# Pacific N cycle from a global flux perspective

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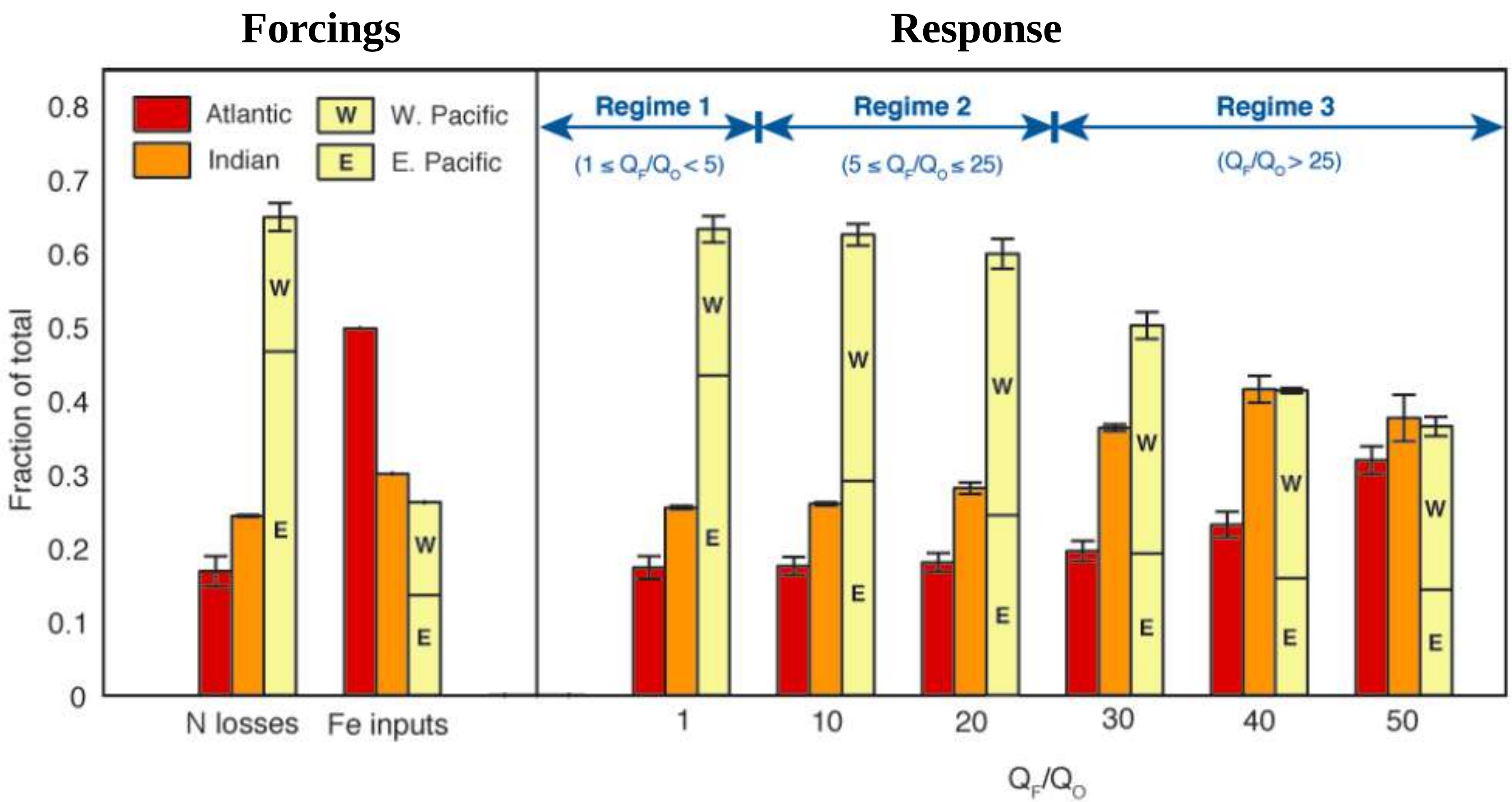
**Outline**

1) $N_2$ fixation
2) Denitrification

Acknowledgements:
J. Penn, T. Ito, T. Weber, D. Bianchi

# $N_2$ Fixation: Opposing Stimuli




**Diazotroph Fe limitation governed by cellular Fe:P quota ($Q_F/Q_o$)**
**At low Fe limitation, $N_2$ Fixation distributed like denitrification.**
**As Fe limitation increases it starts to reflect dust deposition.**

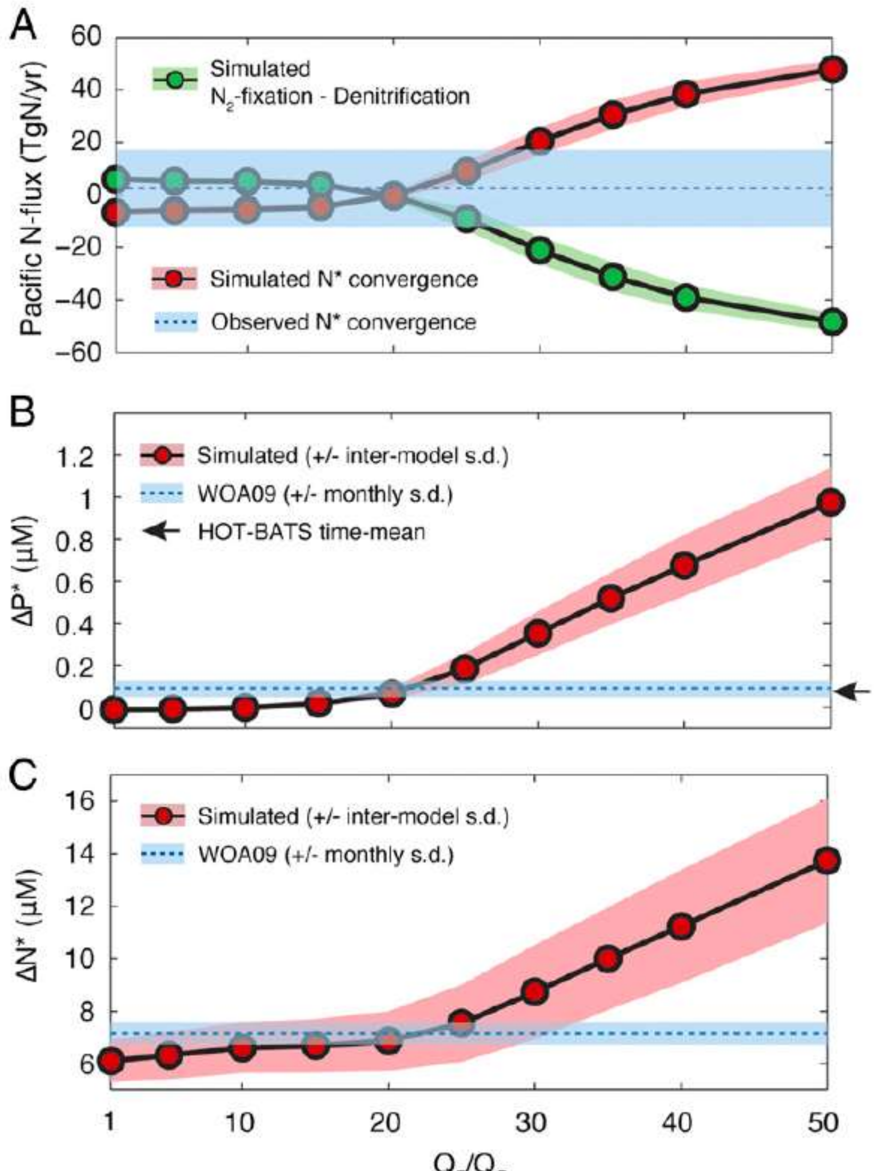
***Weber and Deutsch [2014]***

# Which regime are we in?

**Pacific Basin**
**Budget imbalance**

**Surface excess $PO_4$**
**Pacific-Atlantic**

**Thermocline $NO_3$**
**deficit**
**Pacific-Atlantic**



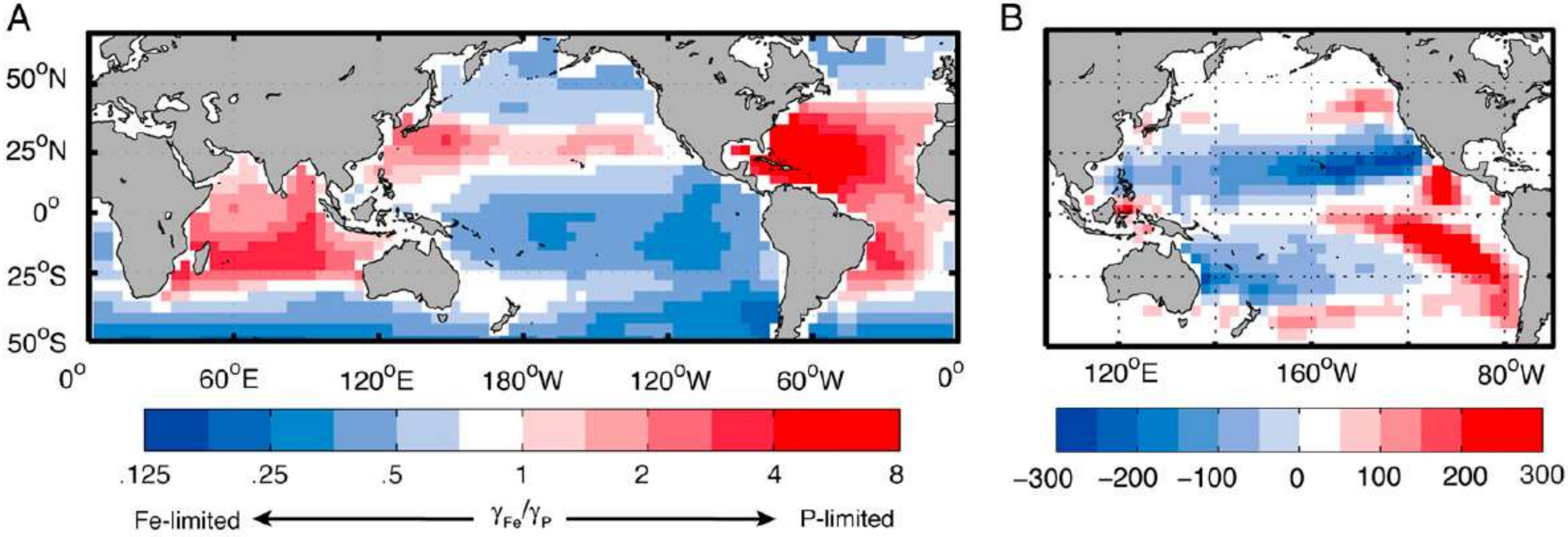

**All these data constraints (and more) are best matched in the intermediate Fe limitation regime (Regime 2).**

***Weber and Deutsch [2014]***

# Scale-dependent Limitation

Fe vs $PO_4$ limitation

Response to fertilization




**→ While locally Fe limitation is widespread in Pacific, Basin scale $N_2$ fixation is limited by supply of excess P.**

***Weber and Deutsch [2014]***

# Changing ‘excess’ P supply

$$DS \sim \overline{w}\,DP^{*} + Dw\,\overline{P}^{*}$$

Denitrification effect | Circulation effect

<u>A few mechanisms:</u>

1) Tropical Winds
   - A double whammy
2) Microbial community
   - Ecological amplifier
3) Aerosol pollution
   - Trace metal revenge

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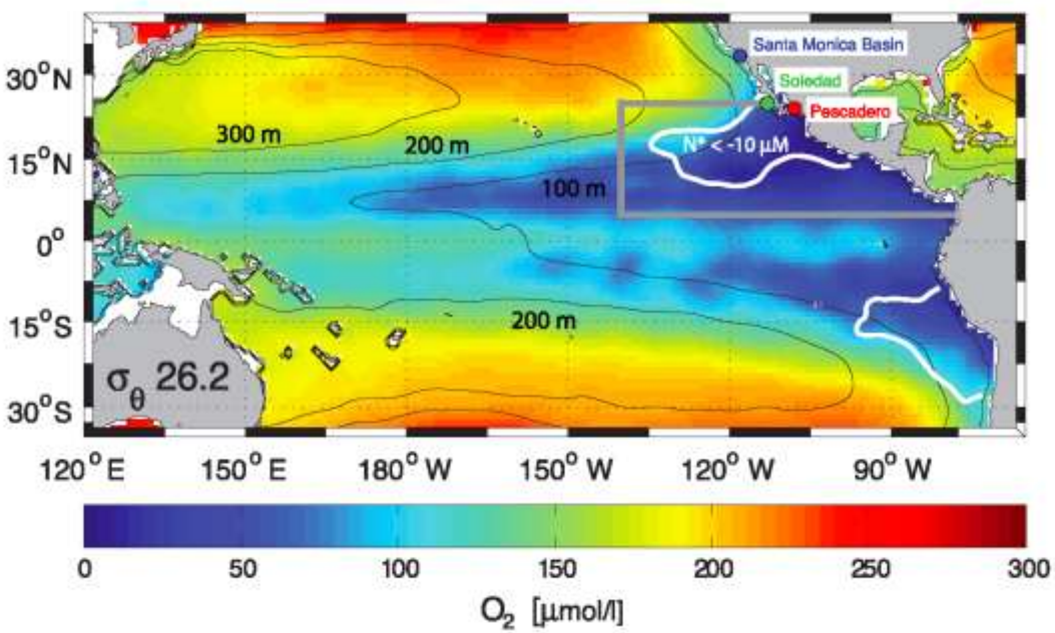
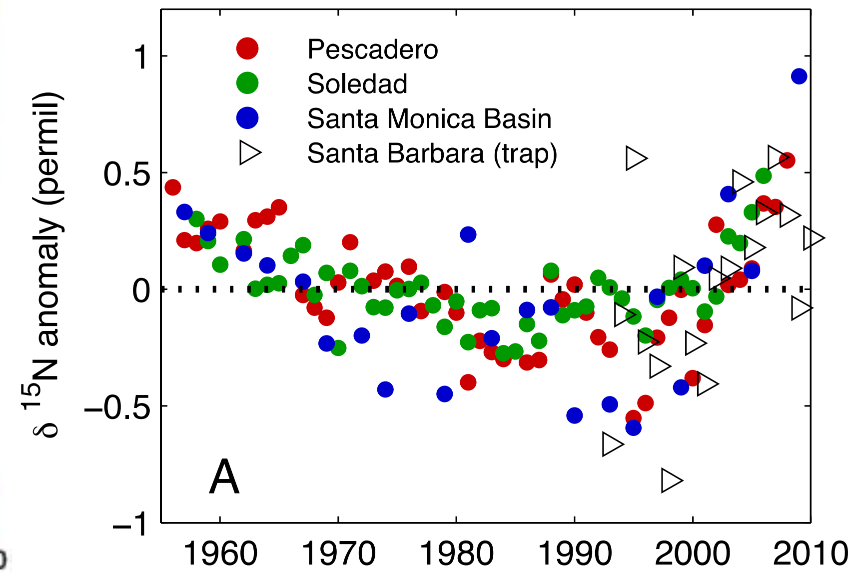
# Reconstructing N loss



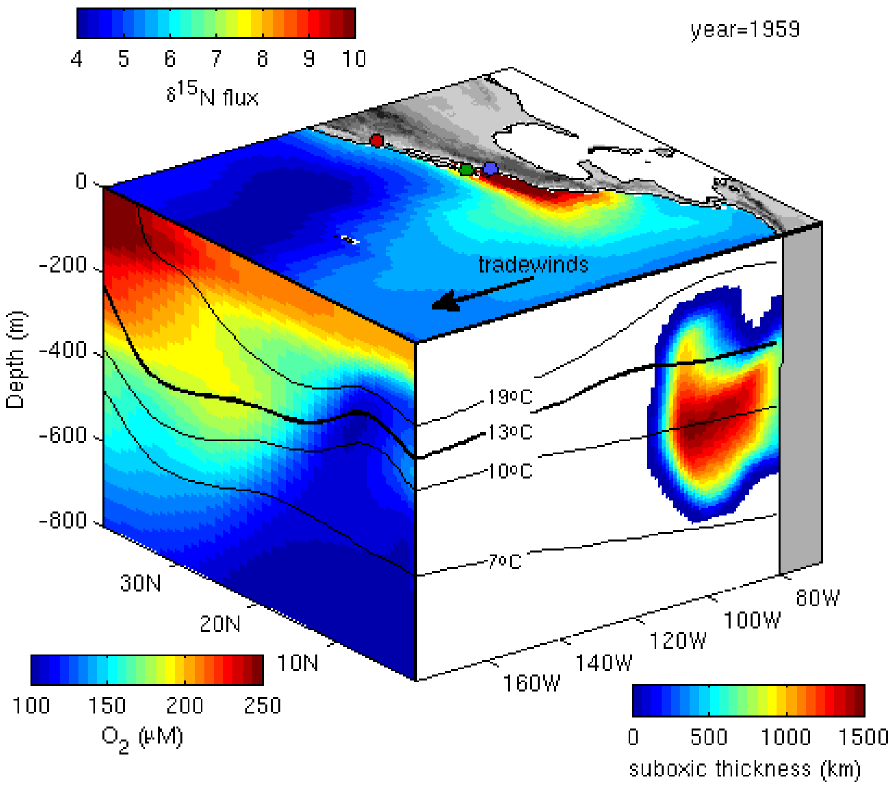

*Data: VanGeen, Berelson, Thunell*

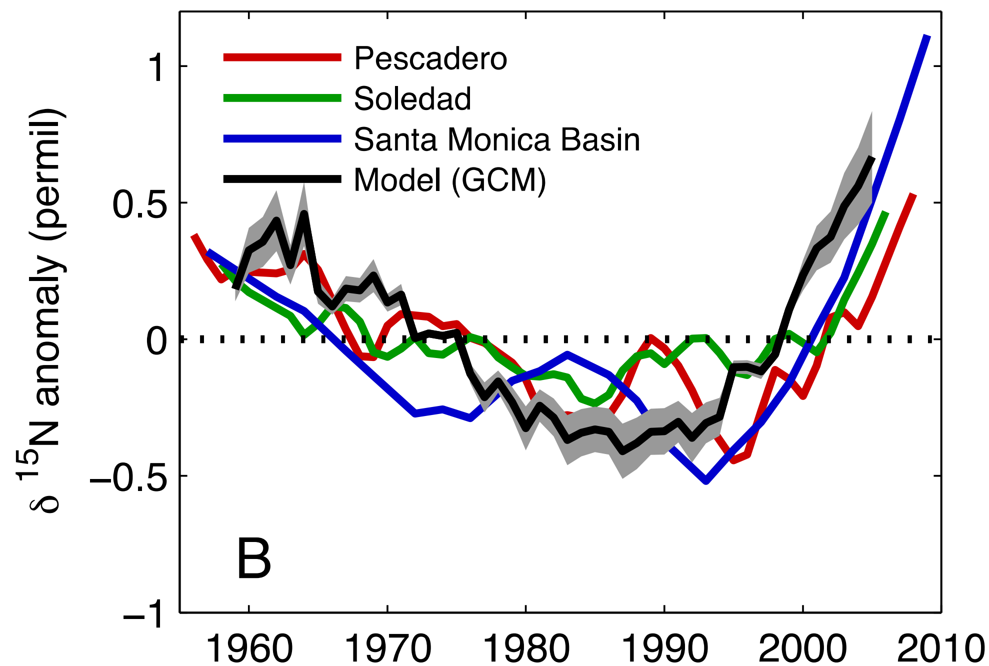
N isotope ratio elevated by N loss via denitrification.
Signal upwelled, transferred to phytoplankton, deposited onto sediments.

→ Recent increase in N loss since ~1990, preceded by a $\delta^{15}N$ decrease.

***Deutsch et al. [2014]***

# Attribution by Ocean Model



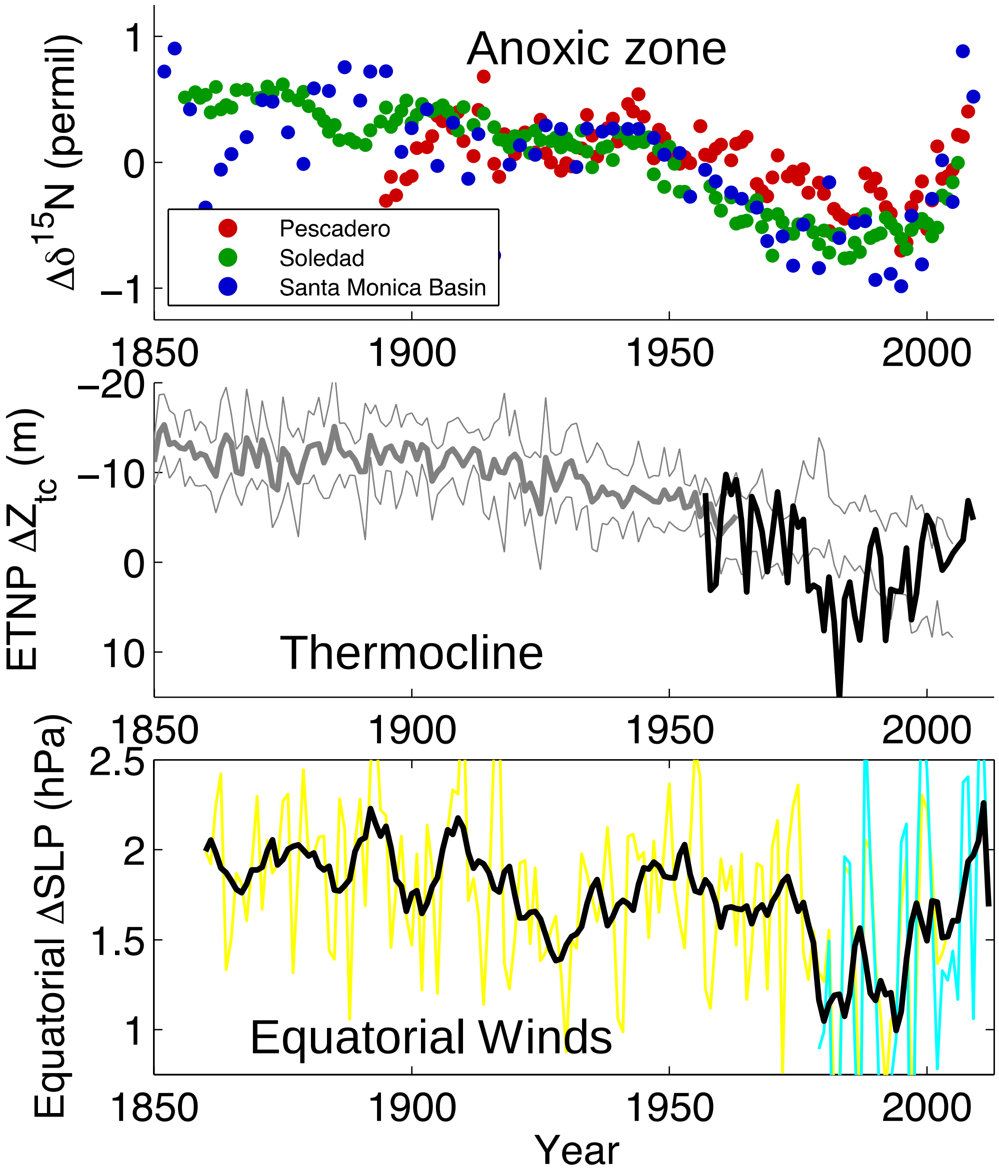




Global circulation model with isotope-enabled N cycle, driven by historical surface conditions (winds, heat flux, etc.)

Hindcast of 20th Century climate variability with geochemical N cycle directly reproduces observed sedimentary isotope record.

***Deutsch et al. [2014]***

# Link to centennial wind trends




The recent changes in N loss appear to be driven by intensified trade winds.

Future Pacific trade winds are projected to decline with further warming.

***Deutsch et al. [2014]***

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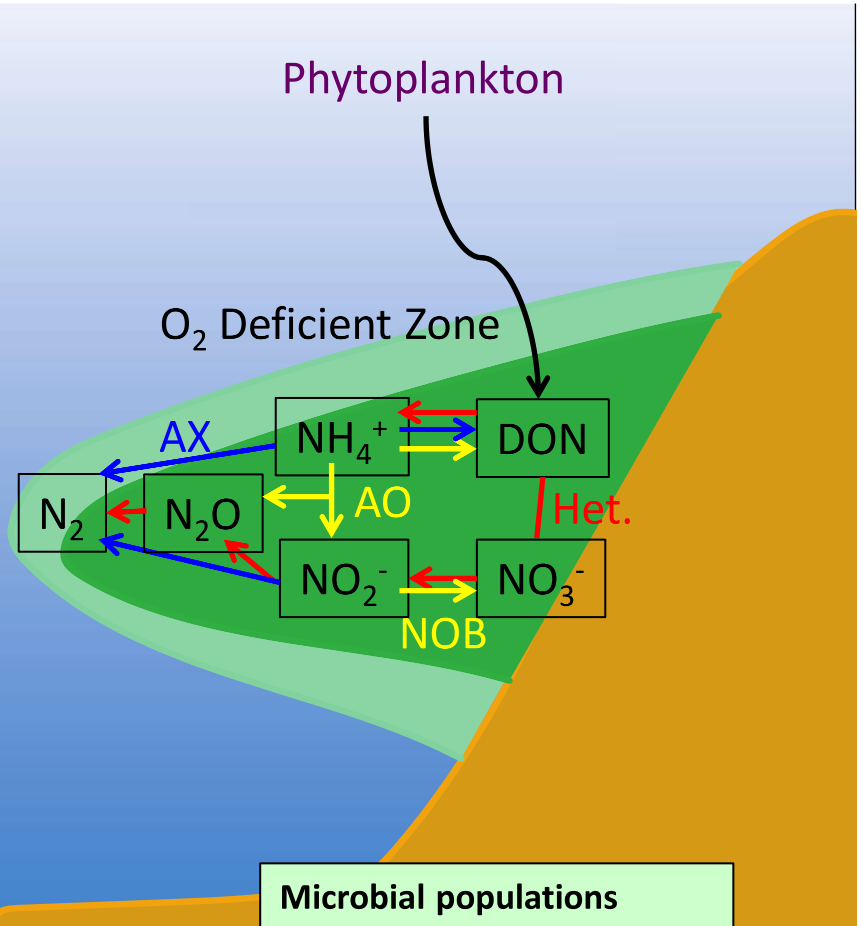
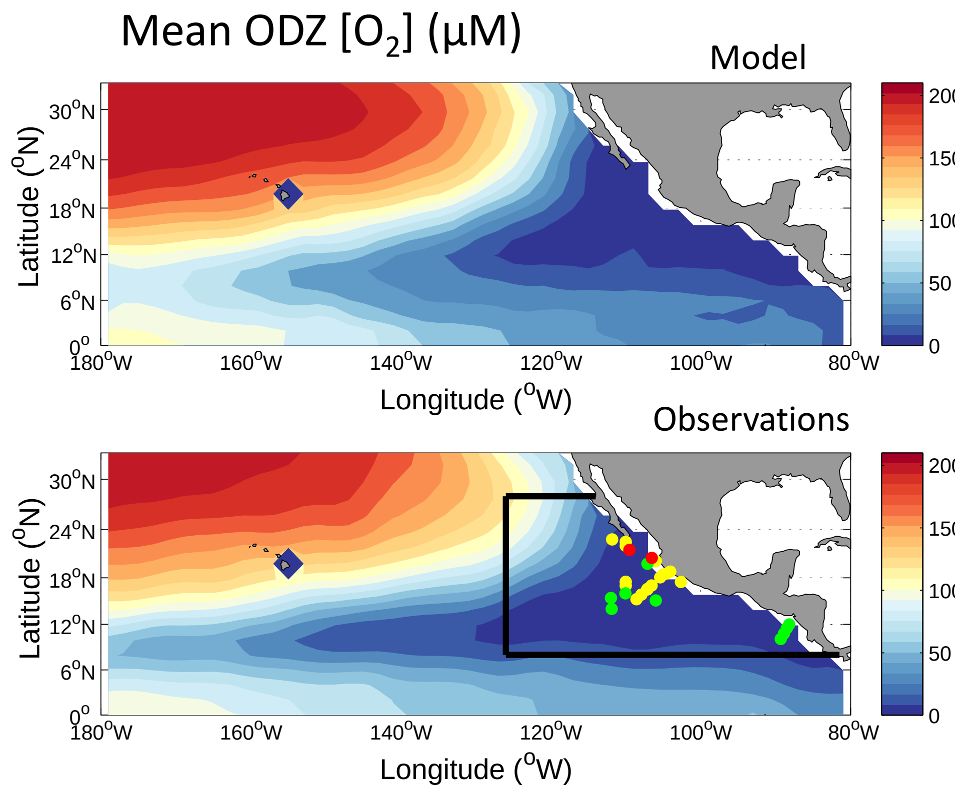
# Microbial Ecosystem Model



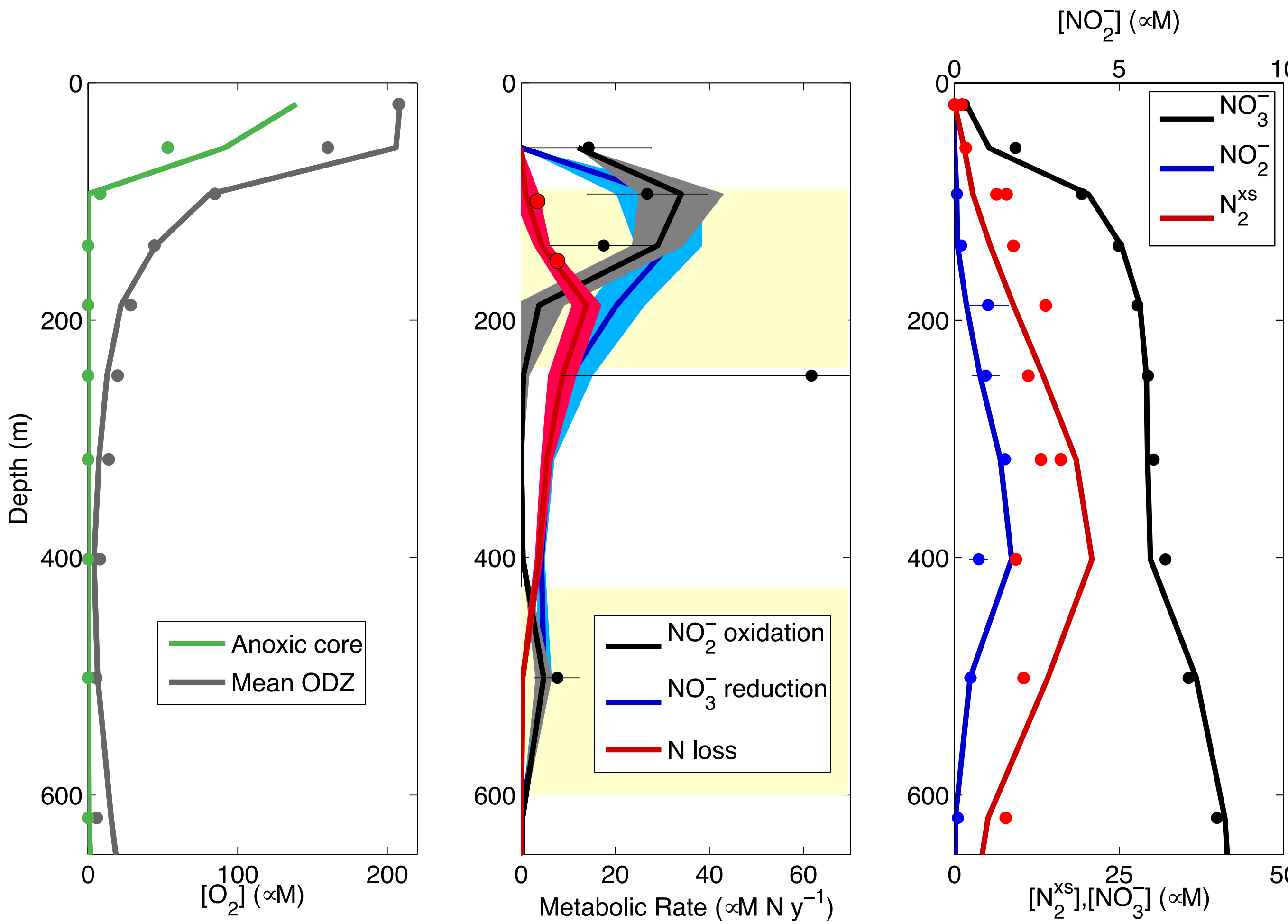




**Microbial populations**
$NH_4$ oxidizing archaea (AO)
$NO_2$ oxidizing bacteria (NOB)
Anammox bacteria (AX)
Heterotrophic bacteria (H) – facultative denitrifier

Ammonium NH4
Nitrite (NO2)
Nitrogen gas (N2)
Nitrate (NO3)
Oxygen (O2)
Nitrous Oxide (N2O)

*Penn et al. [in review]*

# Metabolic Rates & Tracers




Model reproduces observed metabolic rates and chemical levels within the North Pacific.

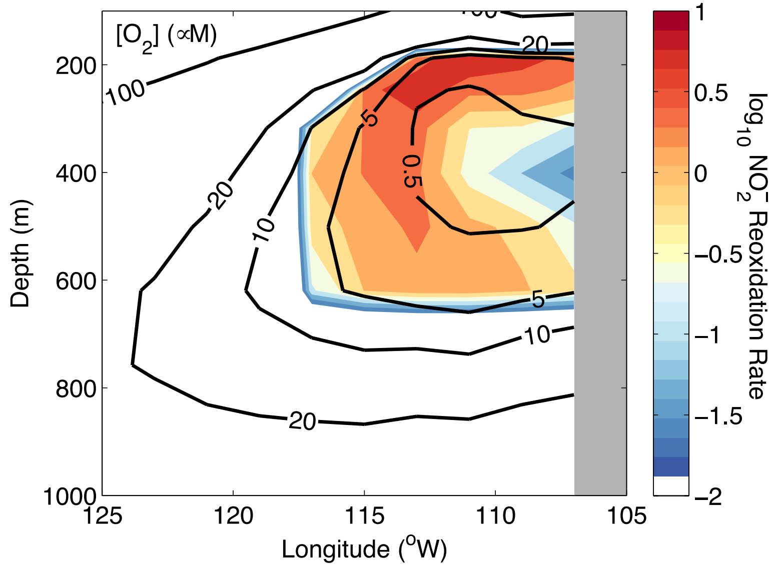
$O_2$ controls habitat partition.

Microbial coexistence patterns produce distinct chemical regimes.

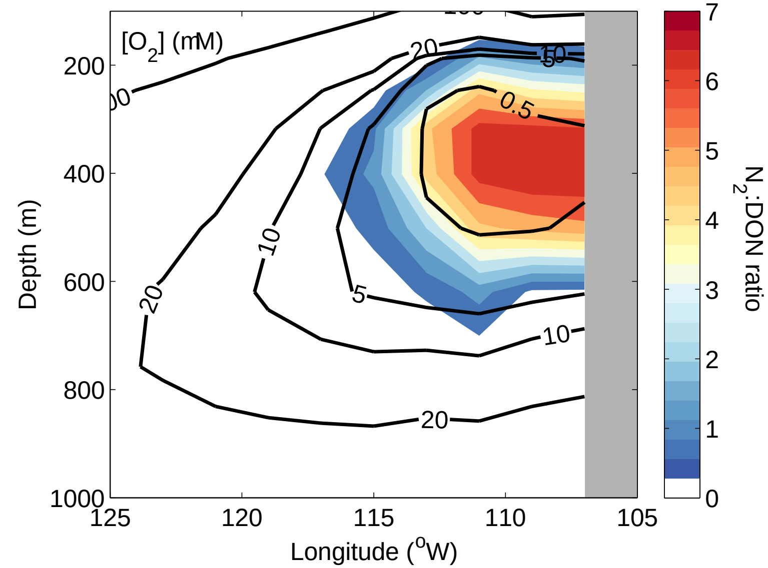
***Penn et al. [in press]***

# Aerobic/Anaerobic overlap

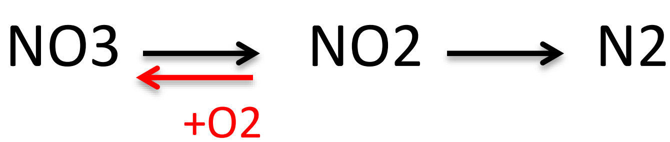
Log$_{10}$ $NO_2$ reoxidation rate




$N_2$:DON ratio




Denitrification




NO2 reoxidation

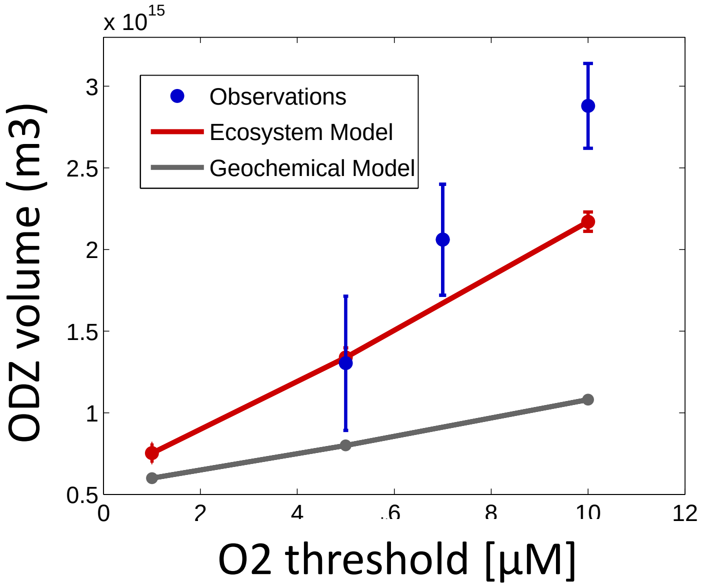
Coexistence of nitrifiers and denitrifiers allows $NO_2$ to be reoxidized back to $NO_3$.

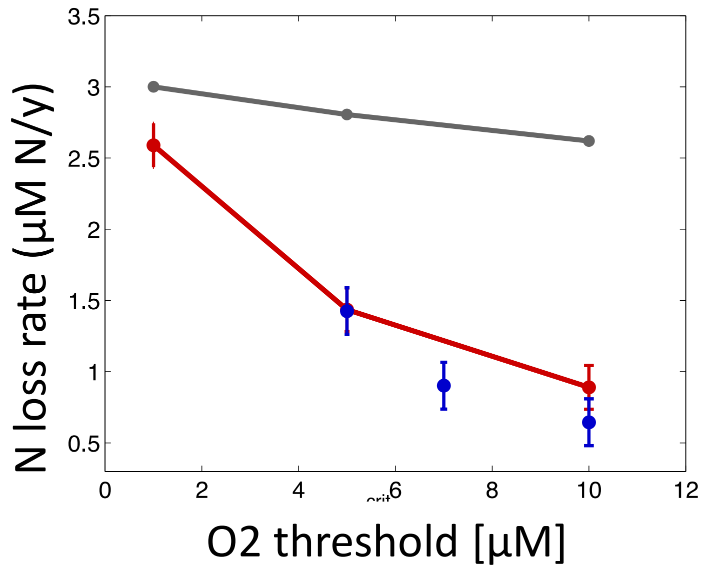
This increases $O_2$ consumption and lowers the stoichiometry of N loss.

***Penn et al. [in press]***

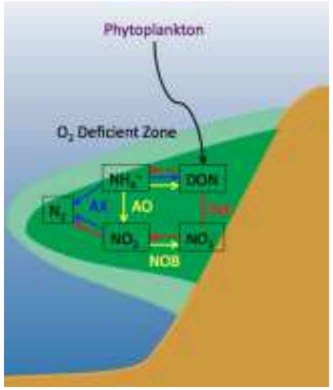
# Biogeochemical Implications

## 1) Mean state of ODZ

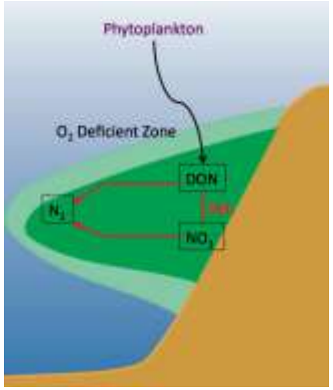



Ecosystem




Geochemical



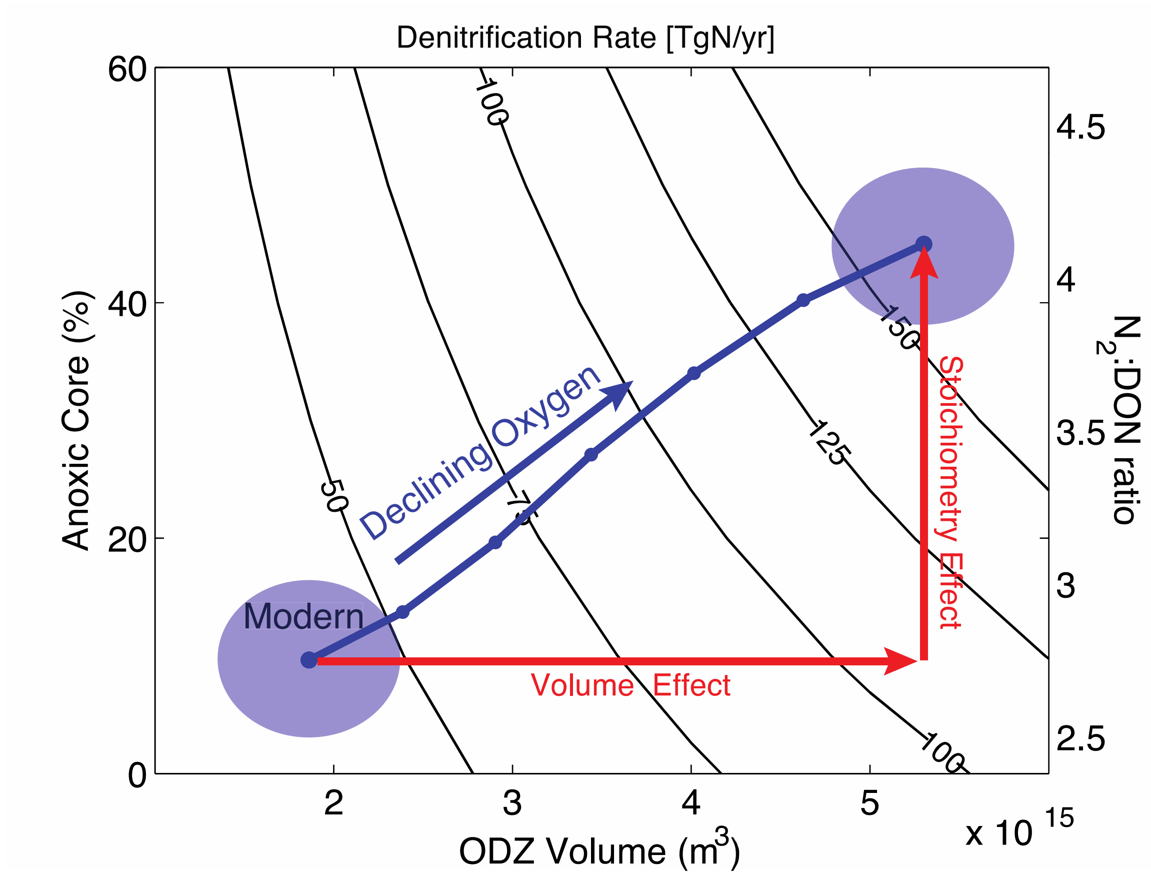

Compared to a geochemical model the ecosystem produces a larger anoxic zone, but a slower rate of N loss, aligning it with observations.

Ecosystem model predictions are most sensitive to the $O_2$ threshold for denitrification ($O_2^{crit}$), but opposing sensitivities make total N loss insensitive to $O_2^{crit}$.

***Penn et al. [in press]***

# Biogeochemical Implications

## 2) Sensitivity of N loss




Changes in microbial community structure associated with the geometry of the ODZ amplify the rate of N loss in response to deoxygenation.

***Penn et al. [in review]***

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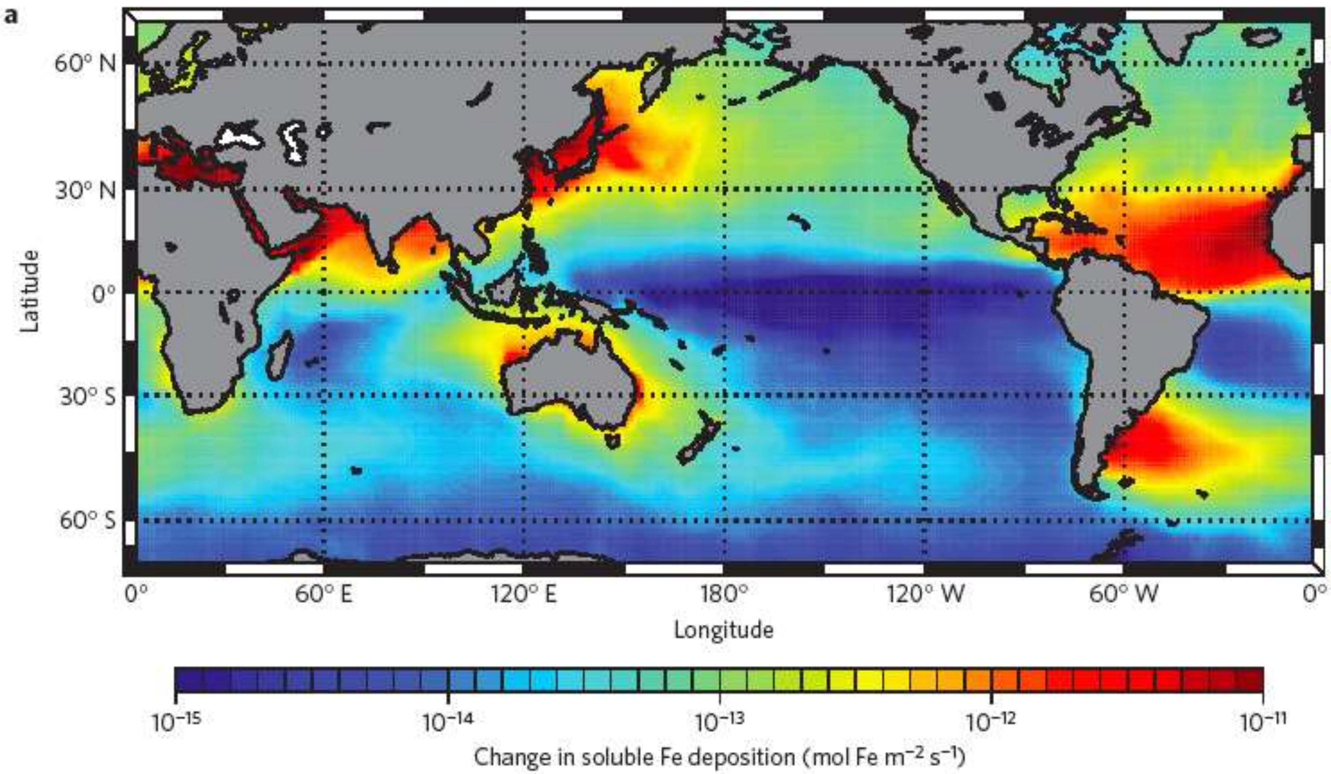
# Solubilization of Fe

Estimated change in soluble Fe from acidification of atmospheric aerosols.

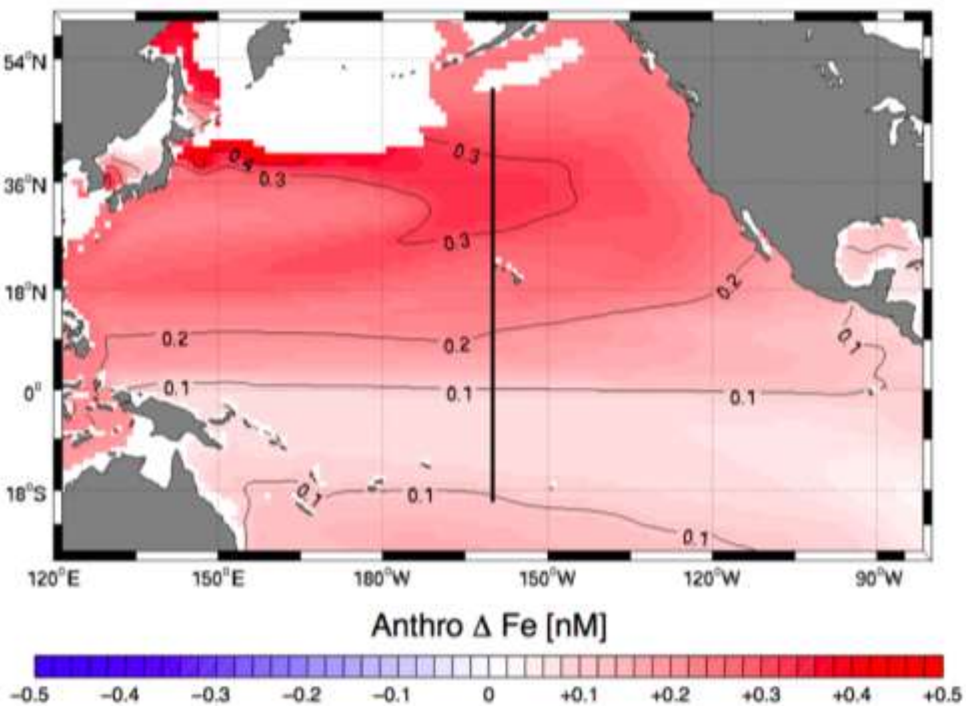


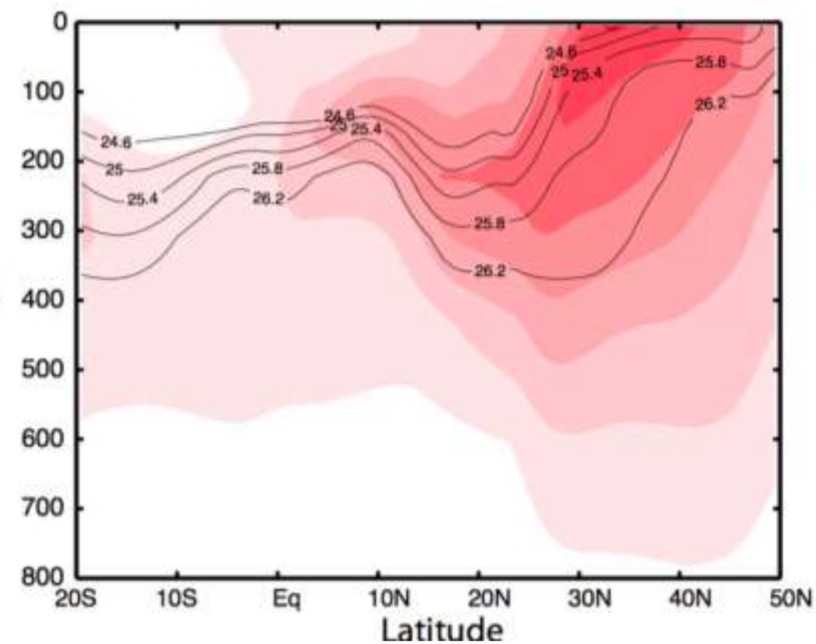

Could this have altered the ocean's oxygen minimum zones?

***Ito et al. [2016]***

# Spreading of Fe perturbation

Simulations with an ocean model ecosystem and Fe cycle (MITgcm).

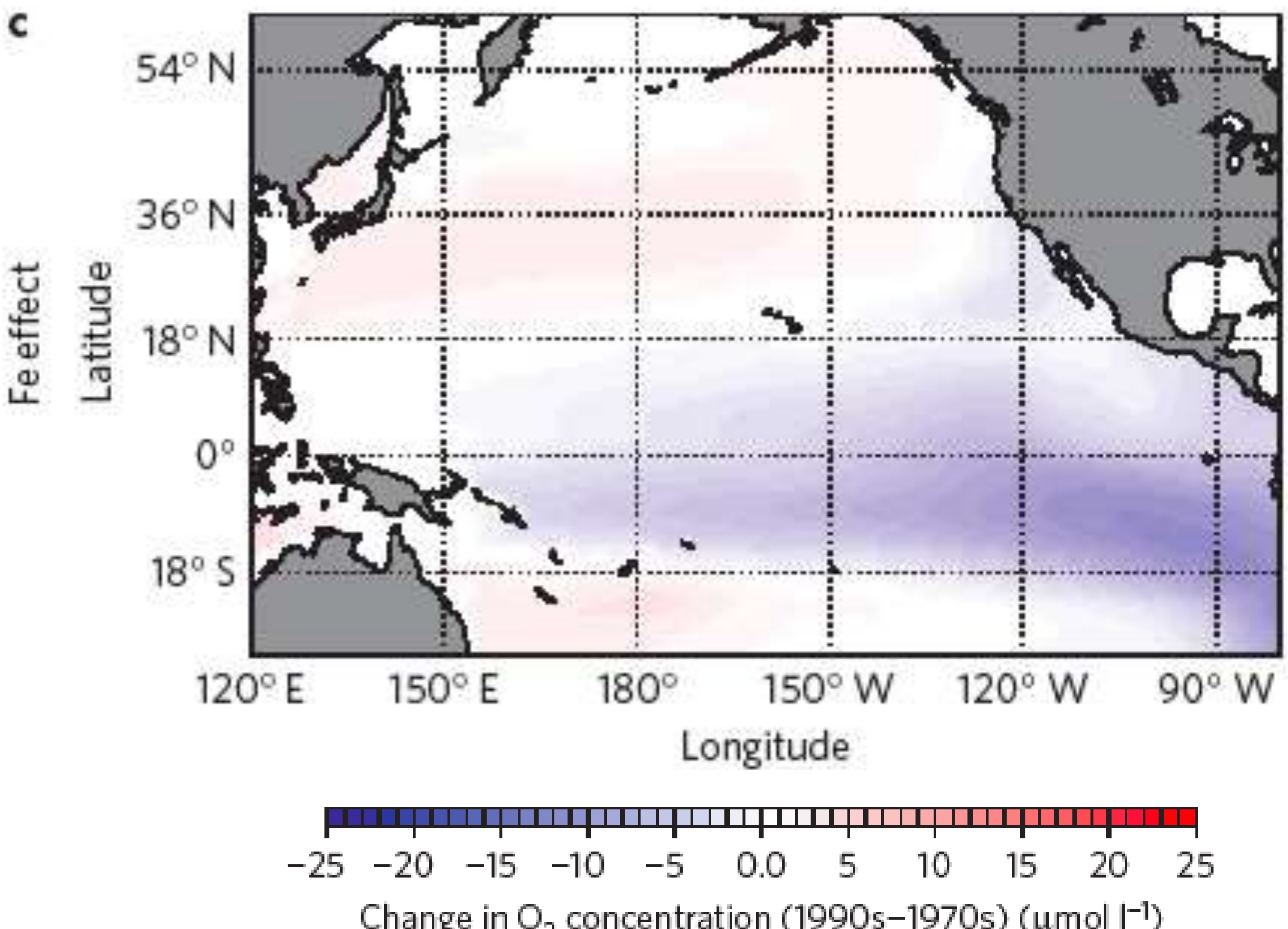



Increasing mid-latitude Fe deposition spreads along isopycnals to the tropical thermocline.

*Ito et al. [2016]*

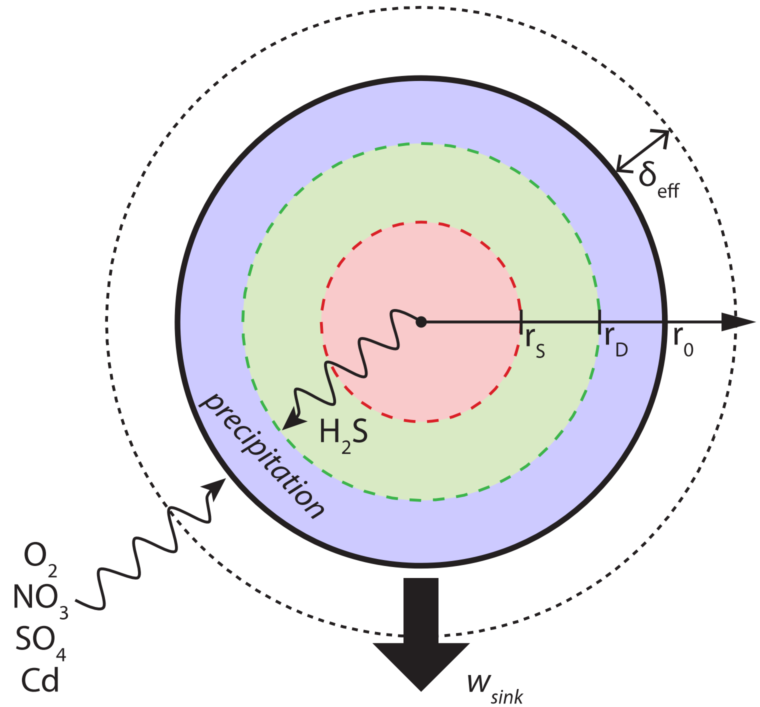
# Remote effects




Increased upwelled Fe supply to equatorial HNLC depletes subsurface $O_2$ by 5-10 uM.

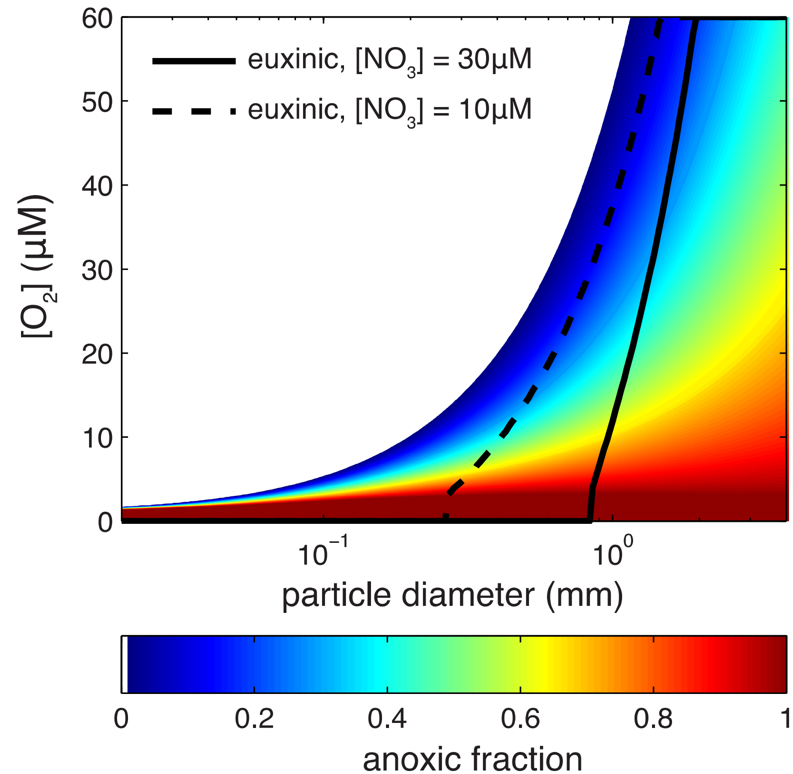
***Ito et al. [2016]***

# Anoxic Microenvironments?




$$\frac{d^2X}{dr^2} + \frac{2}{r}\left(\frac{dX}{dr}\right) = \frac{R}{D_{agg}}$$

Reactions (R) include consumption of oxidants and precipitation of Cd




*Bianchi, Weber, Deutsch [in prep]*

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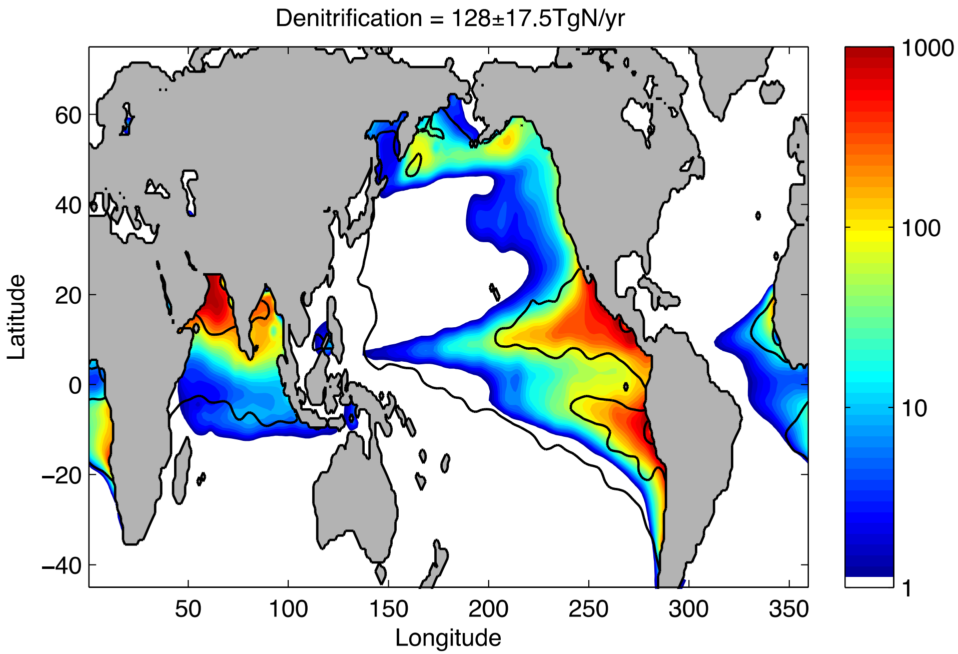
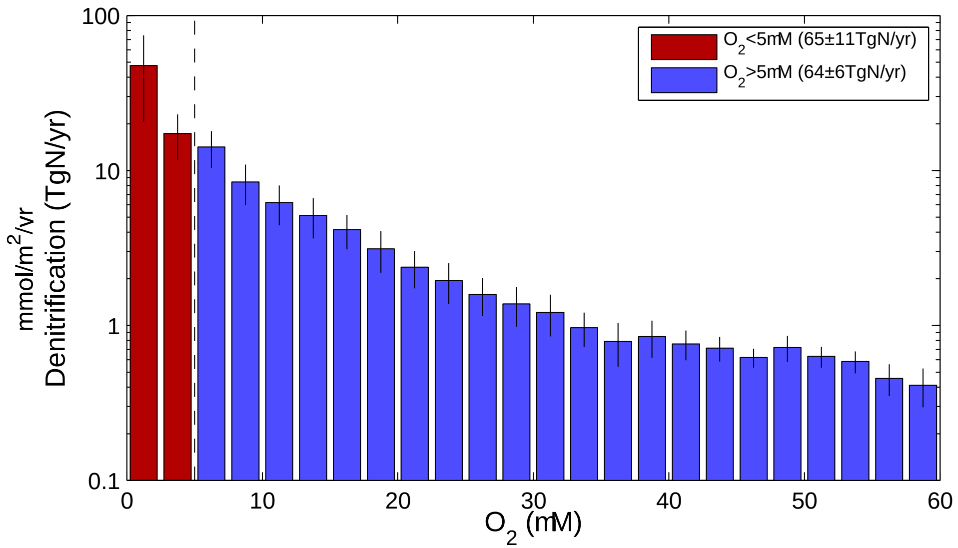


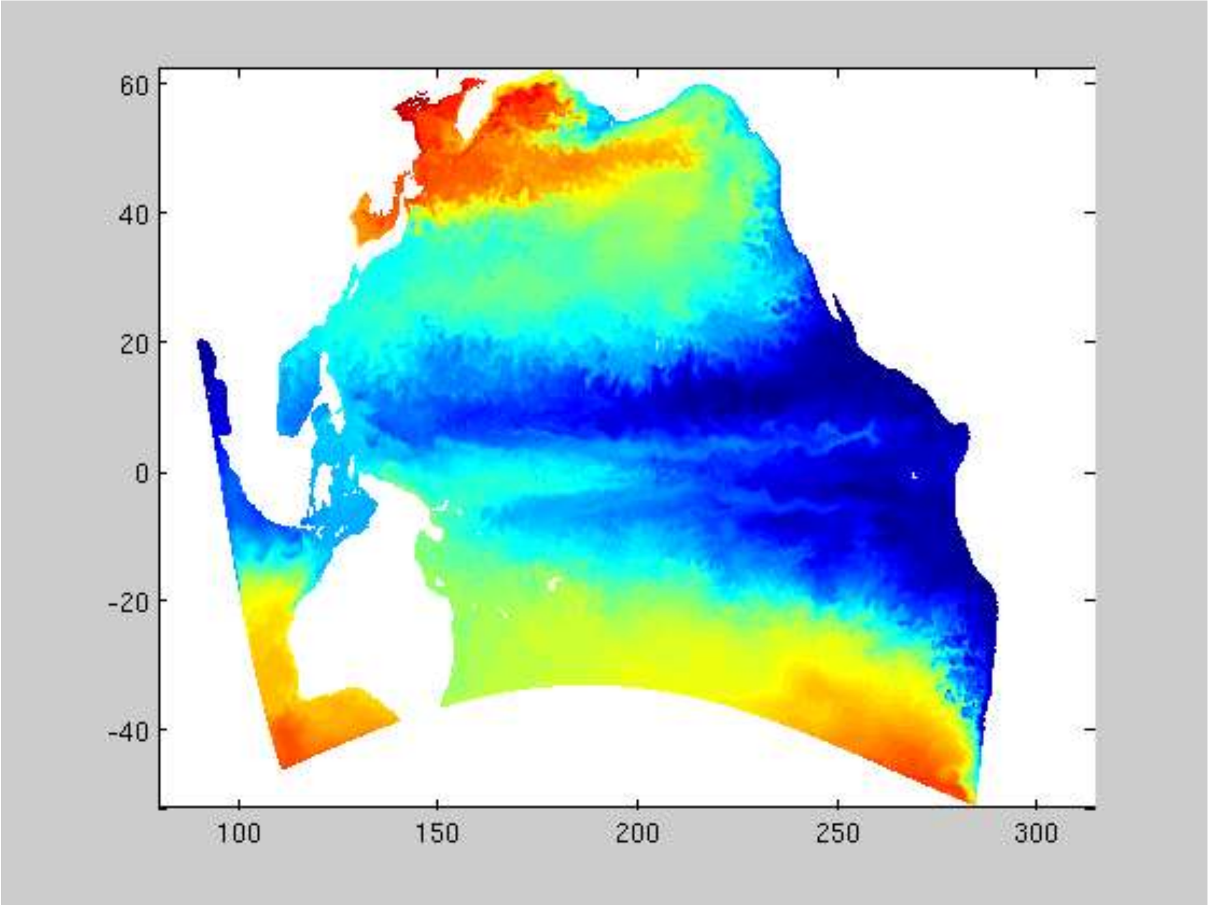




Diffuse particle-bound denitrification in hypoxic waters may contribute as much N-loss as suboxic zones themselves

*Bianchi, Weber, Deutsch [in prep]*

# Models and Geotraces data

Pacific $O_2$ on density surface ($\sigma$ 26.5) in eddying ocean model

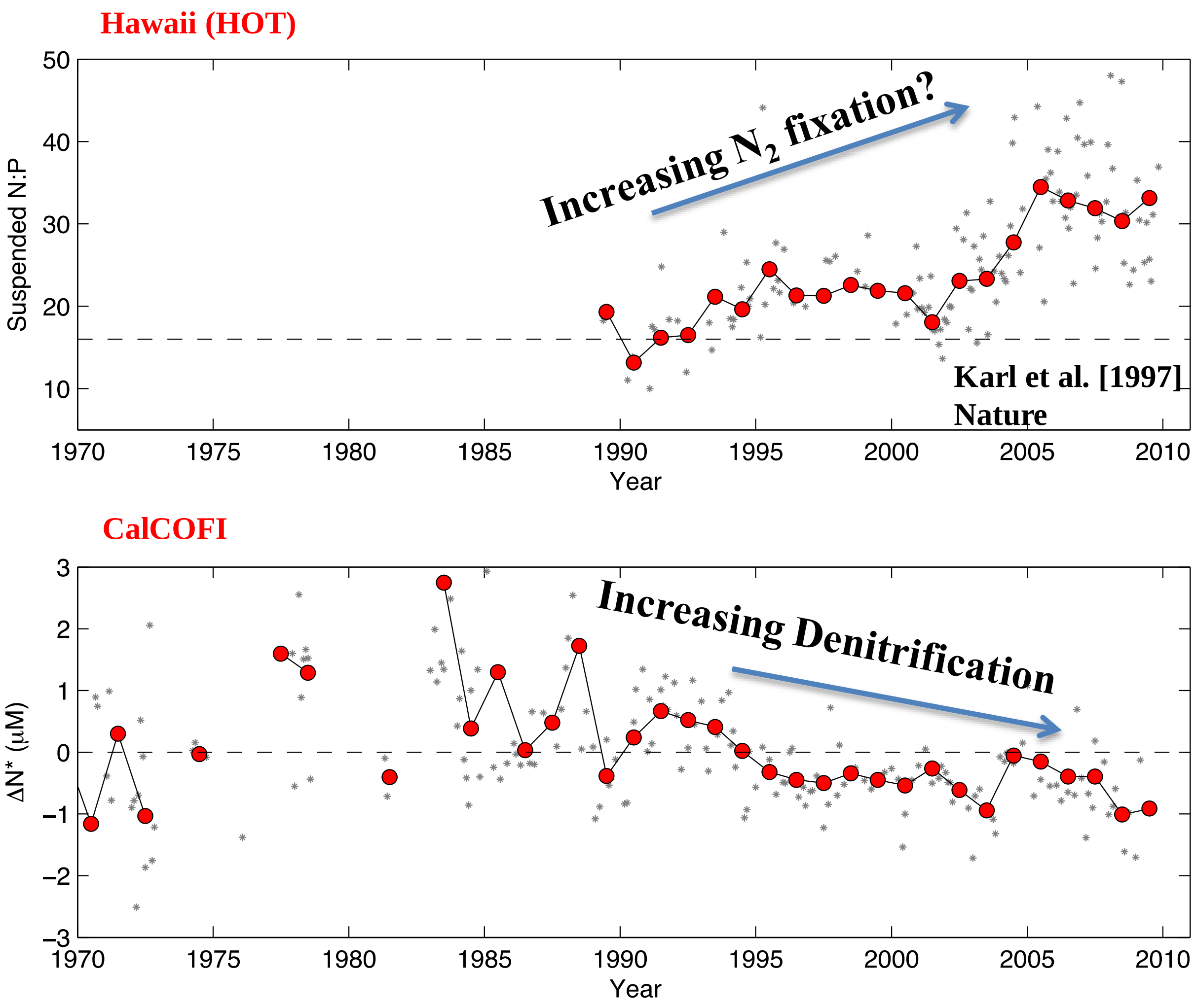



Biogeochemical processes in dynamic physical models facilitates model validation against synoptic data (e.g. Geotraces).

# Conclusions

- $N_2$ fixation redistributed by Fe supply within basins, but integrated rate set by N losses.
- Integrated N losses influenced by… everything! Including Fe deposition
- Anaerobic processes extend into P16 transect via zonal currents and particle reactions

# Denitrification vs $N_2$ fixation



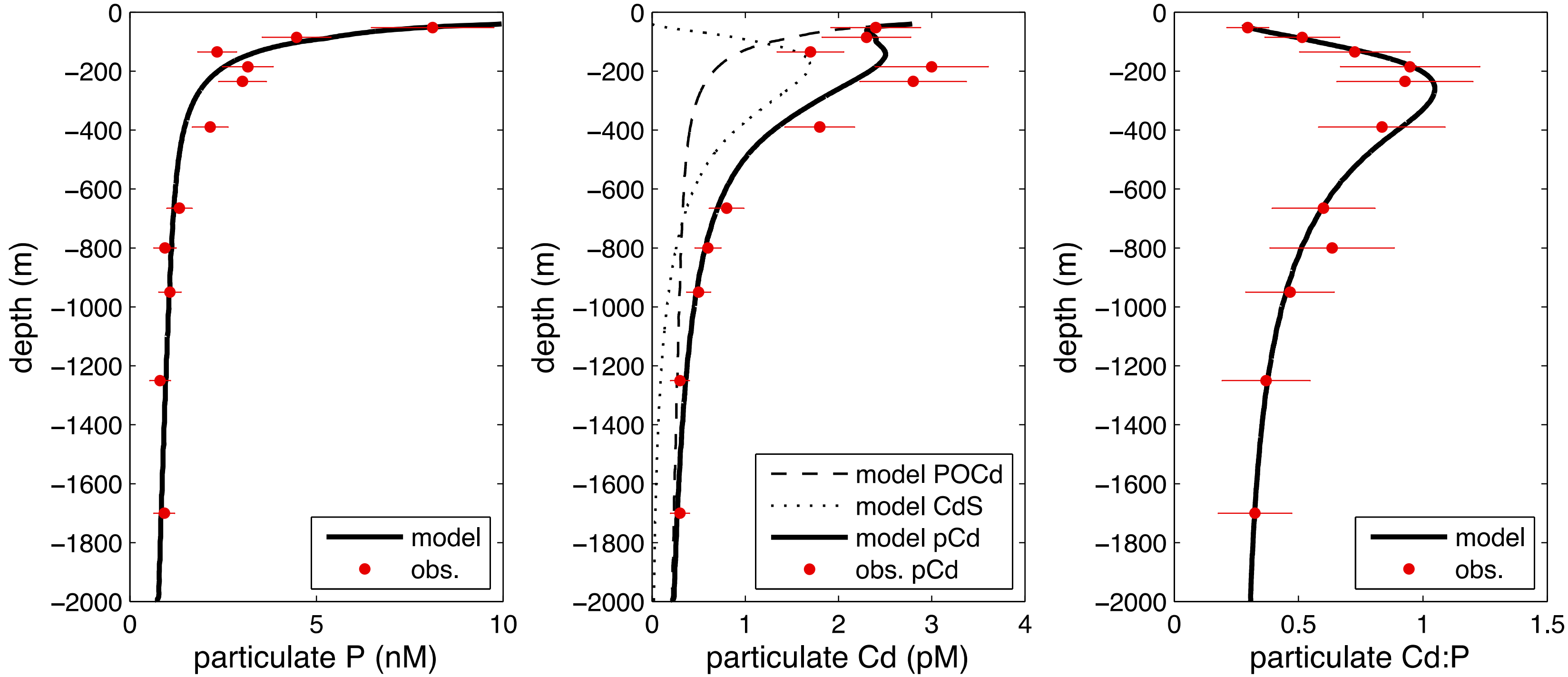

1) **Coincidence?**

2) **Evidence of feedback?**

1) **A common forcing?**

**Deutsch and Weber [2012]**
***Annual Reviews of Marine Science***

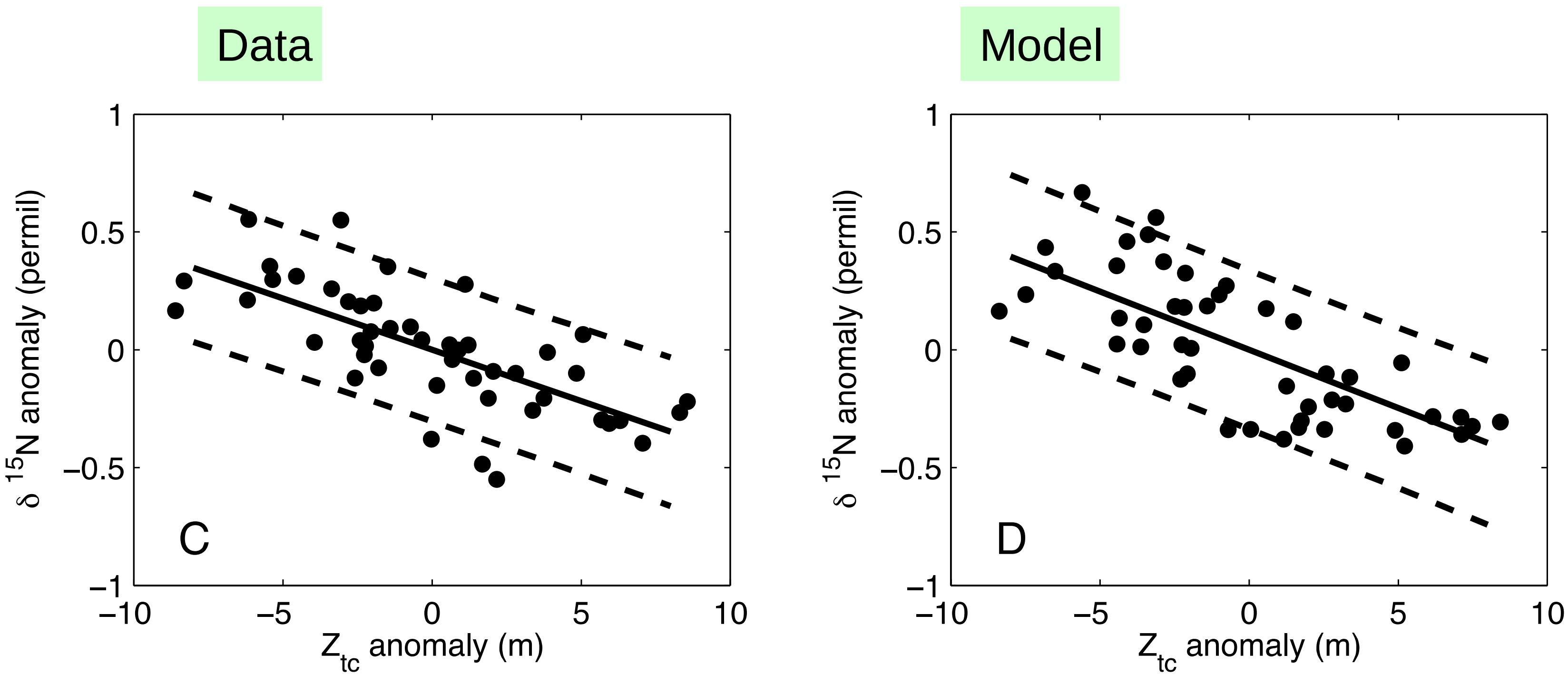
# Observational Validation




*Data: Janssen [2015]*

*Bianchi, Weber, Deutsch [in prep]*

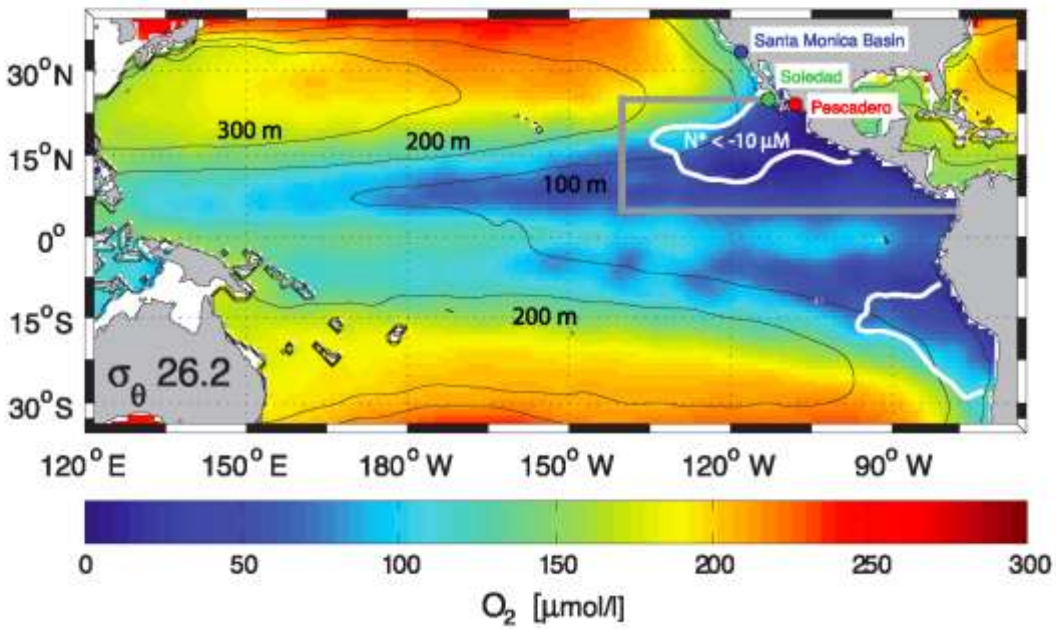
# Validating the mechanism

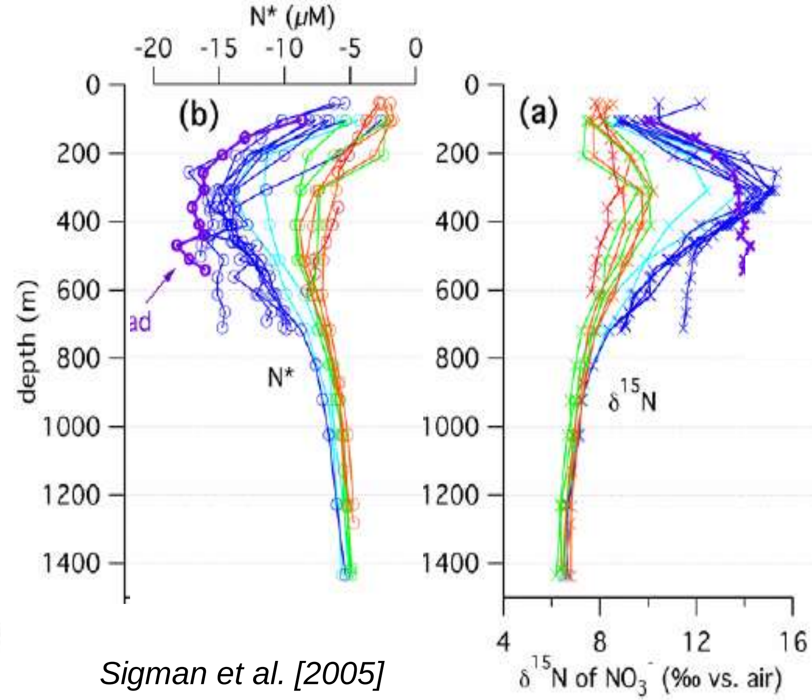



Relationship between thermocline depth and N isotope record is the same in model and data, confirming mechanism.

*Deutsch et al. [2014]*

# Geochemical signature




*Sigman et al. [2005]*

N isotope ratio elevated by N loss via denitrification.
High $^{15}NO_3$ upwelled, transferred to phytoplankton, deposited onto sediments.