climatic benefits, low public and political acceptability
- “Because of the many technical, environmental and governance issues relating to marine productivity enhancement...there is low confidence that such open ocean manipulations provide a viable mitigation measure” IPCC SROCC conclusion 2019
- IPCC AR6 2021 comes to same conclusion

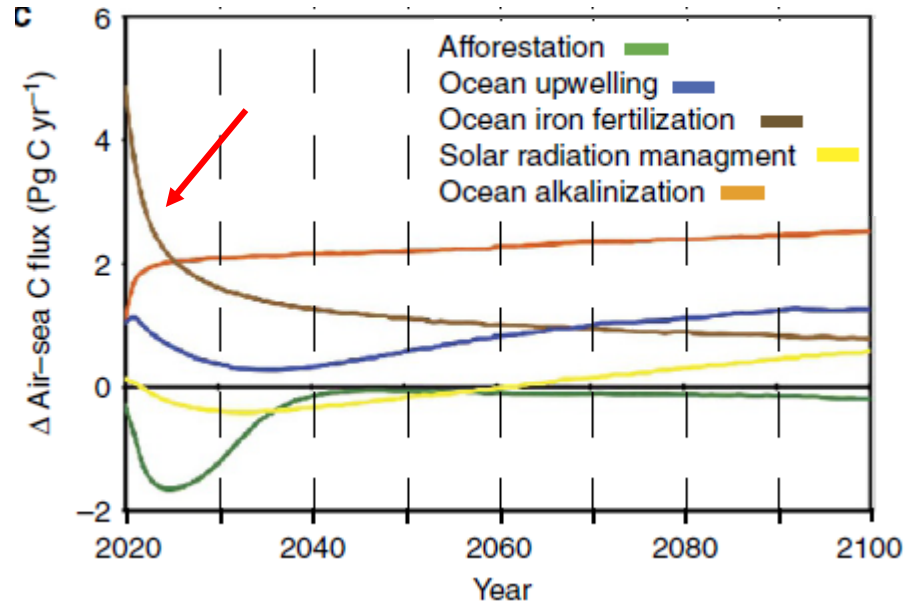
Research questions

- Understanding ecosystem impacts – mess with one part of the ecosystem, what happens to the rest?
- Quantifying Earth system feedbacks – mess with one part of the Earth's carbon sink, what happens to the rest?

References

- Blain, S., Quéguiner, B., Armand, L. *et al.* Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. *Nature* **446**, 1070–1074 (2007). <https://doi.org/10.1038/nature05700>
- Harrison, D. (2017), Global negative emissions capacity of ocean macronutrient fertilization, *Environ. Res. Lett.* **12** 035001, doi: 10.1088/1748-9326/aa5ef5
- IPCC AR5 Chapter 6 (2013) <https://www.ipcc.ch/report/ar5/wg1/>
- IPCC SROCC Chapter 5 (2019) <https://www.ipcc.ch/srocc/download-report-2/>
- IPCC AR6 Chapter 5 (to be published in 2nd half of 2021)
- Keller, David P., Elias Y. Feng, and Andreas Oschlies. 2014. “Potential Climate Engineering Effectiveness and Side Effects during a High Carbon Dioxide-Emission Scenario.” *Nature Communications* 5 (1): 3304. <https://doi.org/10.1038/ncomms4304>.
- Oschlies, A, W Koeve, W Rickels, and K Rehdanz. 2010. “Side Effects and Accounting Aspects of Hypothetical Large-Scale Southern Ocean Iron Fertilization.” *Biogeosciences* 7 (12): 4017–35. <https://doi.org/10.5194/bg-7-4017-2010>.
- Pollard, R., Salter, I., Sanders, R. *et al.* Southern Ocean deep-water carbon export enhanced by natural iron fertilization. *Nature* **457**, 577–580 (2009). <https://doi.org/10.1038/nature07716>
- Robinson, J., Popova, E. E., Yool, A., Srokosz, M., Lampitt, R. S., and Blundell, J. R. (2014), How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean, *Geophys. Res. Lett.*, 41, 2489– 2495, doi:[10.1002/2013GL058799](https://doi.org/10.1002/2013GL058799)
- Salter, Ian, Ralf Schiebel, Patrizia Ziveri, Aurore Movellan, Richard Lampitt, and George A Wolff. 2014. “Carbonate Counter Pump Stimulated by Natural Iron Fertilization in the Polar Frontal Zone.” *Nature Geoscience* 7 (12): 885–89. <https://doi.org/10.1038/ngeo2285>.
- Williamson, P. and C. Turley (2012), Ocean acidification in a geoengineering context, *Phil. Trans. A*, 370, 1974, <https://doi.org/10.1098/rsta.2012.0167>
- Yoon, Joo-Eun, Kyu-Cheul Yoo, Alison M. Macdonald, Ho-Il Yoon, Ki-Tae Park, Eun Jin Yang, Hyun-Cheol Kim, et al. 2018. “Reviews and Syntheses: Ocean Iron Fertilization Experiments – Past, Present, and Future Looking to a Future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) Project.” *Biogeosciences* 15 (19): 5847–89. <https://doi.org/10.5194/bg-15-5847-2018>.

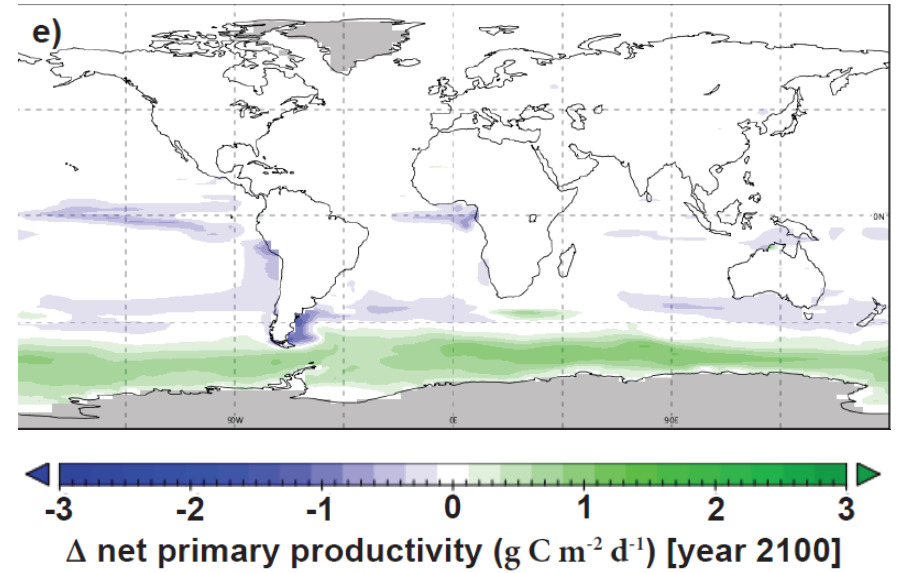
Potential CO2 drawdown effect



- Initial ocean uptake of CO2 of 2-4PgC yr-1 for the first decade, then ~ 0.5 PgC yr-1 thereafter with *continuous application of iron to entire Southern Ocean*
- Up to 1/3 of carbon returned to surface after 100 years if fertilisation is terminated [*Robinson et al., 2014*]

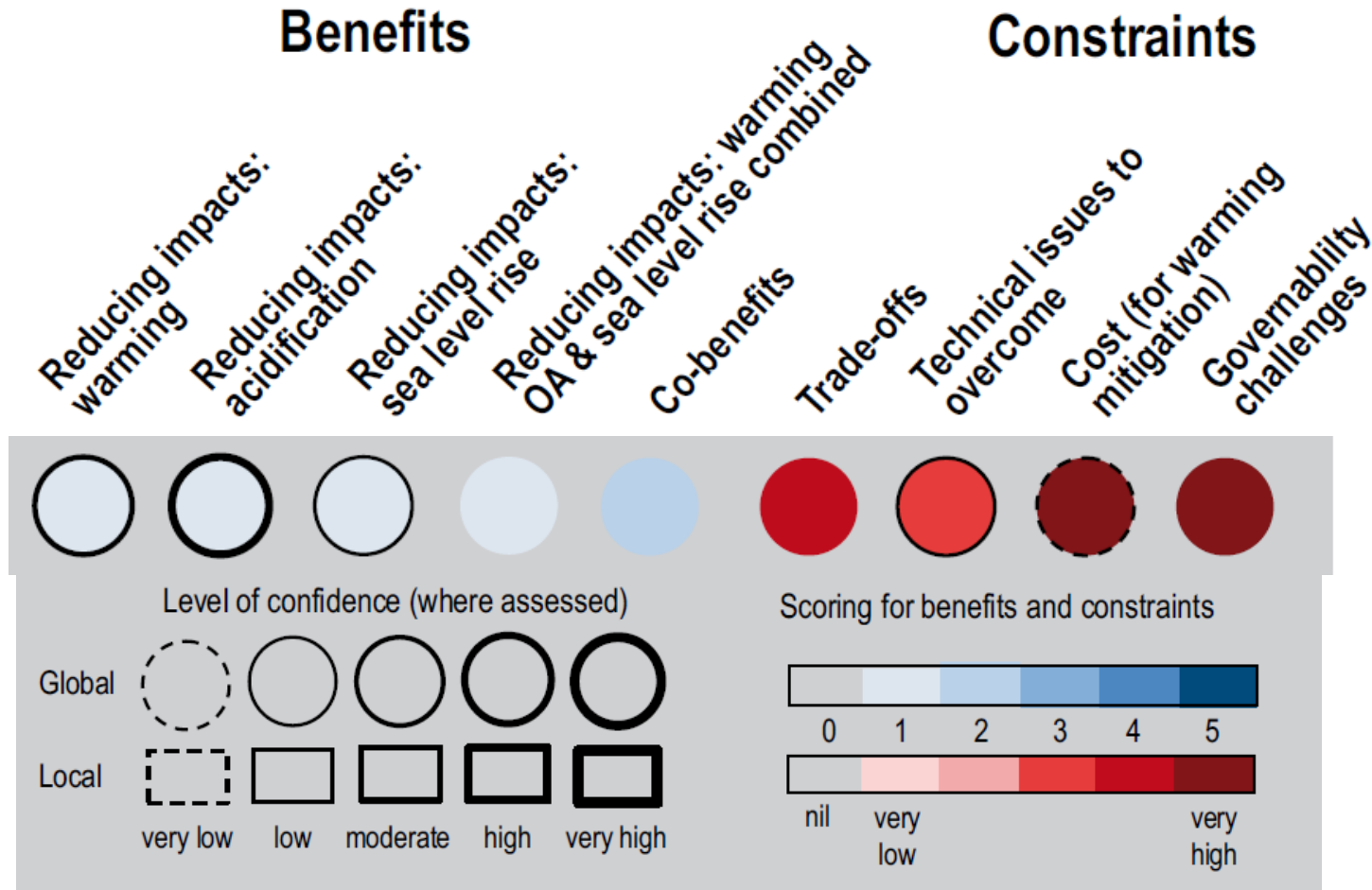
Side effects of fertilisation

- Decreased productivity in unfertilised regions
- Enhanced ocean acidification
- Increased production of N₂O and CH₄
- Increased suboxic zone extent in fertilised areas
& shrinkage of suboxic zones outside fertilised areas
- Perturbation to marine ecosystems via reorganisation of community structure, including possibly toxic algal blooms
- (Oschlies, 2009; Keller et al., 2014; Jin and Gruber, 2003; Lampitt et al., 2008; Oschlies et al., 2010; Williamson et al., 2012; Cao and Caldeira, 2010; Oschlies, 2010)



Keller et al. (2014)

Trade-offs and constraints



- Maximum potential effectiveness by 2100 in reducing climatic drivers, assuming full theoretical implementation: very low
- Co-benefits: low
- Technological feasibility: moderate constraint
- Cost-effectiveness: very strong constraint
- Governance issues: very strong constraint

Public perception & governance

- Ocean fertilisation is currently banned under the London Protocol (except for research purposes)
- Additional governance constraints in Southern Ocean

Role of modeling in assessing CDR by iron fertilization

Prof. Fei CHAI
University of Maine

- **Past (15-20 years ago) global model** estimates and some issues
- **Local and regional** physical and biogeochemical conditions are important for iron fertilization experiments and CDR effectiveness
- **Mesoscale processes** (eddies, fronts, vertical exchange, etc.), timing and duration for fertilization experiments
- **Natural and artificial** iron fertilization in the equatorial and North Pacific
- **Suggestions** for future experiments and high-resolution modeling

The Global Biosphere

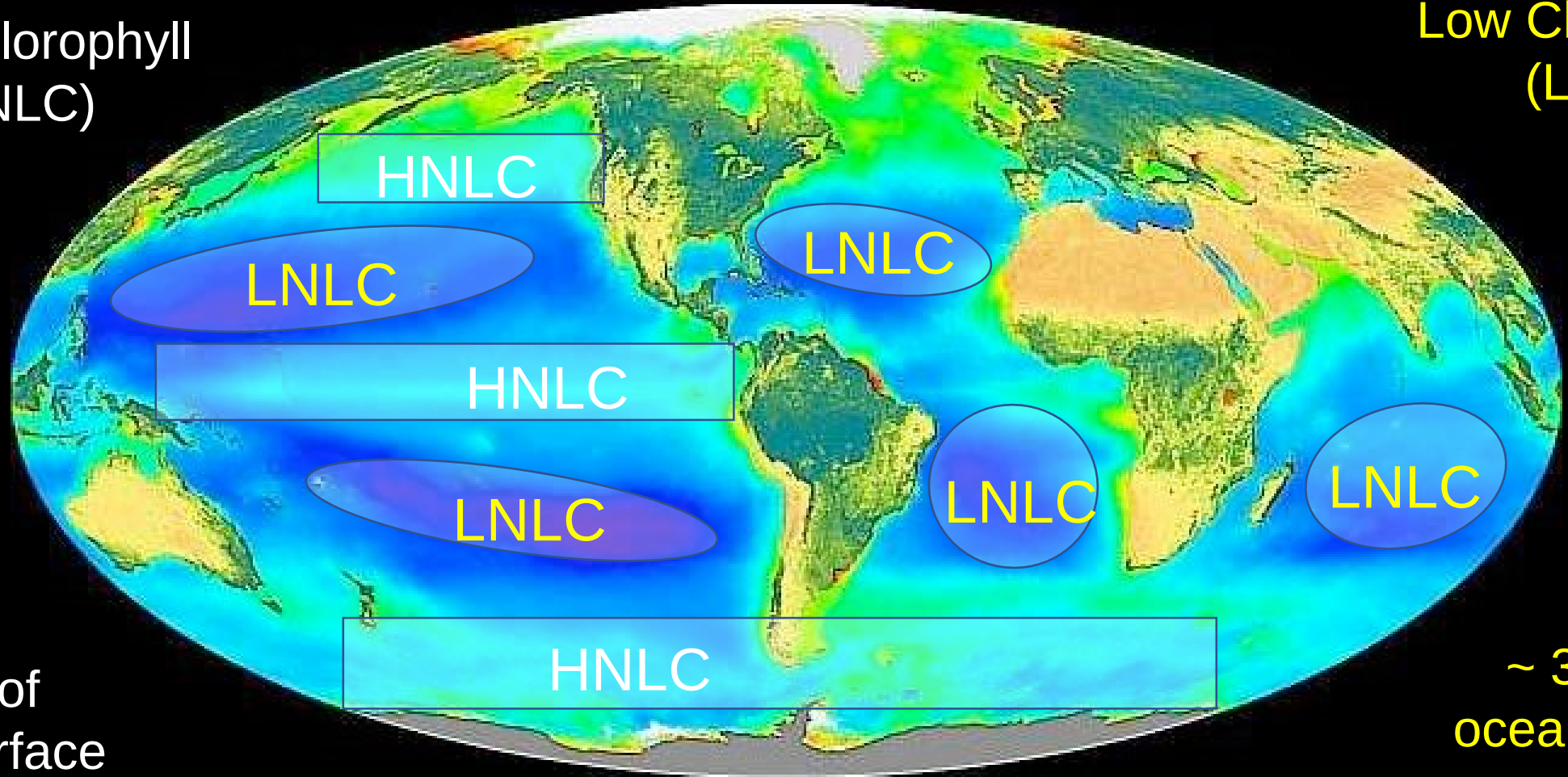
Ocean Colors: SeaWiFS

High Nutrient
Low Chlorophyll
(HNLC)

Low Nutrient
Low Chlorophyll
(LNLC)

Fe
limited

N & P
limited



~ 30% of
ocean surface

~ 30% of
ocean surface

217 million square kilometers (ocean surface: 361×0.6)
(land surface: 149 million square kilometers)

Past global model estimates of CDR for HNLC regions

Globalizing results from ocean in situ iron fertilization studies

O. Aumont¹ and L. Bopp²

Received 22 July 2005; revised 19 January 2006; accepted 10 February 2006; published 14 June 2006.

Feasibility of ocean fertilization and its impact on future atmospheric CO₂ levels

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D. Archer

Geophysical Sciences, University of Chicago, Illinois, USA

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Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production

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Controls on ocean productivity and air-sea carbon flux: An adjoint model sensitivity study

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Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization

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Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO₂ and ocean chemistry

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Efficiency of small scale carbon mitigation by patch iron fertilization

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Past global model estimates of CDR for HNLC regions

Over 100 years period:

Global cumulative ocean carbon uptake (air-sea flux)
due to iron fertilization is 20 to 200 GtC

0.2 to 2 GtC/year

Atmosphere CO₂ reduction is about 10 to 100 ppm

0.1 to 1 ppm/year

Ratio of cumulative air-sea CO₂ flux to
export production (at ~100m) due to iron fertilization is

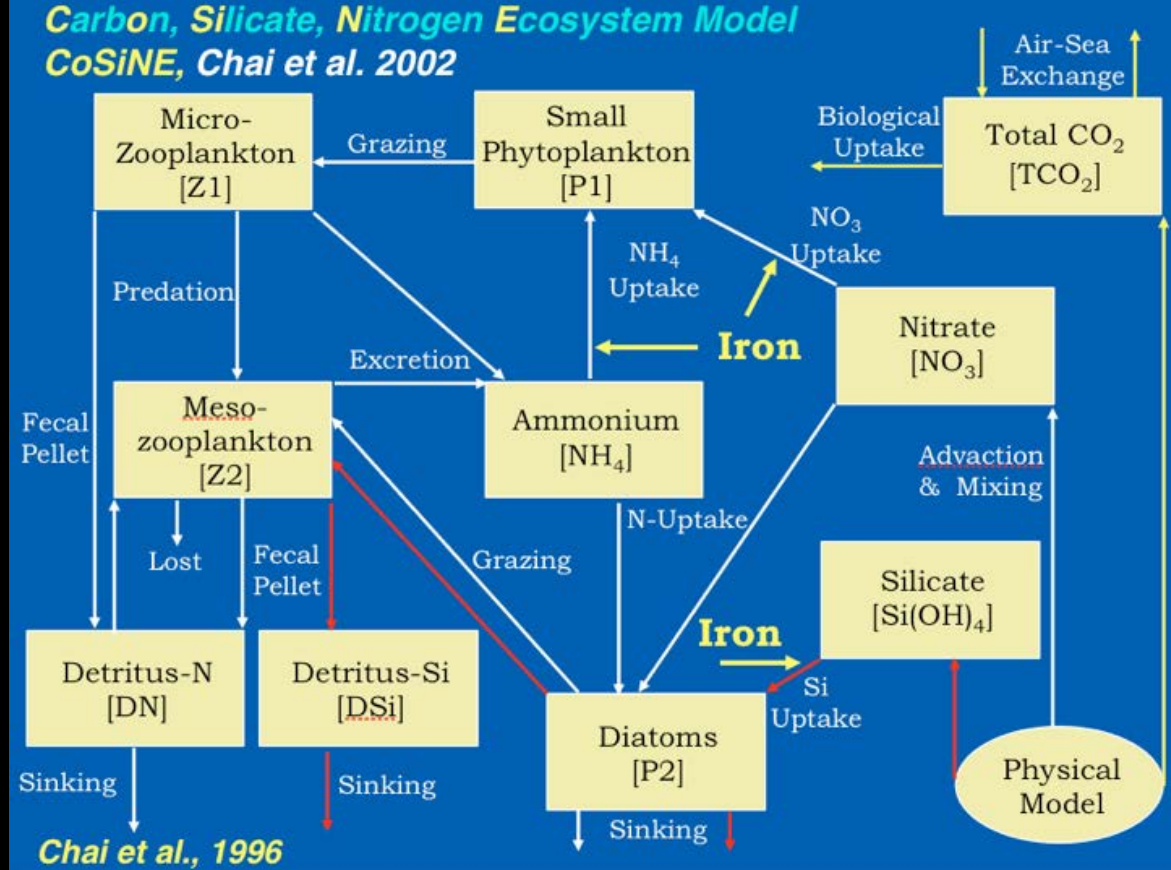
0.1 to 0.5

The efficiency of fertilization for CDR decreases as the
duration increases (due to respiration and other limiting factors)

Some issues with previous global model estimates

- Early version of global ocean general circulation models (GCMs) with coarse resolution (100 km)
- Inconsistency among models and often poor performance for the Southern Ocean
- Different designs and approaches to conduct model iron fertilization experiments
 - ✓ Upper ocean nutrient restoring for different regions and time scaling issues
 - ✓ Increase phytoplankton growth rates to release iron limitation
 - ✓ Adding iron to the upper ocean (~50 to 100m)
 - ✓ Large range of C:Fe ratio (10,000 to 100,000)
 - ✓ Different fertilization periods and areas: one fertilization per year for the Southern Ocean, continue fertilization for the Equatorial Pacific, for 1, 10, 50, and 100 years. Some selected areas with different patch sizes or the entire Southern Ocean, etc.
- Using different atmospheric CO₂ values (pre-industrial, current condition, or future RCPs)
- Responses of non-fertilized areas are very different among models and approaches, mainly due to nutrient and carbon transport processes, and downstream compensation effects

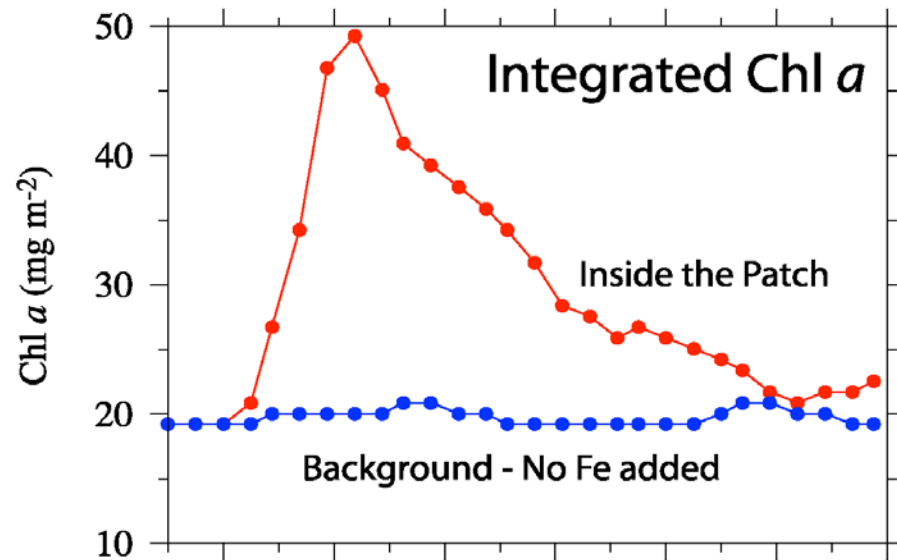
Regional Ocean Model System (ROMS) for Pacific Ocean 10-km, 1991 to 2020



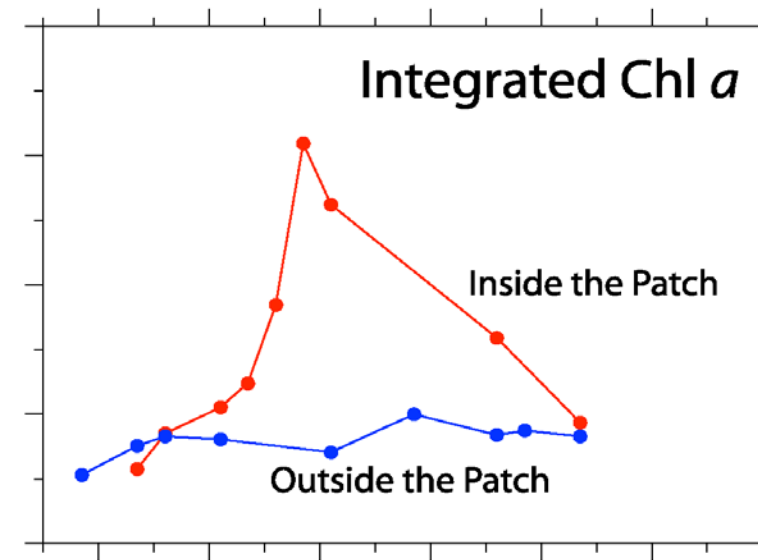
Carbon, Silicate, Nitrogen Ecosystem Model (CoSiNE)

(Chai et al., 2002, 2003, 2007, 2009; Fujii and Chai, 2007; Liu and Chai, 2009; Xiu and Chai, 2011, Palacz et al., 2011, Xu et al., 2013, Xiu and Chai, 2013, 2014, Guo et al., 2014; 2015; Zhou et al., 2017; Liu et al., 2018; Xiu and Chai et al., 2018; Zhou et al., 2018; 2020, Lin et al., 2020, Guo et al., 2020)

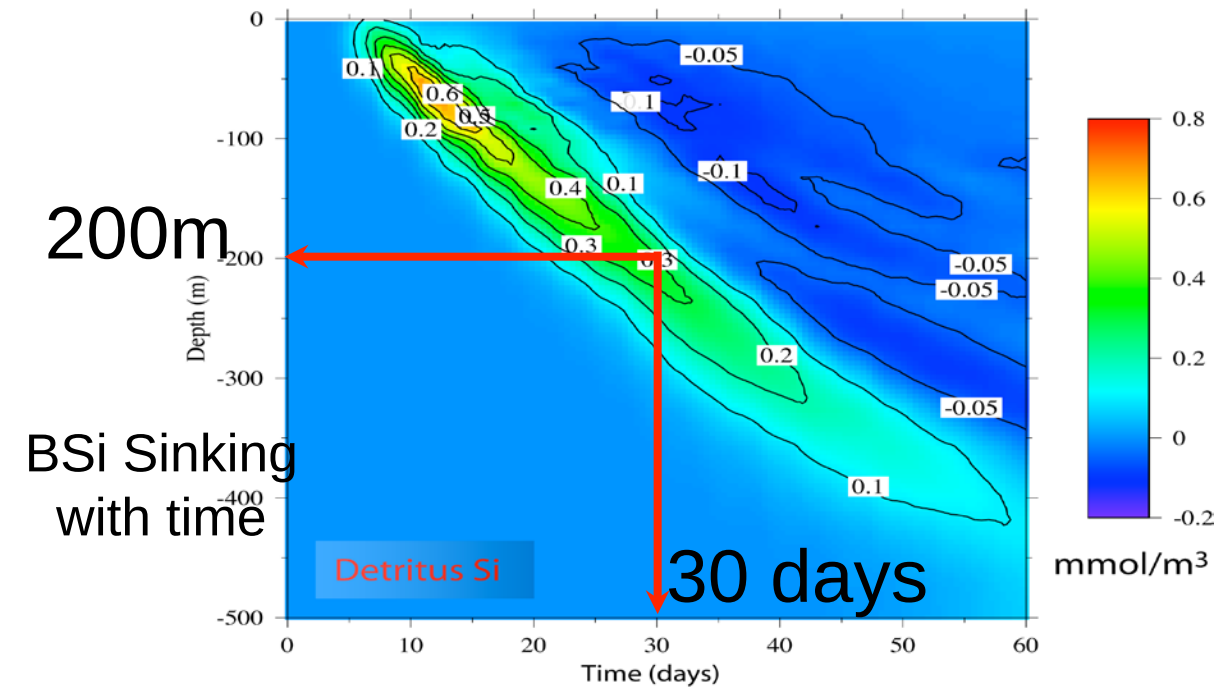
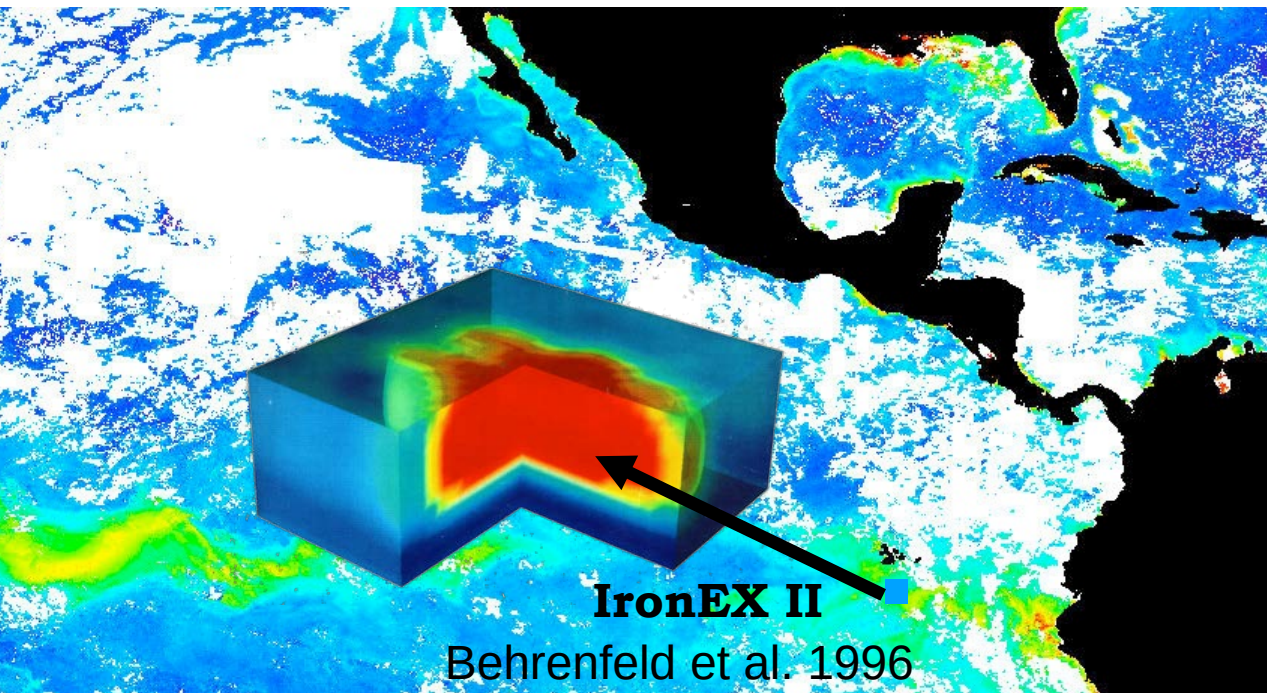
Modeled Fe Fertilization



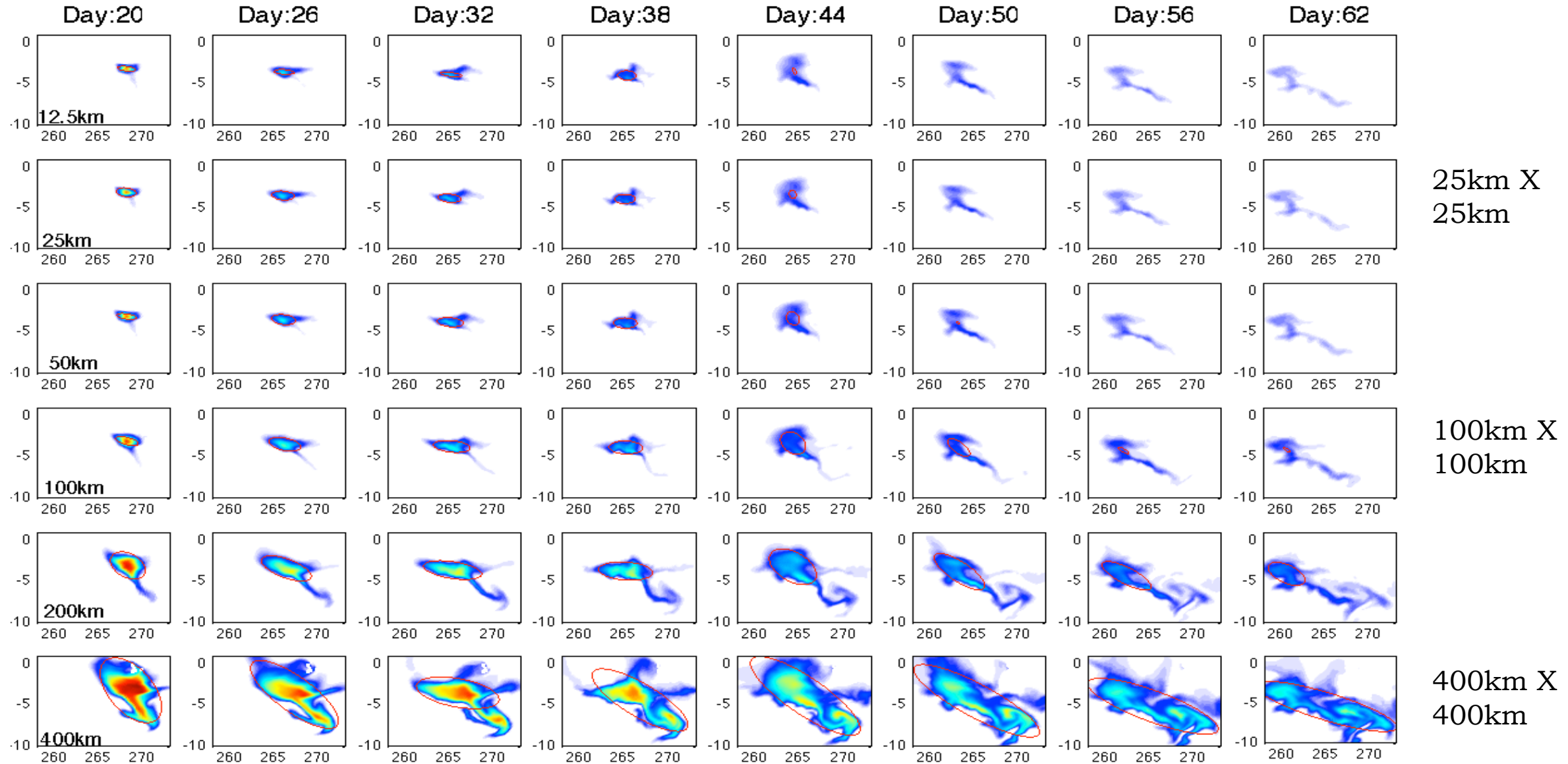
IronEX II Results



Chai et al.,
2007, GBC



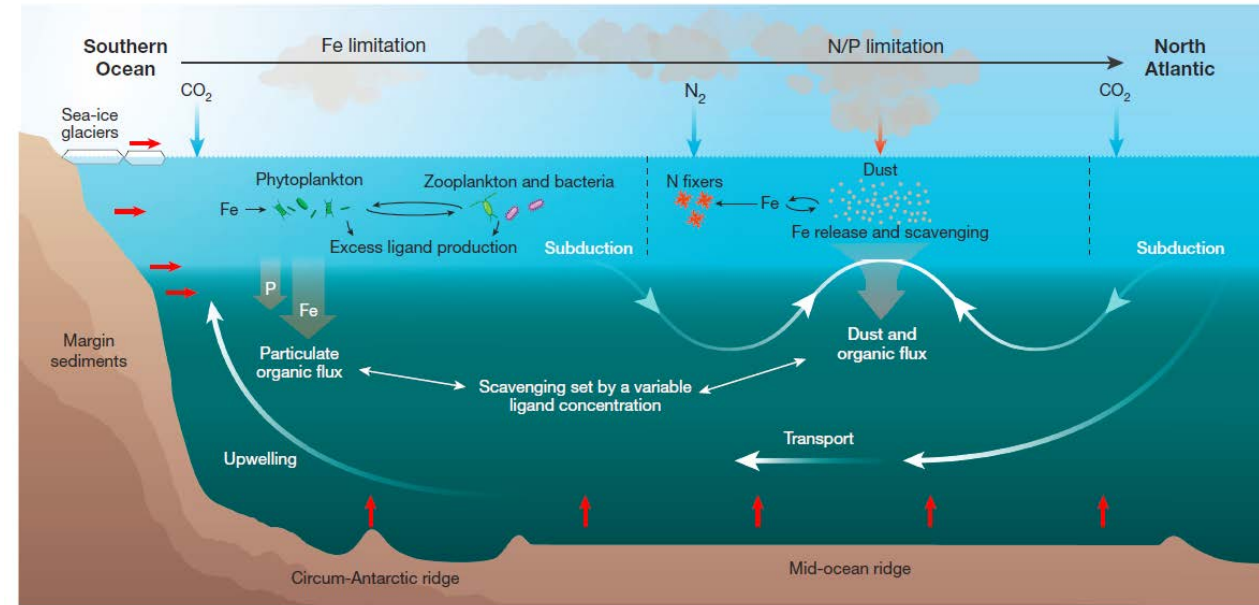
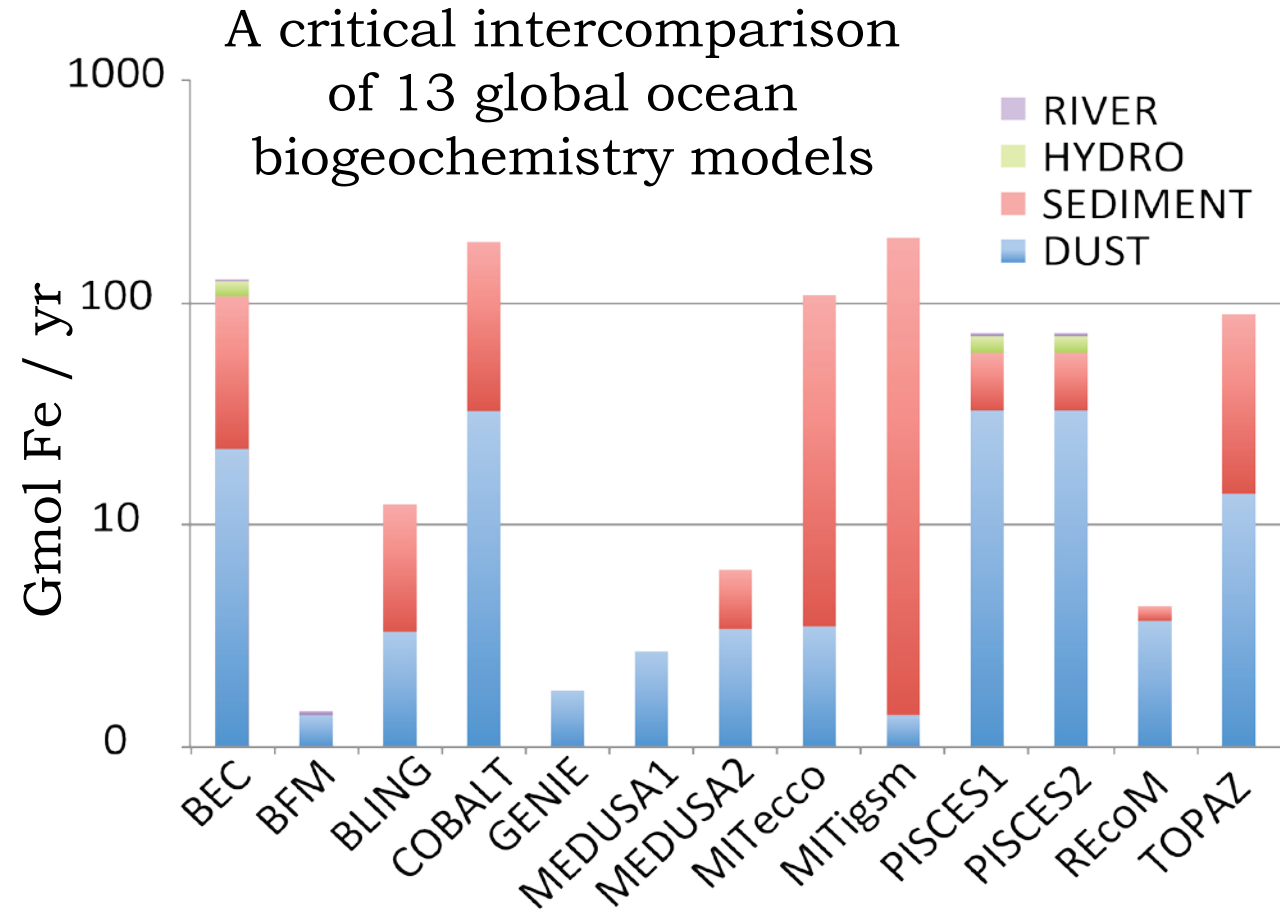
Size of fertilization patch matters



Ocea

200km)
nds

Fe biogeochemical cycling and natural sources of Fe in different global models

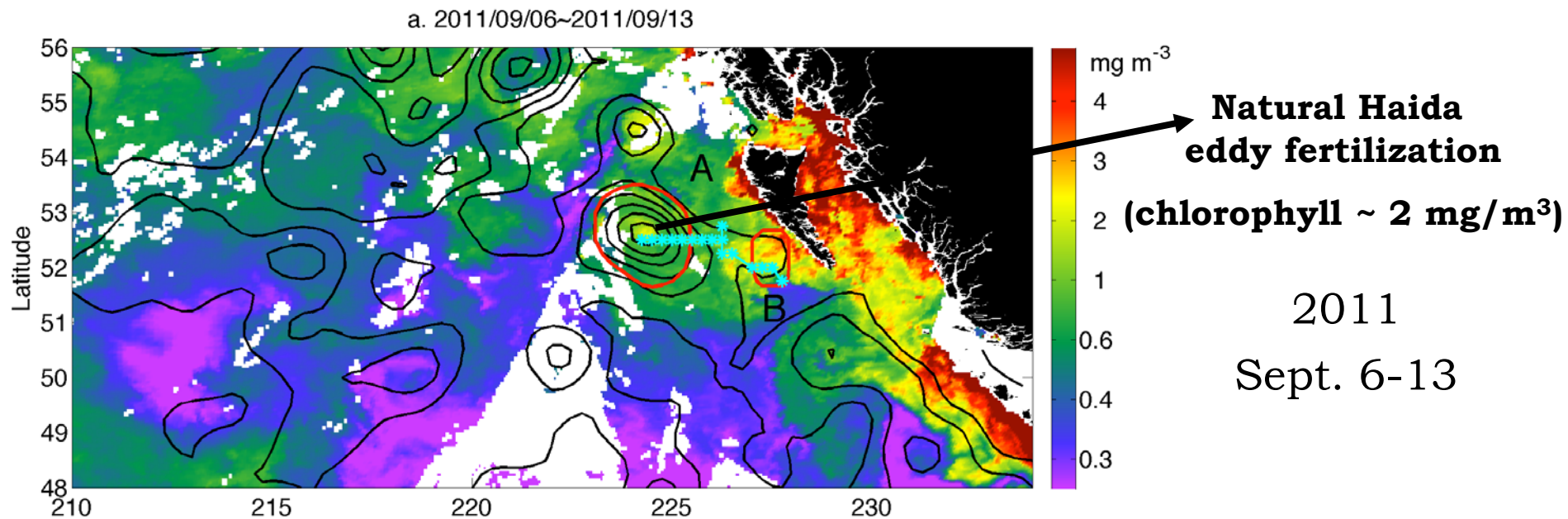


Tagliabue et al., 2017, Nature

FeMIP

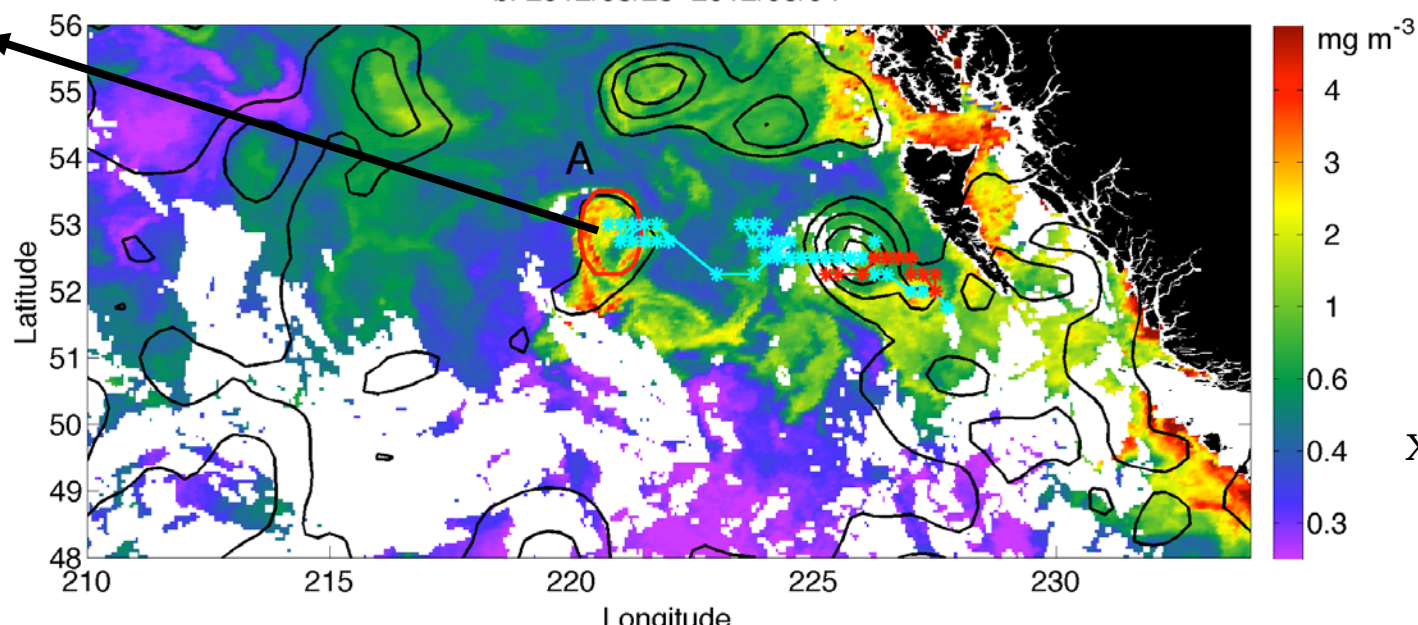
Tagliabue et al.
2016, GBC

Enormous inter-model variability in the total Fe input. Even “well known” sources are very variable Inter-model mean = 67 ± 67 Gmol Fe /year



MODIS chlorophyll

b. 2012/08/28~2012/09/04



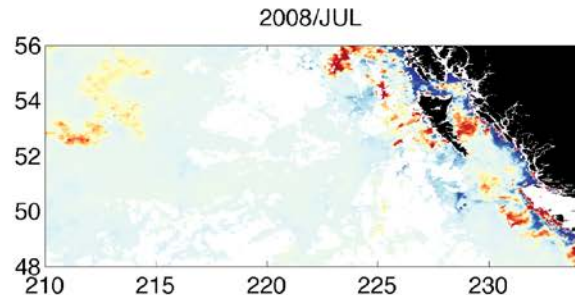
**Haida eddy +
Artificial Fe fertilization**
(chlorophyll ~ 5 mg/m³)

2012
Aug. 28 - Sept. 4

Xiu, Thomas, Chai, 2014
Remote Sensing of
the Environment

2008

July



A factor of
3 increase

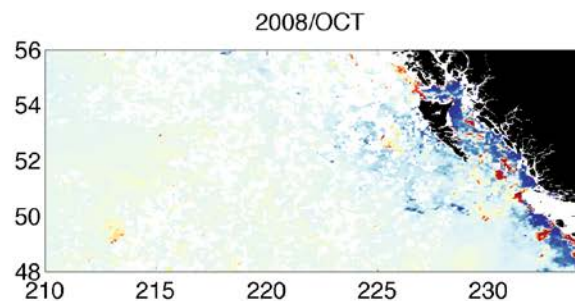
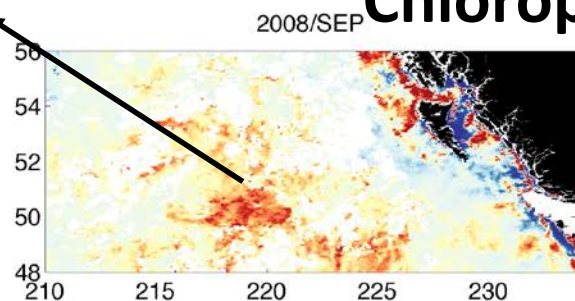
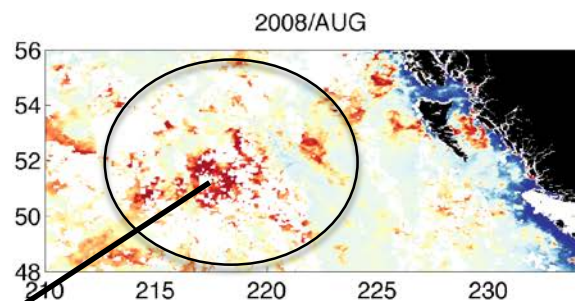
August

800km X 800km

Volcanic
ash induced

September

October



2008/JUL

2008/AUG

2008/SEP

2008/OCT

Chlorophyll Anomaly

2012/JUL

2012/AUG

2012/SEP

2012/OCT

2012

July

A factor of
10 increase

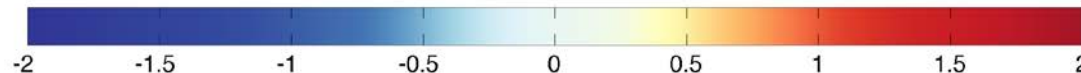
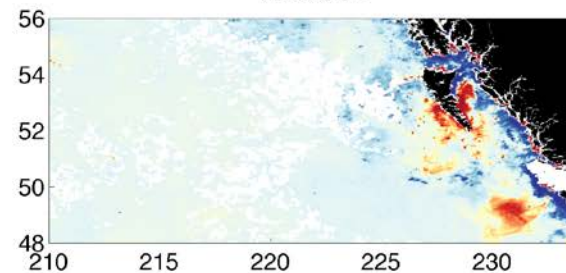
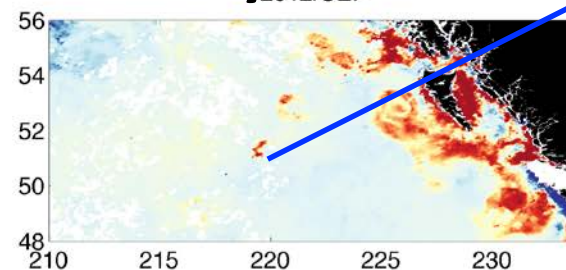
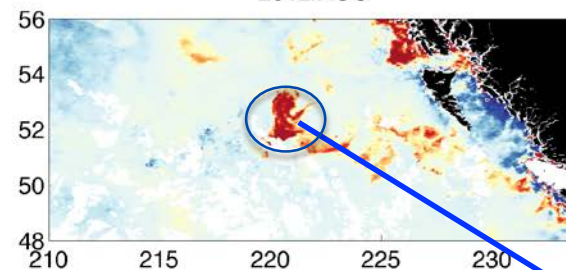
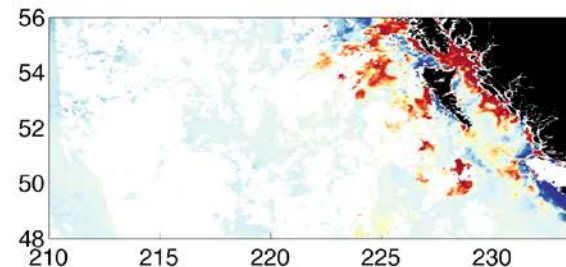
August

100km X 100km

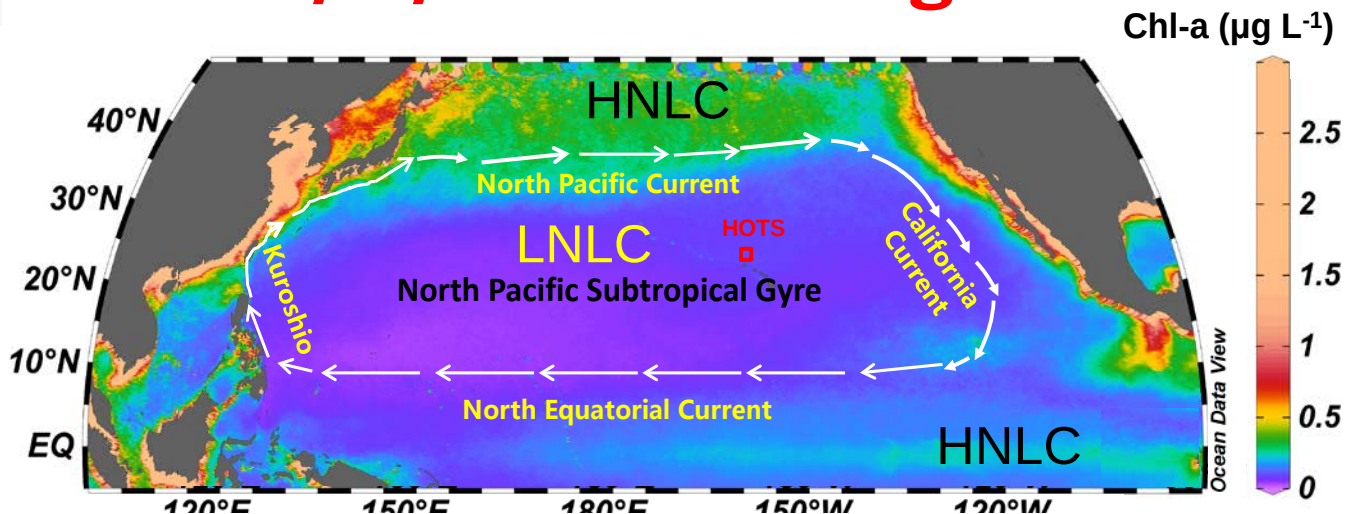
Artificial iron
fertilization

September

October



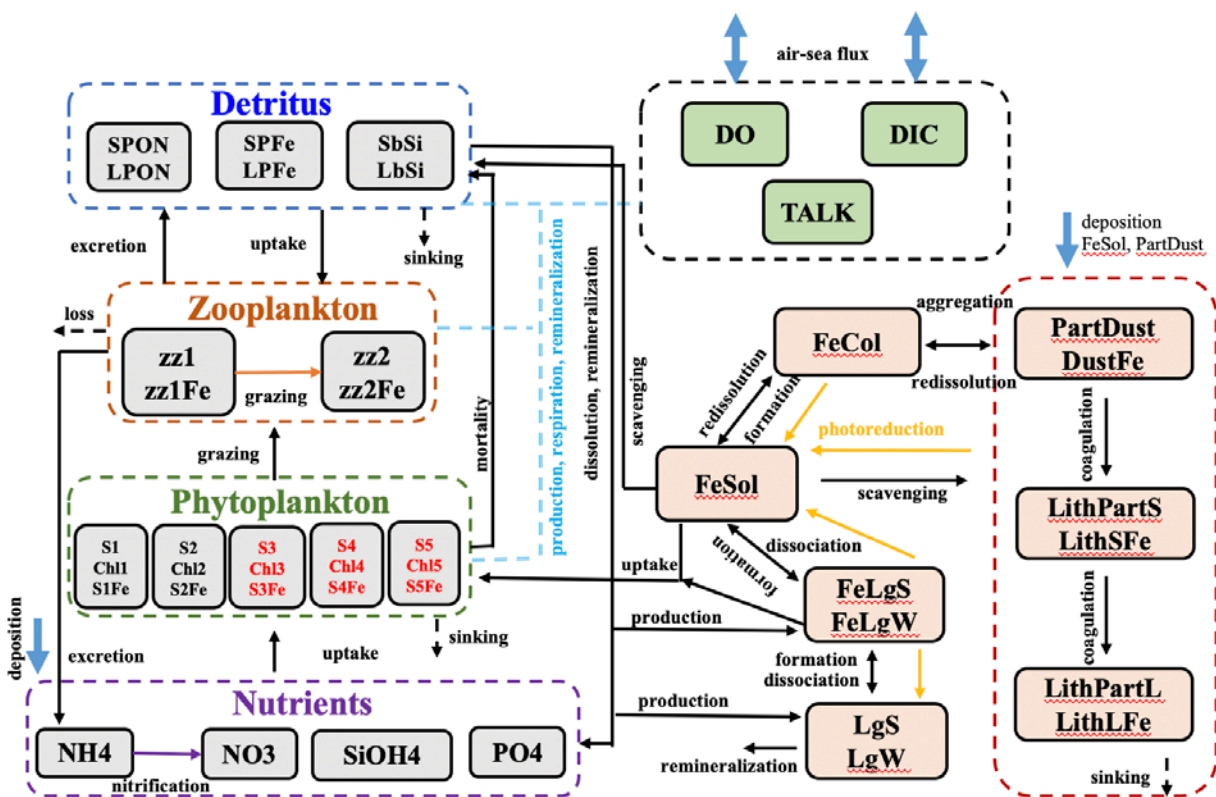
Pacific Ocean and NPSG : Fe/N/P limited regions



Collaboration with Minhan Dai at XMU
Peng Xiu at SCSIO, Mark Wells at UMaine

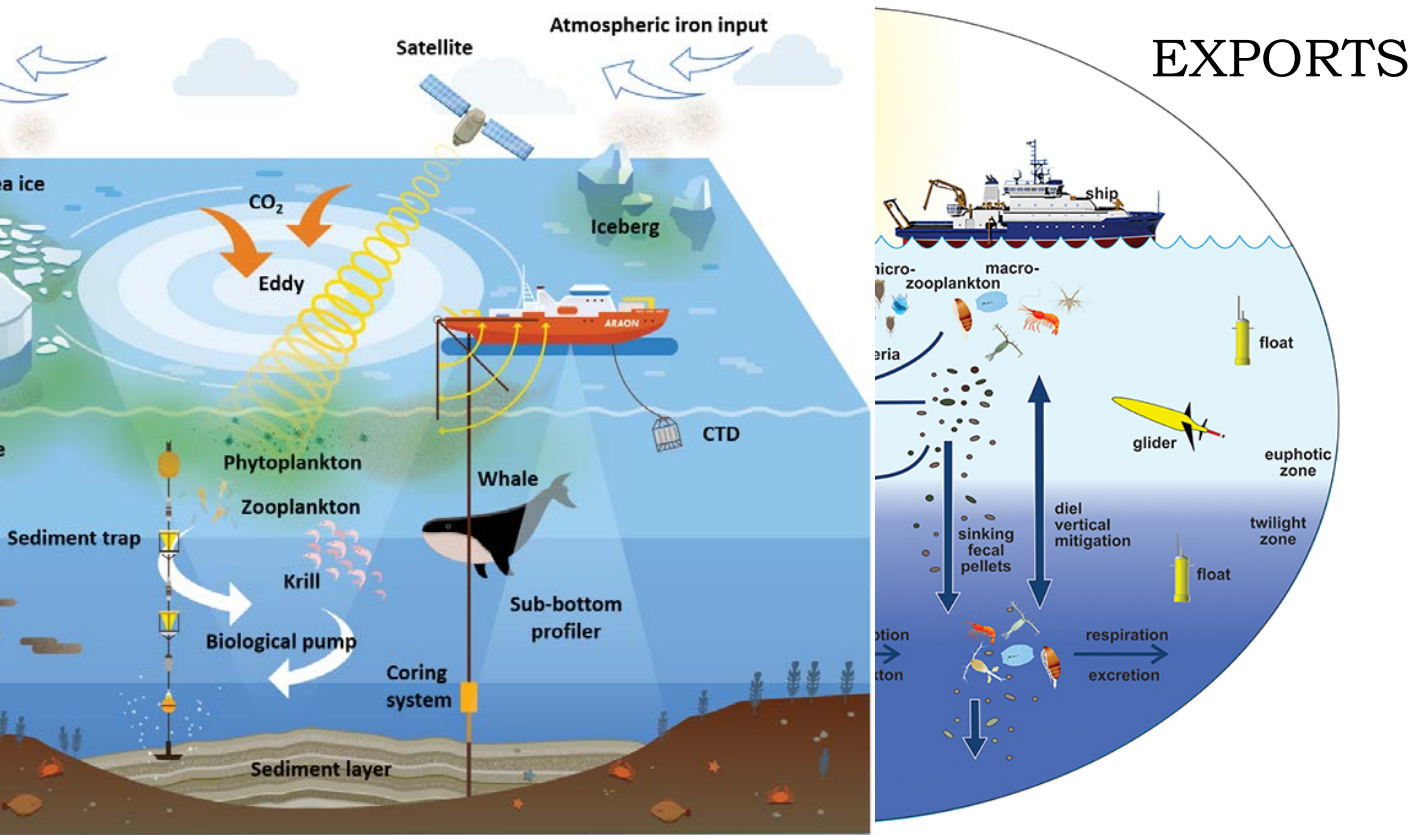
High Resolution (10km & 60 layers) ROMS-CoSiNE-Fe

- Resolve mesoscale eddies
- Seasonal cycle and ENSO dynamics
- Detailed Fe cycle and N-fixation
- Conducting +Fe, and +Fe+P model experiments



Reviews and syntheses: Ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project

Yoon et al., Biogeosciences, 2018



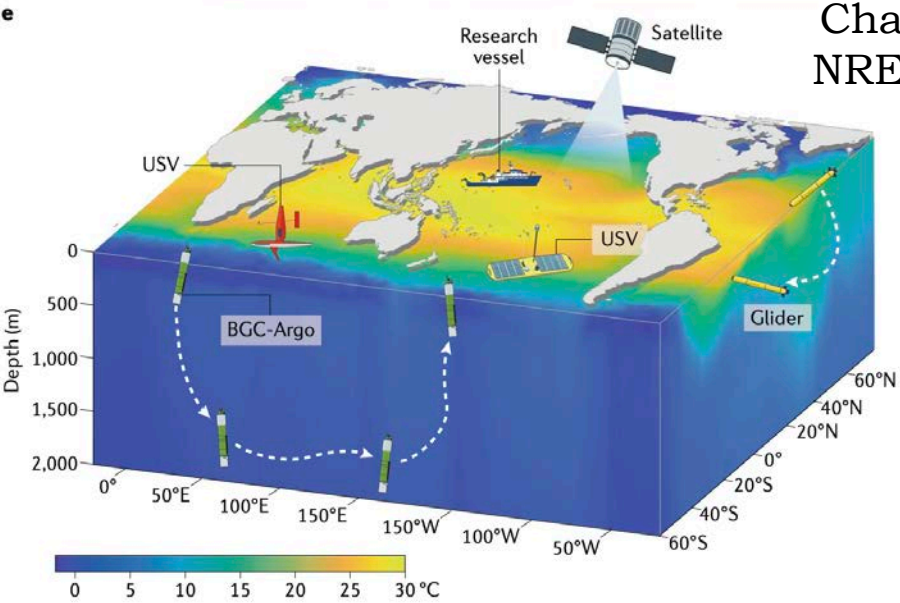
High resolution 3D
physical-biogeochemical
model & data assimilation

Fertilization experiment
design & implementation
real-time adaptive sampling

Field observations &
autonomous continuing
data collection



Chai et al.,
NREE, 2020



BREAK

We will resume at 1:45 pm EST