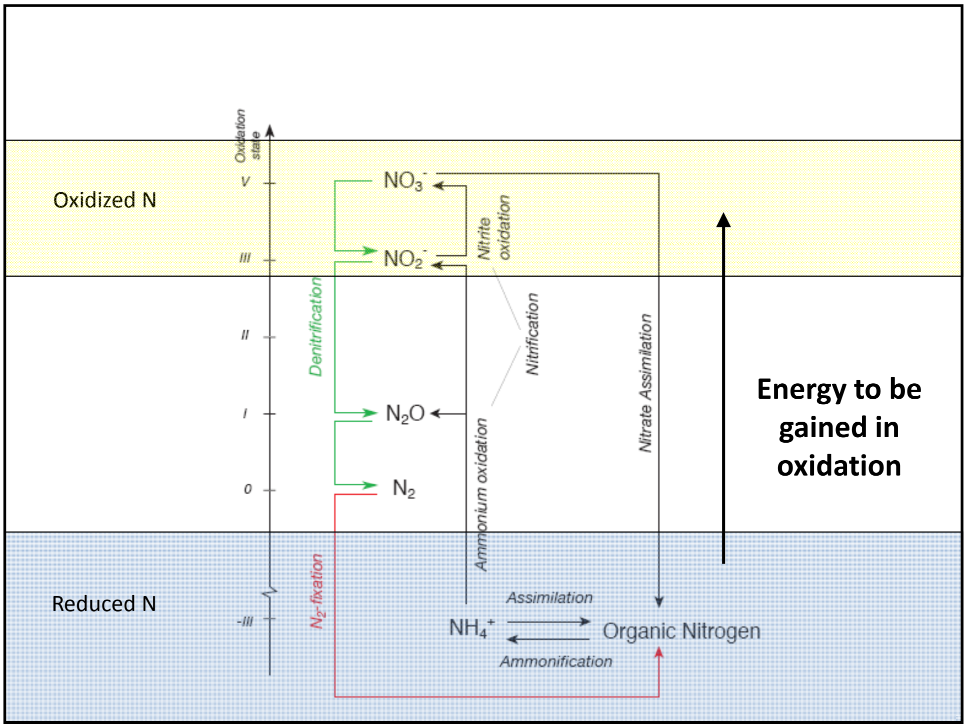


Denitrification

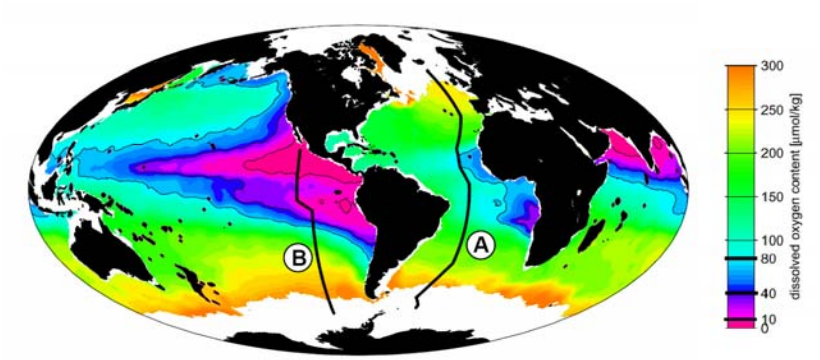
The reduction of NO_3^- and NO_2^- to N_2 during heterotrophic respiration of organic matter. Occurs predominately in anaerobic or suboxic environments.

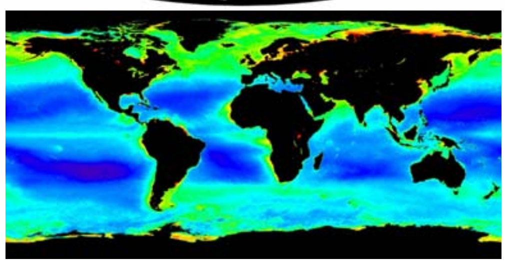
$$C_{106}H_{175}O_{42}N_{16}P + 104\ NO_3^- \Rightarrow 106CO_2 + 60N_2 + H_3PO_4 + 138\ H_2O$$

NO_3^- and NO_2^- are used as terminal electron acceptors during heterotrophic respiration.

Removal of NO_3^- by this mechanism in the ocean alters the $CO_2 : NO_3^- : PO_4^{3-}$ ratios

Oxygen concentrations along the 26.9 kg m^{-3} isopycnal surface (~500 m in the N. Pacific)

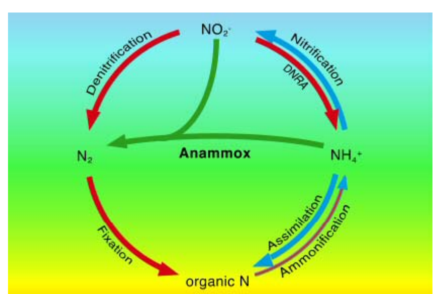




Chlorophyll distributions

Anaerobic ammonium oxidation (anammox)

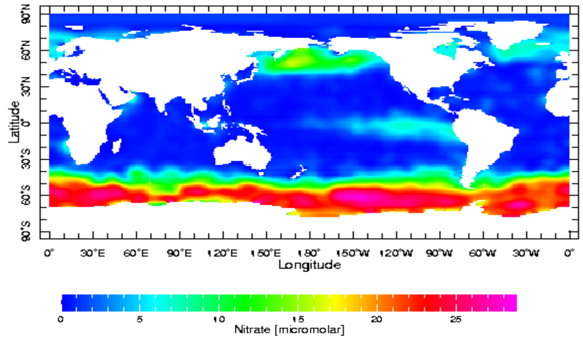
- $NH_4^+ + NO_2^- \Rightarrow 2N_2 + 2H_2O$
- Anaerobic ammonium oxidation
- Major source of N_2 gas (along with denitrification)
- Anoxic sediments, marine water column, and sewage wastewater
- Mediated by *Planctomyces*

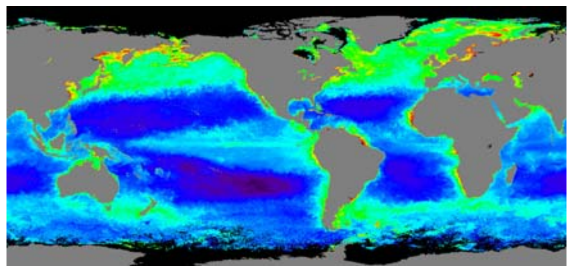


Average surface ocean nitrate concentrations

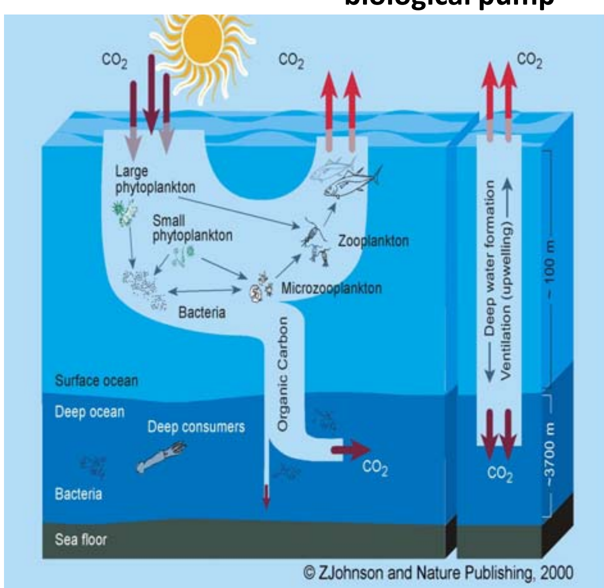
In ~1/3 of the ocean, excess nutrients are perennially available yet phytoplankton biomass is relatively low.

Such regions are termed High Nitrate Low Chlorophyll (HNLC) waters

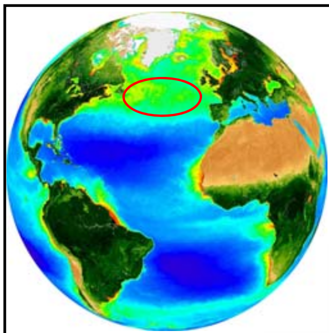




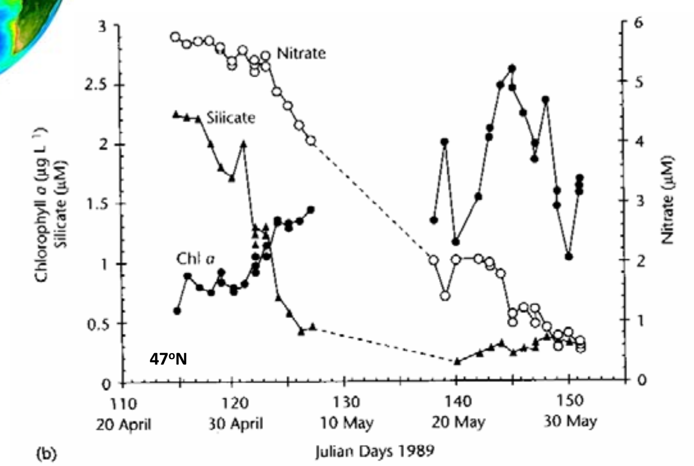
Whatever factors limit complete utilization of nutrients in HNLC regions have important consequences on the functioning of the biological pump



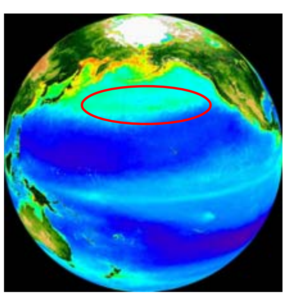
Such processes limit new production and thus ultimately export of carbon to the deep sea.



North Atlantic Spring Bloom



Subarctic North Pacific



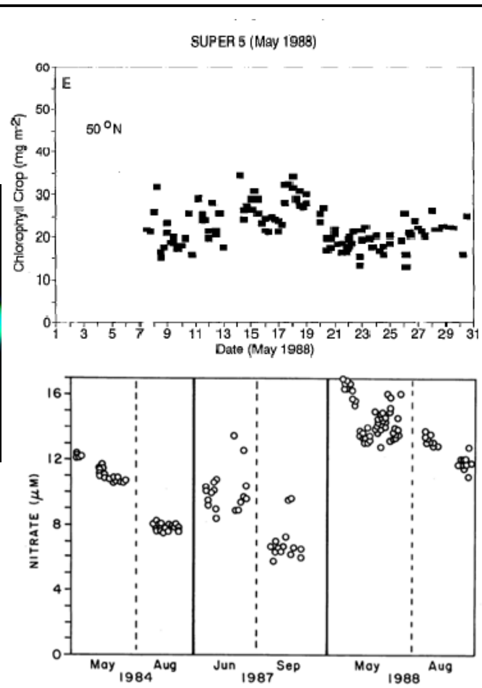
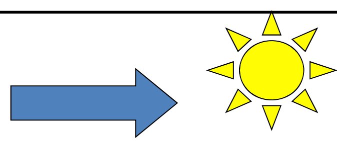


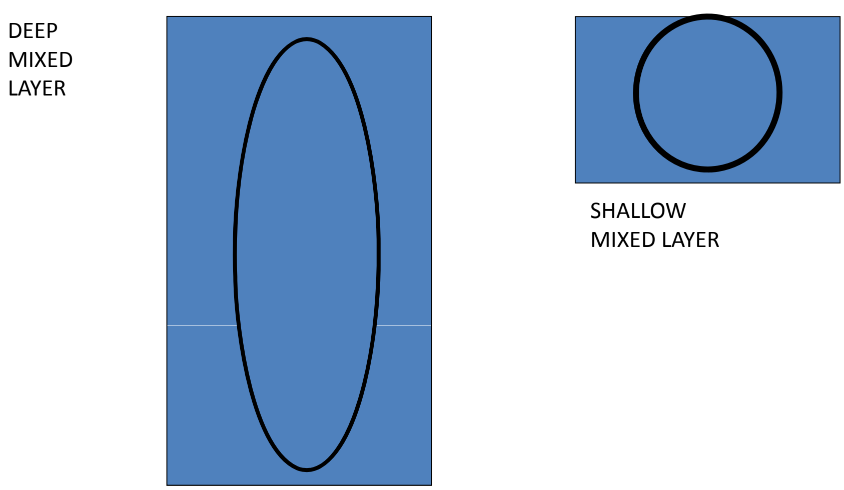
Fig. 7. Interannual variation in NO_3 concentration as seen during three spring and summer cruises.

What limits the accumulation of phytoplankton in large regions of the oceans?

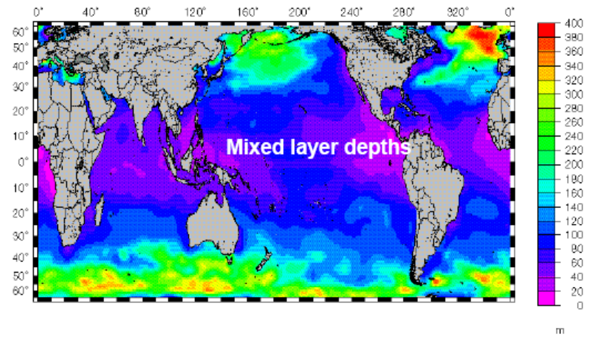
- H1: Phytoplankton growth is limited by light (due to deep mixing)
- H2: Plankton biomass is kept low by vigorous predation
- H3: Nitrate uptake is inhibited by uptake of ammonium
- H4: Phytoplankton growth is limited by availability of specific nutrients

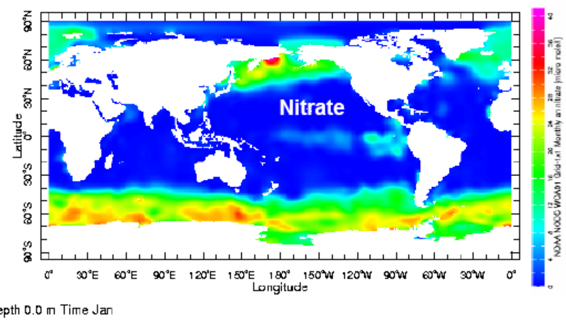
H1: Deep mixing results in light limited growth





Remember the Critical Depth?





Cold temperatures and high winds often results in very deep mixing in Southern Ocean; however, the Subarctic North Pacific and Equatorial Pacific typically do not mix as deep (<120 m) as other systems that experience regular nutrient drawdown.

Conclusion: although light limitation may be important in some HNLC systems, light alone is insufficient to explain lack of seasonal nitrate drawdown.

What limits the accumulation of phytoplankton in large regions of the oceans?

- ~~H1: Phytoplankton growth is limited by light (due to deep mixing)~~
- H2: Plankton biomass is kept low by vigorous predation
- H3: Nitrate uptake is inhibited by uptake of ammonium
- H4: Phytoplankton growth is limited by availability of specific nutrients

H2: Food web control of plankton biomass--grazers keep biomass cropped to low levels, allow nutrients to accumulate

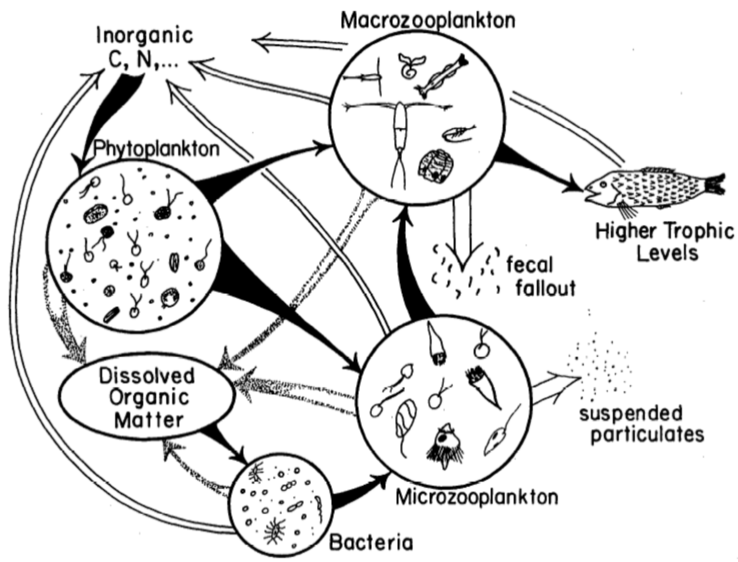
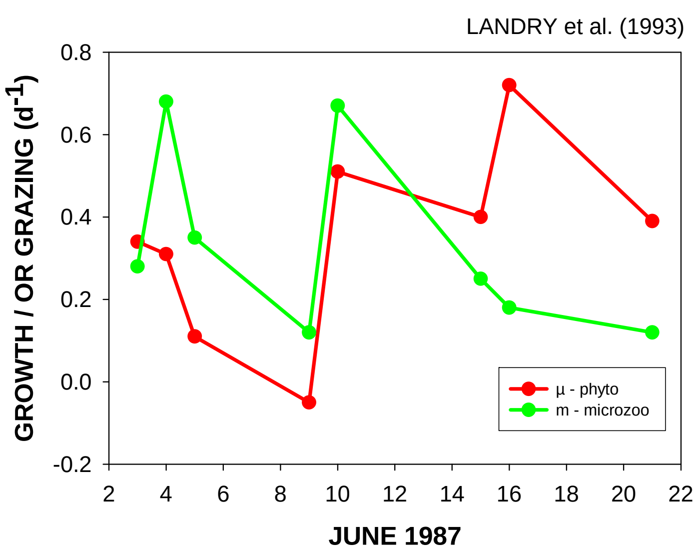


Fig. 4. Diagram of principal food-web connections in the subarctic Pacific. Black arrows—consumption; white arrows—regeneration processes; stippled arrows—transfers to dissolved organic pool.

Tightly coupled growth and grazing

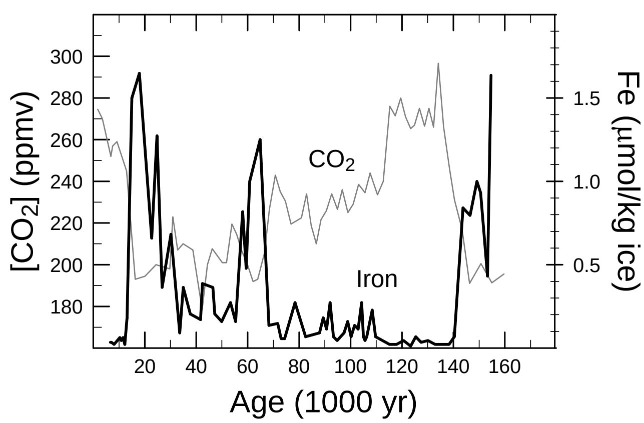


In the subarctic North Pacific and Eastern Equatorial Pacific, strong evidence supporting micrograzer control of algal biomass.

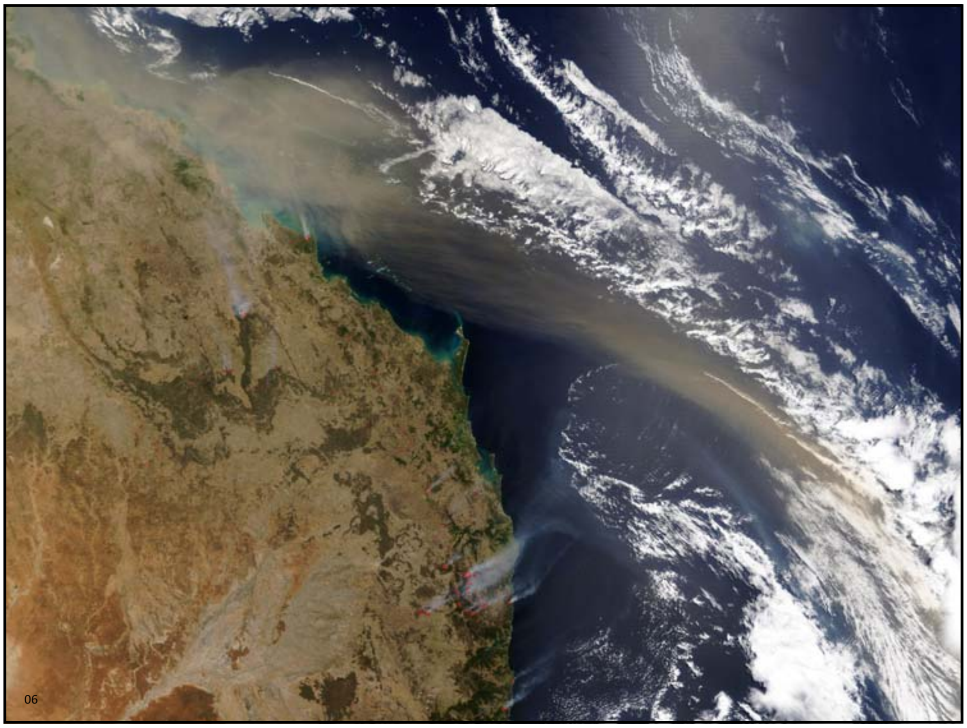
The case for Iron

- Iron is essential for life: required for synthesis of chlorophyll, component of cytochromes (electron transport chain), needed for nitrate utilization (nitrate reductase), essential for N_2 fixation (nitrogenase).
- Iron is highly insoluble in oxygenated seawater; readily precipitates.
- In regions far removed from continental shelves primary Fe input occurs via atmospheric deposition and upwelling.
- In areas of active upwelling, demand for Fe is elevated; however, many of these regions are also far removed from terrestrial Fe sources.

There is evidence suggesting that changes in Fe supply influence atmospheric CO_2



Glacial-interglacial variations in CO_2 demonstrate inverse relationships to the availability of iron in seawater



The "Iron Hypothesis", John Martin, MLML

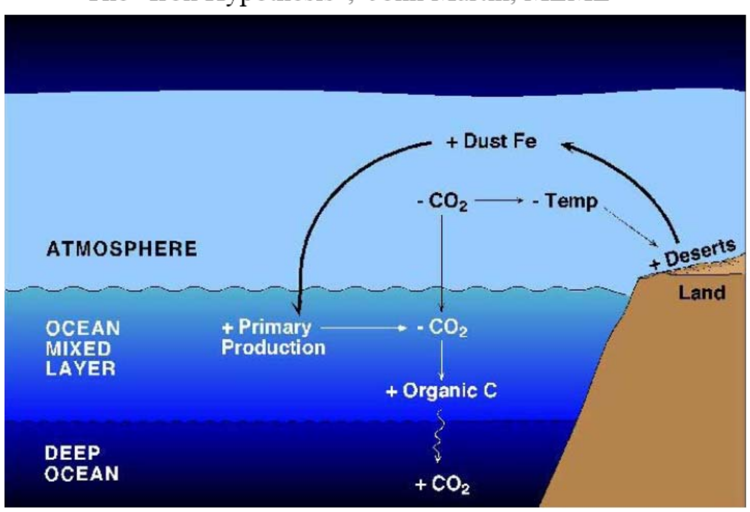
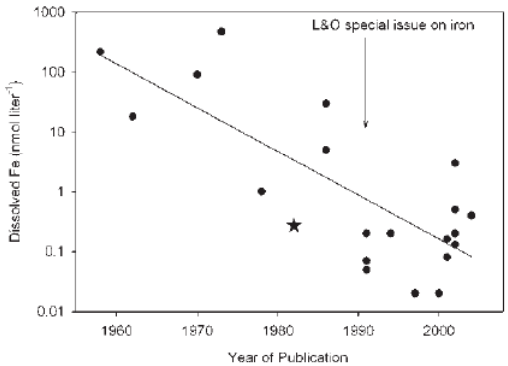
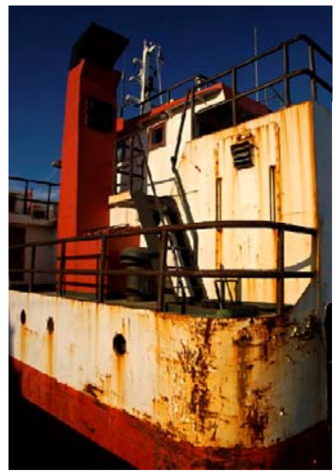


Figure 2. Total dissolved Fe concentrations in marine waters reported by papers published in *L&O* since 1958. The star is Fitzwater et al. (1982), which has been cited 307 times.



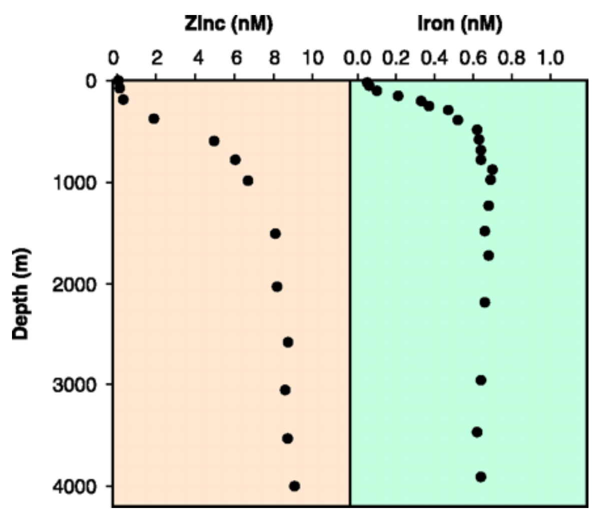
Obtaining accurate measurements of Fe concentrations in the open ocean has plagued oceanographers for many years.



Various metals essential to life demonstrate nutrient like distributions in the oceans

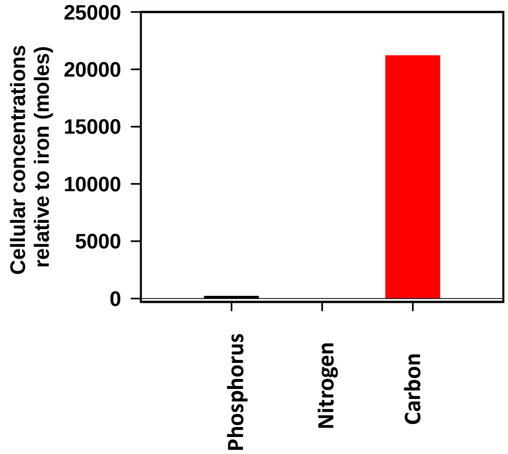
Surface depletion due to algal uptake; increasing concentrations increase through remineralization

In many HNLC regions, upper ocean concentrations of Fe <0.1 nM



From Morel and Price [2003]

A little bit of Fe goes a long way…



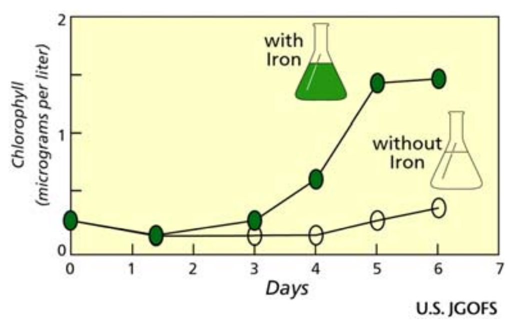
GENERAL PURPOSE
20-10-20
(For Continuous Liquid Feed Programs)

Guaranteed Analysis	F1143
Total nitrogen (N)	20%
7.77% ammoniacal nitrogen	
12.23 % nitrate nitrogen	
Available phosphate (P_2O_5)	10%
Soluble potash (K_2O)	20%
Magnesium (Mg) (Total)	0.05%
0.05% Water Soluble Magnesium (Mg)	
Boron (B)	0.0068%
Copper (Cu)	0.0036%
0.0036% Chelated Copper (Cu)	
Iron (Fe)	0.05%
0.05% Chelated Iron (Fe)	
Manganese (Mn)	0.025%
0.025% Chelated Manganese (Mn)	
Molybdenum (Mo)	0.0009%
Zinc (Zn)	0.0025%
0.0025% Chelated Zinc (Zn)	

Derived from: ammonium nitrate, potassium phosphate, potassium nitrate, magnesium sulfate, boric acid, copper EDTA, manganese EDTA, iron EDTA, zinc EDTA, sodium molybdate. Potential acidity: 487 lbs. calcium carbonate equivalent per ton.

Phytoplankton biomass:

106C : 16N : 1P : 0.005Fe



Experiments done in carboys and bottles confirmed that phytoplankton growth was limited by Fe

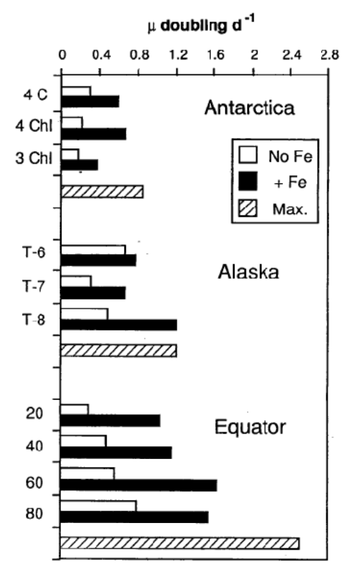
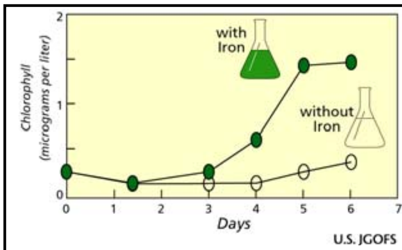


Fig. 7. A comparison of doubling rates from the Antarctic, Gulf of Alaska, and equatorial Pacific with and without added Fe (data from Table 2); theoretical maxima for various temperatures are also shown.

Martin et al. (1990)



Bottle experiments demonstrated increases in Chl by the addition of iron; however, there were concerns about what might have been missed...exclusion of large grazers, sinking, mixing, etc.

Limnol. Oceanogr., 36(8), 1991, 1793–1802
© 1991, by the American Society of Limnology and Oceanography, Inc.

The case for iron

John H. Martin, R. Michael Gordon, and Steve E. Fitzwater
Moss Landing Marine Laboratories, Moss Landing, California 95039

THE RESULTS OF BOTTLE EXPERIMENTS MADE A BIG SPLASH –

BUT NOT EVERYONE WAS CONVINCED…

Limnol. Oceanogr., 35(3), 1990, 772–775
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Does iron really limit phytoplankton production in the offshore subarctic Pacific?

Karl Banse
School of Oceanography, WB-10
University of Washington
Seattle 98195

Limnol. Oceanogr., 35(3), 1990, 775–777
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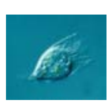
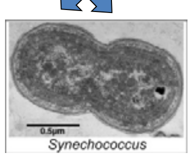
Yes, it does: A reply to the comment by Banse

- **Bottle experiments indicated that the addition of iron shifted the phytoplankton assemblage from small cells (subject to tight grazing) to large cells (diatoms) that grow rapidly, consume nutrients, and sink.**
- **But was this due to a bottle effect? Exclusion of grazers….**

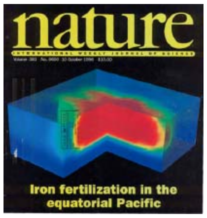
No iron controls

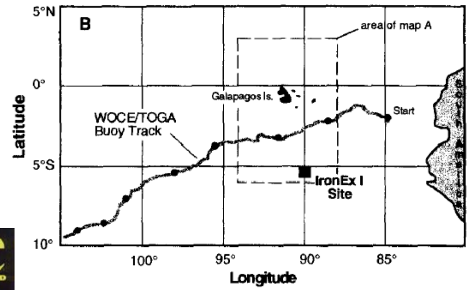




+Fe

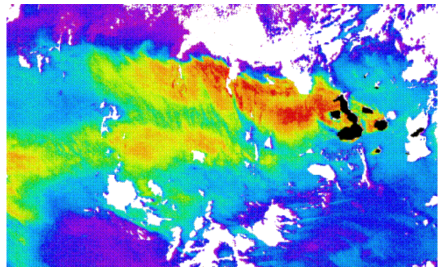
Solution: Mesoscale (100s of km) enrichment experiments to examine community level responses to iron.

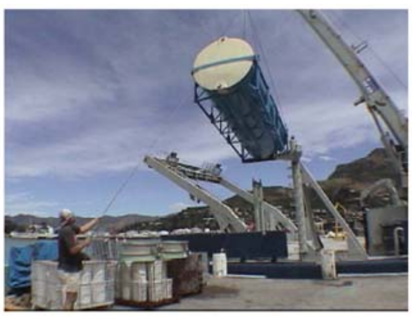


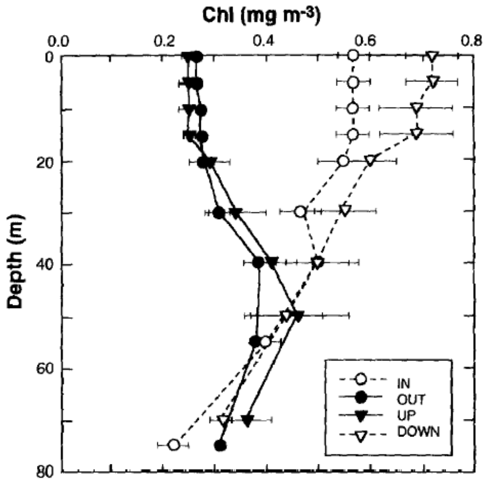


Iron added as acidic iron sulfate. The inert tracer SF_6 is added along with iron.

IronEX I: 1993, Equatorial Pacific near Galapagos Islands. 443 kg of Fe into a 64 km^2 patch. Initial Fe concentrations ~0.1 nM, final target Fe concentration was 4 nM. Added 17,500 L of 0.5 M Fe solution (pH 2.0). A separate batch of 2000 L of SF6 was mixed into the iron solution.





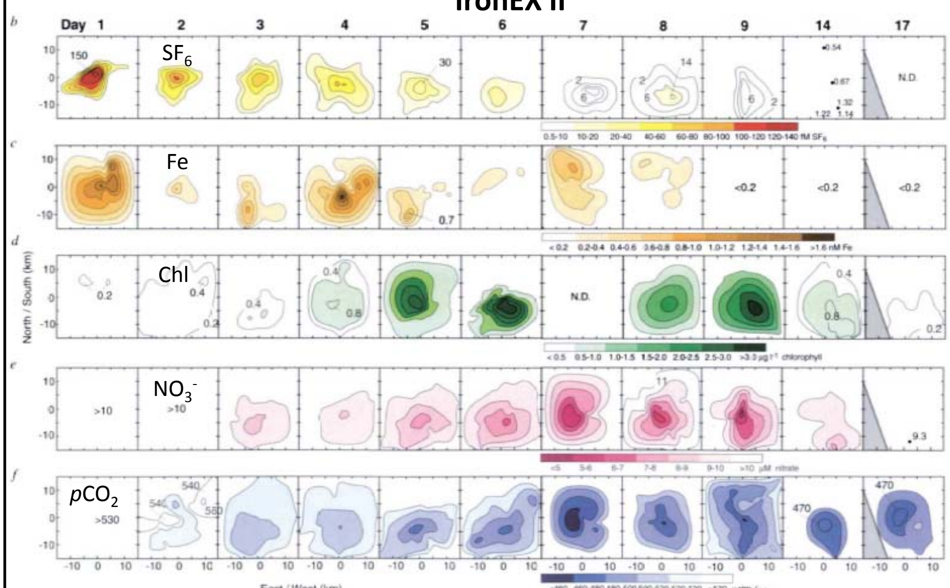


Coale et al. (1998)

IronEX I: Chl concentrations enriched in the patch and downstream of natural Fe source (Galapagos Islands). However, only weak drawdown of nitrate observed over course of experiment…perhaps Fe is not the only limiting nutrient? Grazing? After day 4, the patch subducted beneath a low salinity front.

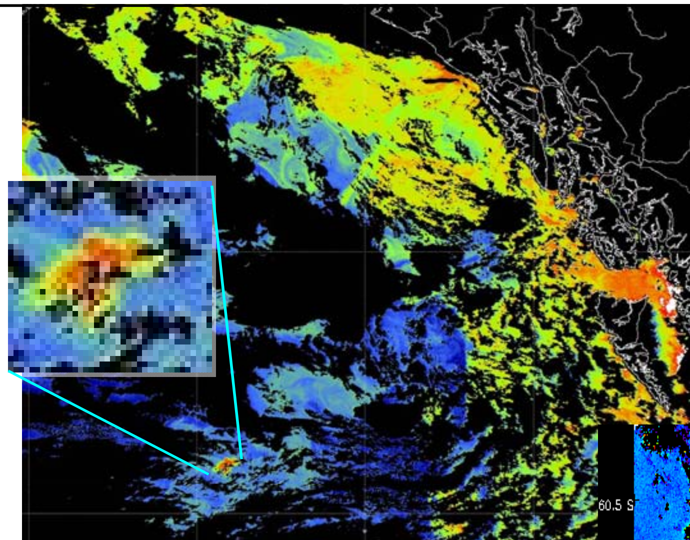
Fe concentrations downstream of the Galapagos Islands (in the island plume) were ~1 nM.

IronEX II



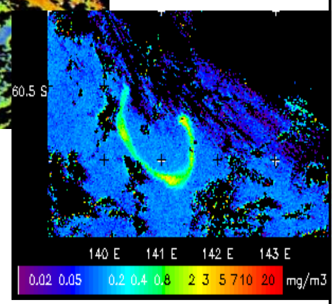
Coale et al. (1996)

June 1995, Equatorial Pacific; 225 kg Fe in 72 km^2; Day 1 Fe concentrations ~2 nM. Fe added again on days 3 and 7 (to bring surface water concentrations to ~1 nM)



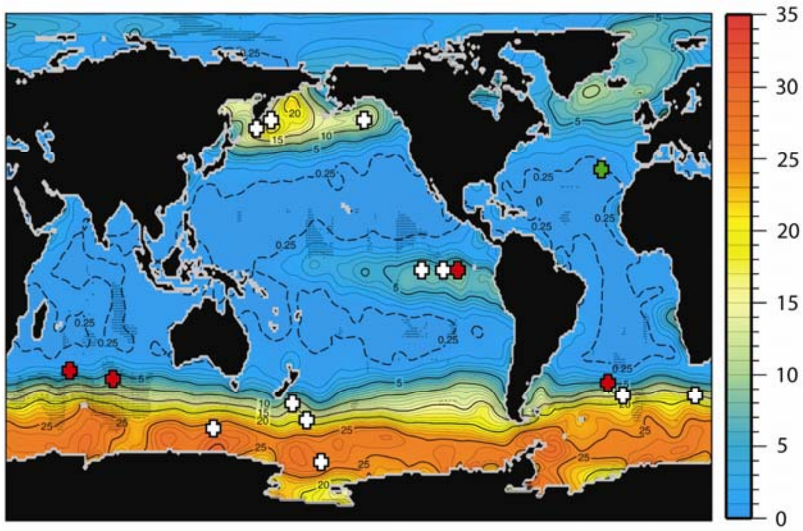
SERIES (Subarctic North Pacific)

The resulting blooms are large enough to be viewed from space



SOIREE (Southern Ocean)

12 mesoscale Fe experiments in > 10 years



+Fe (HNLC) **High Fe** **+Fe (LNLC)**

Boyd et al. (2007)

The HNLC condition-lessons learned from large scale manipulation experiments

- HNLC conditions are maintained by low Fe supply which suppresses phytoplankton growth and biomass production.
- Low concentrations of Fe appear to favor smaller cells (picoplankton).
- Growth of dominant picoplankton also suppressed by Fe supply but to a lesser extent than larger, rarer cells.
- Active mircrozooplankton grazing keeps picoplankton biomass low and relatively invariant, providing a highly regenerative upper ocean (rapid NH_4^+ cycling).