The potential for Low Nutrient Low Chlorophyll Ocean Iron Fertilization (LNLC-OIF)

Seth John, USC

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Supported by the Marine Biomass Regeneration Project
and the Thornton Family Foundations

Outline

1. A natural Fe addition to the South Pacific
2. The carbon sequestration potential of LNLC-OIF
3. Flexibility of ocean Redfield ratios
4. Towards an *in situ* field test of LNLC-OIF

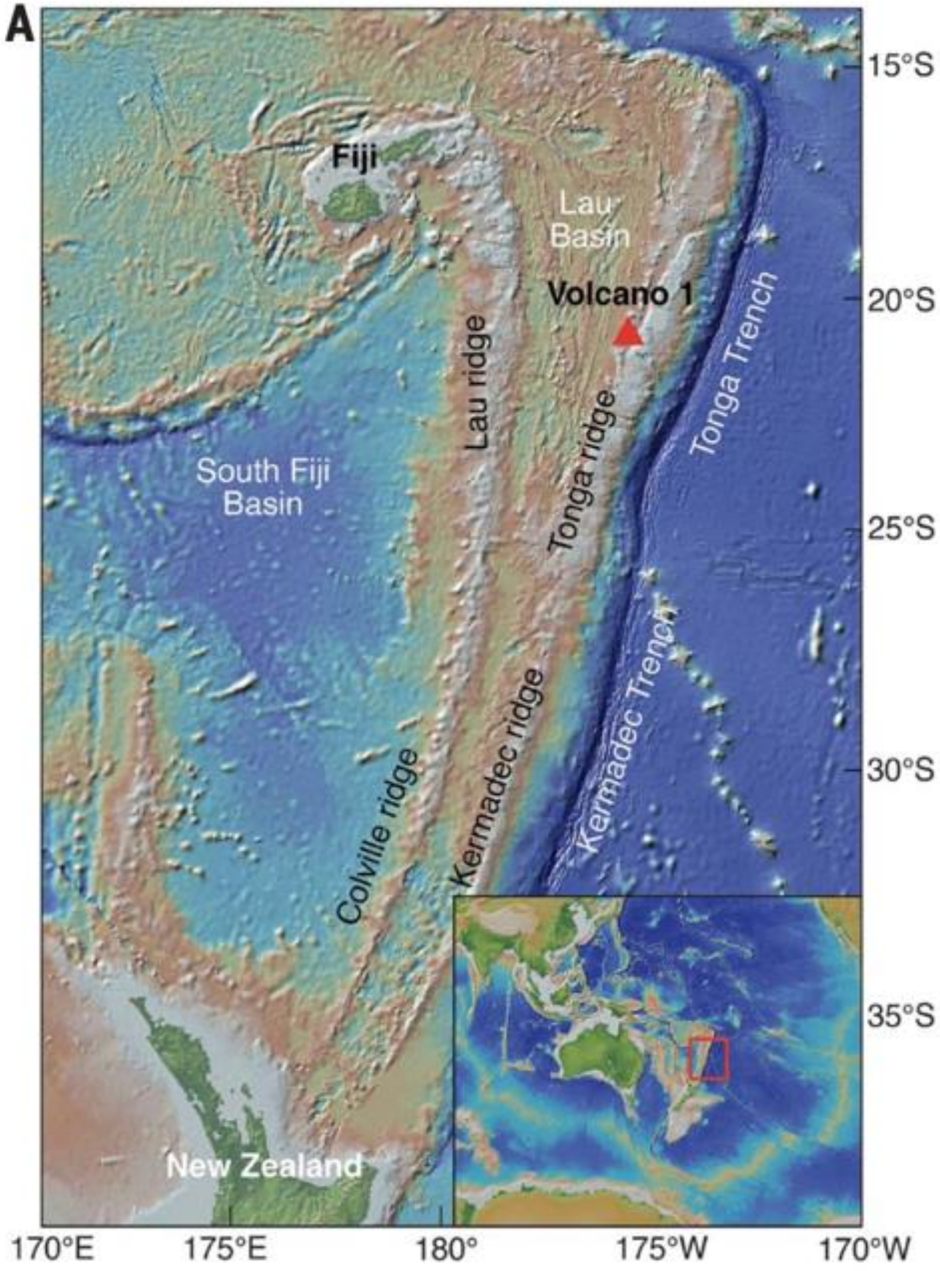
A natural Fe fertilization experiment in the South Pacific

RESEARCH ARTICLE

OCEAN NUTRIENTS

Natural iron fertilization by shallow hydrothermal sources fuels diazotroph blooms in the ocean

Sophie Bonnet[1*], Cécile Guieu[2*], Vincent Taillandier[2], Cédric Boulart[3], Pascale Bouruet-Aubertot[4], Frédéric Gazeau[2], Carla Scalabrin[5], Matthieu Bressac[2], Angela N. Knapp[6], Yannis Cuypers[4], David González-Santana[7,8], Heather J. Forrer[6], Jean-Michel Grisoni[9], Olivier Grosso[1], Jérémie Habasque[7], Mercedes Jardin-Camps[1], Nathalie Leblond[9], Frédéric A. C. Le Moigne[1,7], Anne Lebourges-Dhaussy[7], Caroline Lory[1], Sandra Nunige[1], Elvira Pulido-Villena[1], Andrea L. Rizzo[10,11], Géraldine Sarthou[7], Chloé Tilliette[2]

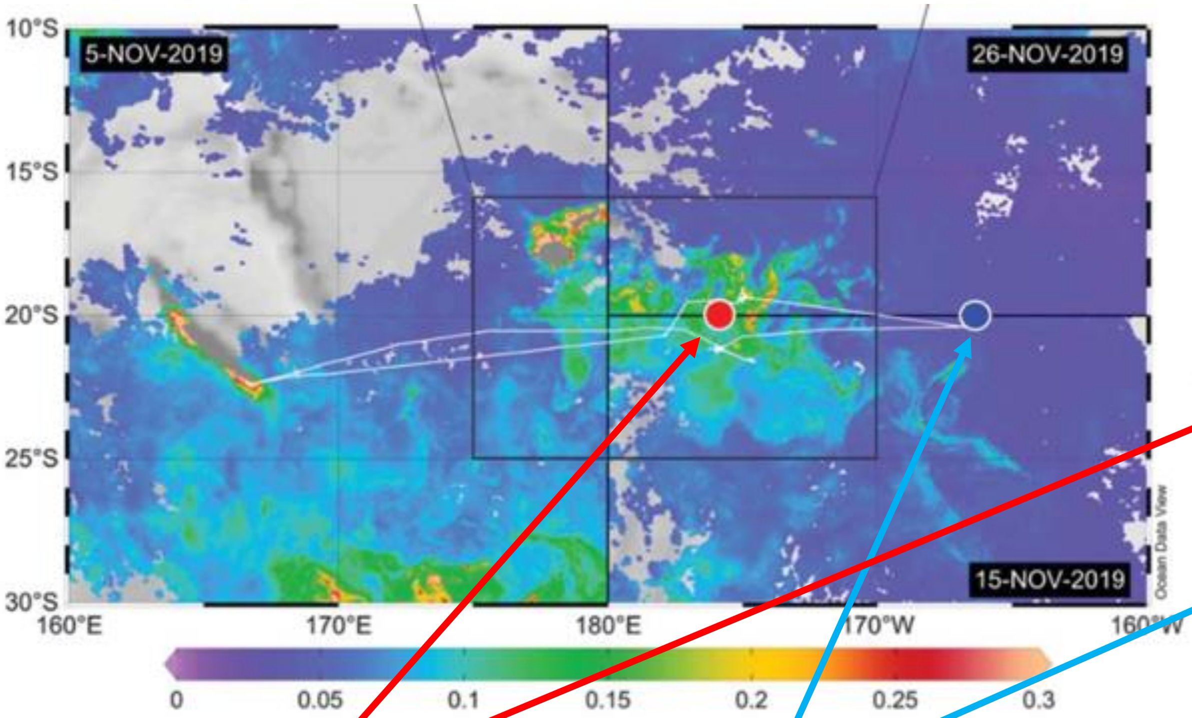


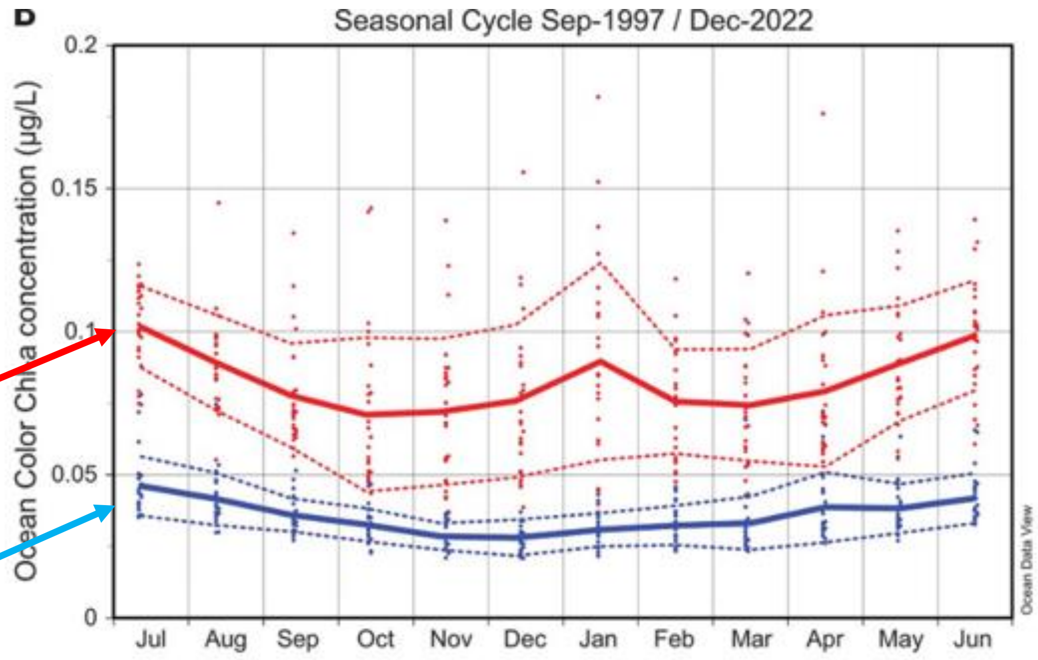
Bonnet et al., *Nature*, 2023.

Spatial extent of the TONGA bloom

A chlorophyll bloom above the site of hydrothermal Fe input.

Consistently high chlorophyll at this site over many years





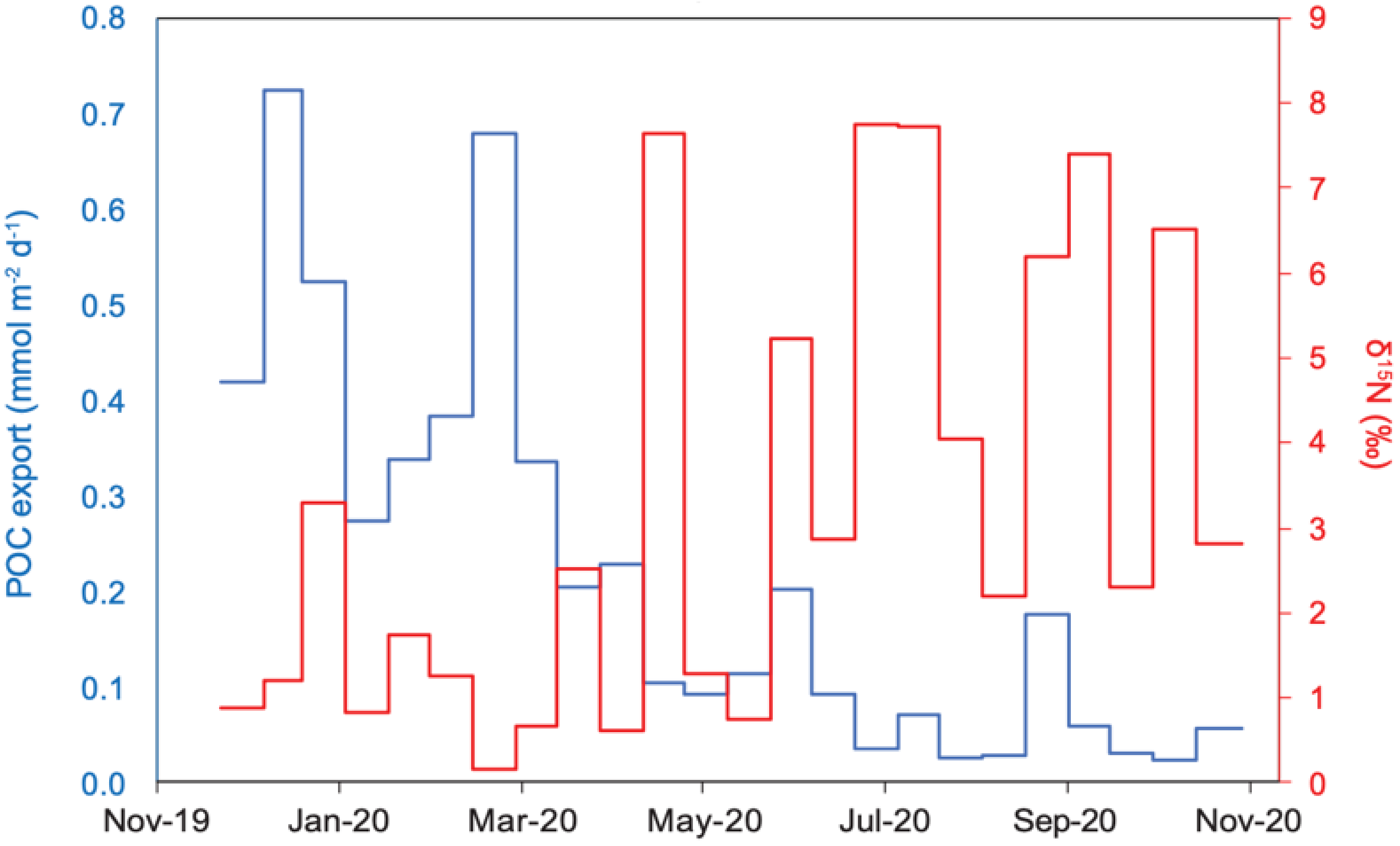
Tonga ridge volcano

Control site

Bonnet et al., *Nature*, 2023.

Increased N fixation leads directly to POC export

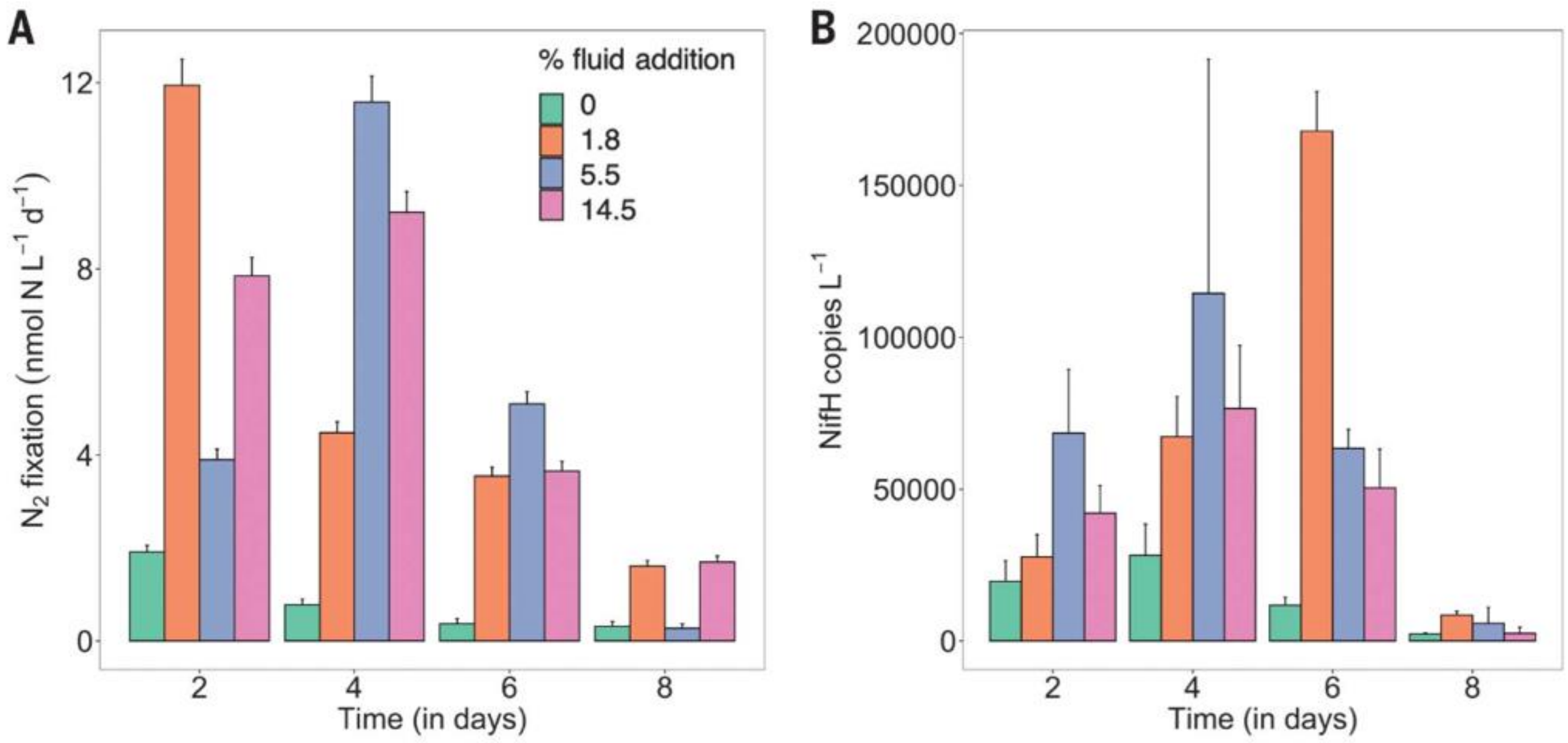
Higher POC export



More N fixation

Bonnet et al., *Nature*, 2023.

Fe addition with hydrothermal fluids stimulates N fixation


Higher N-fixation rates

Higher abundance of NifH

10 nmol L^{-1} N fixation, over a 100 m water column, extrapolated across the entire South Pacific is equivalent to annual sequestration of ***4 GT CO_2 y^{-1}***

Bonnet et al., *Nature*, 2023.

Key calculations for the TONGA experiment

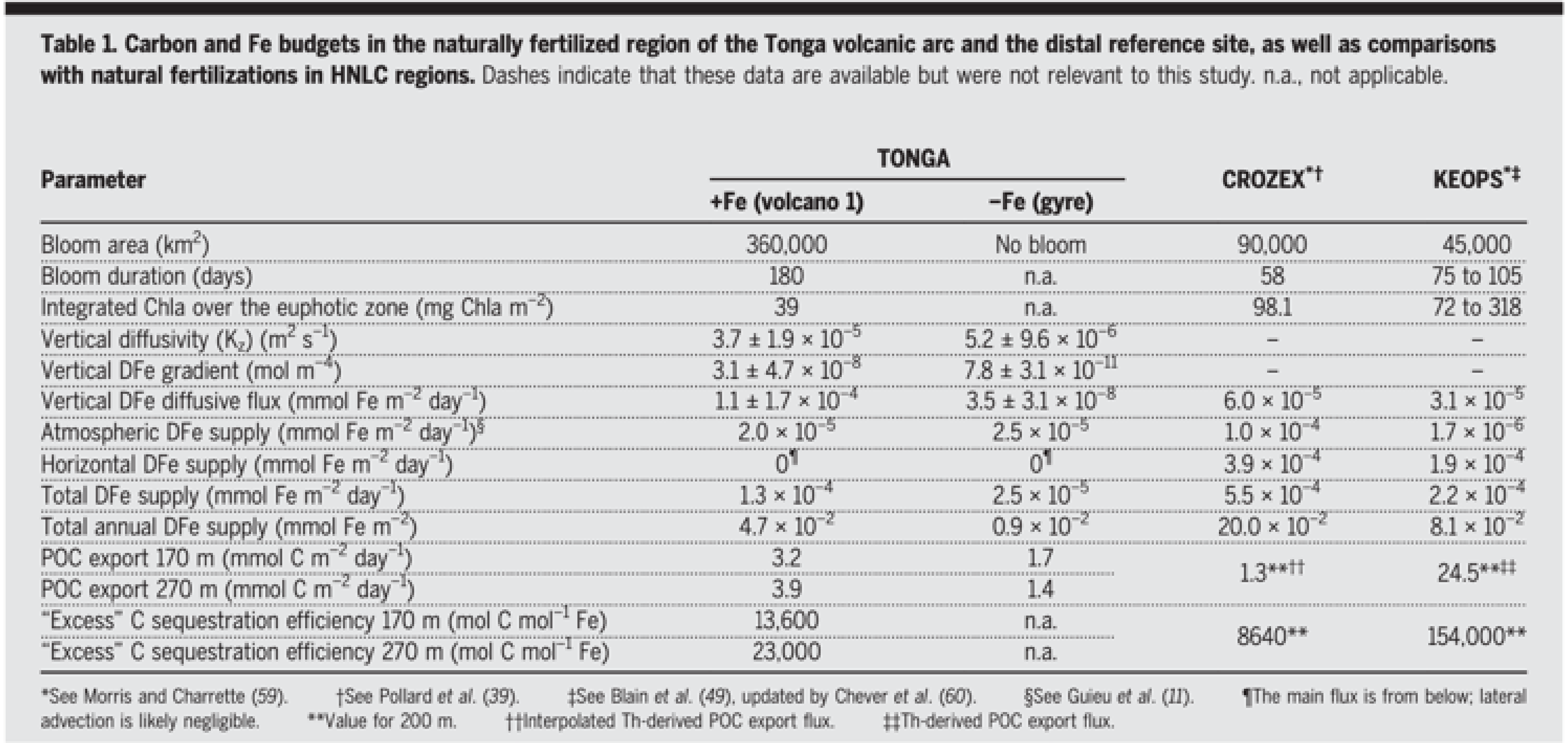


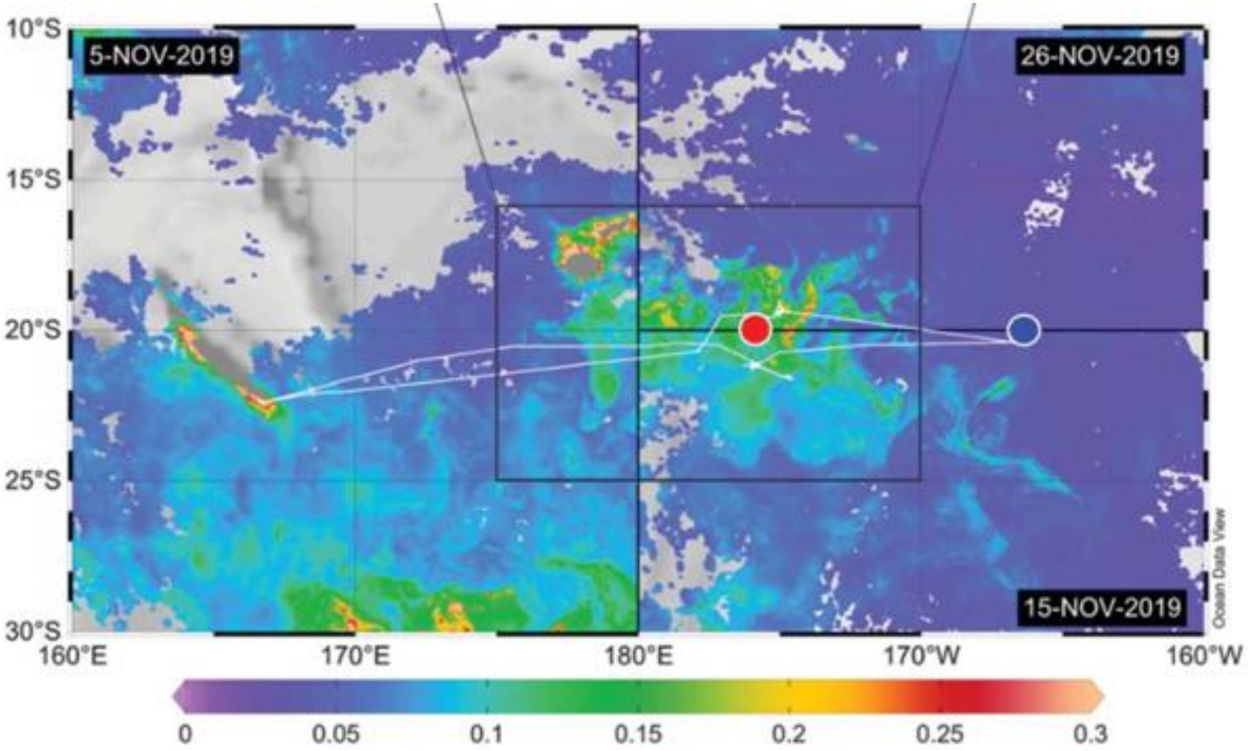
Table 1. Carbon and Fe budgets in the naturally fertilized region of the Tonga volcanic arc and the distal reference site, as well as comparisons with natural fertilizations in HNLC regions. Dashes indicate that these data are available but were not relevant to this study. n.a., not applicable.

Parameter	TONGA		CROZEX[*,†]	KEOPS[*,‡]
	+Fe (volcano 1)	−Fe (gyre)		
Bloom area (km^2)	360,000	No bloom	90,000	45,000
Bloom duration (days)	180	n.a.	58	75 to 105
Integrated Chla over the euphotic zone (mg Chla m^{-2})	39	n.a.	98.1	72 to 318
Vertical diffusivity (K_z) ($m^2\ s^{-1}$)	$3.7 \pm 1.9 \times 10^{-5}$	$5.2 \pm 9.6 \times 10^{-6}$	–	–
Vertical DFe gradient (mol m^{-4})	$3.1 \pm 4.7 \times 10^{-8}$	$7.8 \pm 3.1 \times 10^{-11}$	–	–
Vertical DFe diffusive flux (mmol Fe m^{-2} day^{-1})	$1.1 \pm 1.7 \times 10^{-4}$	$3.5 \pm 3.1 \times 10^{-8}$	6.0×10^{-5}	3.1×10^{-5}
Atmospheric DFe supply (mmol Fe m^{-2} day^{-1})[§]	2.0×10^{-5}	2.5×10^{-5}	1.0×10^{-4}	1.7×10^{-6}
Horizontal DFe supply (mmol Fe m^{-2} day^{-1})	0[¶]	0[¶]	3.9×10^{-4}	1.9×10^{-4}
Total DFe supply (mmol Fe m^{-2} day^{-1})	1.3×10^{-4}	2.5×10^{-5}	5.5×10^{-4}	2.2×10^{-4}
Total annual DFe supply (mmol Fe m^{-2})	4.7×10^{-2}	0.9×10^{-2}	20.0×10^{-2}	8.1×10^{-2}
POC export 170 m (mmol C m^{-2} day^{-1})	3.2	1.7	1.3[**,††]	24.5[**,‡‡]
POC export 270 m (mmol C m^{-2} day^{-1})	3.9	1.4		
"Excess" C sequestration efficiency 170 m (mol C mol^{-1} Fe)	13,600	n.a.	8640[**]	154,000[**]
"Excess" C sequestration efficiency 270 m (mol C mol^{-1} Fe)	23,000	n.a.		

[*] See Morris and Charrette (59). [†] See Pollard *et al.* (39). [‡] See Blain *et al.* (49), updated by Chever *et al.* (60). [§] See Guieu *et al.* (11). [¶] The main flux is from below; lateral advection is likely negligible. [**] Value for 200 m. [††] Interpolated Th-derived POC export flux. [‡‡] Th-derived POC export flux.

2.5 mmol excess C m-2 d-1, extrapolated over the entire patch yields is equivalent to annual sequestration of ***15 MT CO_2 y^{-1}***

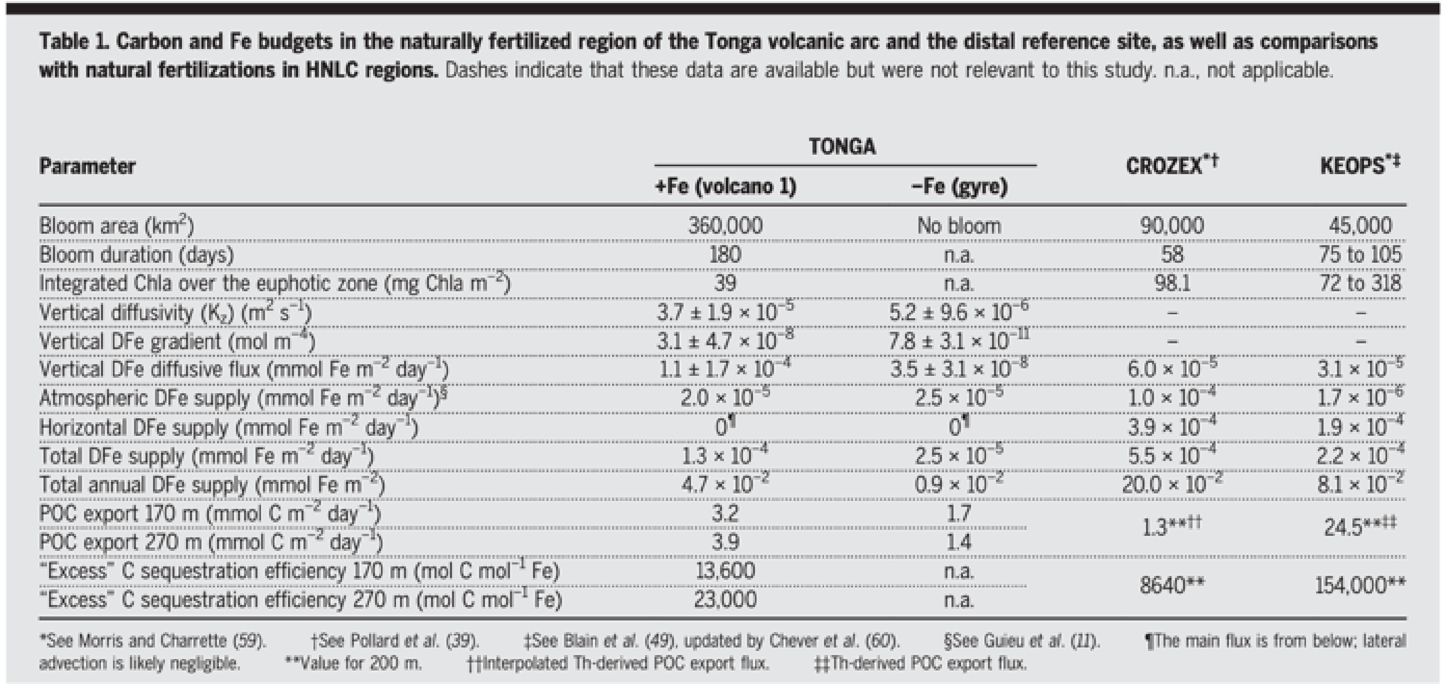
Scaling the TONGA plume over the entire South Pacific



2.5 mmol excess C m-2 d-1, extrapolated over a year over the entire South Pacific yields is equivalent to annual sequestration of ***1.5 GT*** $\boldsymbol{CO_2\ y^{-1}}$

Bonnet et al., *Nature*, 2023.

High efficiency of C export in the TONGA plume



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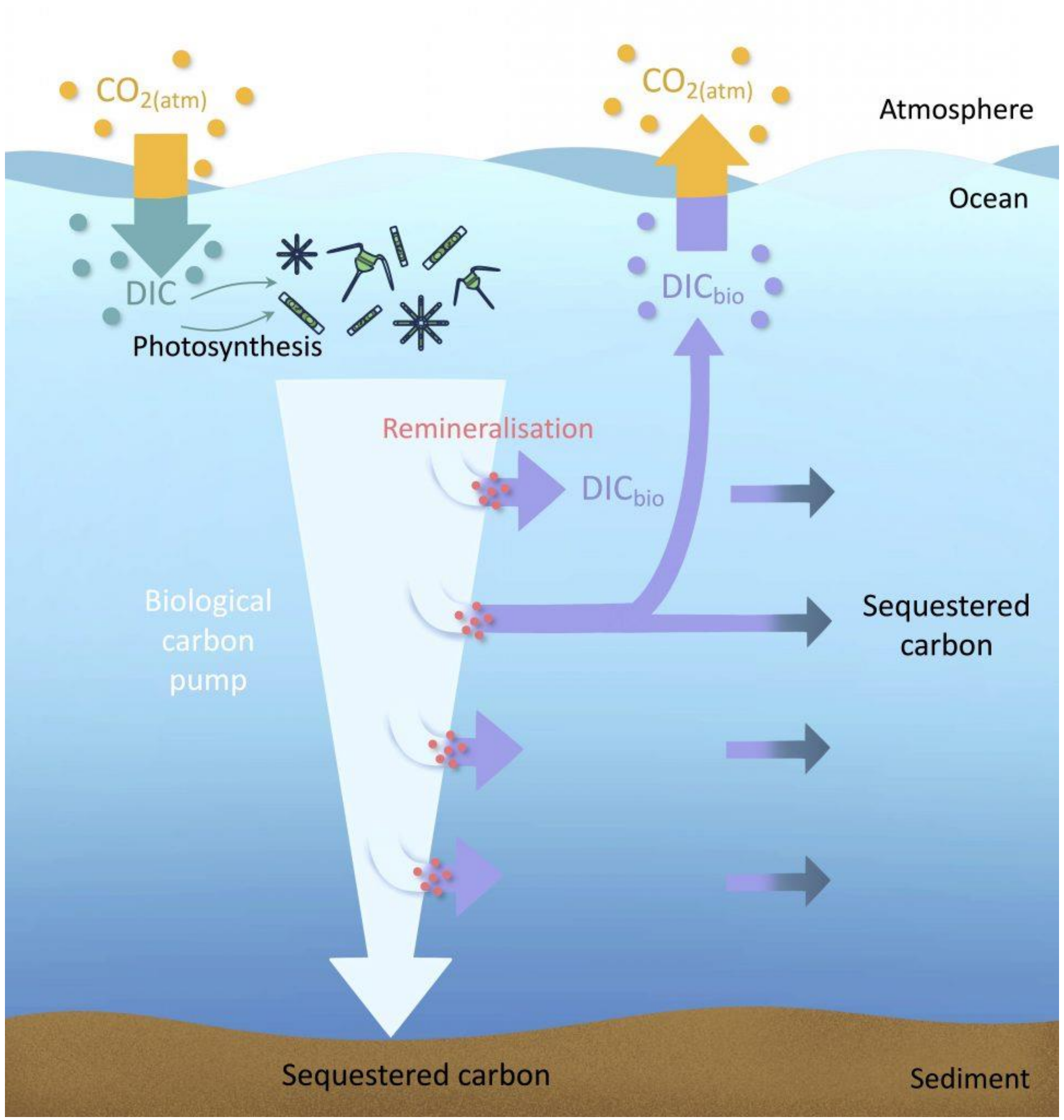
Experiment	**Fe:C**
SEEDS	**4,300**
SERIES	**1,200**
CROZEX	**8,640**
KEOPS	**154,000**
TONGA	**23,000**

Other potential advantages of LNLC-OIF

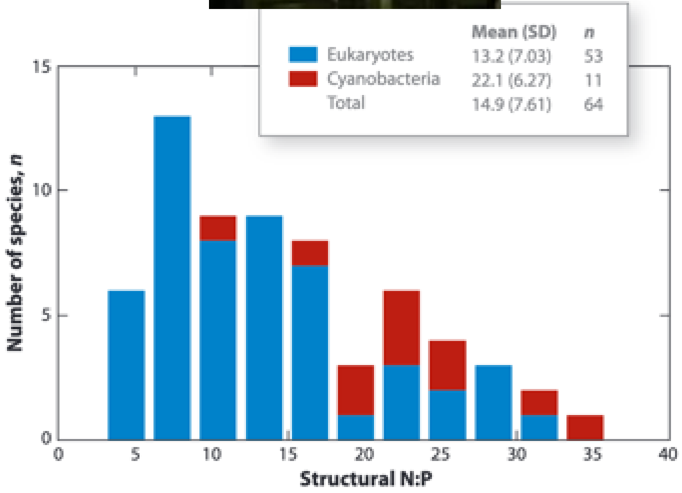
Durability may be quite high; there are no nutrients 'left behind' in the surface oligotrophic gyres!

Relatively long water residence time at the surface will maximize atmospheric equilibration and uptake.



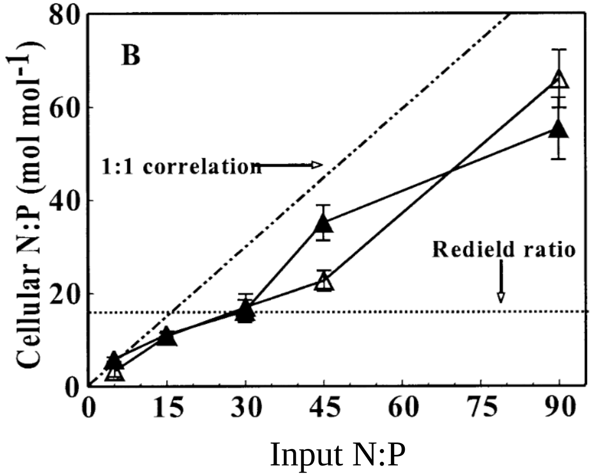
Culture data supporting flexible N:P stoichiometry

Large inter-species variability in N:P when grown under similar conditions.



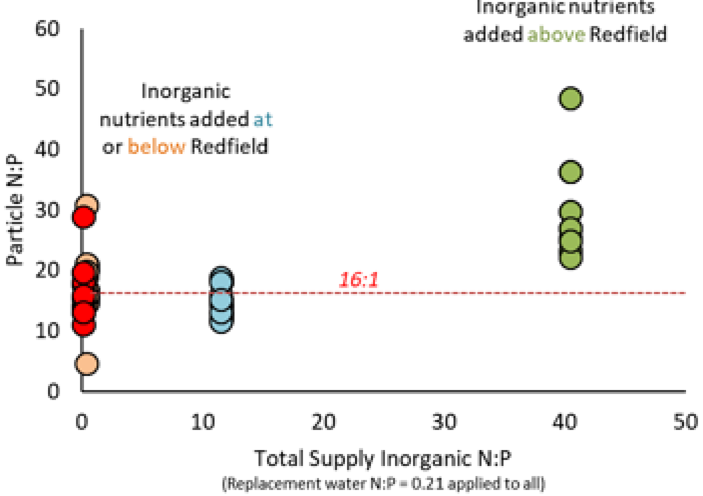
Deutsch and Weber, Ann. Rev., 2012

Cellular N:P in culture scales directly with media N:P.



Leonardos and Geider, L&O, 2004

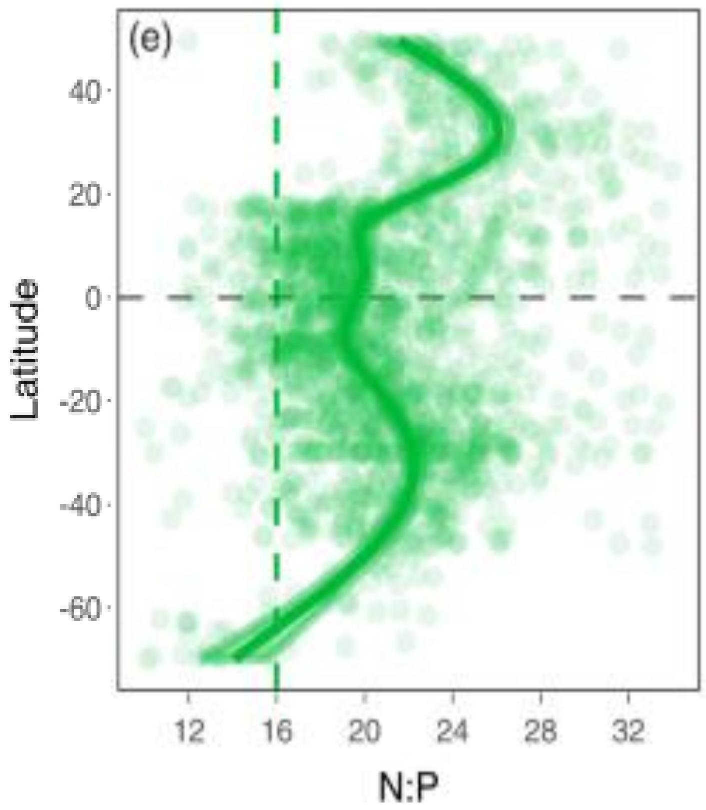
N:P in mixed phytoplankton community incubations scales with N:P.



Seelen et al., Nat Comms, in review

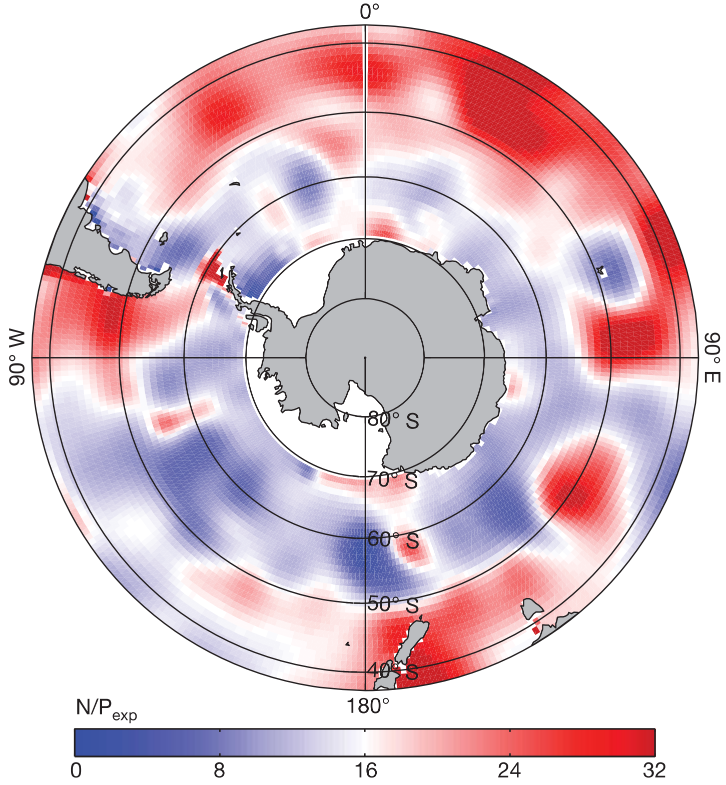
Field data supporting flexible N:P stoichiometry

Wide variations in surface filtered phytoplankton N:P



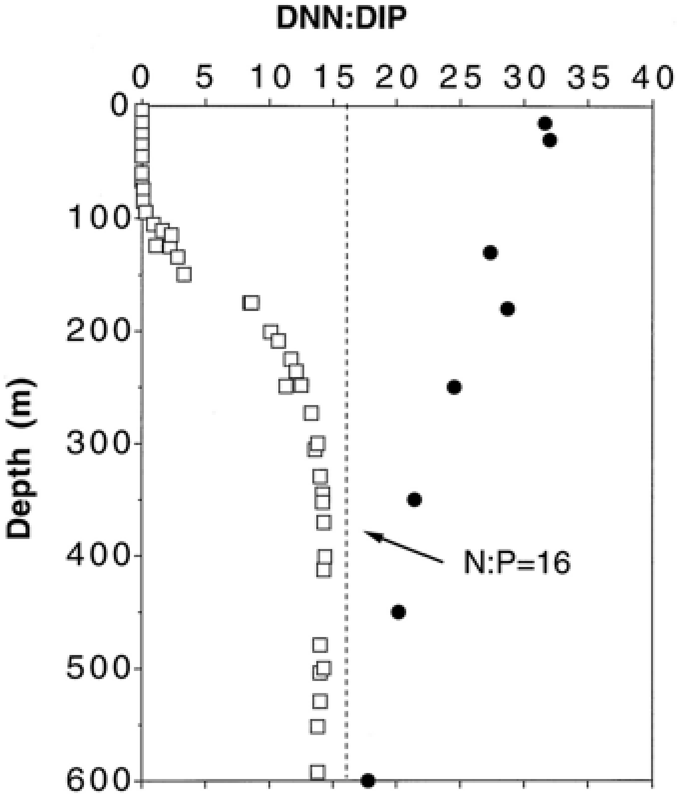
Tanioka et al., Comms Earth & Env., 2022.

Wide variations in inverse-modeled phytoplankton N:P



Weber and Deutsch, Nature, 2010

Nitrogen fixation in the Atlantic despite extremely high N:P

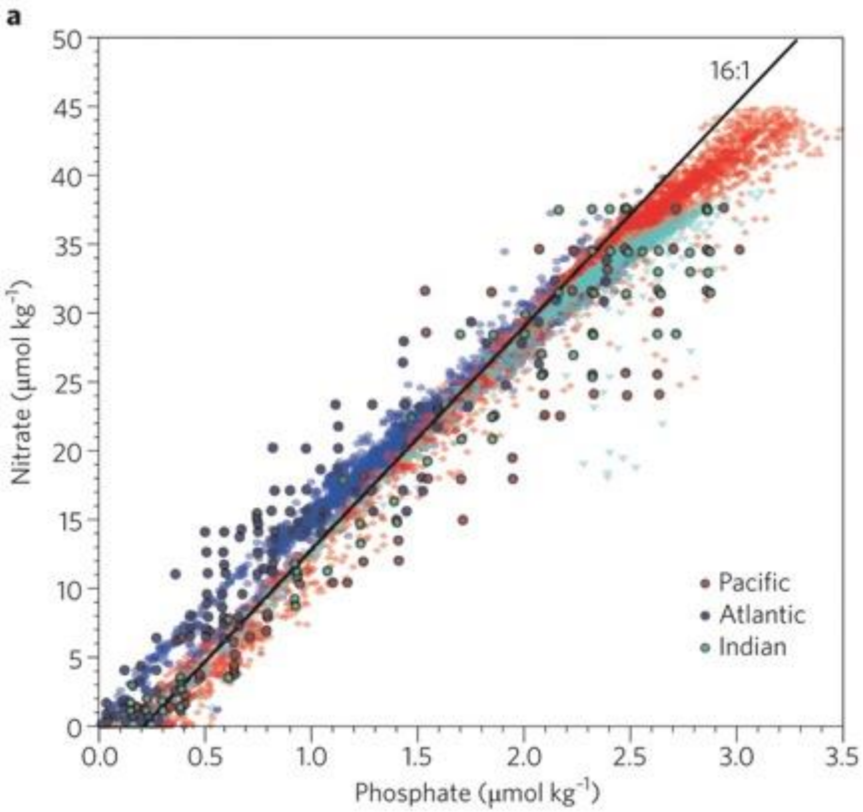


Wu and Boyle, Science, 2000

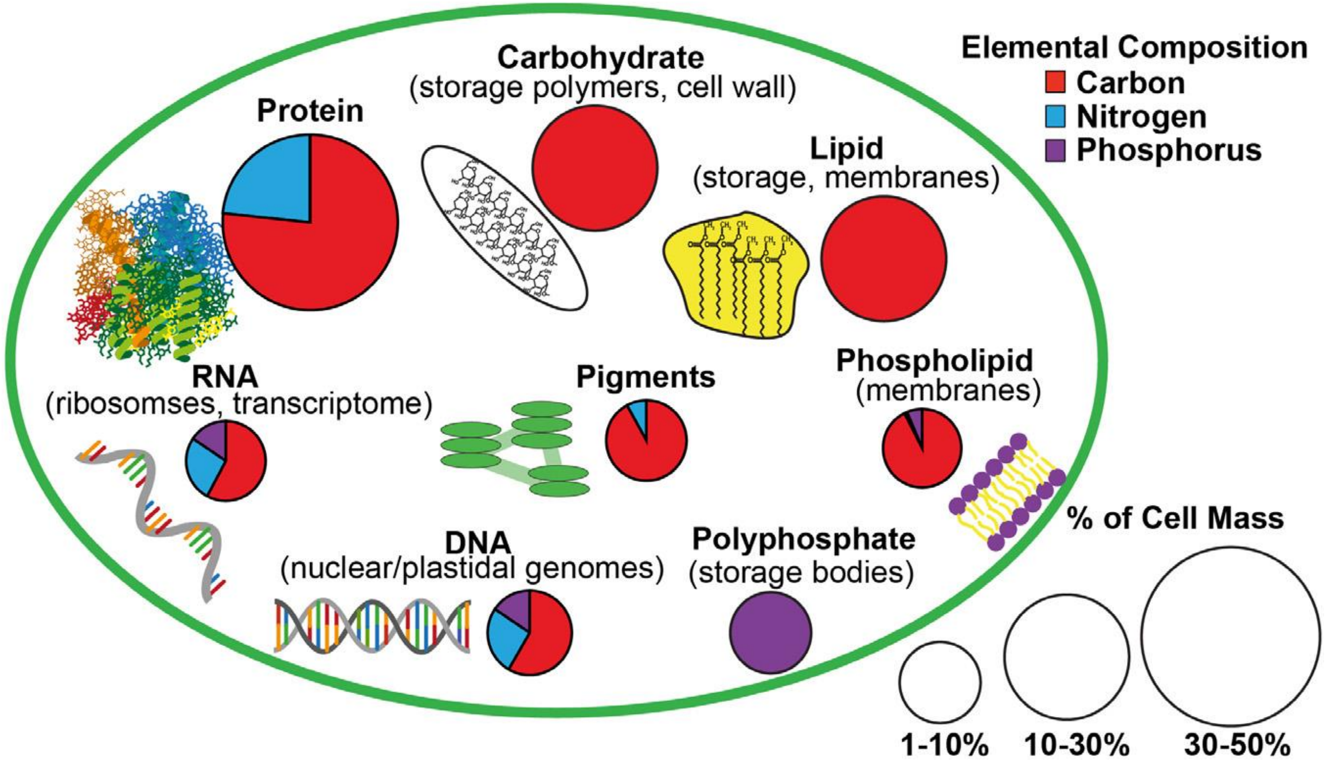
Evidence for an inflexible cellular N:P

N:P is rather constant in the modern ocean.

Cell architecture places constraints on the outer bounds of cellular N:P.



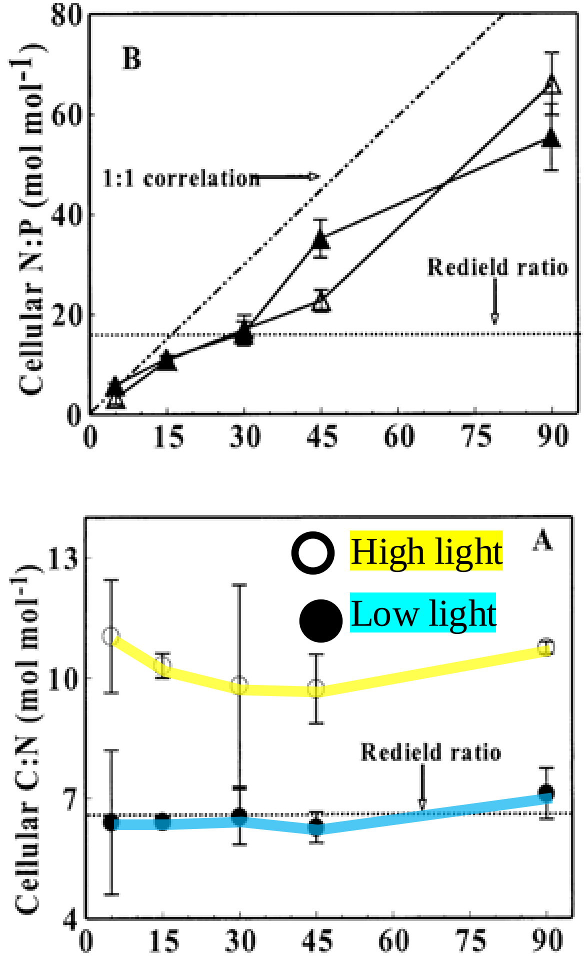
Gruber and Deutsch, Nature Geo., 2014.



Liefer et al., Frontiers, 2019.

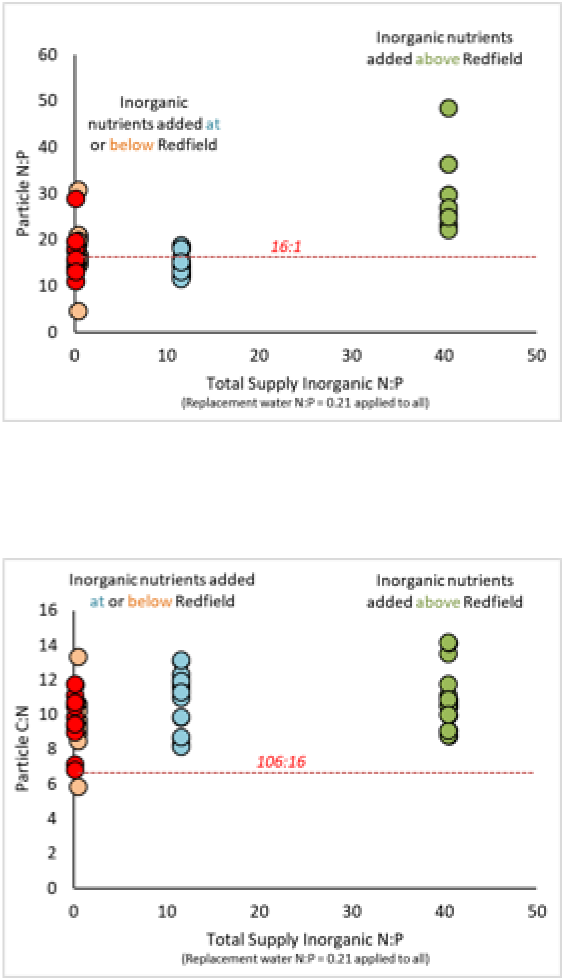
N:C is quite consistent, even when N:P varies

Diatom cultures



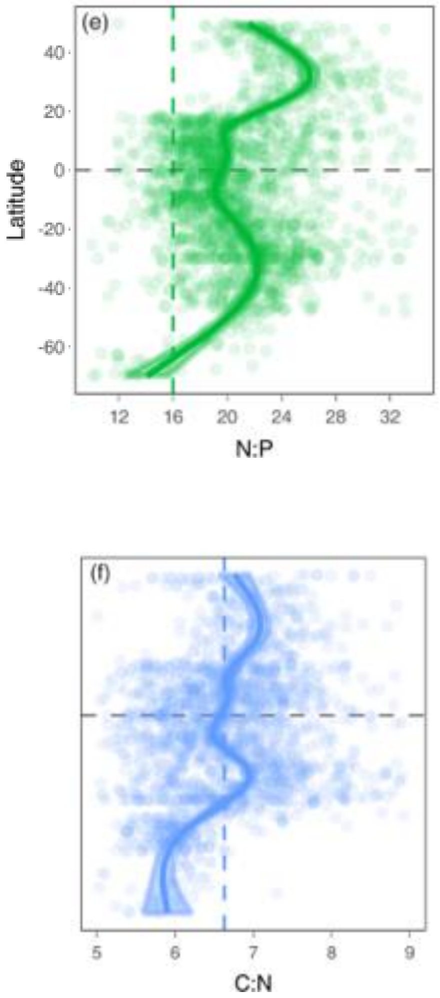
Leonardos and Geider., L&O, 2004

Natural community incubations



Seelen et al., PERI-SCOPE, pers. comm.

In situ plankton



Tanioka et al., Comms Earth & Environment, 2022.

LNLC OIF - seeding the tropical seas

Iron is abundant in Earth's crust, but scarcely present in seawater.

Diazotrophs require iron for their nitrogenase enzymes, which catalyze the conversion of nitrogen gas to ammonia.

Adding just a small amount of iron to seawater therefore results in a massive production of new ammonia.

New ammonia in the nutrient-poor tropical oceans stimulates the growth of phytoplankton which draw CO_2 out of the atmosphere.

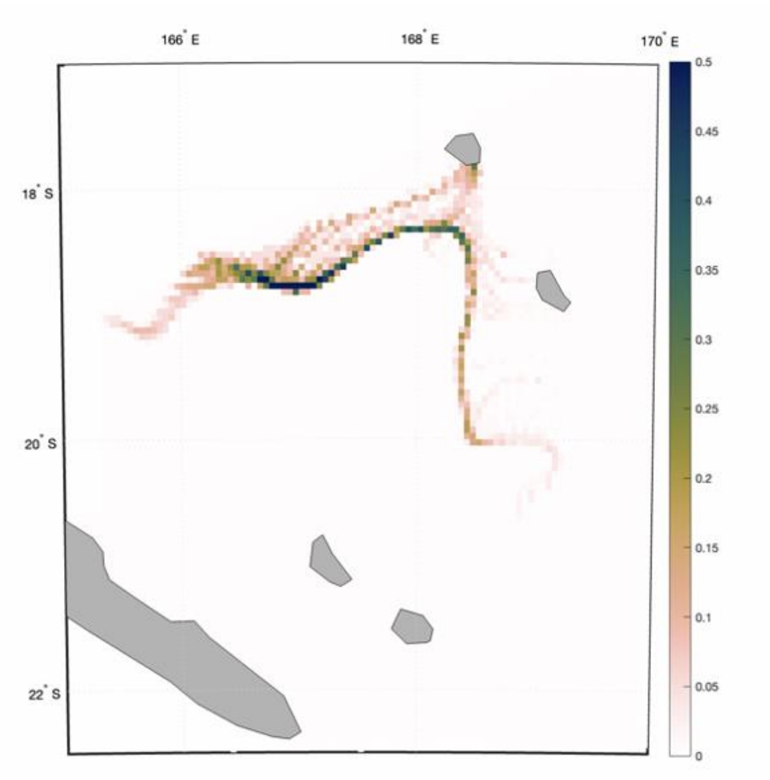
Two early models of LNLC-OIF

Long-term biogeochemical changes

AWESOME OCIM

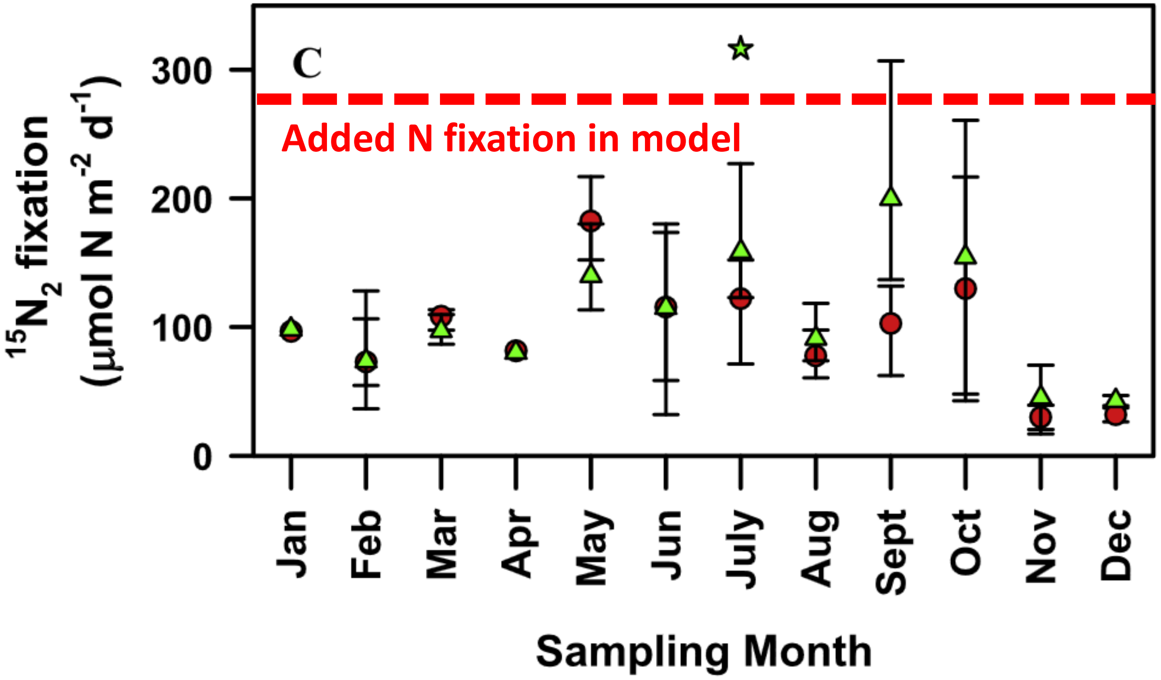
A WORKING ENVIRONMENT FOR SIMULATING OCEAN MOVEMENT AND ELEMENTAL CYCLING

Plume dispersion and bloom formation

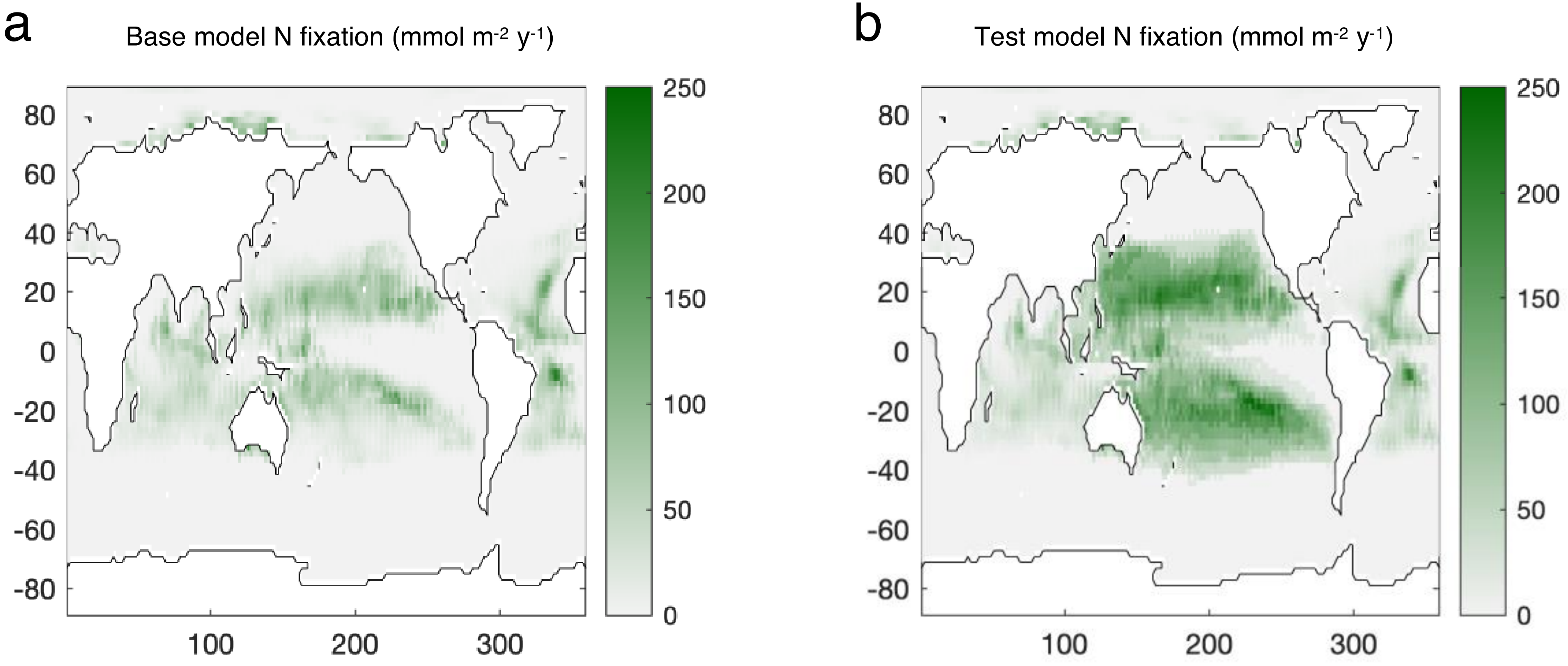


Model N fixation was increased throughout the Pacific

Station ALOHA background nitrogen fixation



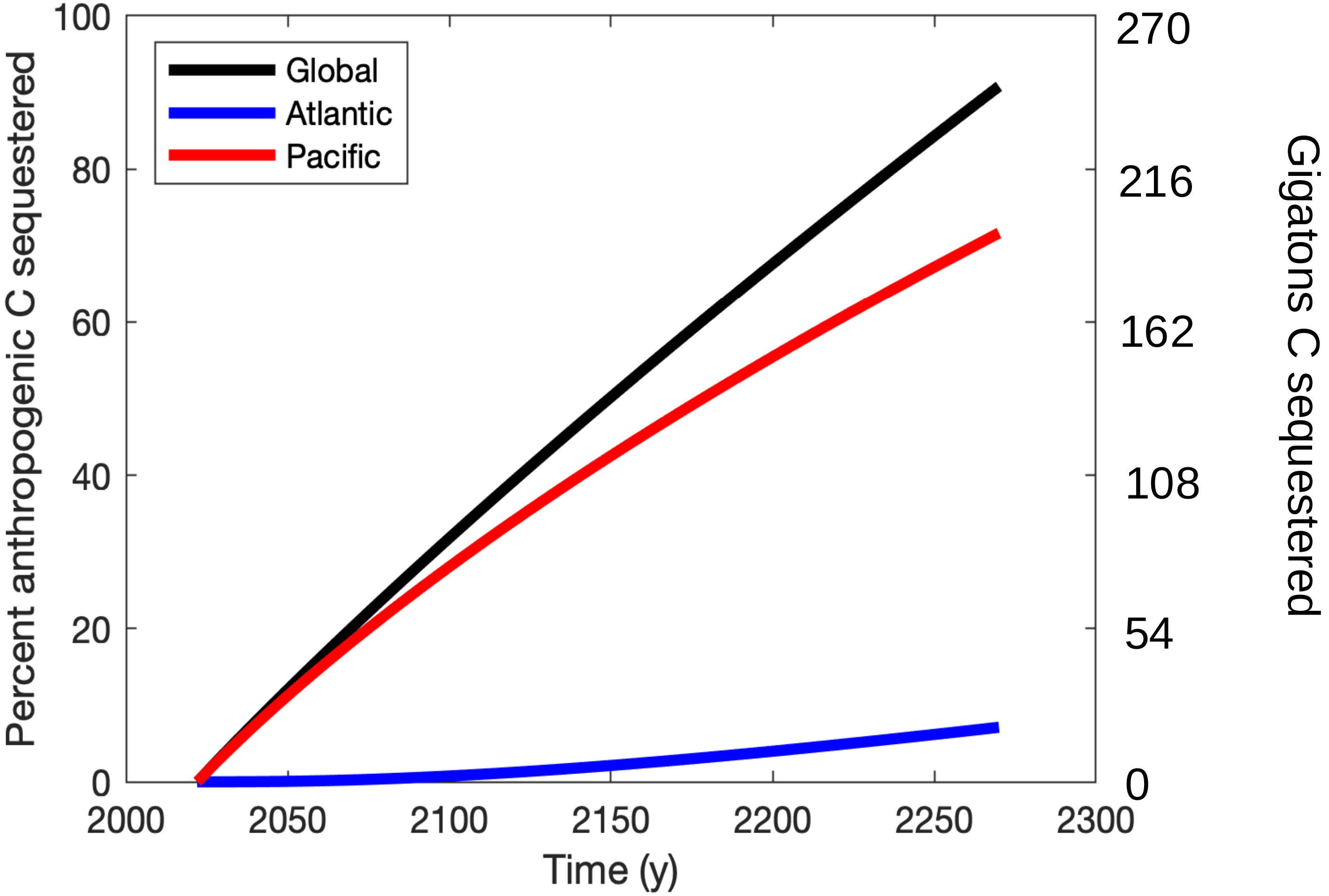
Additional N fixation global map



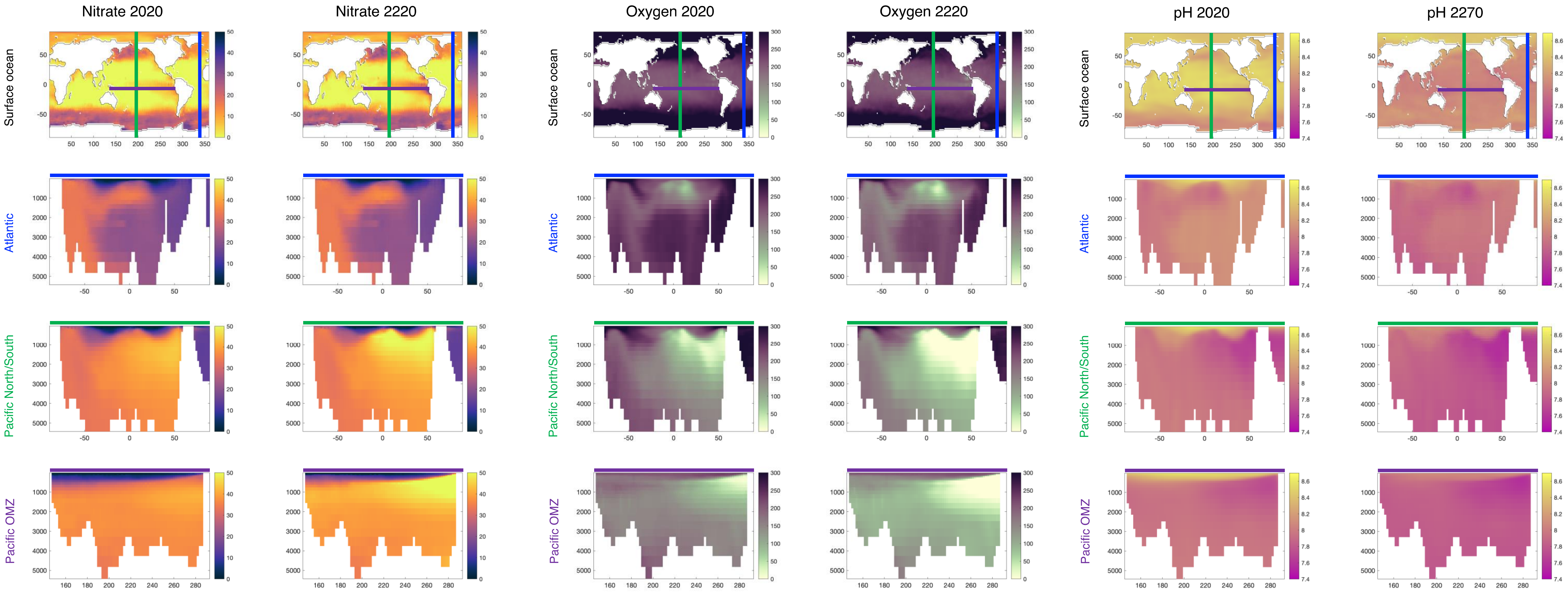
a Base model N fixation (mmol m^{-2} y^{-1})

b Test model N fixation (mmol m^{-2} y^{-1})

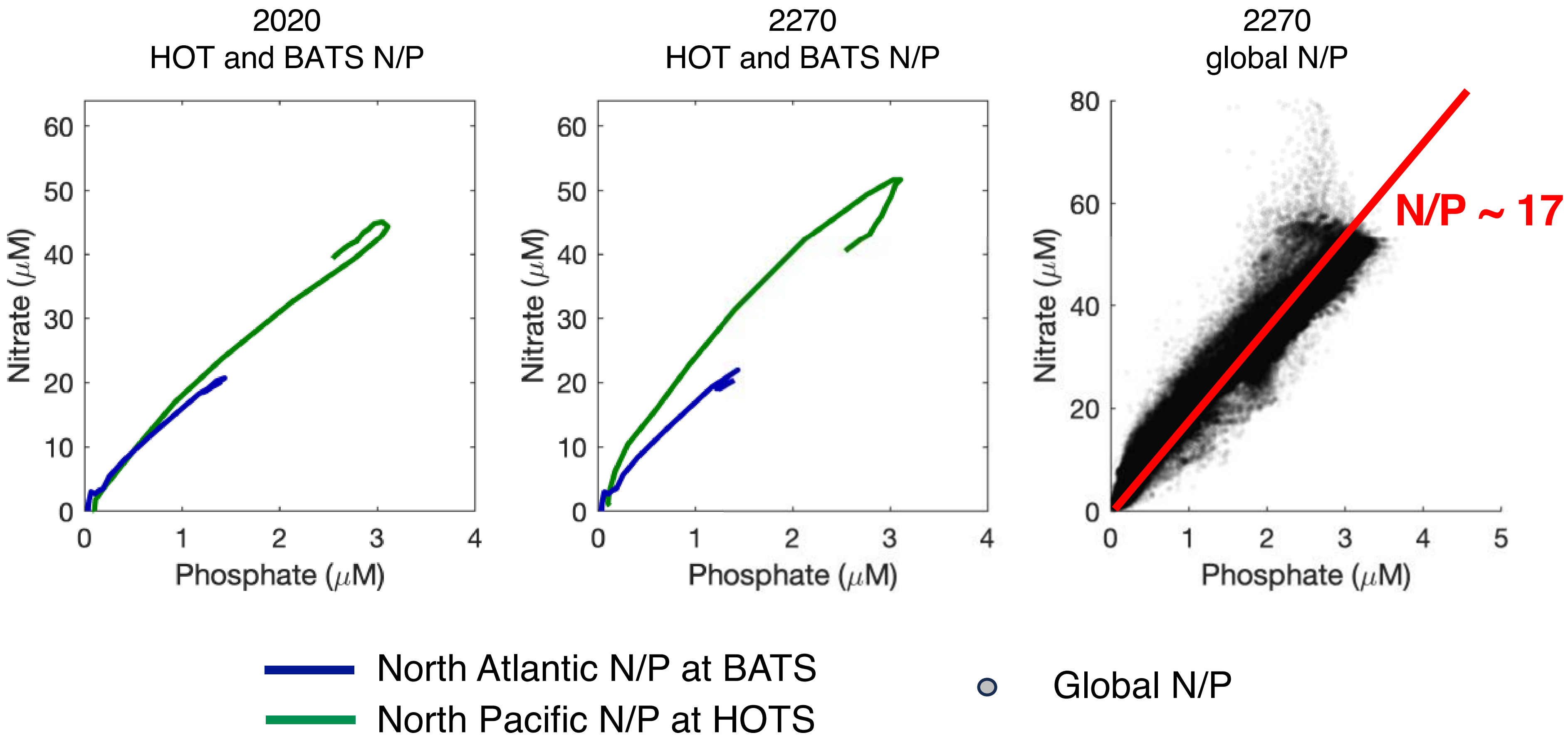
Carbon sequestration through time



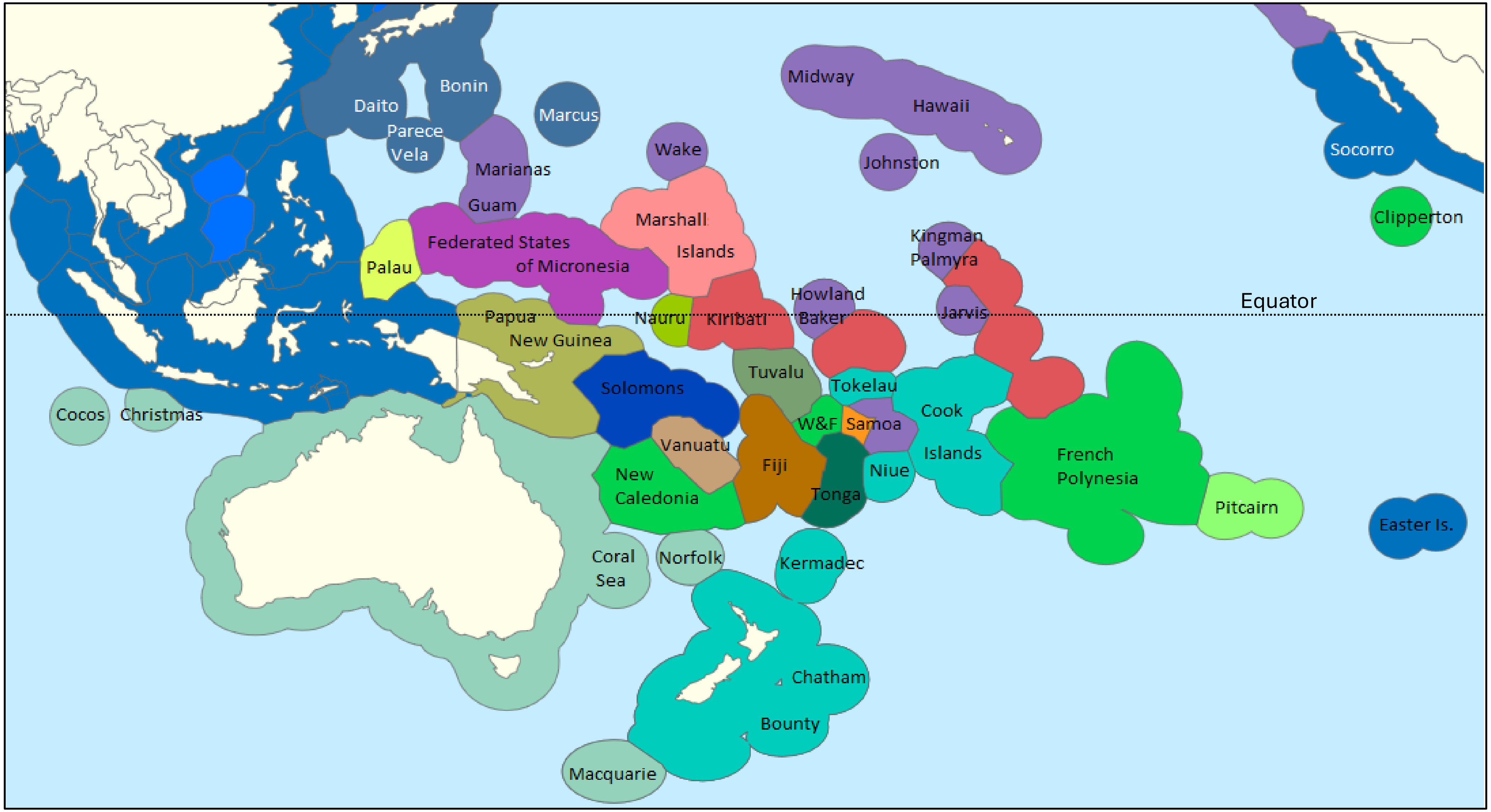
Impact on ocean biogeochemistry



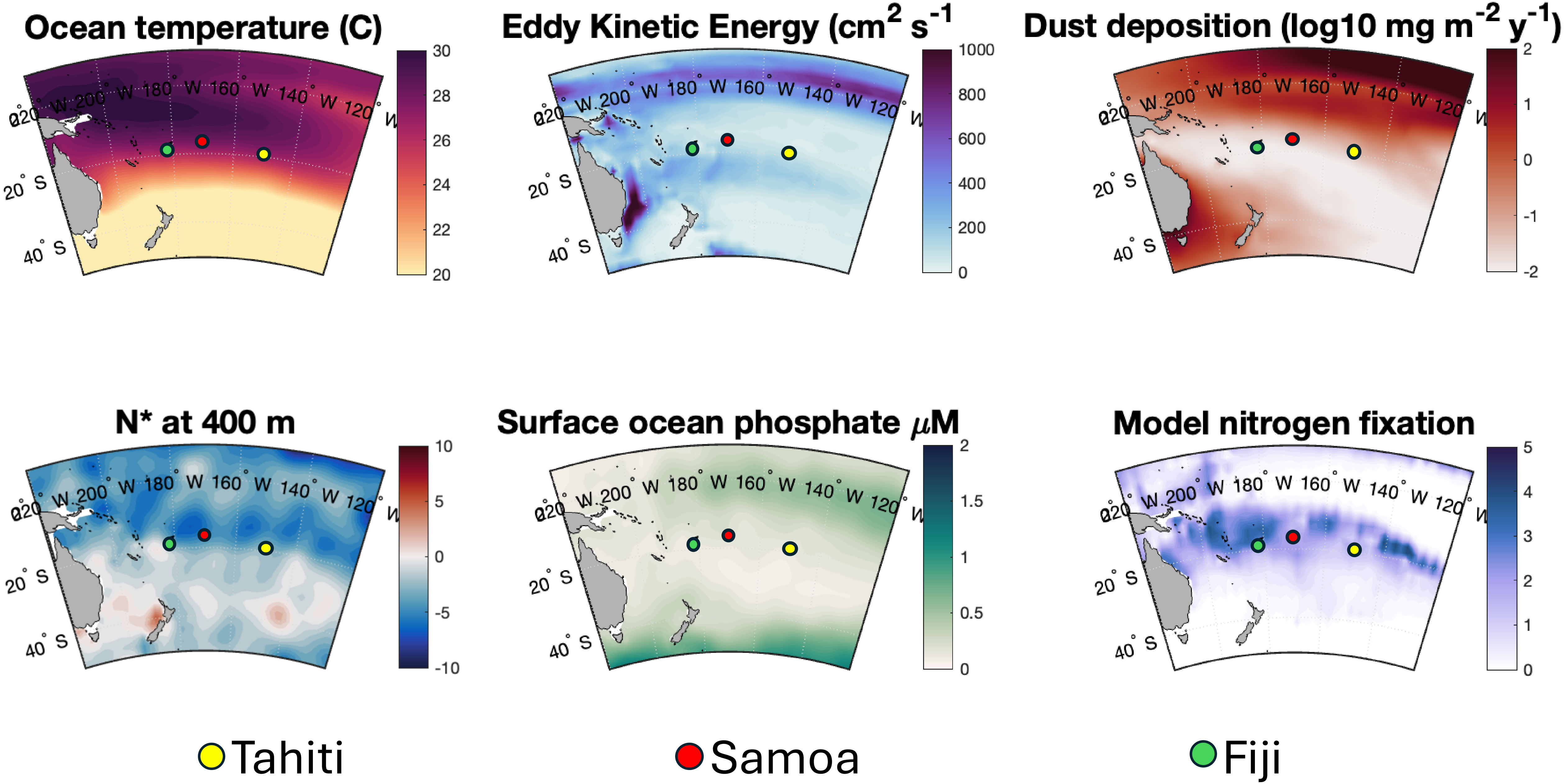
Impact on global N/P



Island locations for a South Pacific Experiment

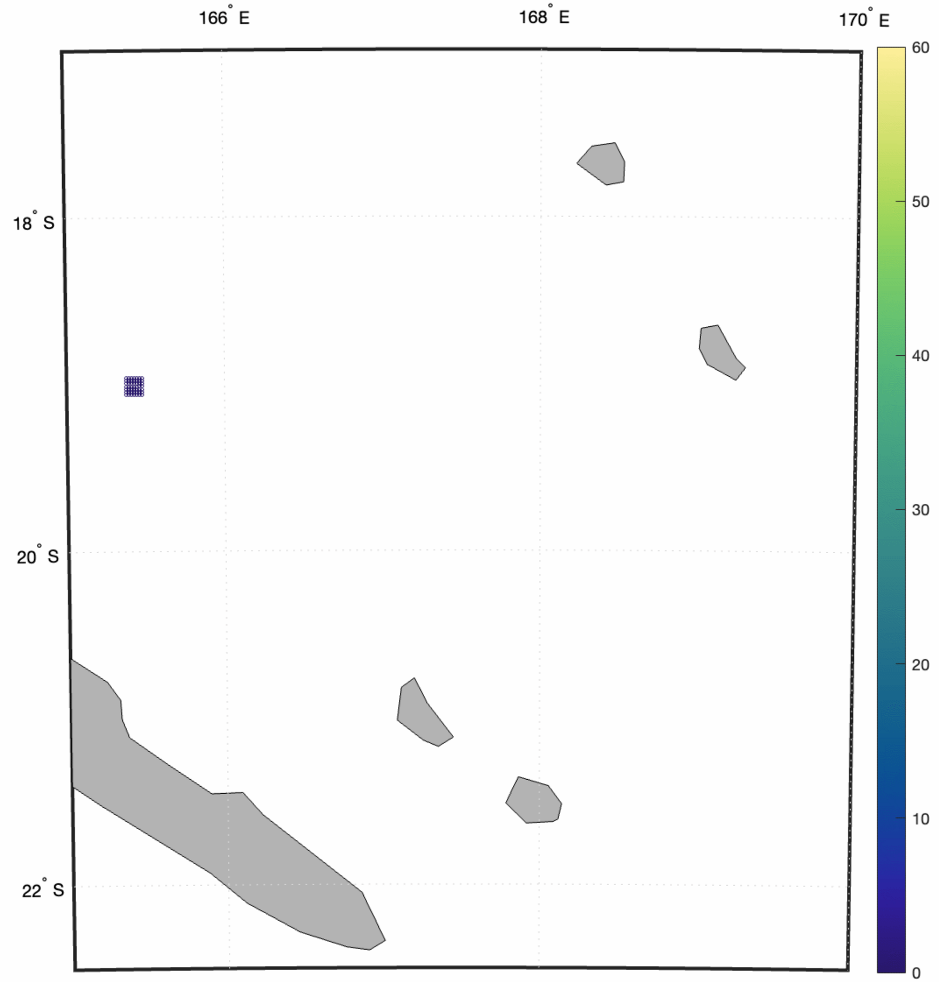


Physical setting of the South Pacific

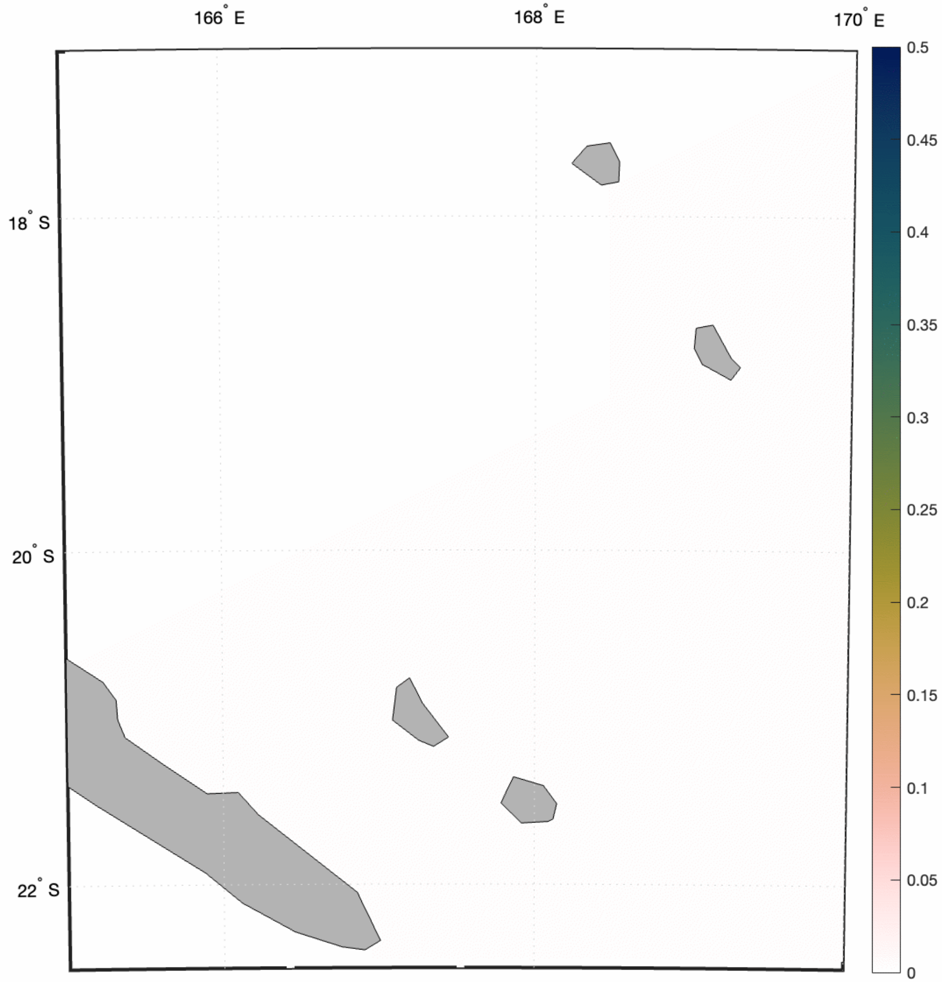


A modeled LNLC bloom

Particle tracing from a release location for 2 months



A simulated LNLC-OIF bloom

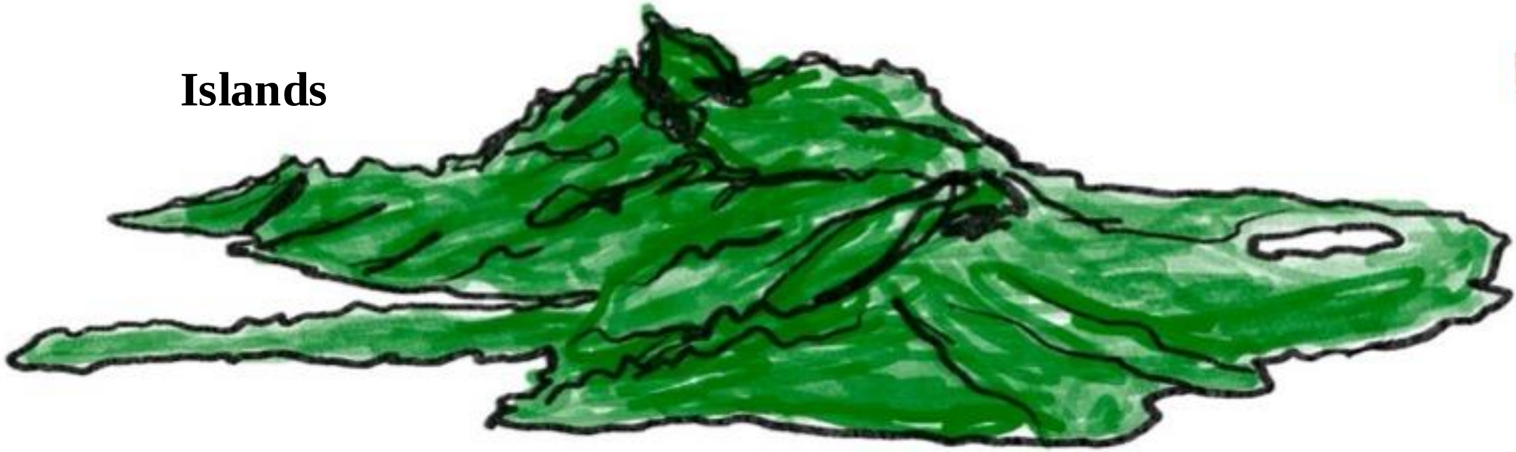


Planning for a South Pacific experiment

Remote sensing

Small vessels

***In situ* drifters/buoys**



Islands

Local collaborators

Legal framework

GEM: **G**lobal **E**xperiment for **M**arine biomass regeneration

Emily Seelen
University of
Alaska Fairbanks

Seth John
University of
So. California

Sarah Fawcett
University of
Cape Town

Core GEM Design Team

in collaboration with the Marine Biomass Regeneration consortium

Part 1:

* GEM Goals

* Overview of the Protocol

Part 2:

* SPOT Test

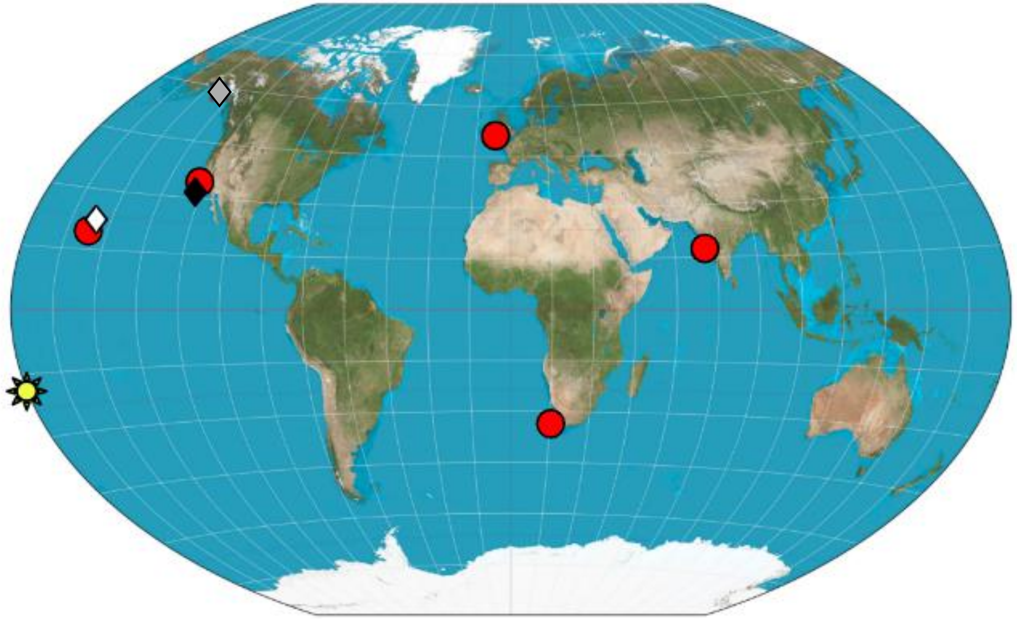
* Planned Experiments

GEM is

a standardized **protocol** for iron addition **microcosm experiments**

designed to evaluate how **iron influences productivity in** and **potential for carbon export from** marine surface waters on several-month long timescales

a means to form partnerships



● MBR Partner Institutions: University of Cambridge, UK; CSIR-NIO, Goa, India; University of Cape Town, South Africa; University of Southern California, USA; University of Hawaii, USA; University of Alaska Fairbanks, USA

◇ Hawaii Ocean Time-series
◆ San Pedro Ocean Time-series
◈ Northern Gulf of Alaska LTER

✵ South Pacific LNLC

Goal for GEM

- Relatively easy to set-up and operate
- Fast and simple sampling protocol
- Used to establish potential areas of interest for OIF
  - Monitoring post OIF?

Motivating Research Questions

- Does Fe stimulate **productivity**
  - in HNLC regions?
  - in LNLC regions? (N_2 fixation?)
- Do different forms of Fe support more/less **carbon export**?
  - If yes, why? (e.g., co-supply of SiO_4)
- Are there regionally different **timescales of response**?

GEM Basics

“All [microcosms] are wrong, but some are useful”

1 Liter Bottles

Lab-Based Incubation
(artificial light and
temperature control)

Subsample for
Three Months

GEM Basics

GEM Standard Treatments:

Control
+Iron Sulfate

MBR Add’l Treatments:

+Rice Husk
+Nitrate
+ Silicate
+Iron Sulfate +Silicate

Core Measurements

*Nitrogen Mass Balance

*Phosphorus Mass Balance (?)

*Macronutrients

**In vivo* chl

Key Variable = Nitrogen

Denitrifier-IRMS Method

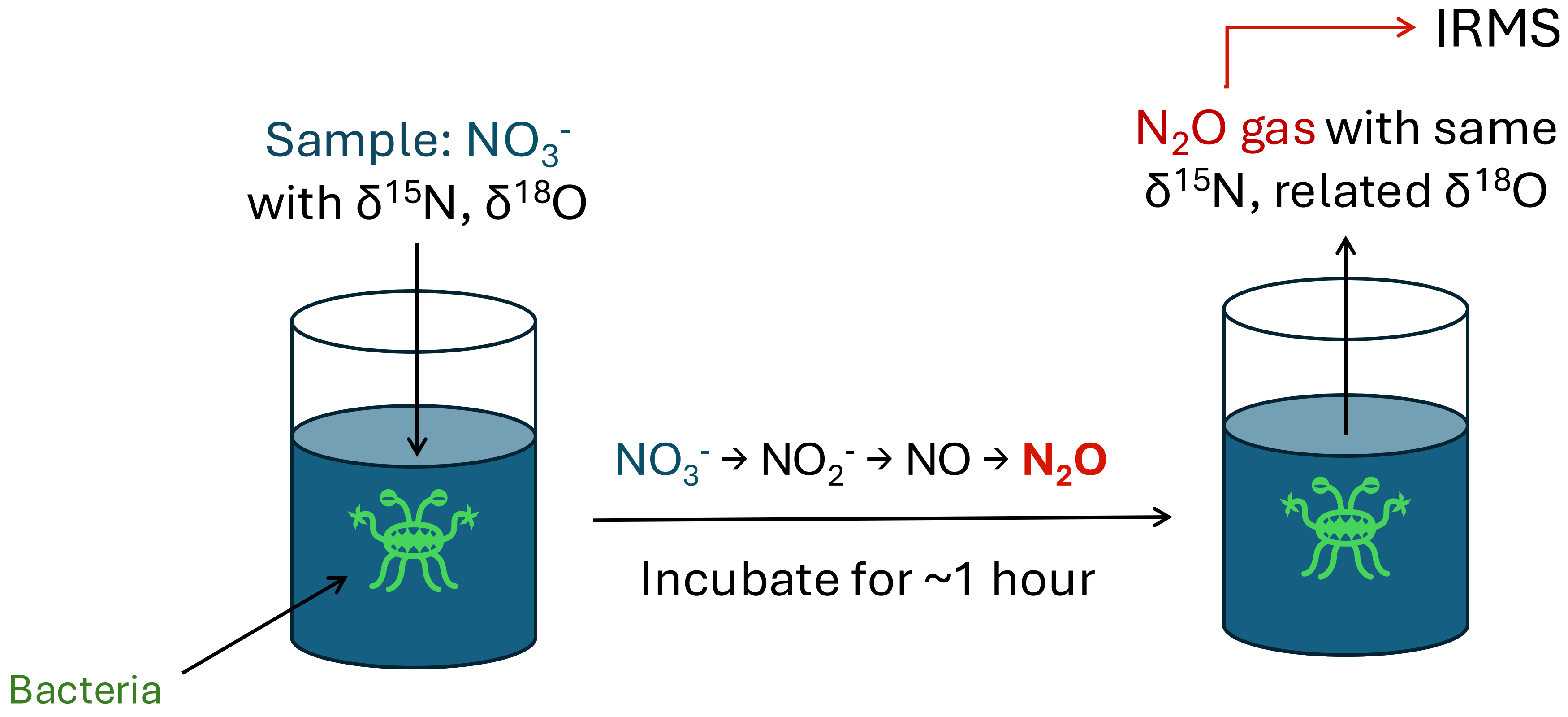
Analytically Sensitive = low volume sample required

No N_2O reductase

Denitrification (bacterially mediated): $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow \cancel{N_2}$

Denitrifier-IRMS Method

Denitrification (bacterially mediated): $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow \mathbf{N_2O}$



IRMS

N_2O gas with same $\delta^{15}N$, related $\delta^{18}O$

Sample: NO_3^- with $\delta^{15}N$, $\delta^{18}O$

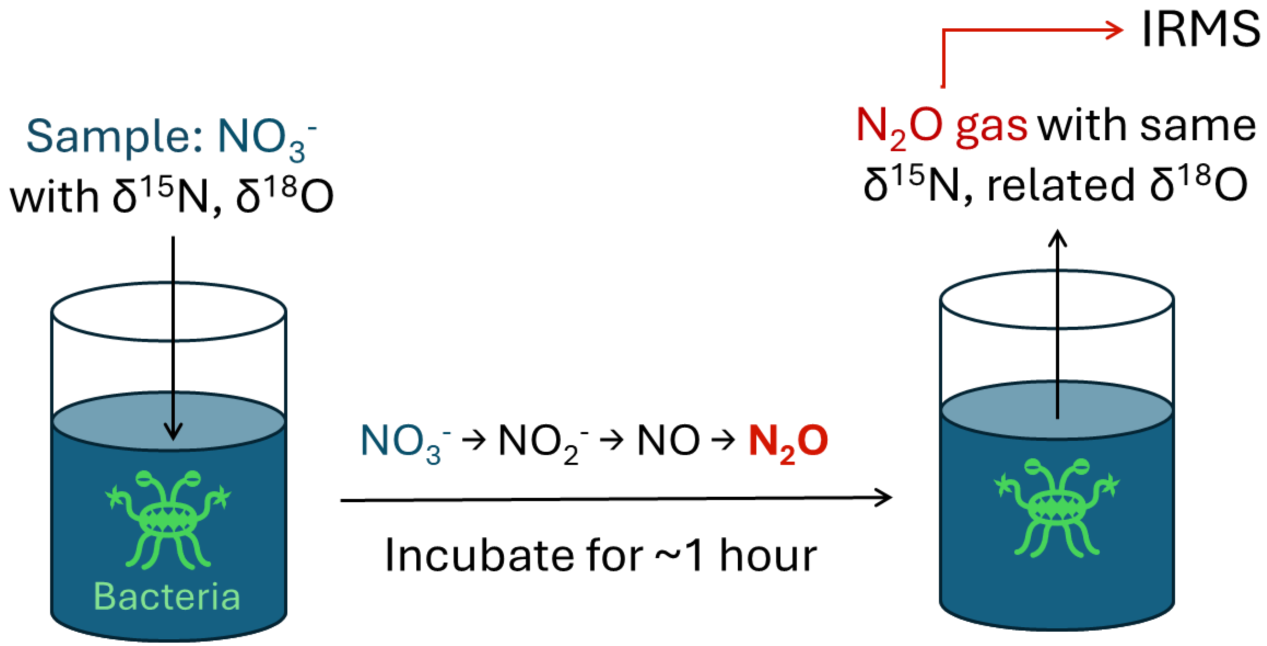
$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow \mathbf{N_2O}$

Incubate for ~1 hour

Bacteria

Denitrifier-IRMS Method

Used for particulate and dissolved phases as well as organic and inorganic N compounds



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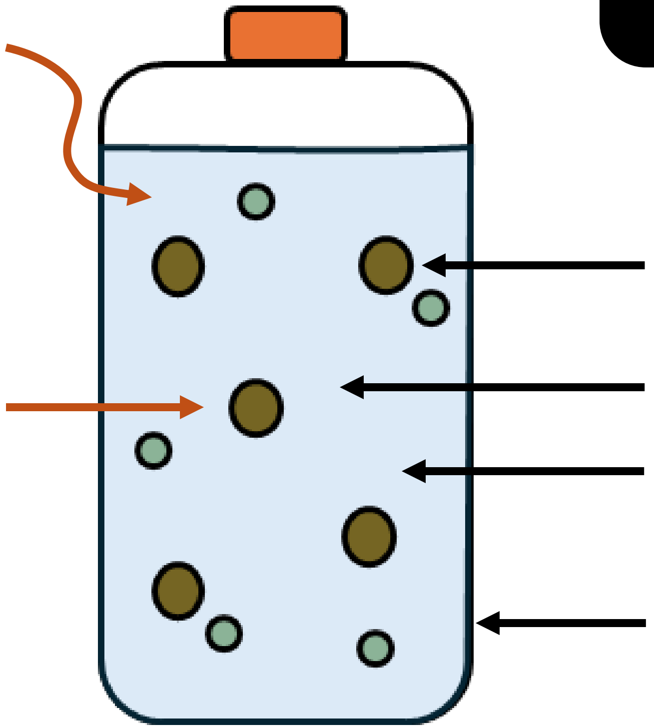
N_2O gas with same $\delta^{15}N$, related $\delta^{18}O$

IRMS

To evaluate changes in **carbon** after iron addition, we will measure **nitrogen**



Nitrogen Fixation

Nitrogen Assimilation

Particulate Nitrogen

Dissolved Organic Nitrogen

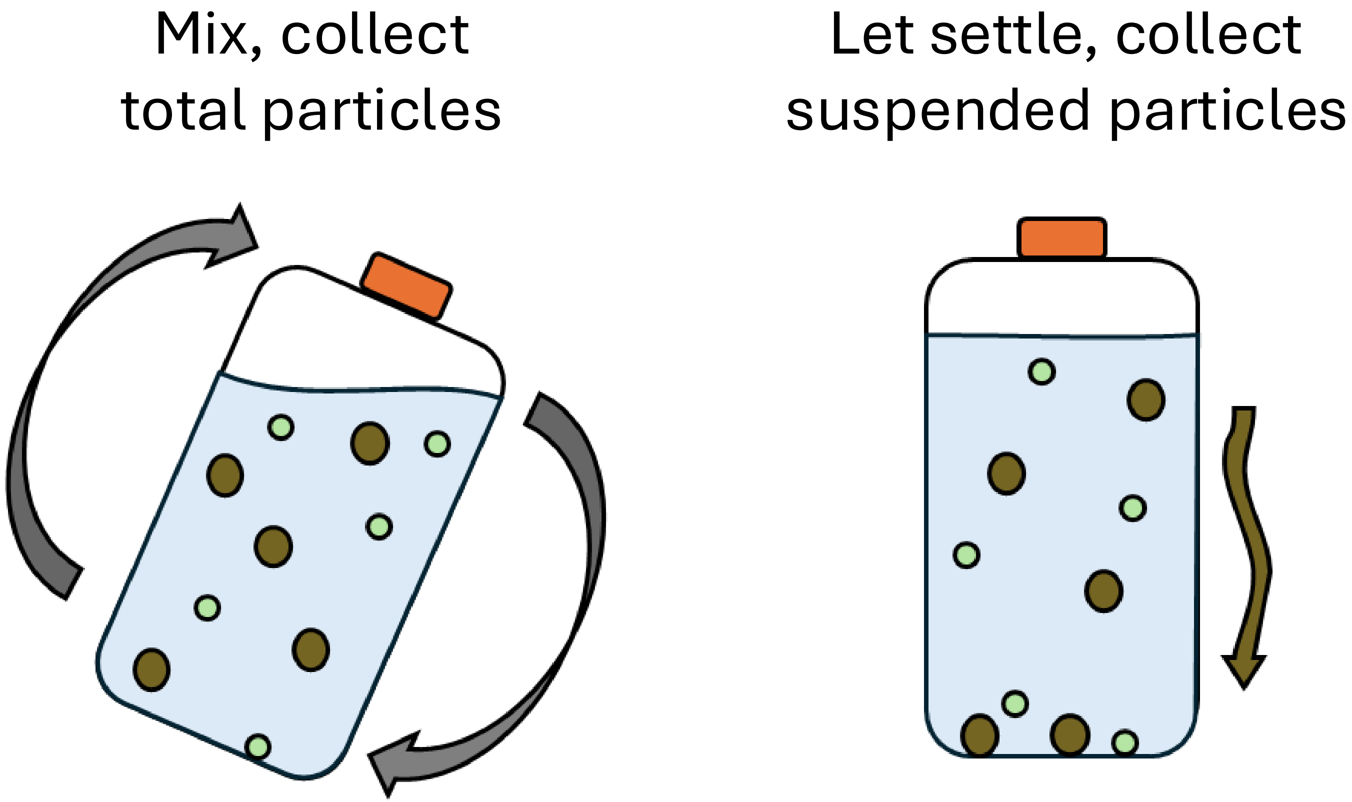
Dissolved Inorganic Nitrogen

Wall Associated Nitrogen (t_{final})

Nitrogen isotopes provide insight to nitrate source

Leverage Redfield C:N

Use Particle Settling to Estimate Carbon Export



Mix, collect
total particles

Let settle, collect
suspended particles

By difference, estimate the amount of sinking particles

Similar techniques in the field

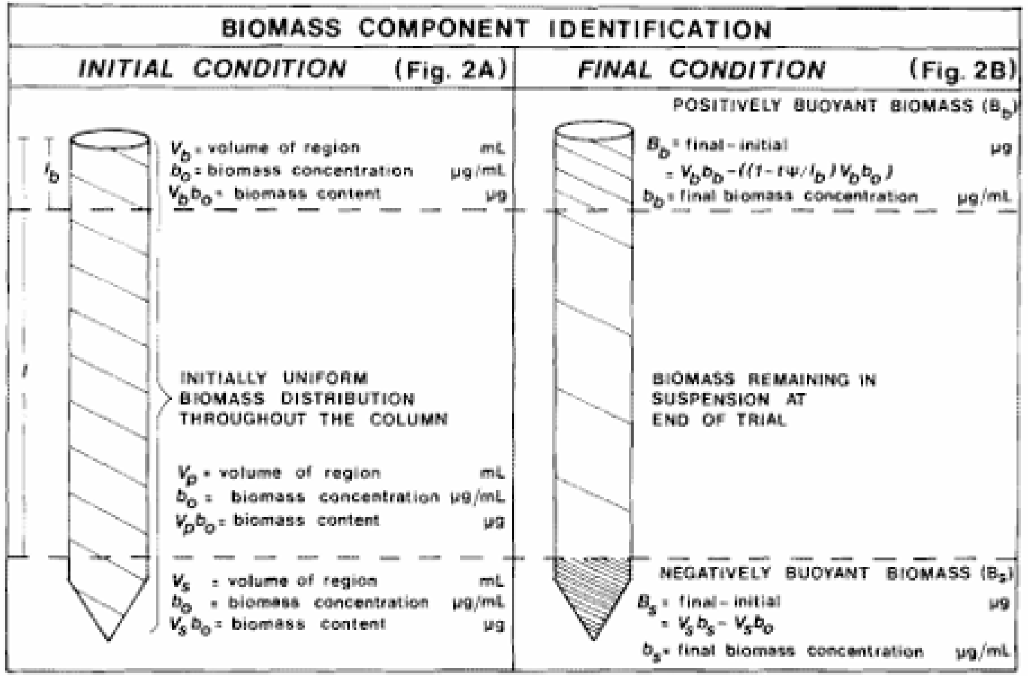


FIG. 2. Biomass separation in SETCOL chambers. Hatch marks indicate biomass density. All symbol identification given in Fig. 1. The mean sinking rate (ψ) and ascent rate (A) necessary to effect the observed final biomass distribution is given by $\psi = (B_s/B_i)l/t$ and $A = (B_b/B_i)l/t$, respectively.

Bienfang SETCOL

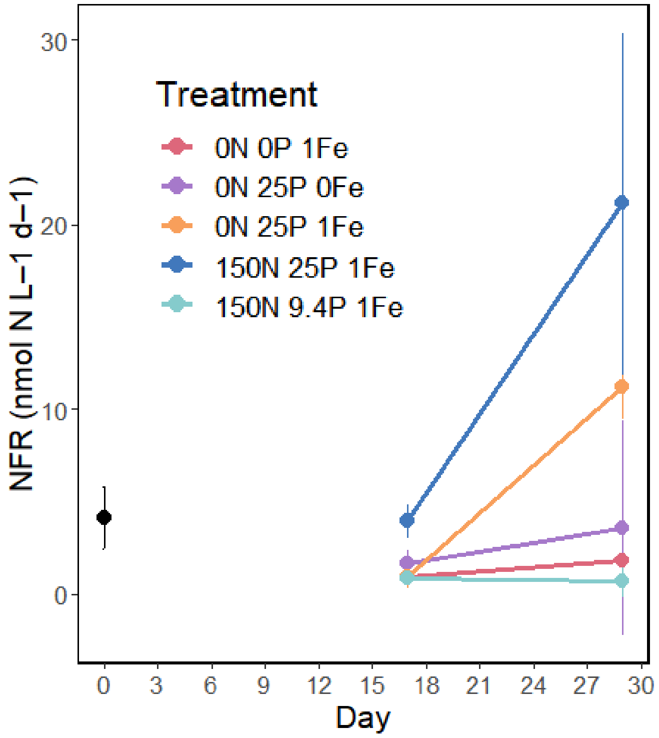
(2011, Can. J. Fish. Aquat. Sci.)

Marine Snow Catcher

(osil.com)

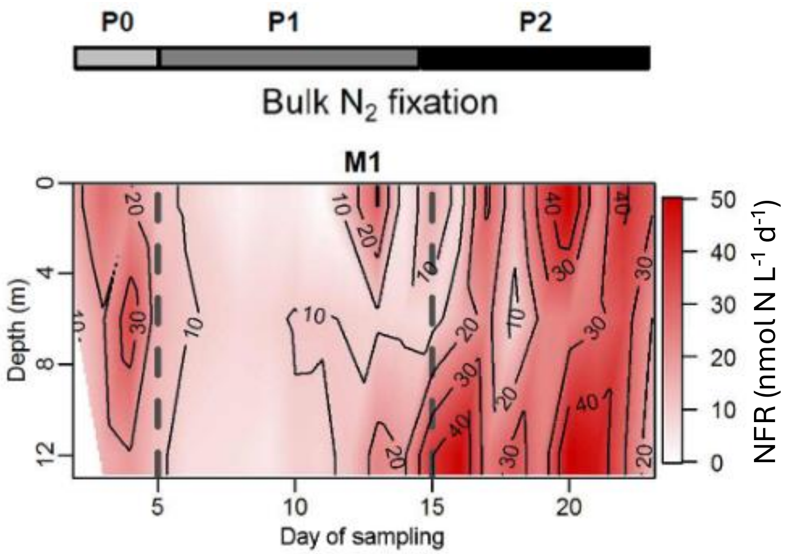
Increasing nitrogen fixation rates in response to nutrient supply can take weeks to develop

North Pacific Gyre

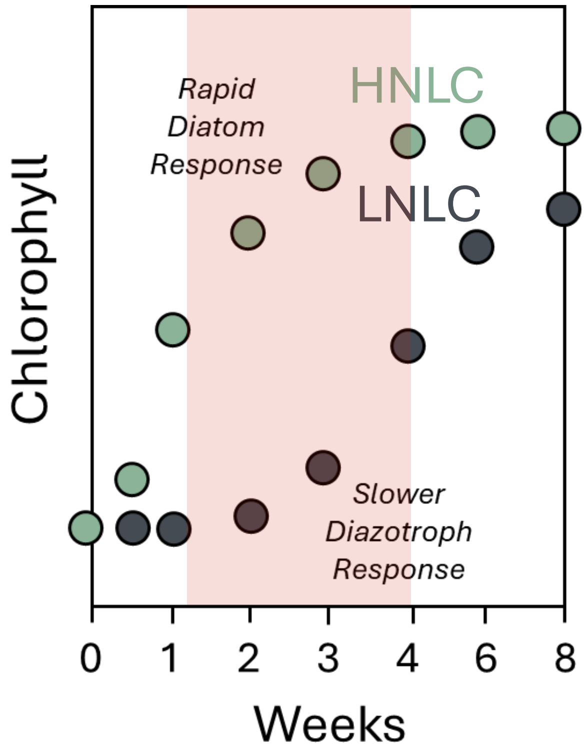


Seelen, unpublished PERI-DICE Incubation

New Caledonian Lagoon



Bonnet et al. 2016, *Biogeosciences*



Part 1:

*GEM Goals
*Overview of the Protocol

Part 2:

*SPOT Test
*Planned Experiments

Test #1: SPOT

Water Collection

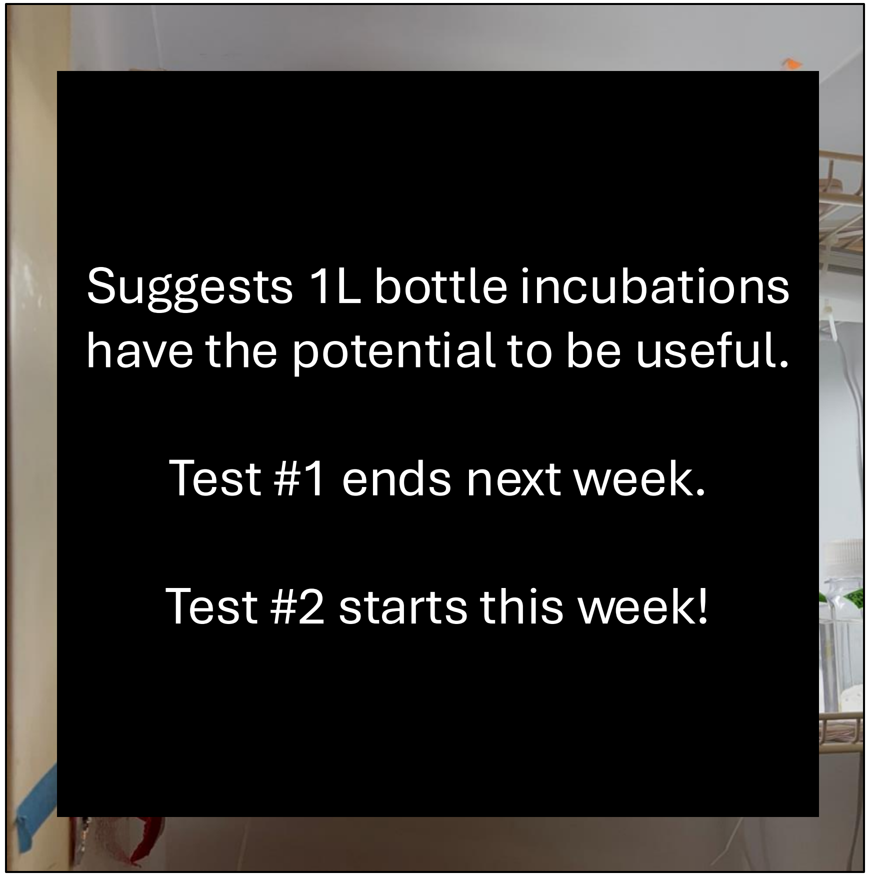
to USC

Treatments

Control
+Rice Husk
+Nitrate
+Nitrate +Husk

Experiment conducted by Nataly Pineda, PhD Student, USC

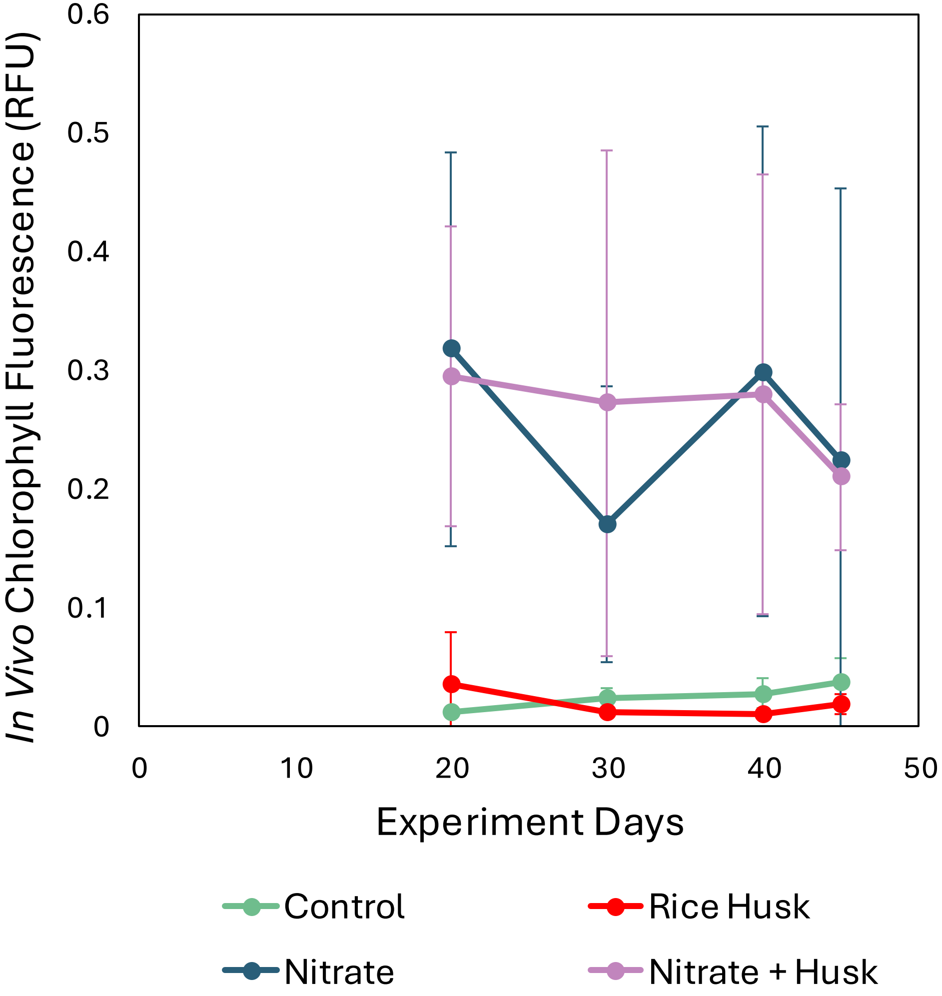
In vivo chl remains elevated in +nitrate treatments.
3x increase in the controls from day 20 to day 45.
No measurable influence due to the addition of rice husks.



Suggests 1L bottle incubations have the potential to be useful.

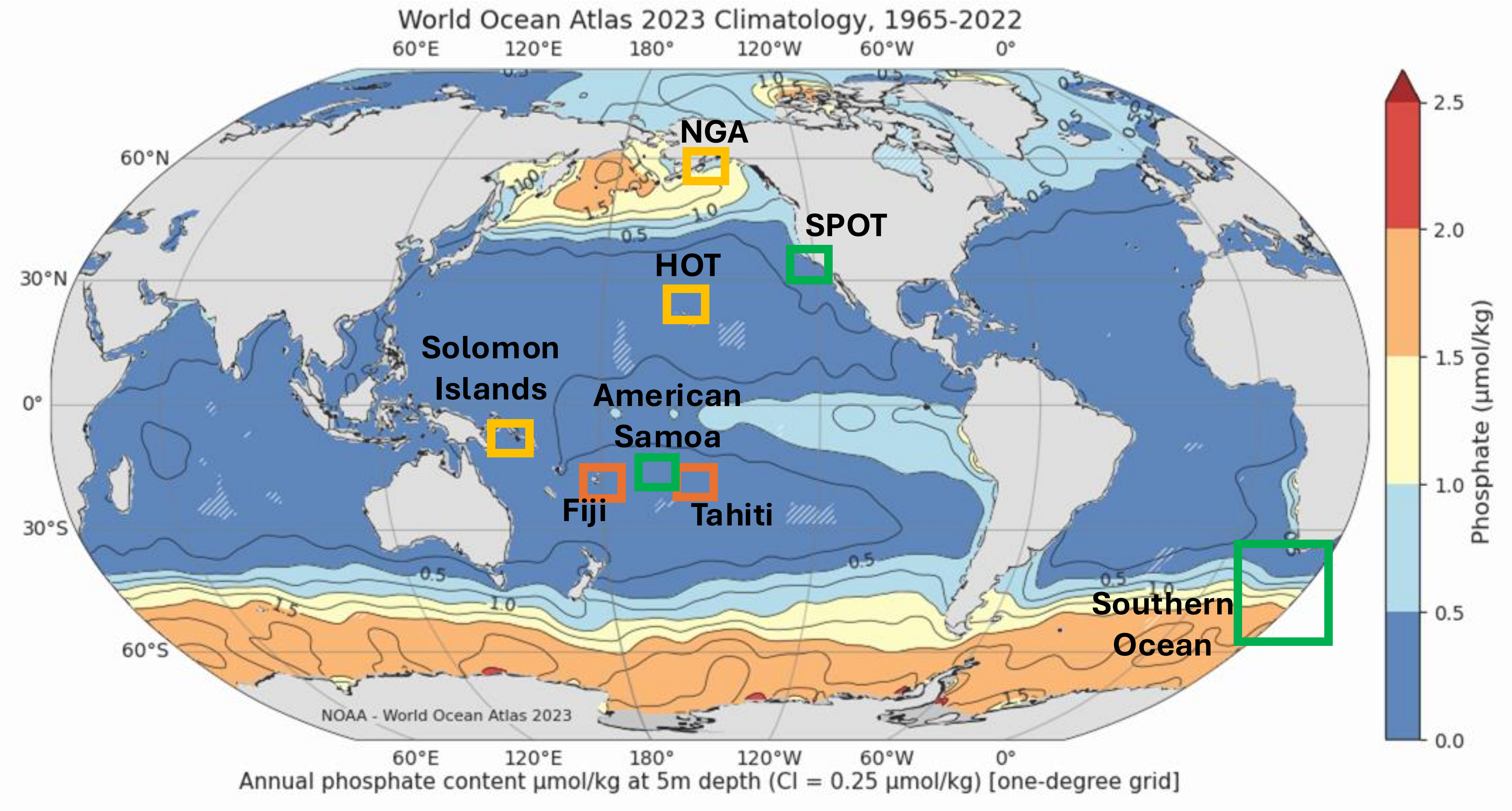
Test #1 ends next week.

Test #2 starts this week!



Diss. iron at SPOT is typically >1 nM in the winter

Where to next?


World Ocean Atlas 2023 Climatology, 1965-2022

Annual phosphate content µmol/kg at 5m depth (CI = 0.25 µmol/kg) [one-degree grid]

Thank you!

in collaboration
with the
Marine Biomass
Regeneration
consortium

GEM

Global
Experiment
for
Marine
Biomass
Regeneration

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