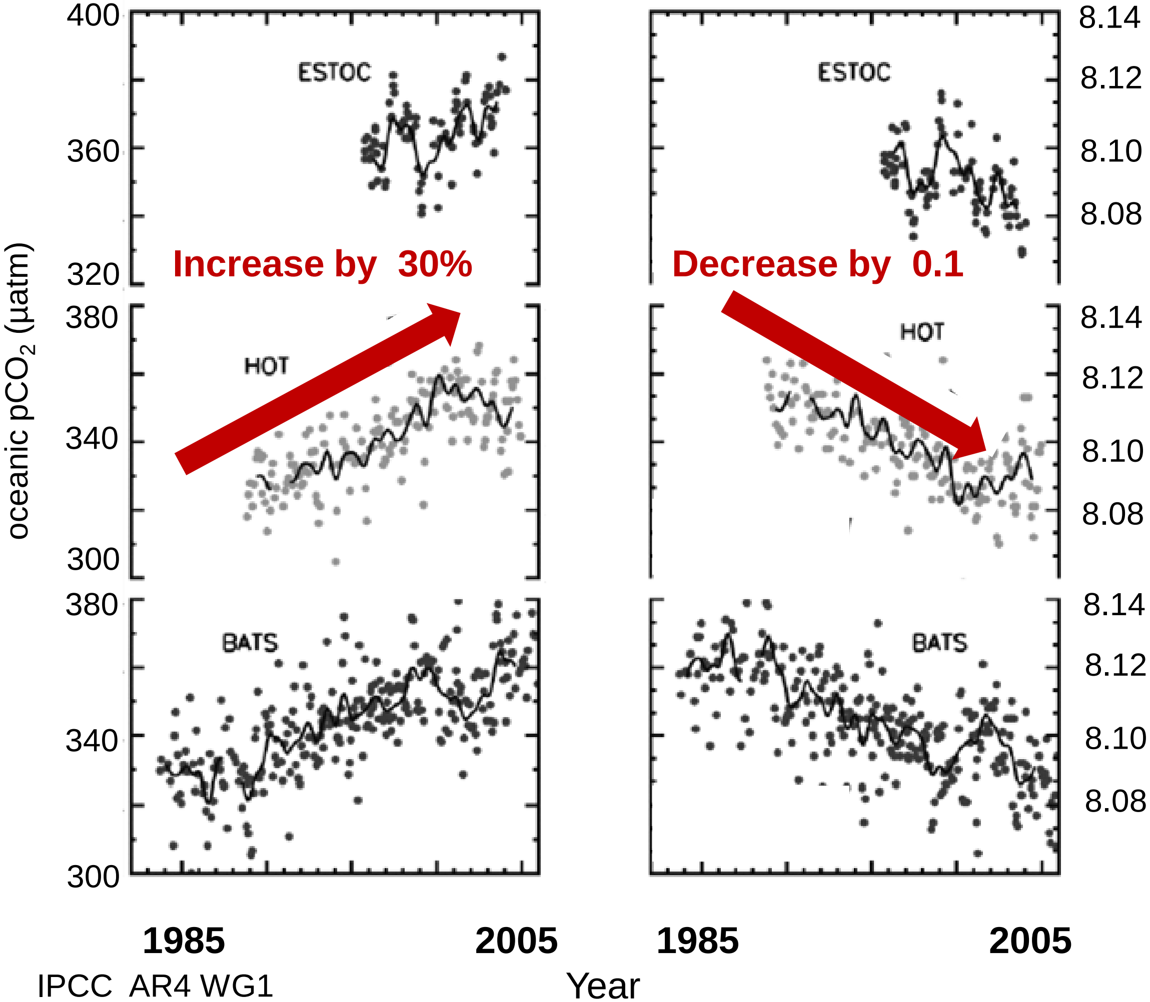
Ocean Acidification and Biogeochemical Cycling

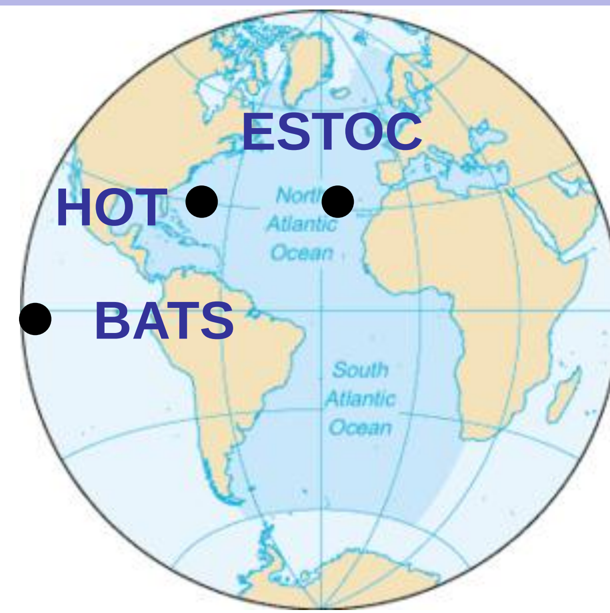
Uta Passow

Facts About Ocean Acidification (OA)

Year	1800	2011	2100	2100 (A1F1)
pCO_2	280 ppm	385 ppm	700 ppm	1050 ppm



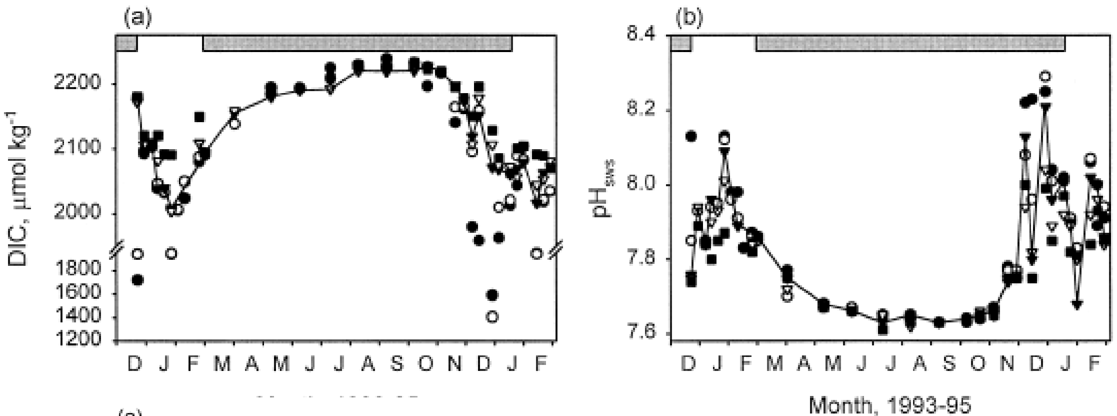
IPCC AR4 WG1

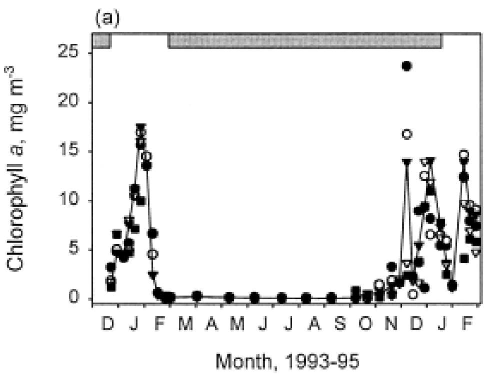


- Burning of fossil-fuel lead to increase in pCO_2
- CO_2 dissolves in ocean water
- Decrease in pH, increase in DIC & pCO_2, TA remains constant

In situ variability of carbonate system parameters

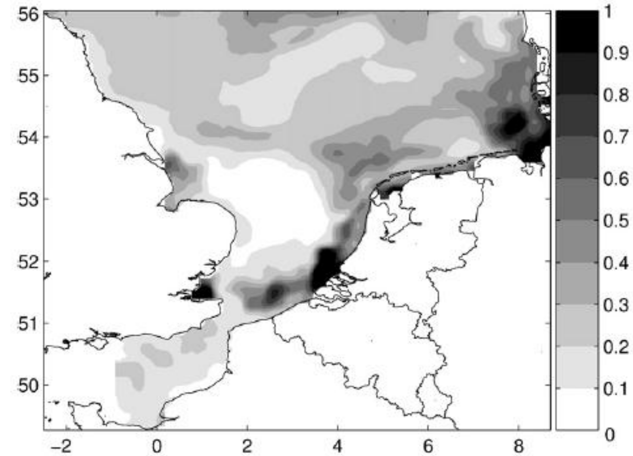
Annual S. Ocean





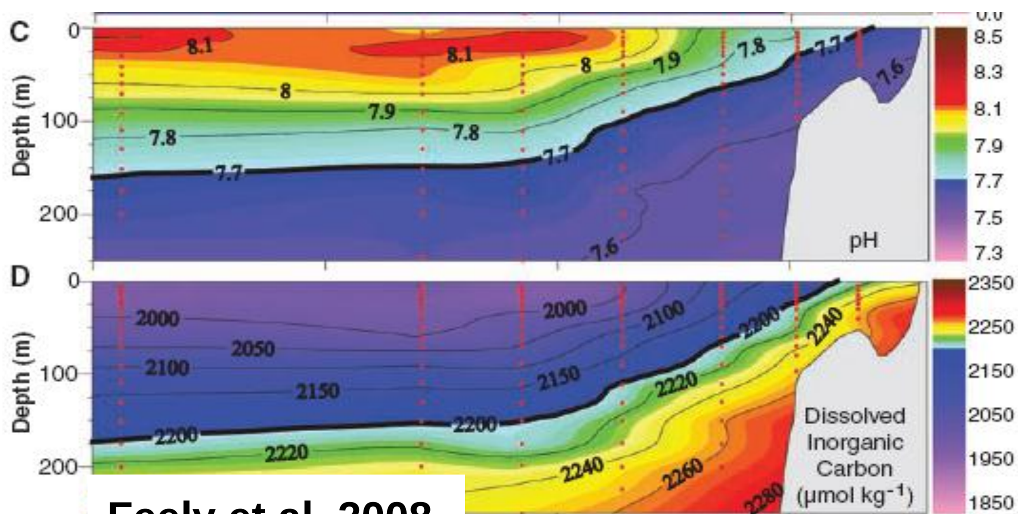
Gibson & Trull 1999

N Sea annual pH range



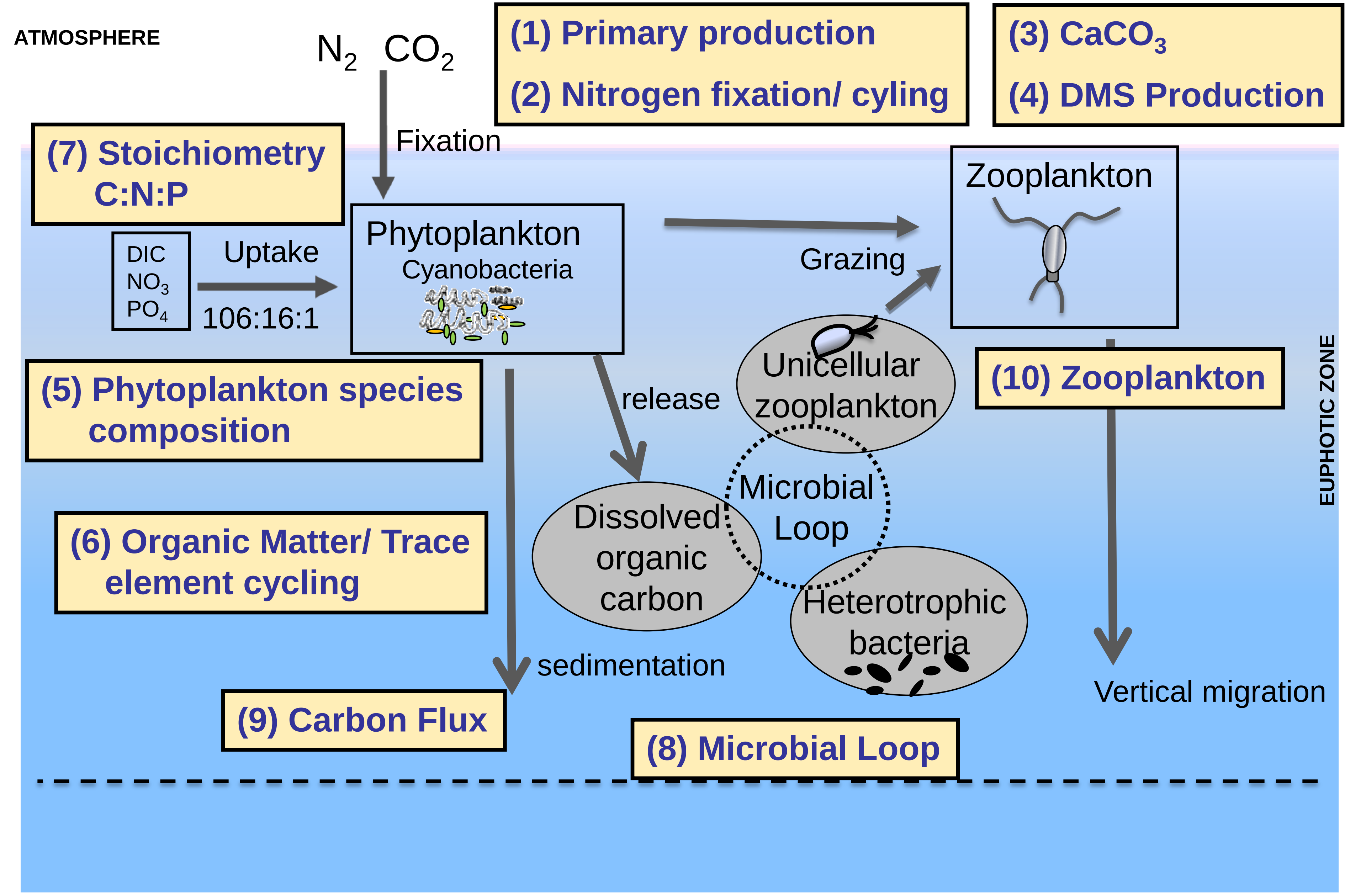
Blackford & Gilbert 2007

W Coast USA



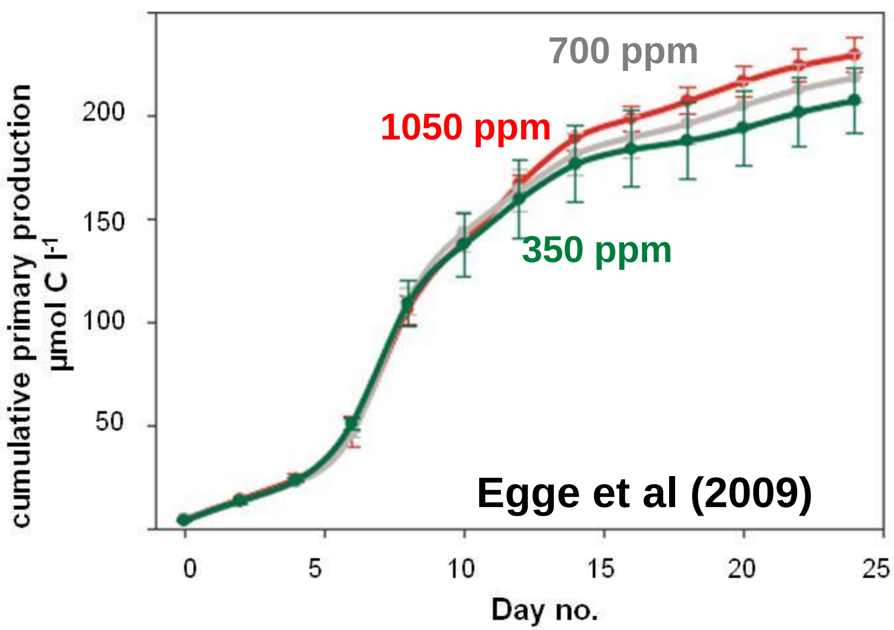
Feely et al. 2008

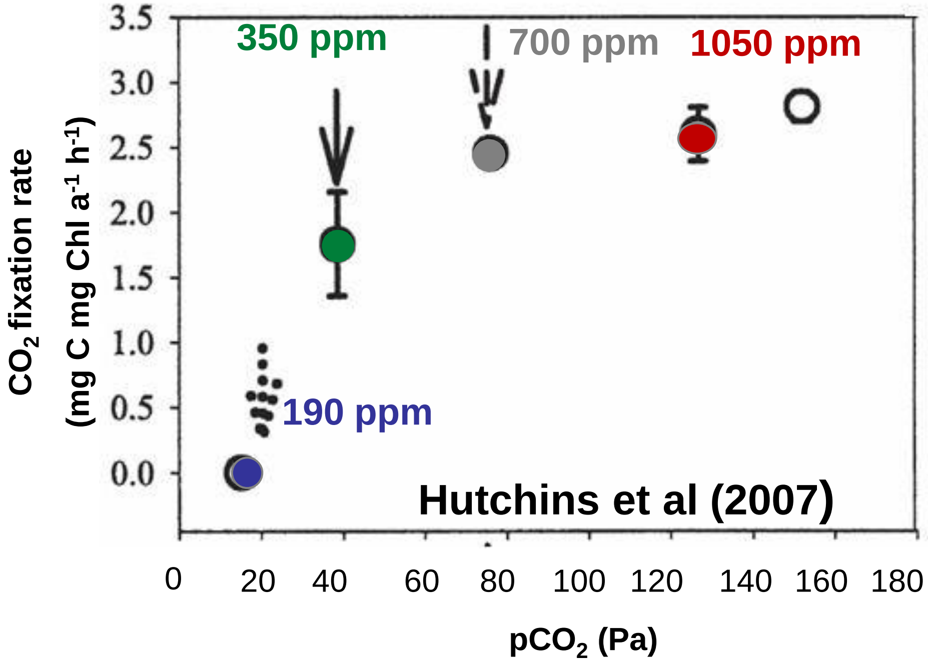
Biogeochemical cycles



(1) Primary Production & growth rate

Number of studies	Impact		Range
15 + 18 (eukaryotes)	No eff.-	Positive	Increase 10-50%
10 (cyanobacteria)	Positive		Increase 15-128%





Pelagic Ecosystem CO_2 Enrichment study (PeECE III 2005), but no difference PeECE I & II (2001 & 2003)

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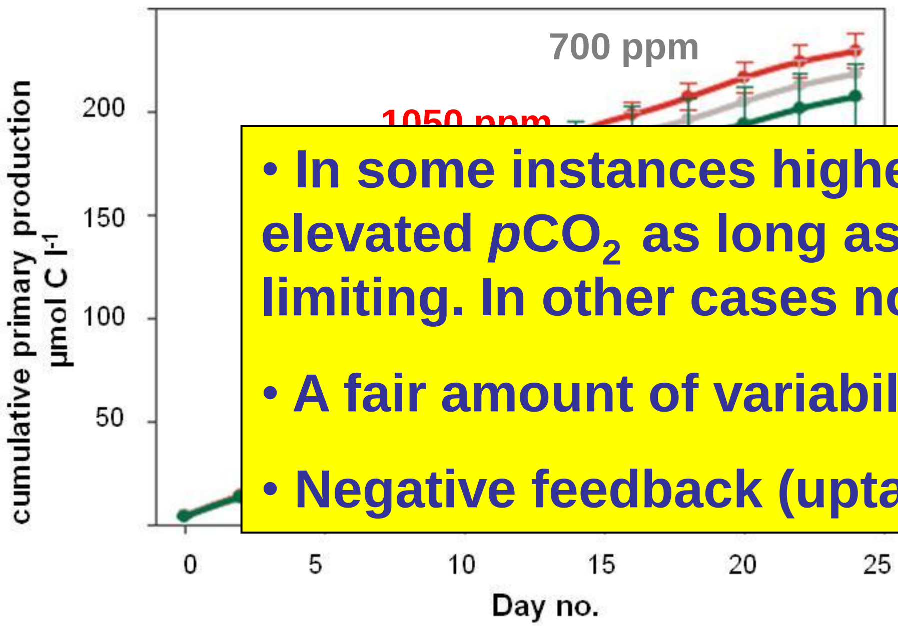
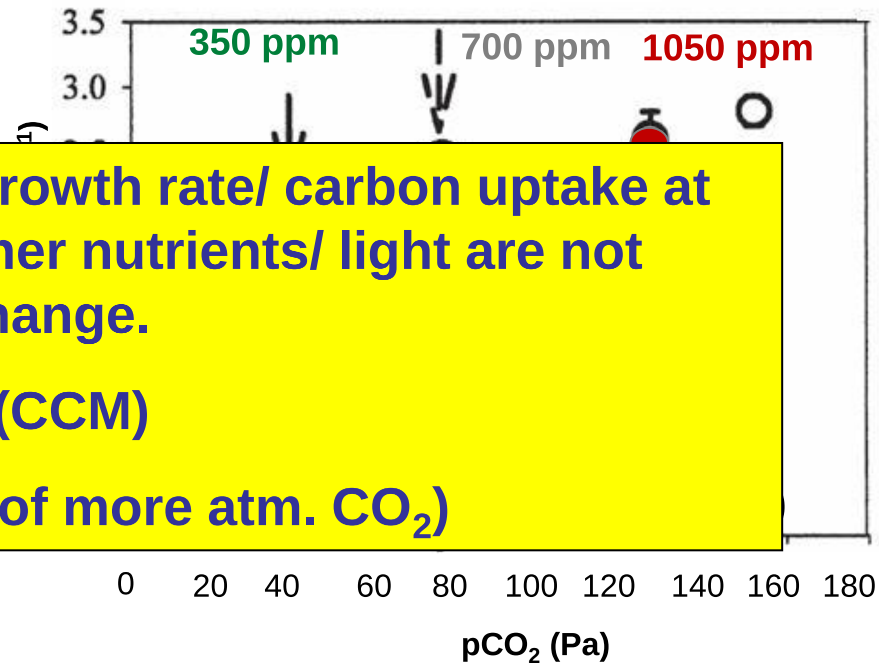


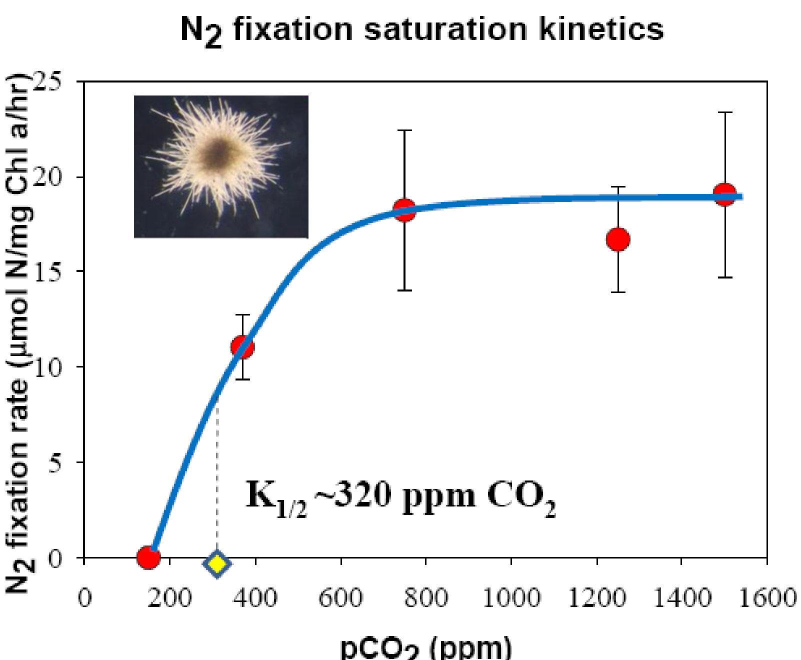


- In some instances higher growth rate/ carbon uptake at elevated pCO_2 as long as other nutrients/ light are not limiting. In other cases no change.
- A fair amount of variability (CCM)
- Negative feedback (uptake of more atm. CO_2)

Pelagic Ecosystem CO_2 Enrichment study (PeECE III 2005), but no difference PeECE I & II (2001 & 2003)

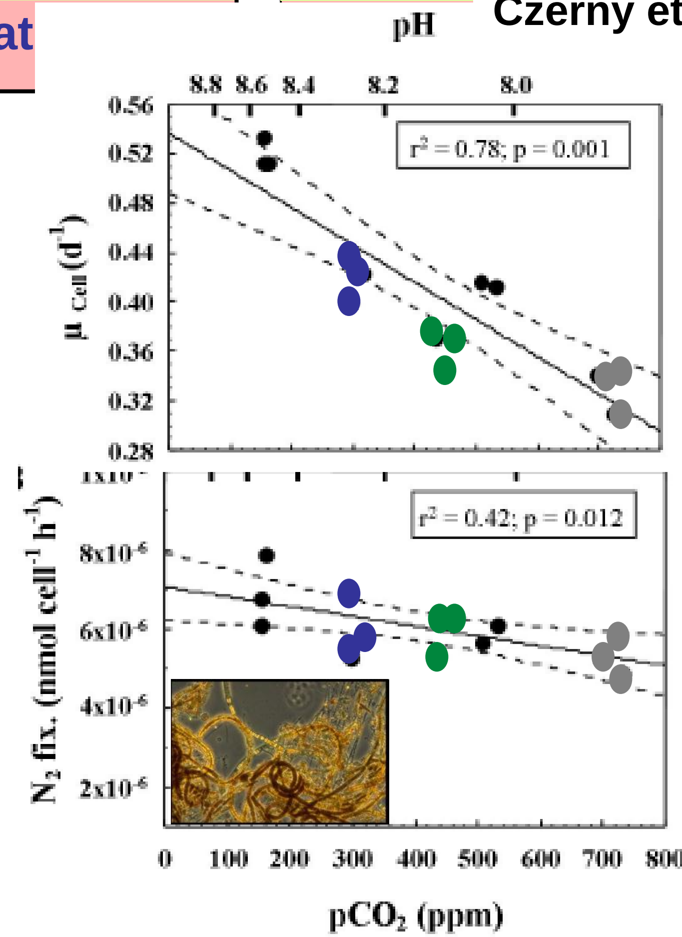
(2a) Nitrogen Fixation by Cyanobacteria

Number of studies	Impact	Range
10	Positive / Negat	Increase up to 100%



Hutchins et al 2007

Czerny et al 2009



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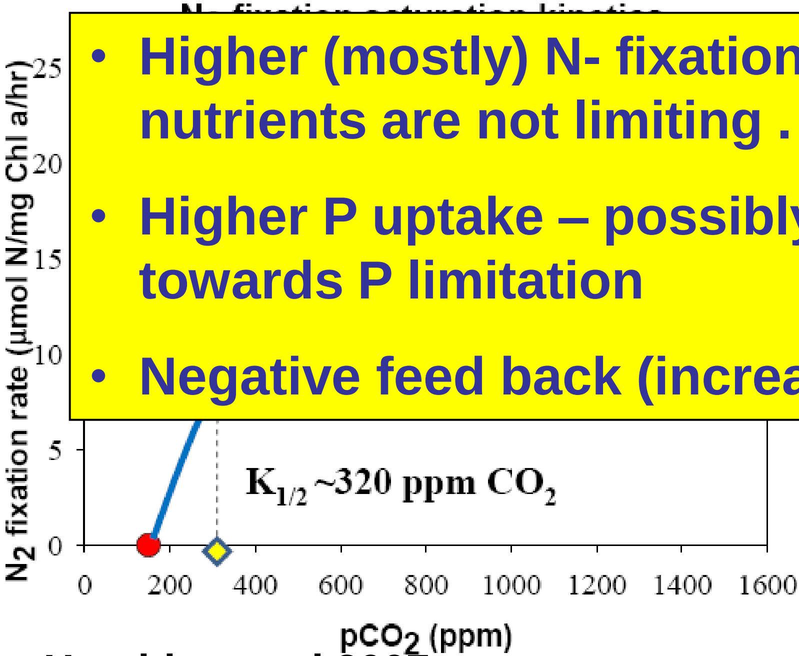
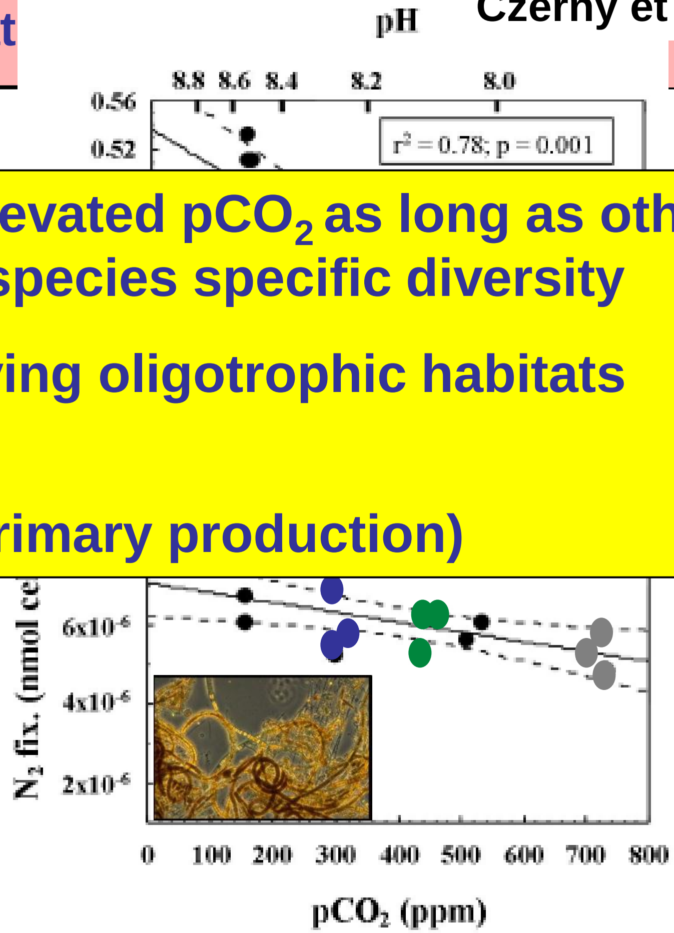


Hutchins et al 2007

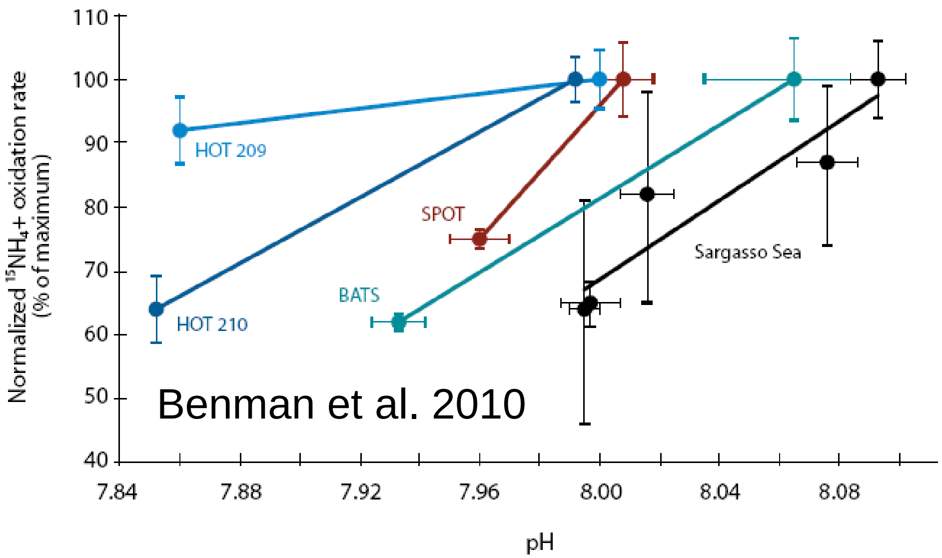


- Higher (mostly) N- fixation at elevated pCO_2 as long as other nutrients are not limiting . But species specific diversity
- Higher P uptake – possibly driving oligotrophic habitats towards P limitation
- Negative feed back (increase primary production)

(2b) Nitrification

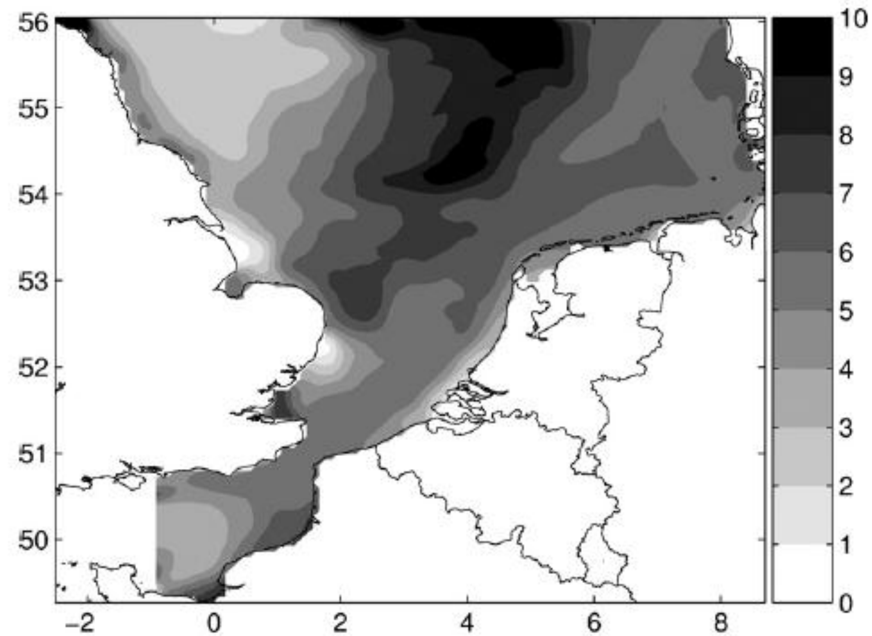
Number of studies	Impact	Range
3	Negative	Decrease 10-40%

Nitrification



Benman et al. 2010

% Change in NO_3: DIN ratio (Δ 385 & 1000 ppm CO_2) based on Husemann et al. 2002.



Blackford & Gilbert 2007

(2b) Nitrification

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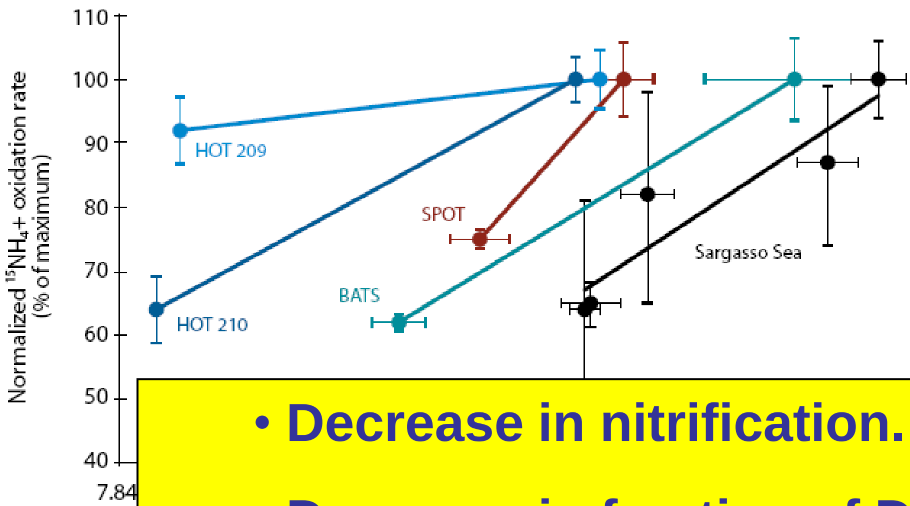
Nitrification



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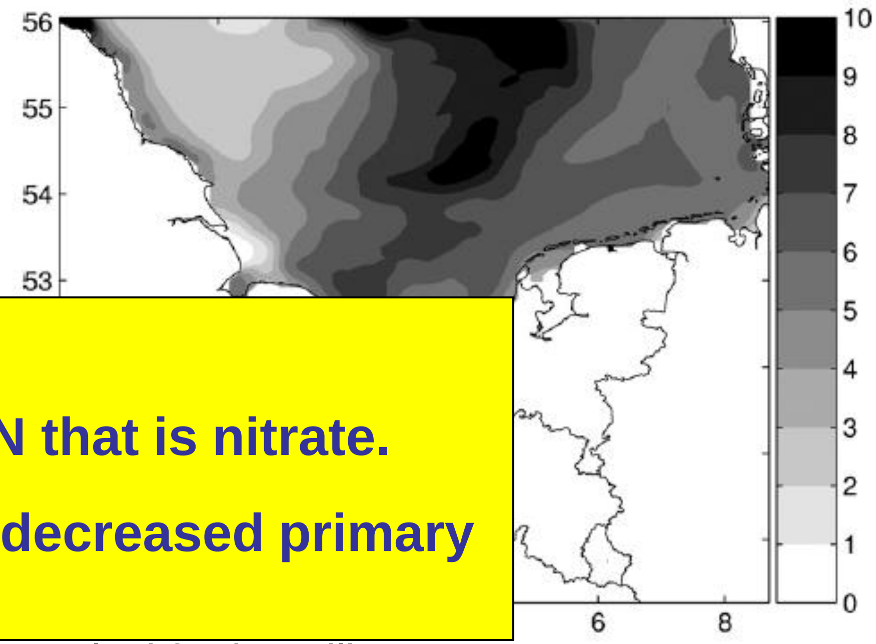


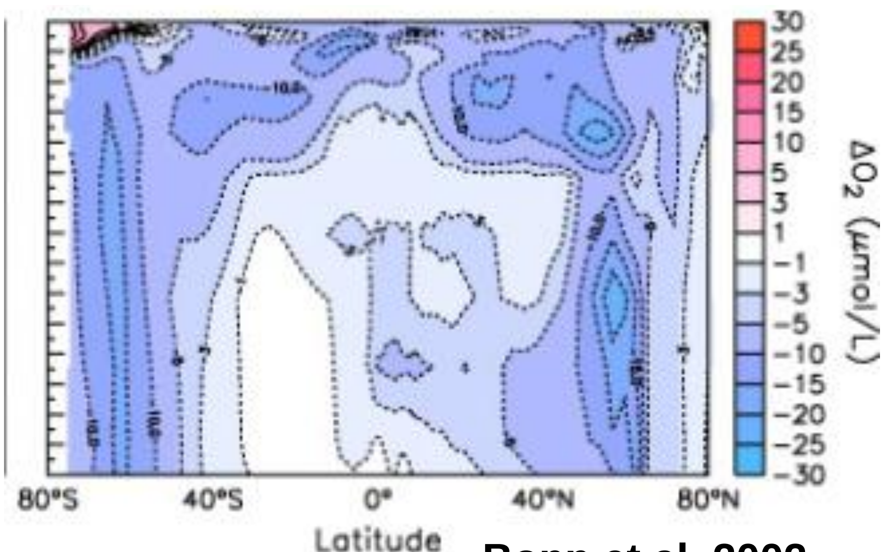
Blackford & Gilbert 2007

- **Decrease in nitrification.**
- **Decrease in fraction of DIN that is nitrate.**
- **Positive feed back due to decreased primary production**

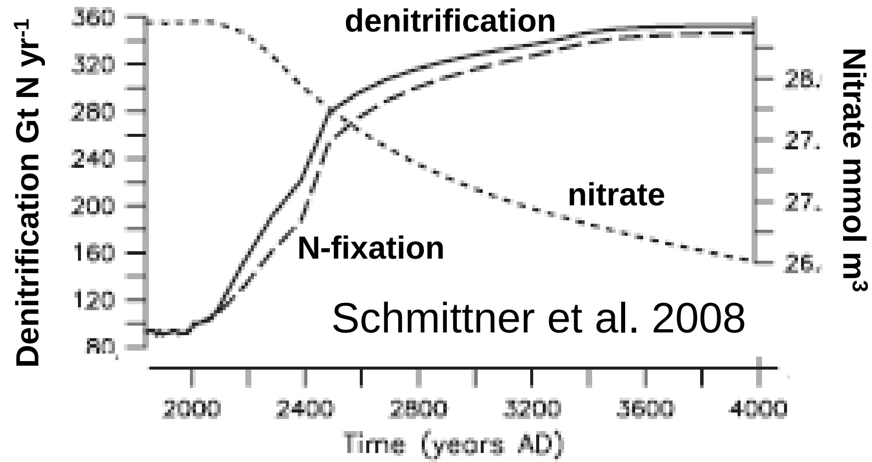
(2c) Denitrification

Number of studies	Impact	Range
3	Increase	quadruple

Δ dissolved of dissolved O_2 between 2080-2100 and 1980-2000



Bopp et al. 2002



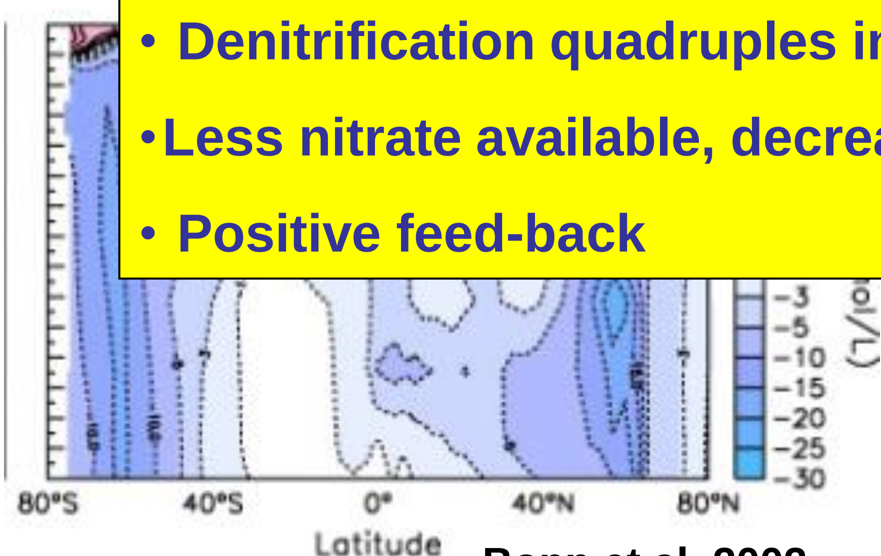
Schmittner et al. 2008

(2c) Denitrification

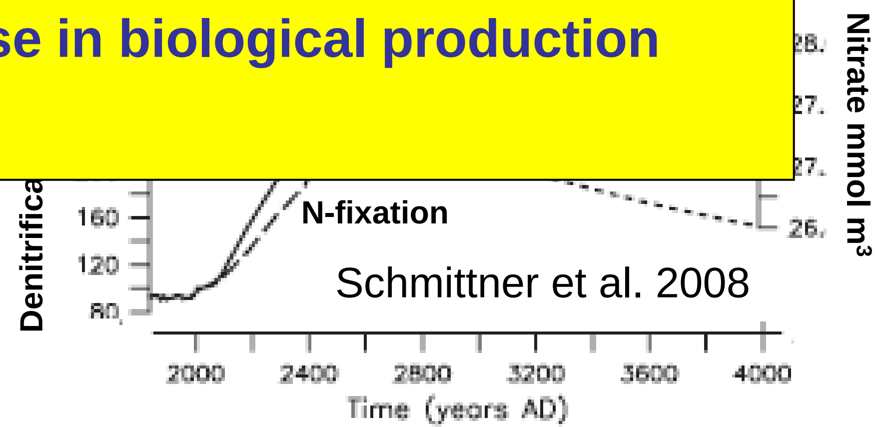
Number of studies	Impact	Range
3	Increase	quadruple

- Any OA effect?
- Stratification increases & shallower remineralization
- Suboxic zones in the ocean increase
- Denitrification quadruples in next 2000 years
- Less nitrate available, decrease in biological production
- Positive feed-back

Δ di

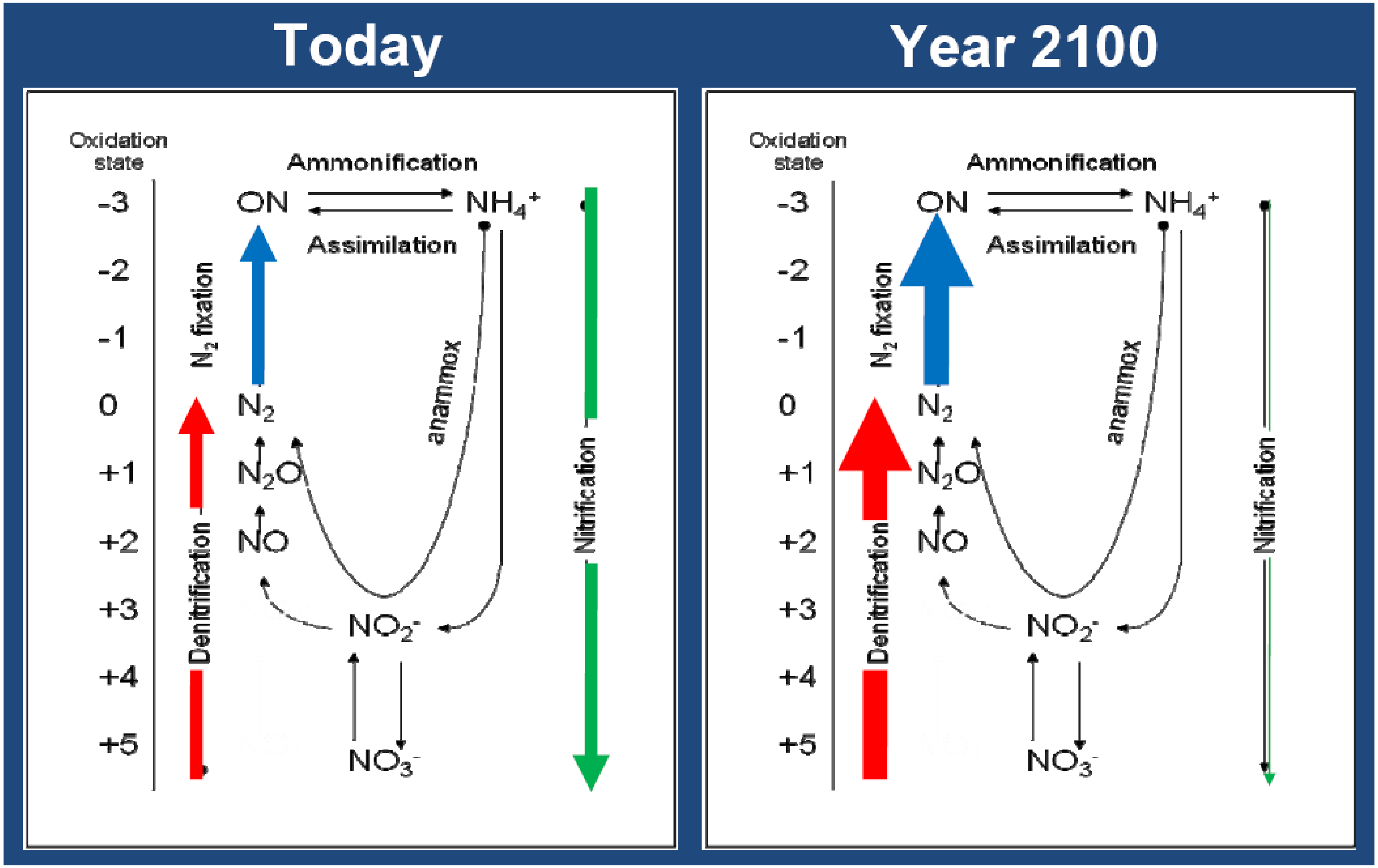


Bopp et al. 2002



Schmittner et al. 2008

(2) Nitrogen Cycle



Hutchins

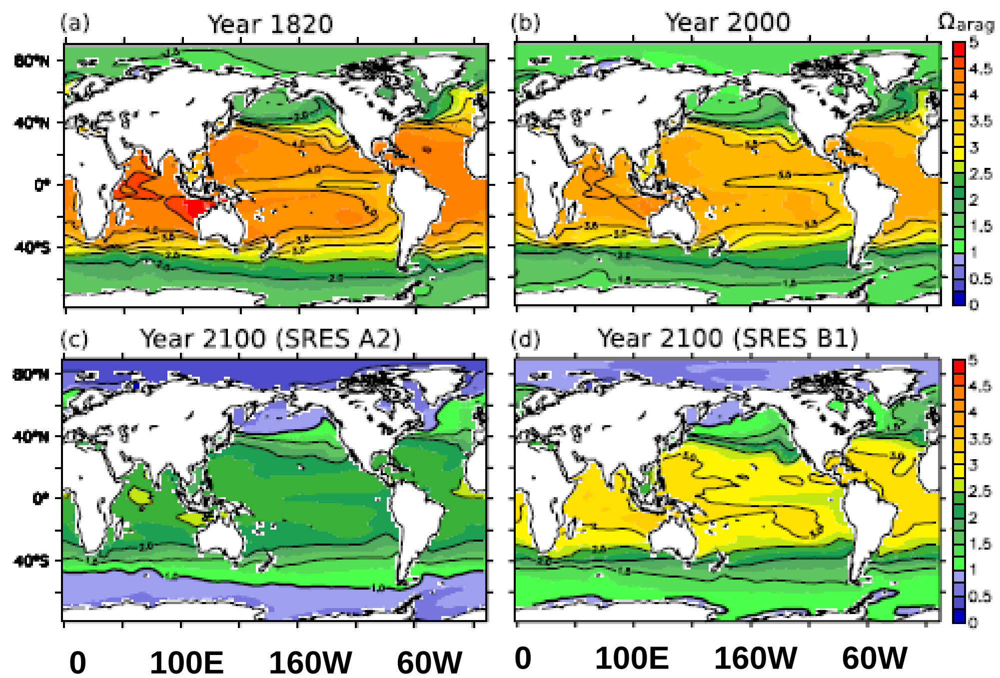
Decrease in fraction of inorganic N that is nitrate

(3a) $CaCO_3$: Saturation Horizon

Number of studies	Impact	Range
> 6	Decrease of Saturation	Decrease

$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$

Simulated aragonite saturation at the surface



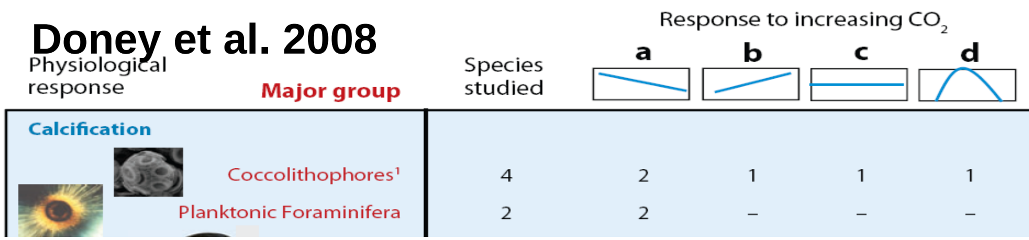
Steinmacher et al. 2009

- Aragonite and Calcite saturation is decreasing rapidly.
- Saturation is spatially variable with low values in the high latitudes

(3b) (Bio-)Calcification: Coccolithophores & Foraminifera

Number of studies	Impact	Range
15 cocco & 5 Forams	Inconsistent	Increase 100% Globally 27% Decrease 25-66%

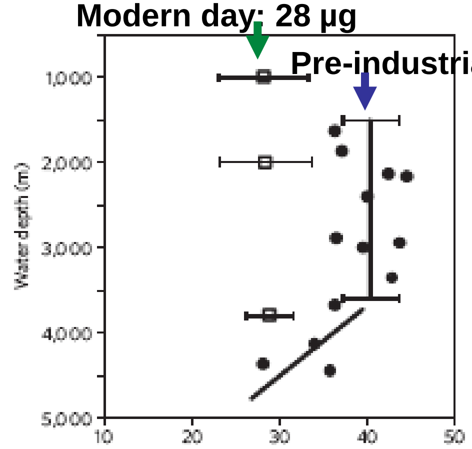
Doney et al. 2008



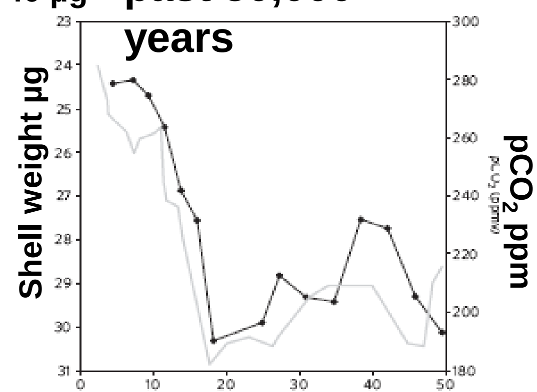
Physiological response	Major group	Species studied	Response to increasing CO_2: a	b	c	d
Calcification						
	Coccolithophores[1]	4	2	1	1	1
	Planktonic Foraminifera	2	2	–	–	–

Globigerina bulloides (no algae symbionts)

Weights of shells 355-425 µm



Shell weights track pCO_2 over past 50,000 years



Moy et al 2009

Irie et al 2010: Optimality-model predicts that natural selection will favors heavy calcification if calcification is a defensive strategy and photosynthesis is enhanced.

(3b) (Bio-)Calcification: Coccolithophores & Foraminifera

Number of studies	Impact	Range

Doney et al. 2008

Response to increasing CO_2

Increase 100%

- Calcification response of Coccolithophores varies (even within one strain
- Calcification of Foraminifera often decreases with OA, but proxy validation controversially discussed
- Growth conditions (function of a suite of parameters) strongly determine calcification
- $CaCO_3$ production decrease from 1 Pg C yr^{-1} to 0.36 – 0.82 Pg C yr^{-1} by 2100 (Gangsto et al 2011).
- Such a global decrease means a small negative feed back on atm. pCO_2 of -1 to -11 ppm.

Shell weight µg

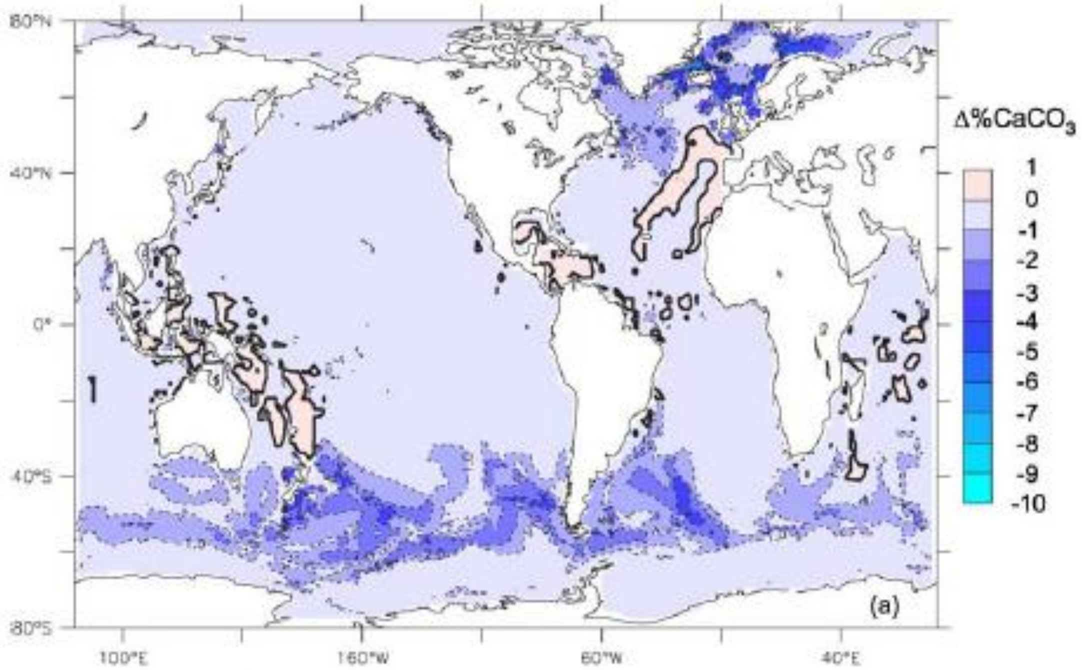
Age kyr

Moy et al 2009

(3c) $CaCO_3$ Dissolution

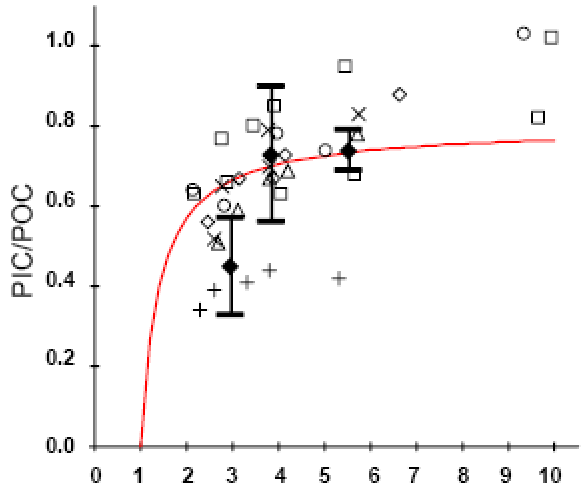
Number of studies	Impact	Range
1 (pteropod)	Positive	Increase
5 carbonate compensation	Positive	Increase (geological time scales) globally 11 %

Global $CaCO_3$ Dissolution:
% Δ $CaCO_3$ 286 ppm to 1144 ppm in 140 years



Gehlen & Bopp 2008

Change in the rain ratio of sinking carbon



Gehlen et al. 2007

(3c) $CaCO_3$ Dissolution

Number of studies	Impact	Range
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5 carbonate compensation	Positive	Increase (geological time scales) globally 11 %

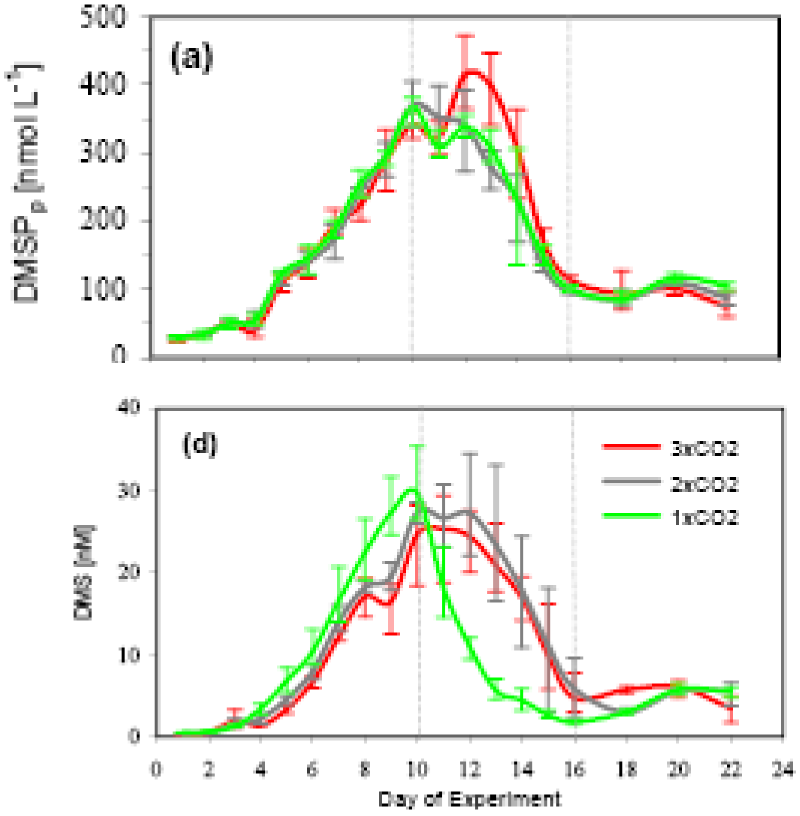
- Decrease in calcification & increase in production of POM potentially results in an increase in rain ratio (POC: PIC) in exported material
- Increased rain ratio → promotes dissolution, timescales of 1000-10,000 years).
- However, less ballasting might reduce sedimentation of POC not leading to an increased rain ratio
- Carbonate compensation: Dissolution of $CaCO_3$ in sediments have a buffer capacity for the deep ocean on geological time scales. Negative feed back!

100°E 160°W 60°W 40°E

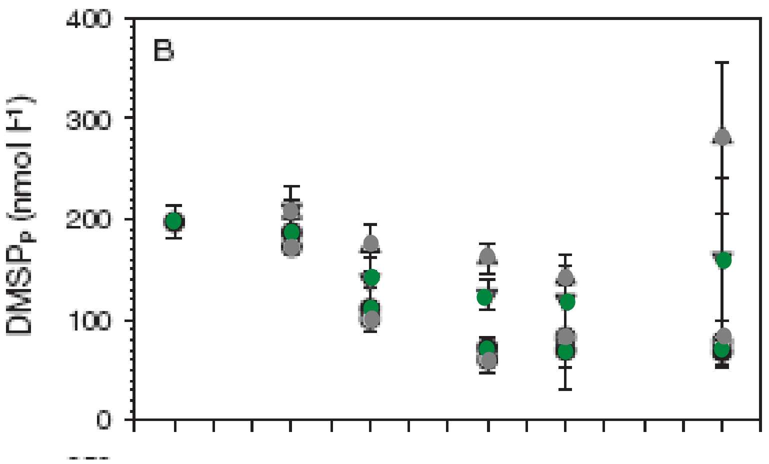
Gehlen & Bopp 2008

(4) DMS, DMSP Production

Number of studies	Impact	Range
3	Inconsistent	No change



Vogt et al 2008

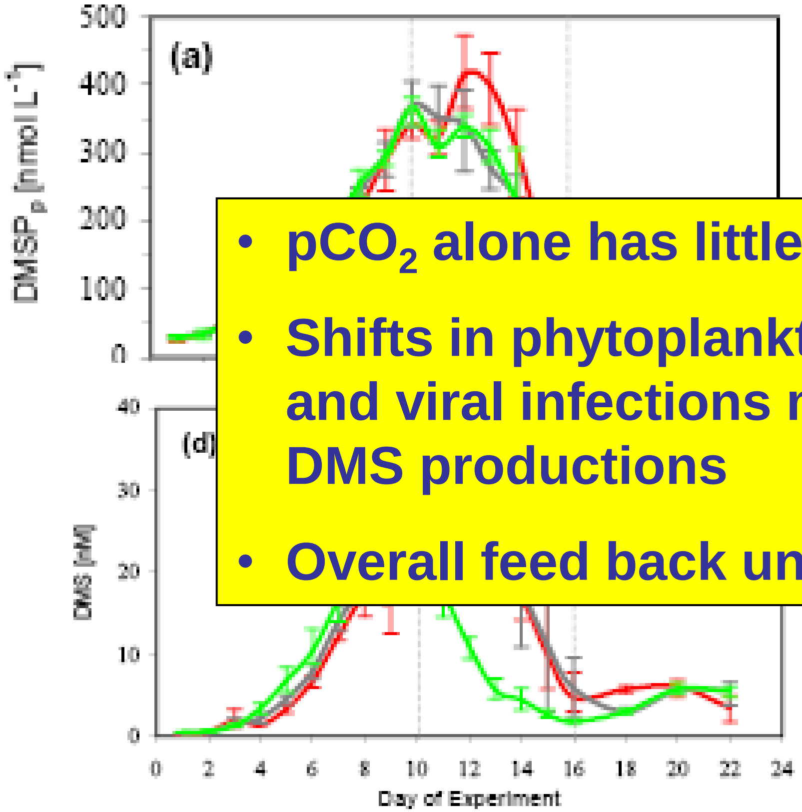


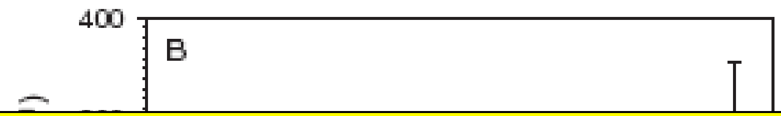
Lee et al. 2009

Process Investigated

(4) DMS, DMSP Production

Number of studies	Impact	Range
3	Inconsistent	No change





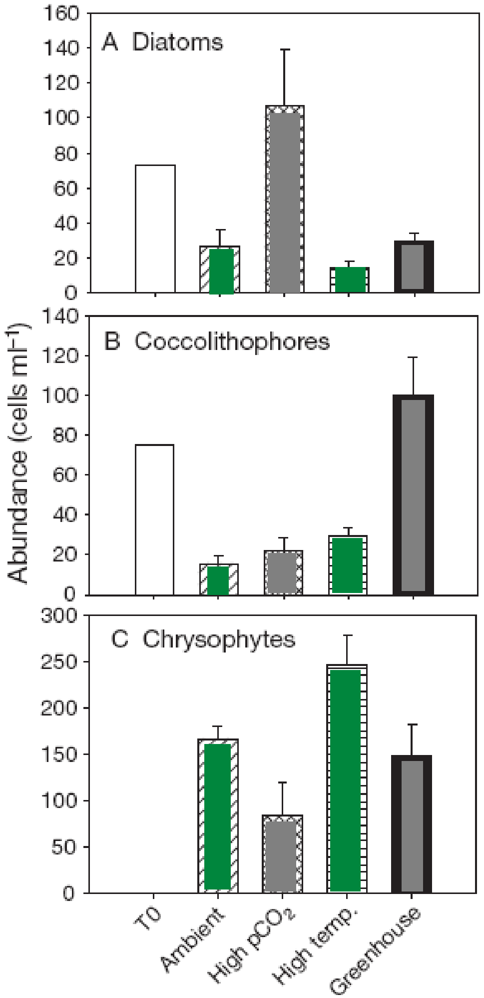
- pCO_2 alone has little effect on DMSP
- Shifts in phytoplankton species composition, grazing and viral infections may indirectly change DMSP & DMS productions
- Overall feed back unclear

Vogt et al 2008

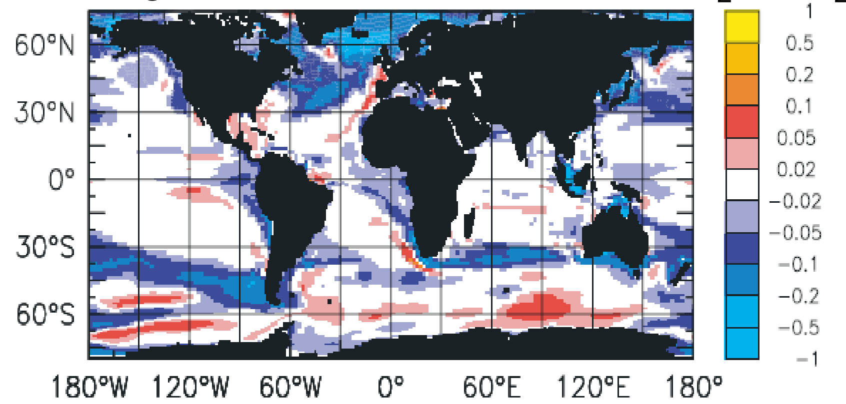
(5a) Phytoplankton Species Composition

Number of studies	Shift
10	Within groups or between groups

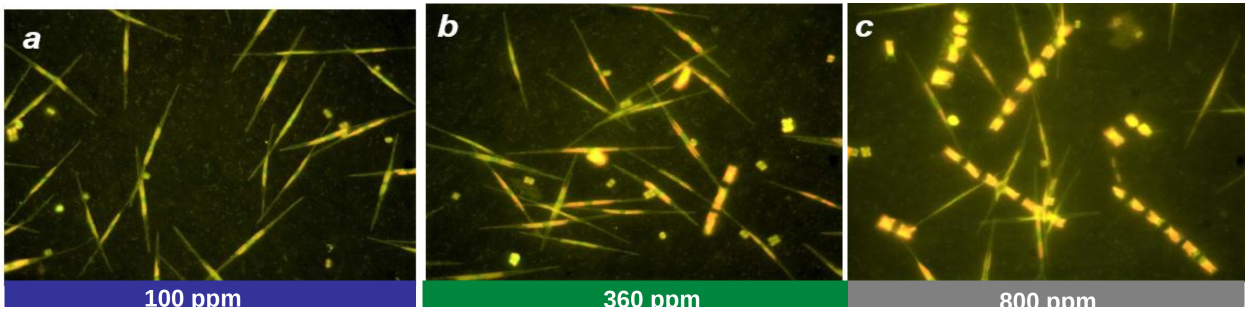
Feng et al. 2009



Change in diatom abundance $4xCO_2$-$1CO_2$



Bopp et al. 2005



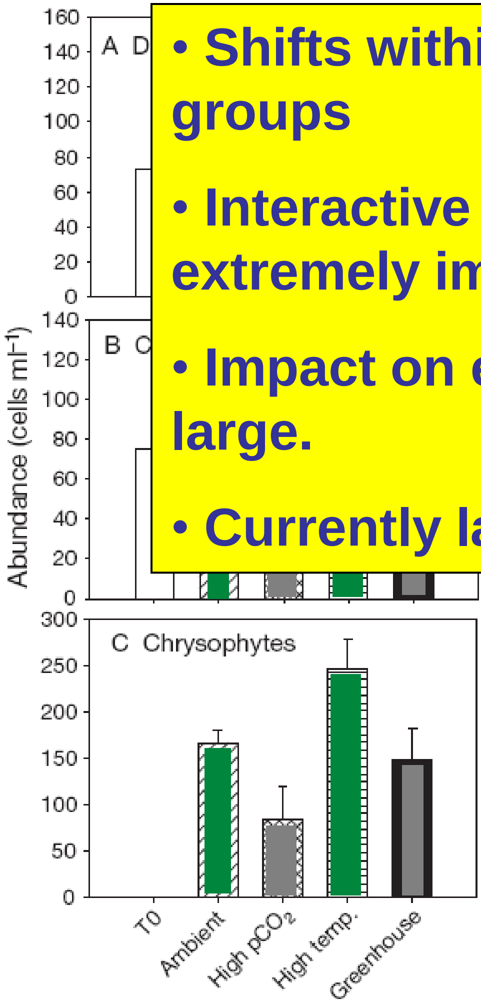
Tortell et al. 2008

(5a) Phytoplankton Species Composition

Number of studies

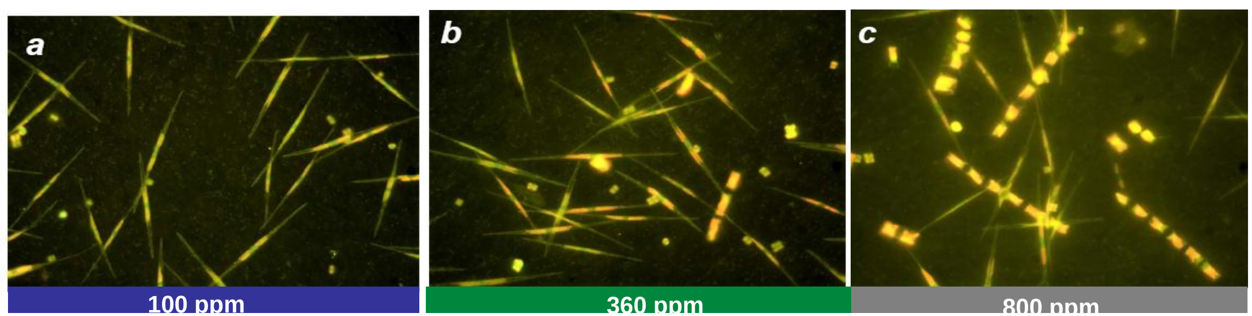
Shift

Feng et al. 2009



- **Shifts within functional or taxonomic groups and between groups**
- **Interactive effects with other environmental parameters extremely important. High variability in results**
- **Impact on export, biogeochemical cycling, stoichiometry large.**
- **Currently large uncertainty**

Bopp et al. 2005



Tortell et al. 2008

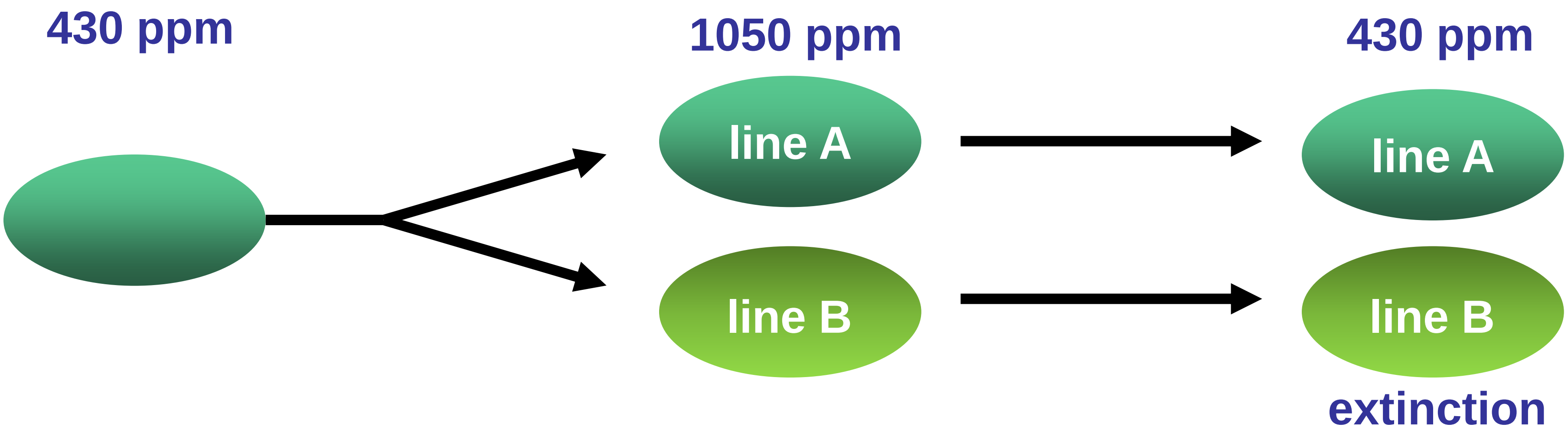
(5b) Genetic Acclimation & Adaptation

Number of studies	Acclimatisation vs. Adaptation
2 >150 generations	No difference, loss of flexibility

Stress response: immediate

Acclimatization: (gene expression) 8 - 10 generations

Adaptation: (genetic change) 200 - 1000 generations



(5b) Genetic Acclimation & Adaptation

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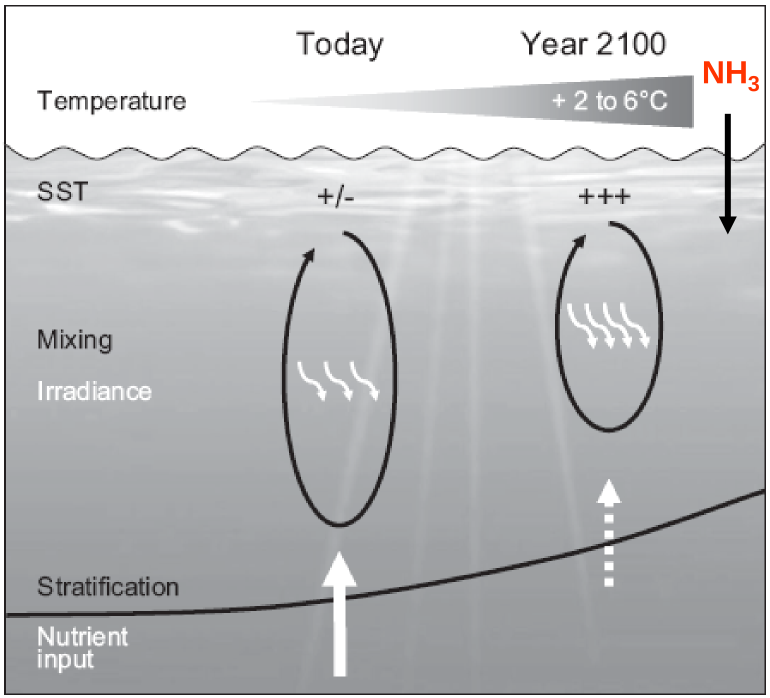
Stress response: immediate

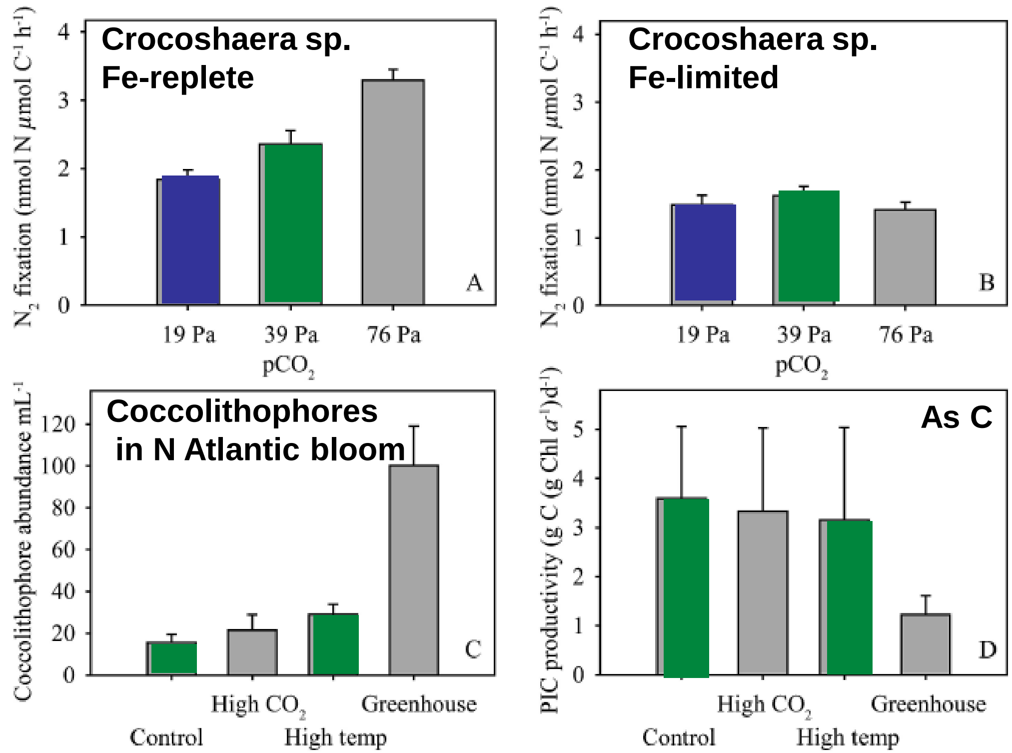
- Green algae *Chlamydomonas* 1000 generations. Some lines did not grow in lower pCO_2 conditions - neutral mutation of CCM making it less efficient - Collins & Bell (2004):
- Similar experiments underway
- Indications from paleo-record of coccolithophores suggest some adaptation
- Evolutionary models
- Impact unknown

Bottom - up Controls of Primary Producers

Synergistic & Antagonistic Interactions between CO_2, temperature, light, nutrients, trace metals



Rost et al. 2008



Boyd et al. 2010

Wyatt et al 2010: surface layer $NH_4 \leftrightarrow NH_3$ (*OA* ←)

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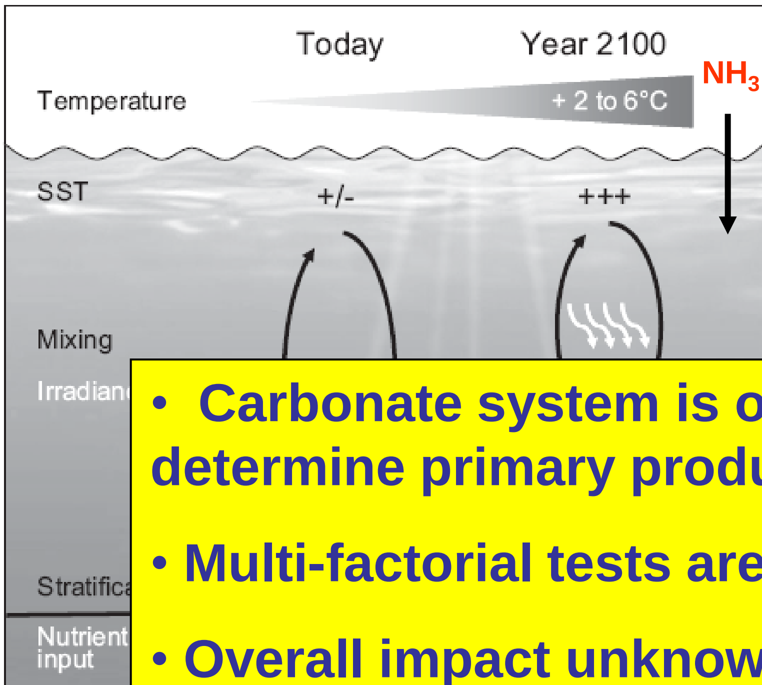
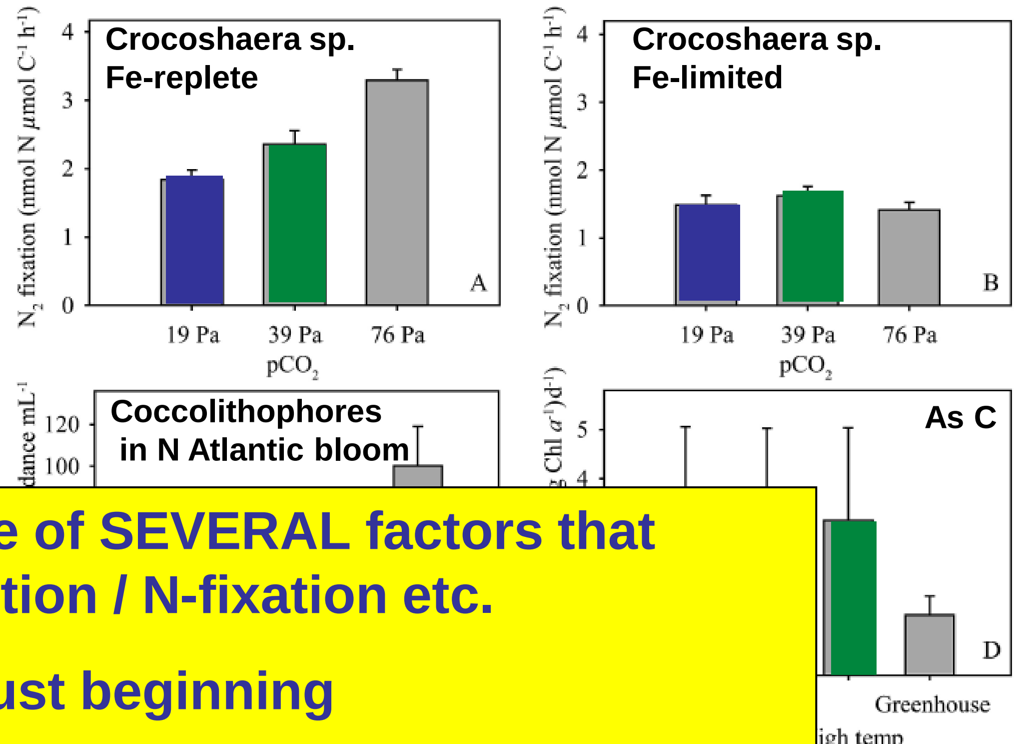


Rost et al. 2008



et al. 2010

- Carbonate system is one of SEVERAL factors that determine primary production / N-fixation etc.
- Multi-factorial tests are just beginning
- Overall impact unknown

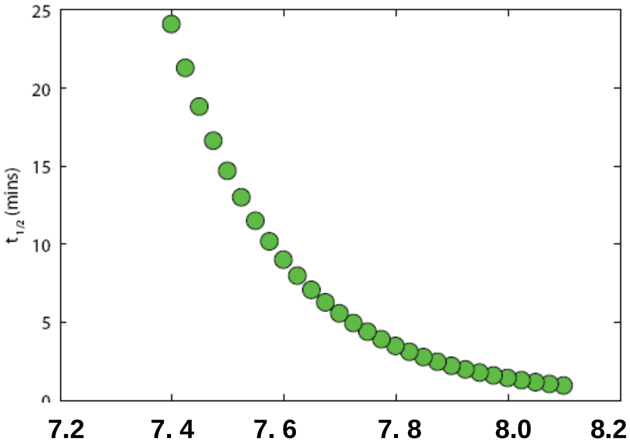
Wyatt et al 2010: surface layer $NH_4 \leftrightarrow NH_3$ (*OA* ←)

Process Investigated

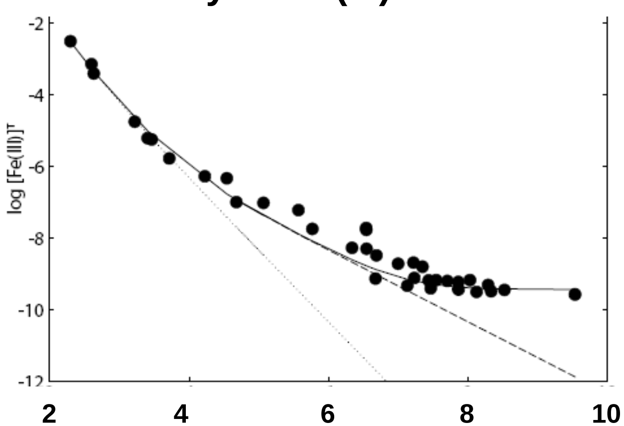
(6) Organic Matter & Trace element cycling

Number of studies	Impact	Range

Half live of Fe (II)

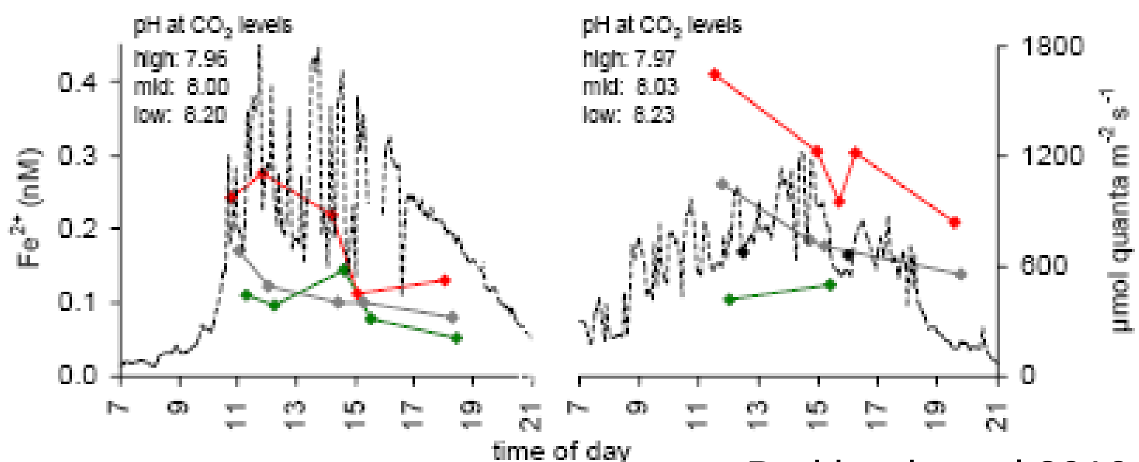


Solubility of Fe (III) in seawater



Millero et al. 2010

Fe^{2+} & PAR days 20 & 22 of PeECE III



Breitbarth et al 2010

(6) Organic Matter & Trace element cycling

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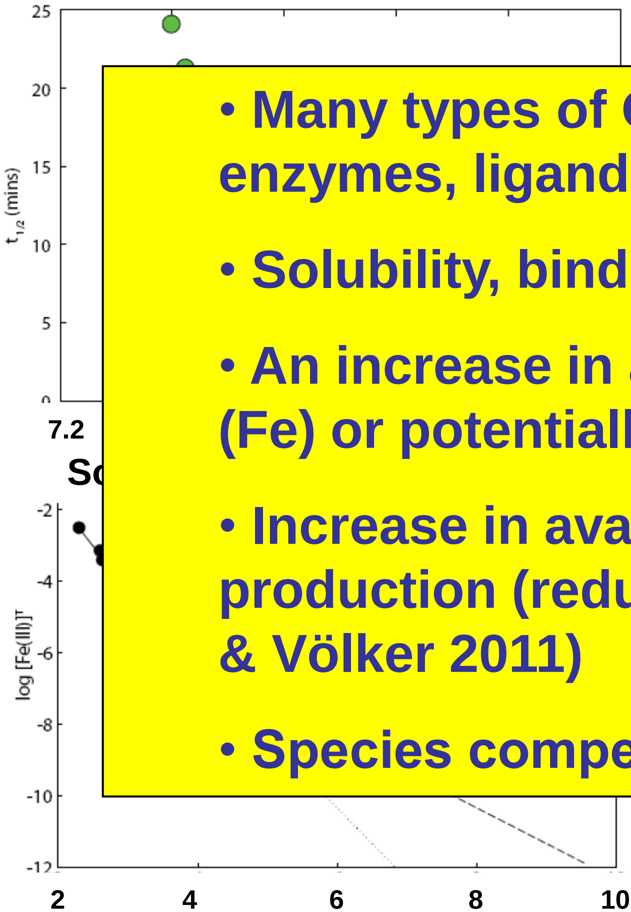


- **Many types of OM are sensitive to pH (trace metals, enzymes, ligands, siderophores,)**
- **Solubility, binding & complexation depends on pH**
- **An increase in availability of trace metals may be profitable (Fe) or potentially toxic (Cu)**
- **Increase in availability of iron may increase primary production (reduction of Fe-limited area by 20%; Tagliabue & Völker 2011)**
- **Species competition may change → shift in composition**

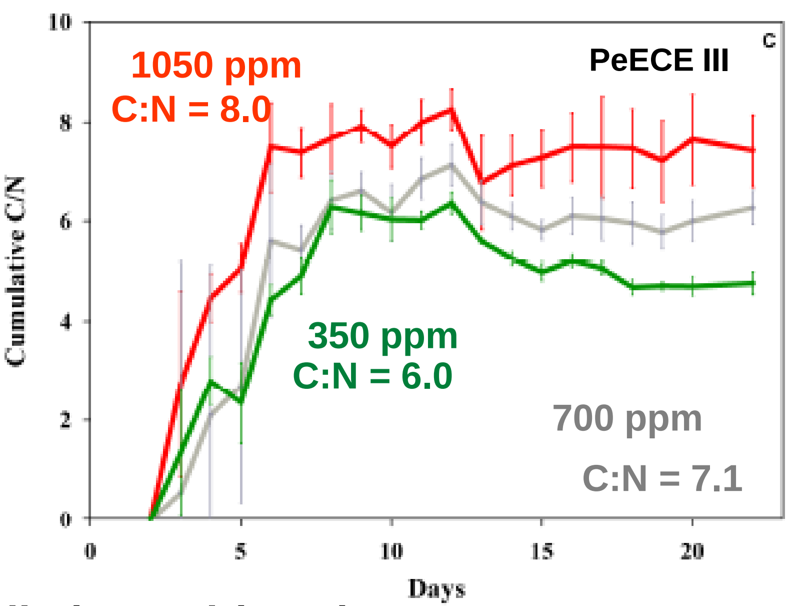
μmol quanta m^{-2} s^{-1}

10

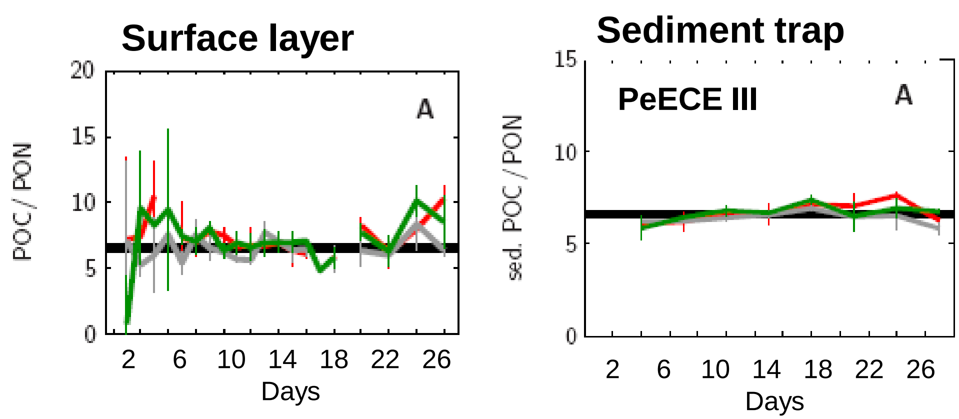
Millero et al. 2010

(7) Stoichiometry of organic matter

Number of studies	Impact	Direction
13	Positive C:Nutrient	Increase
5	Negative C:Nutrient	Decrease
4	Positive N:P	Increase
Uptake Ratio 5	Negative N:P	Decrease



Bellerby et al (2008)

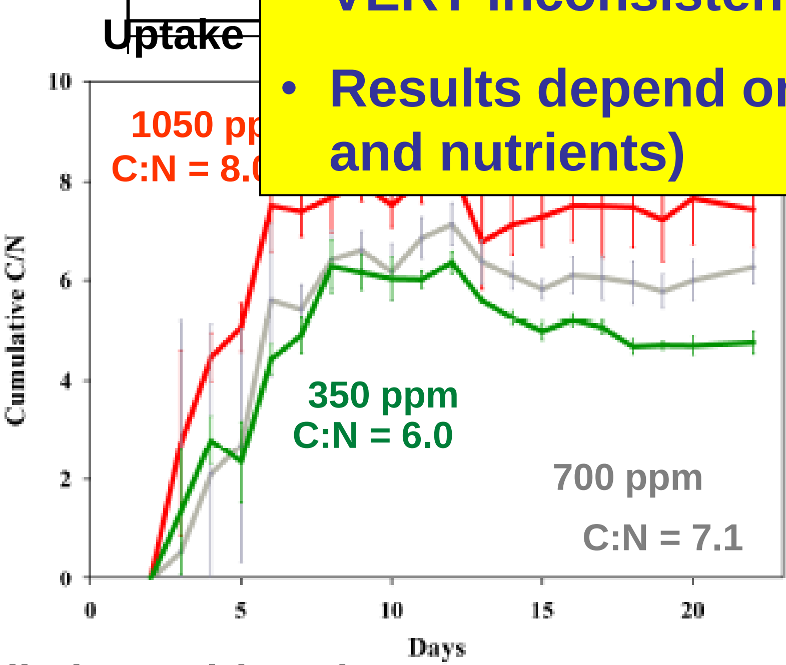


Schulz et al (2008)

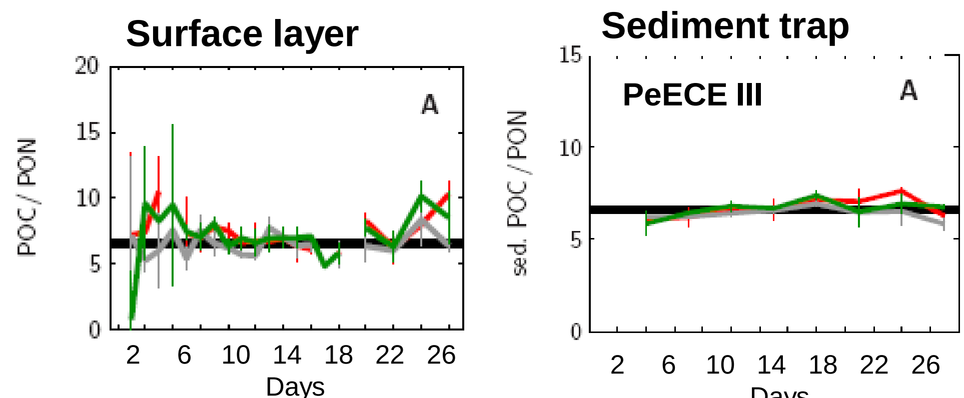
(7) Stoichiometry of organic matter

Number of studies	Impact	Direction
13	Positive C:Nutrient	Increase
5	Negative C:Nutrient	Decrease

- **Enhanced drawdown of CO_2 vs. N, but results VERY inconsistent**
- **Results depend on experimental conditions (light and nutrients)**



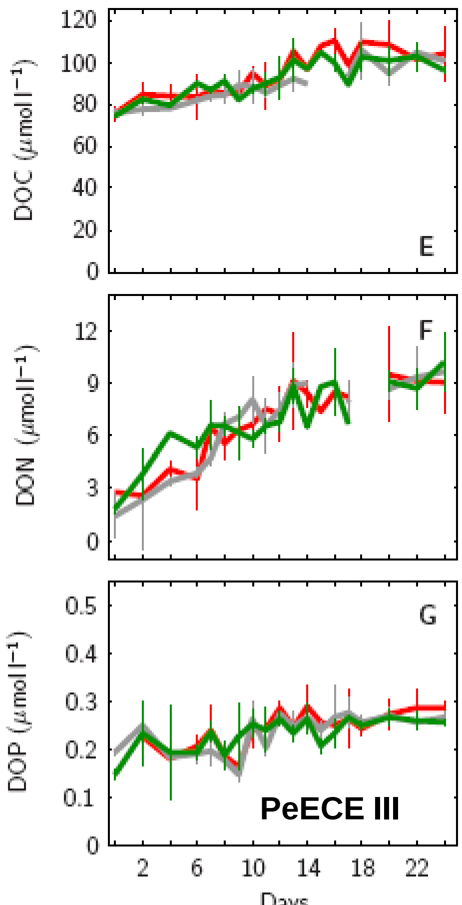
Bellerby et al (2008)



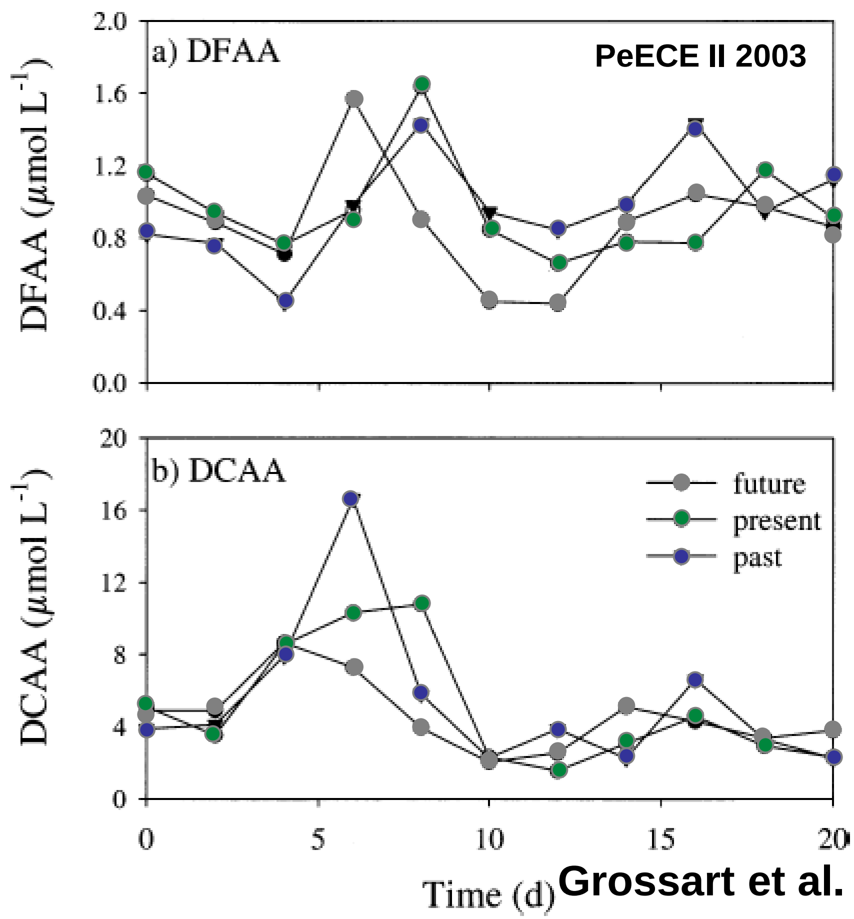
Schulz et al (2008)

(8a) Microbial Loop: DOM Production

Number of studies	Impact	Range
1 Viruses	abundance & diversity	
	Inconsistent	No change



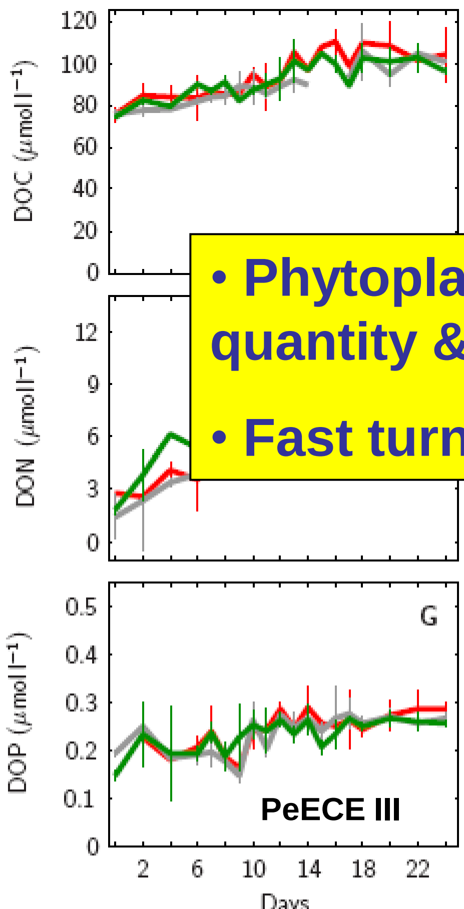
Schulz et al 2008



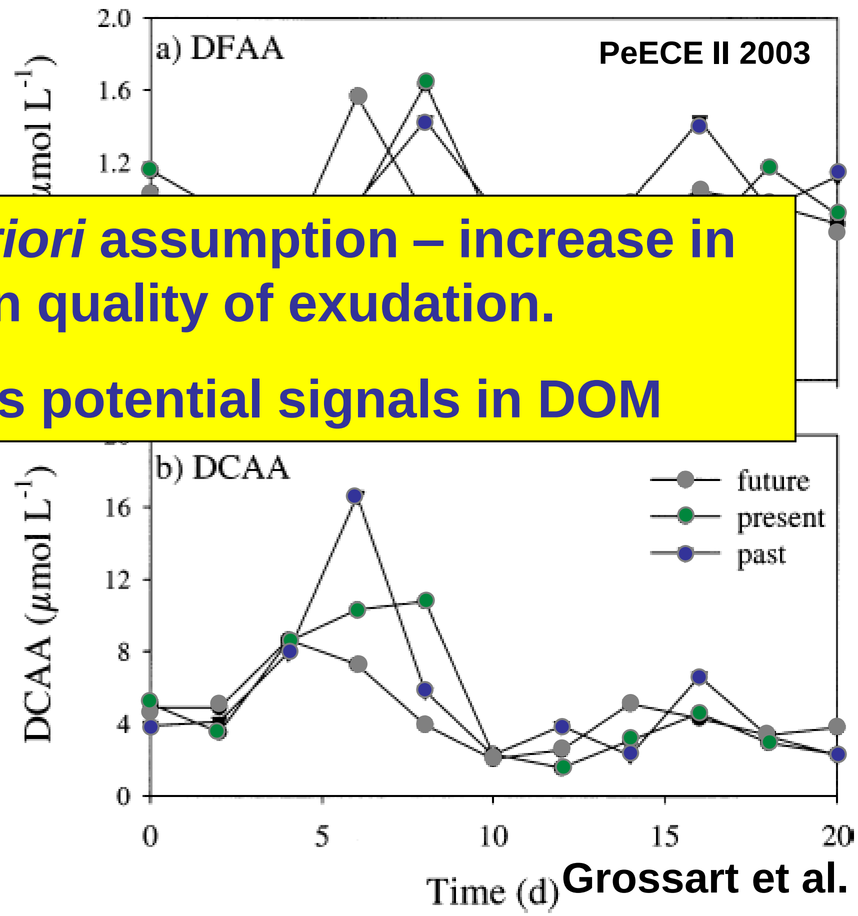
Grossart et al. 2006

(8a) Microbial Loop: DOM Production

Number of studies	Impact	Range
1 Viruses	abundance & diversity	
	Inco	



Schulz et al 2008

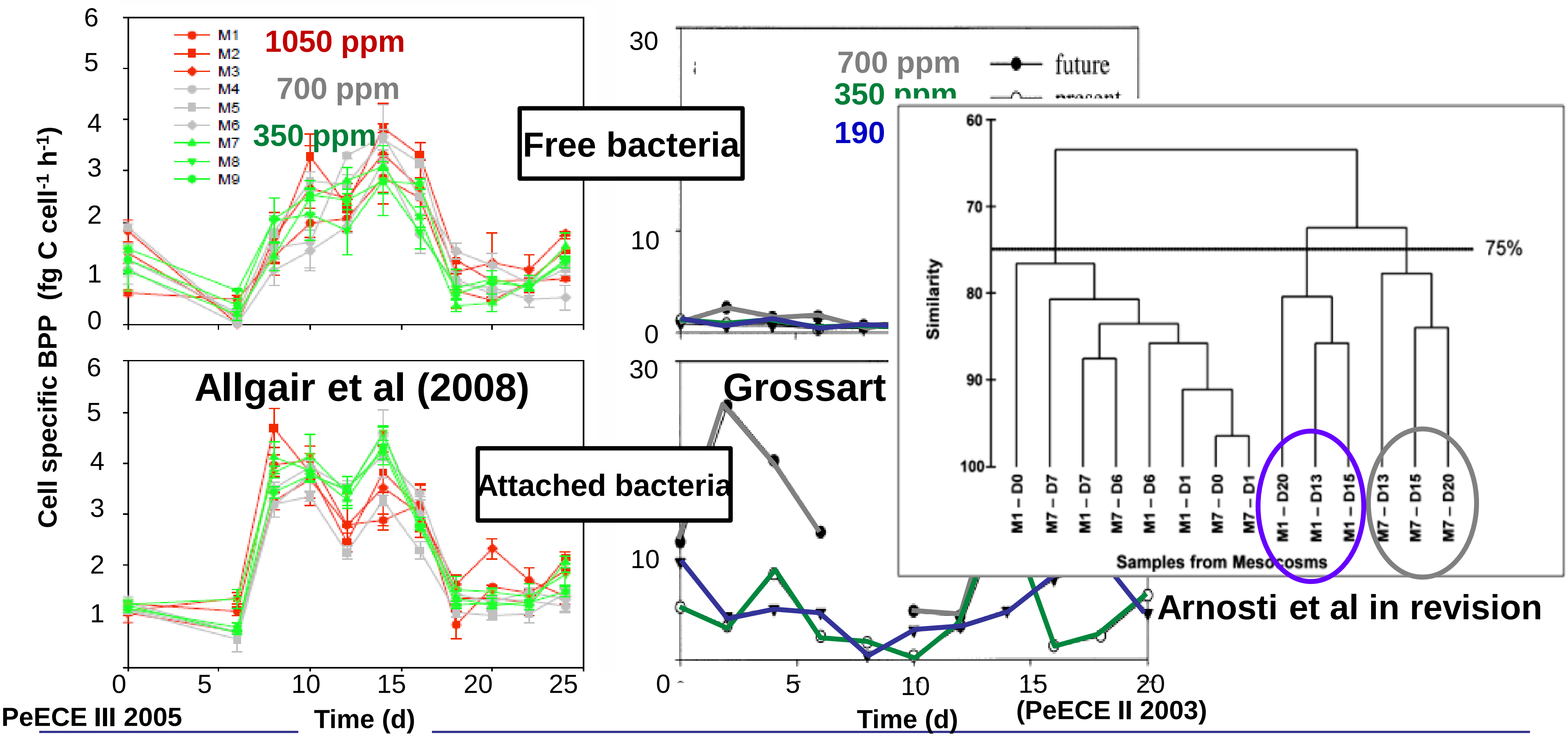


Grossart et al. 2006

- **Phytoplankton: *a priori* assumption – increase in quantity & decrease in quality of exudation.**
- **Fast turn-over masks potential signals in DOM**

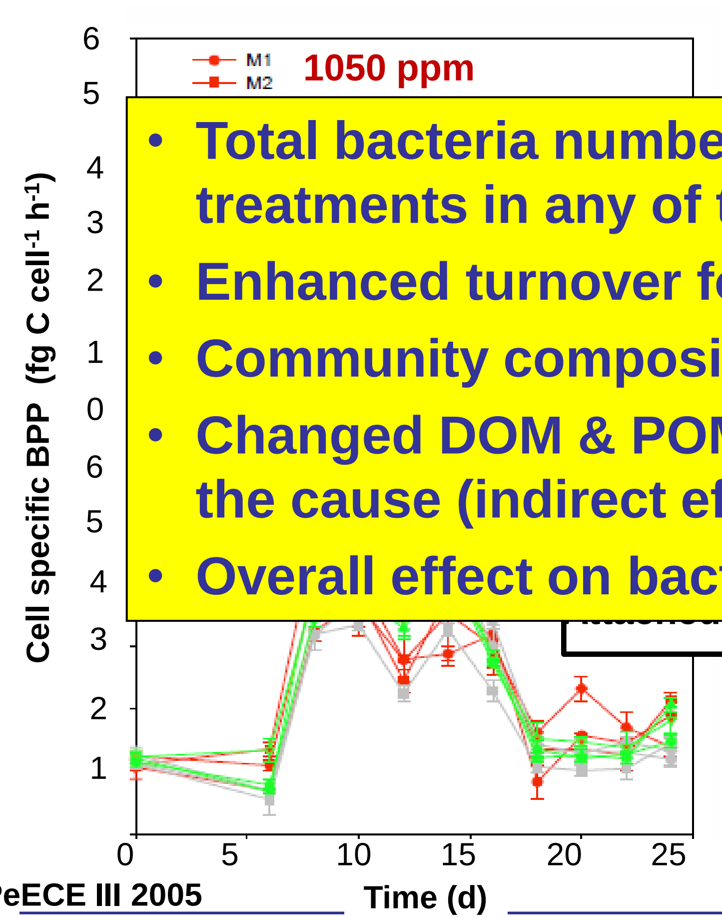
(8b) Microbial Loop: Bacterial Concentration, Turnover and Diversity

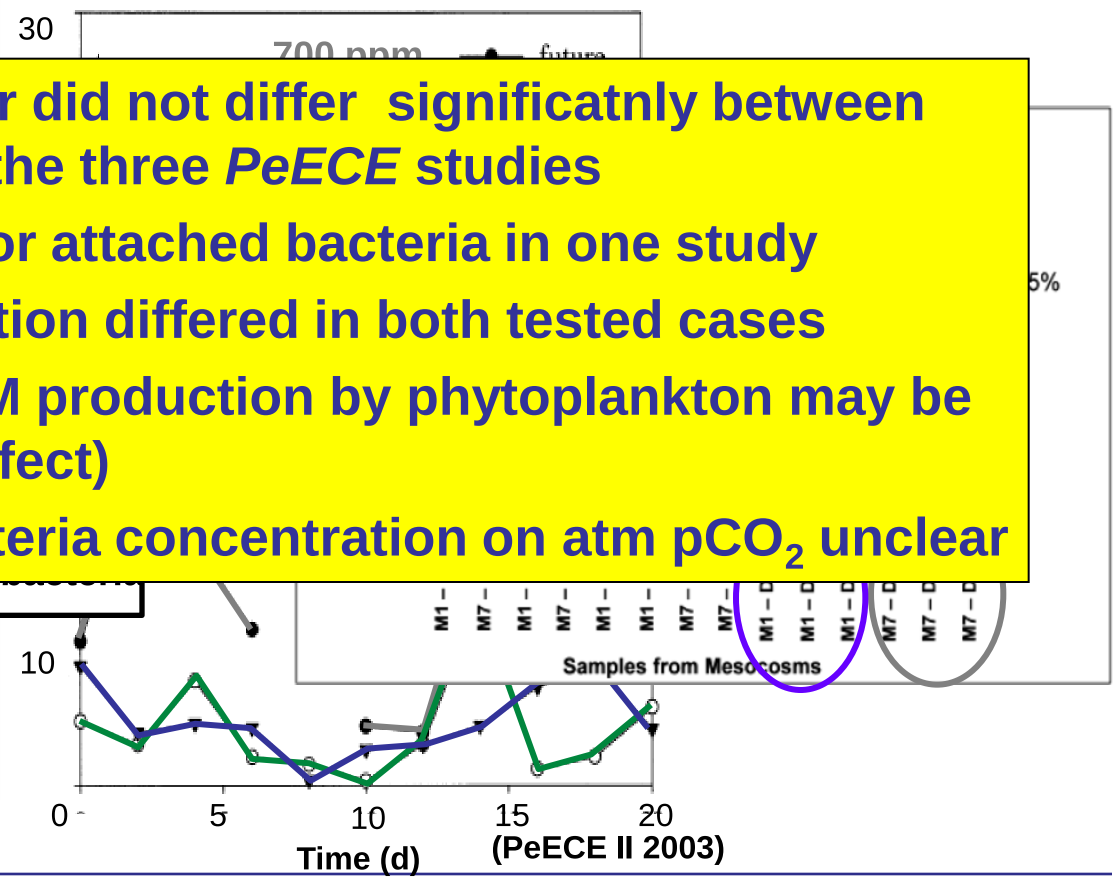
Number of studies	Impact	Range
4	Inconsistent	Increase 46% attached bac.



(8b) Microbial Loop: Bacterial Concentration, Turnover and Diversity

Number of studies	Impact	Range
4	Inconsistent	Increase 46% attached bac.



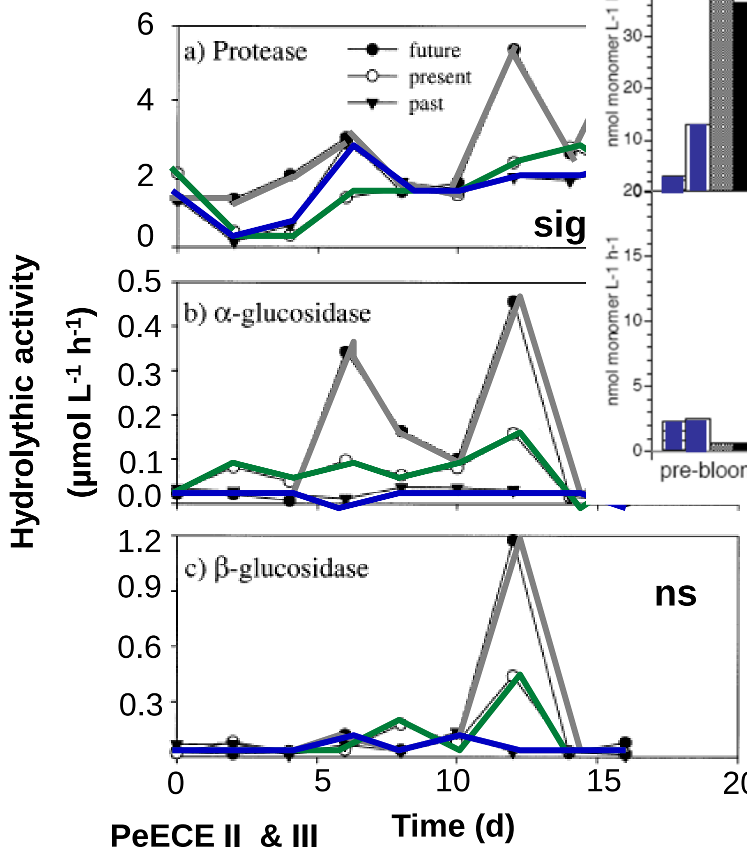


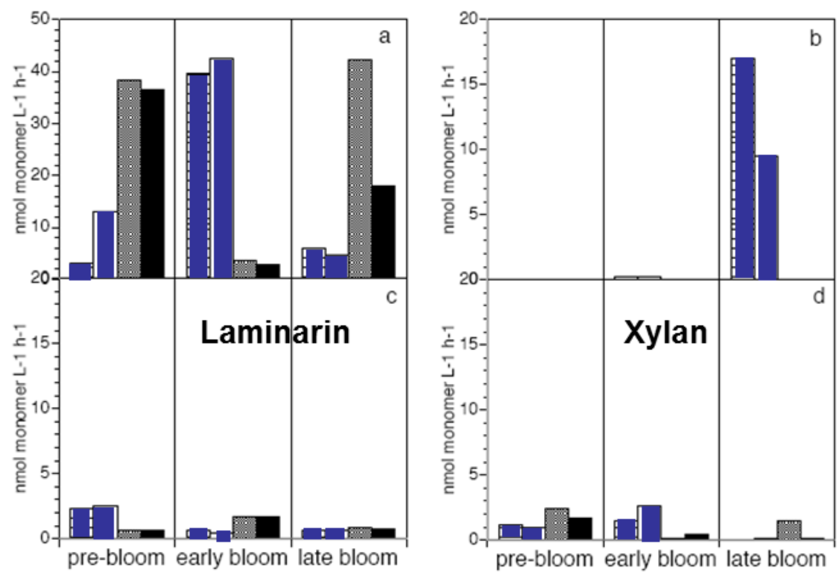
- Total bacteria number did not differ significatnly between treatments in any of the three *PeECE* studies
- Enhanced turnover for attached bacteria in one study
- Community composition differed in both tested cases
- Changed DOM & POM production by phytoplankton may be the cause (indirect effect)
- Overall effect on bacteria concentration on atm pCO_2 unclear

(8c) Microbial Loop: Bacterial Degradation of DOM

Number of studies	Impact	Range
3	Positive/ None	Increase 50-83%

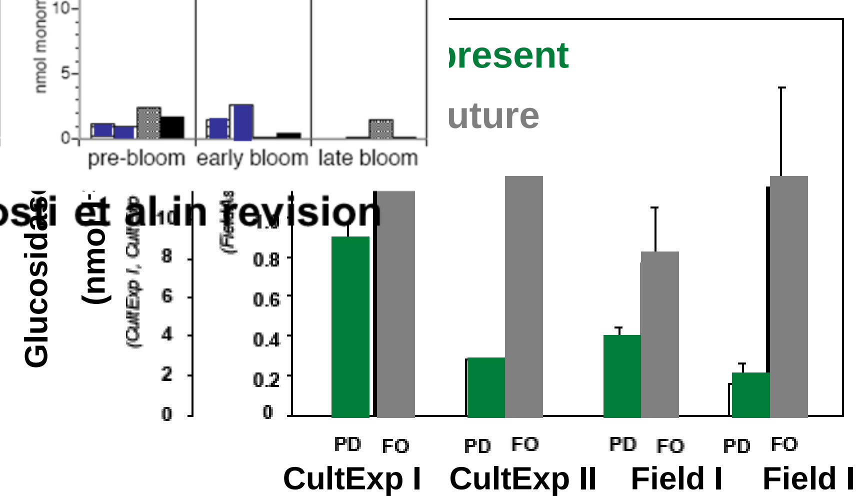
Grossart et al (2006a)





Arnosti et al in revision

ontek et al (2009)

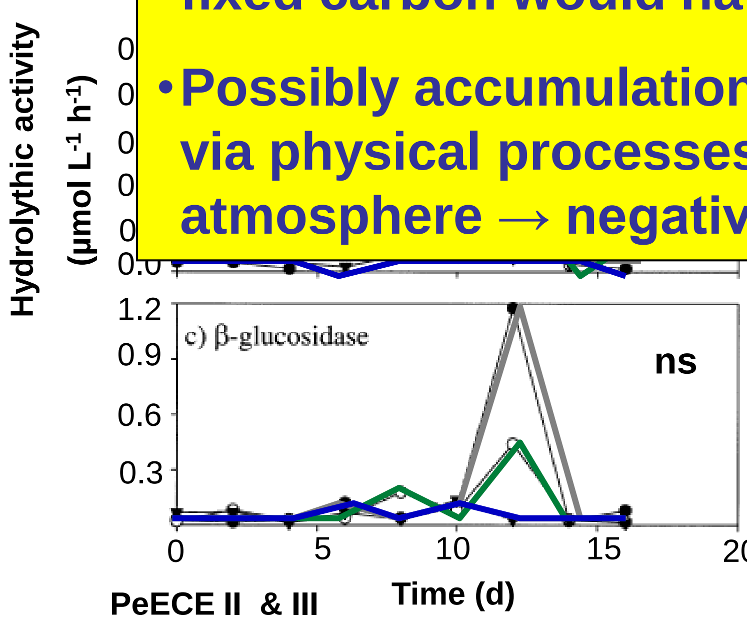


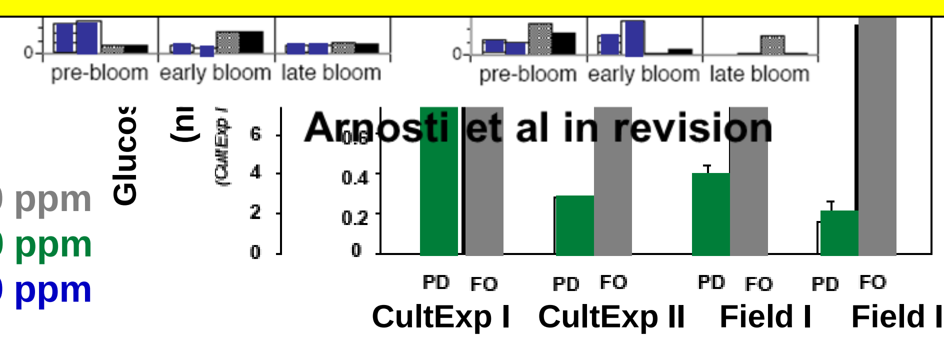
(8c) Microbial Loop: Bacterial Degradation of DOM

Number of studies	Impact	Range
3	Positive/ None	Increase 50-83%

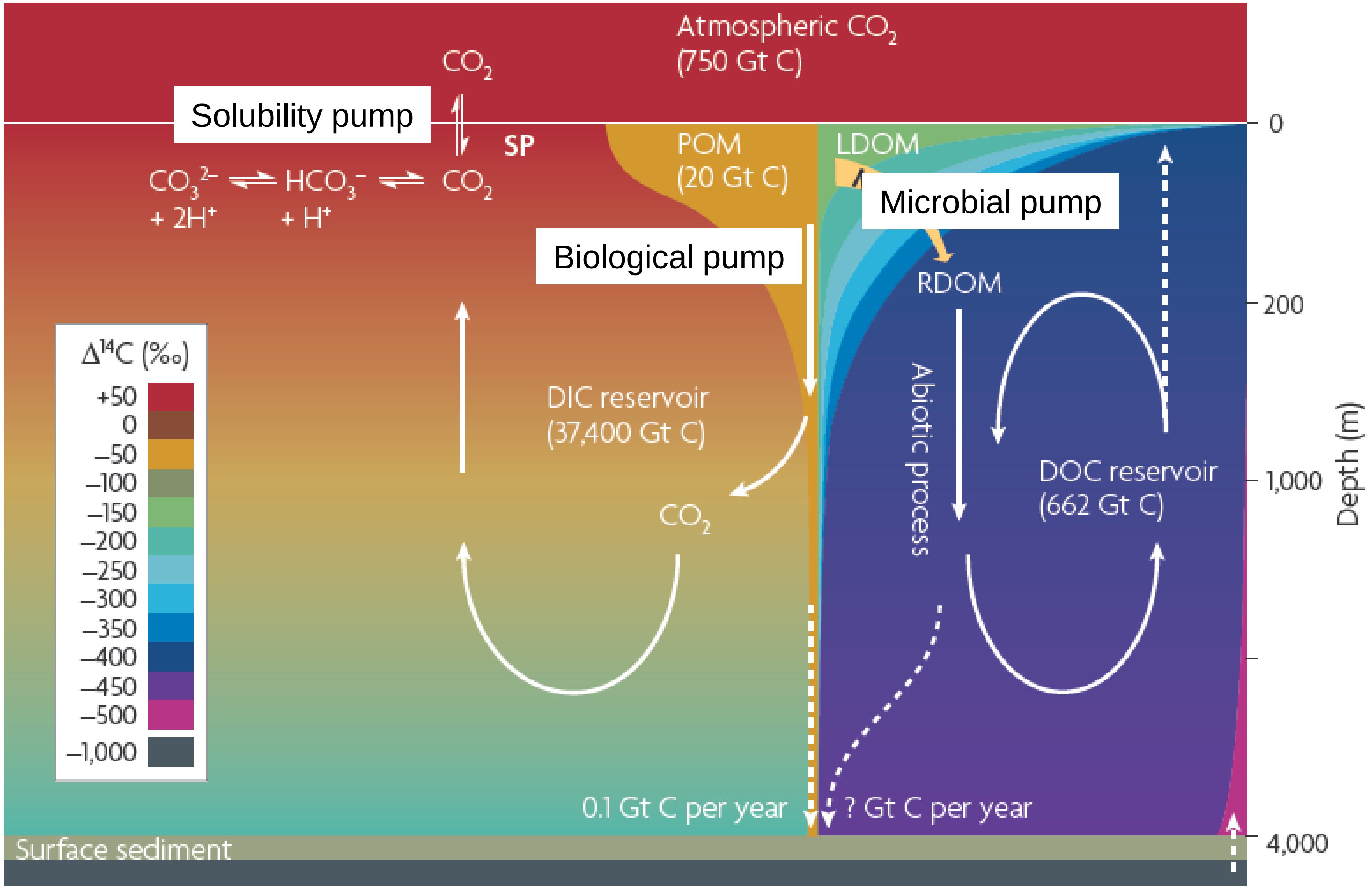
Gross

- Dependant on DOM and mineral nutrients
- Some studies show enhanced degradation in upper water column others do not. Enhanced degradation of additionally fixed carbon would have no net effect on atm. pCO_2.
- Possibly accumulation of DOM in surface ocean & subduction via physical processes removes additional CO_2 from the atmosphere → negative feed back



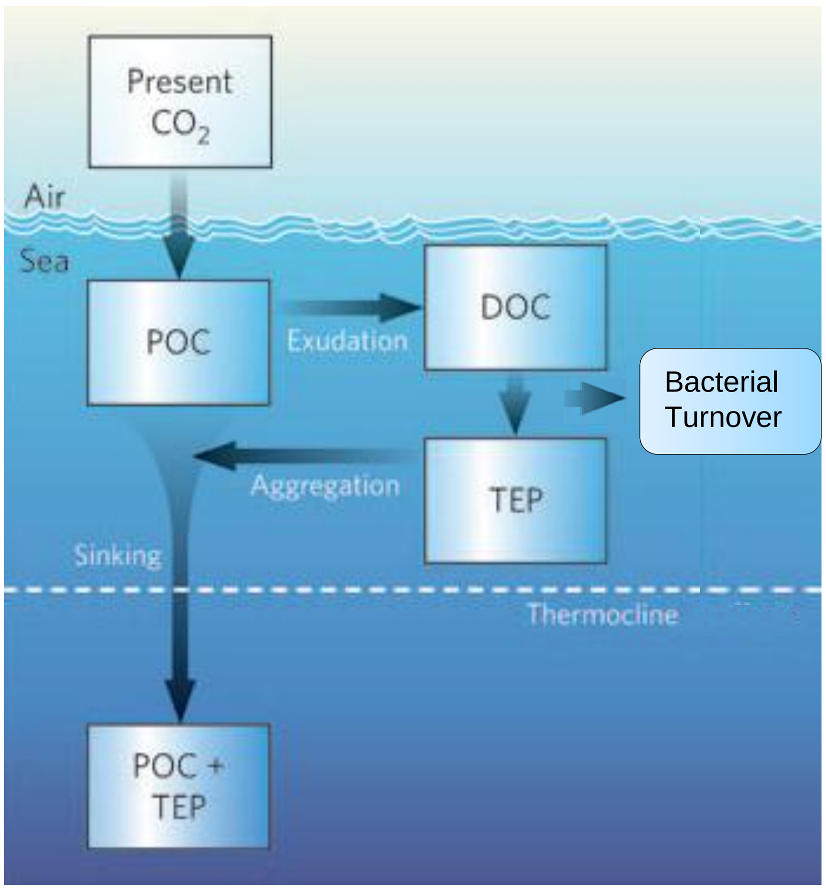


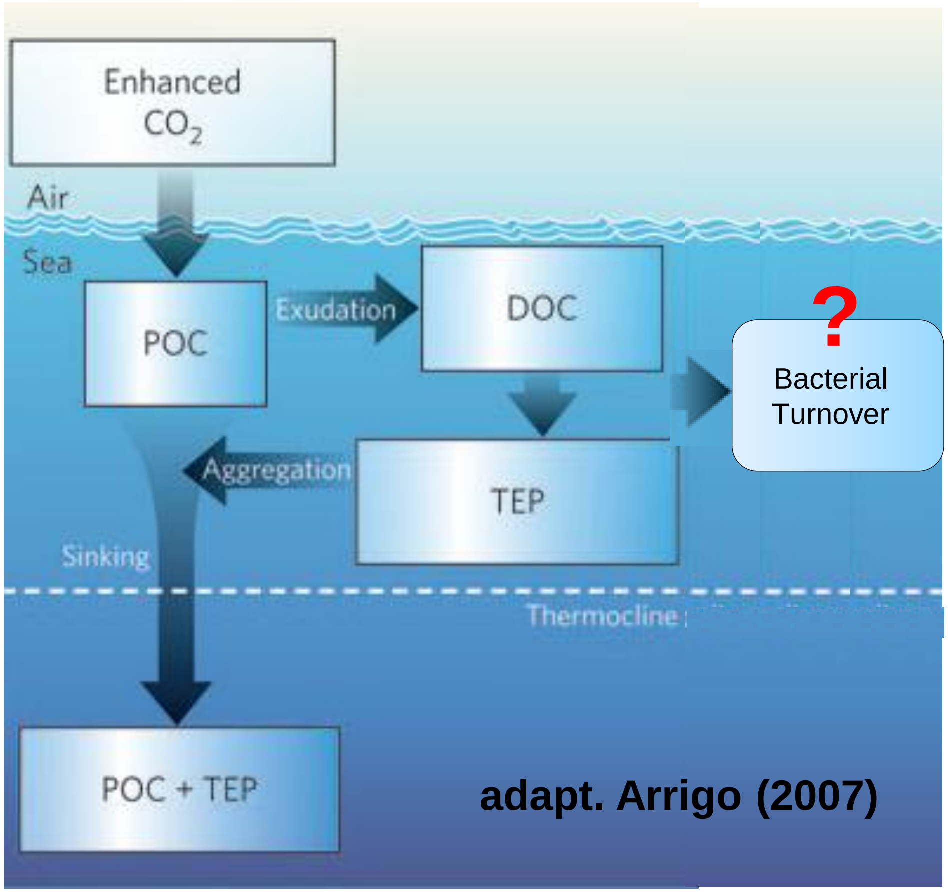
(8) Concept: Microbial Carbon Pump



Jiao et al. Nature Reviews Microbiology 2010

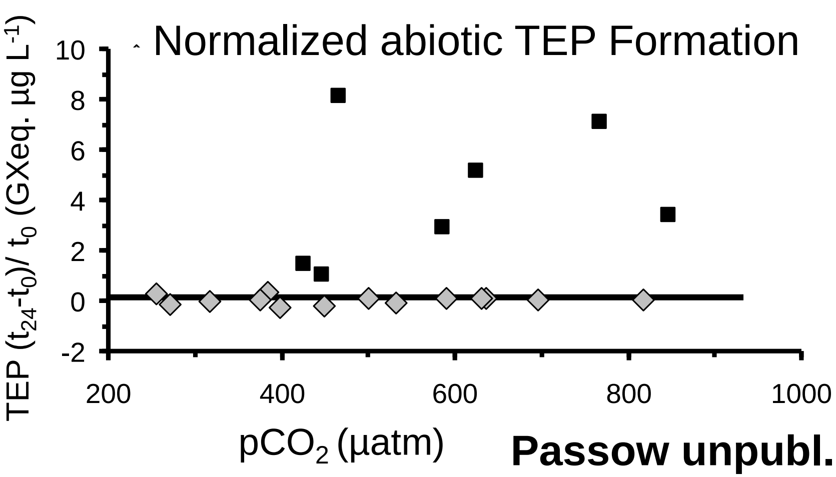
(9) Carbon Flux: Partitioning





(9) Aggregation and Transparent Exopolymer Particles, TEP

Number of studies	Impact	Range
6 (3↑, 3→)	Inconsistent	Increase 20%



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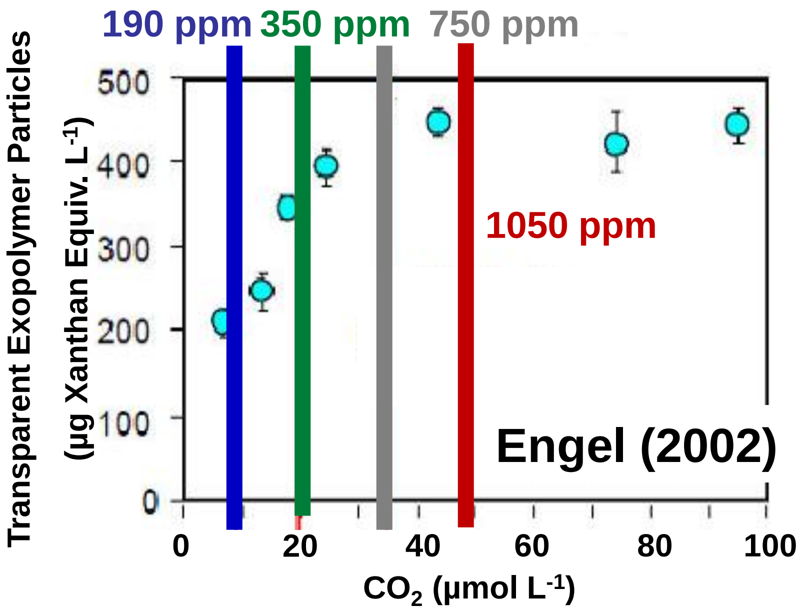
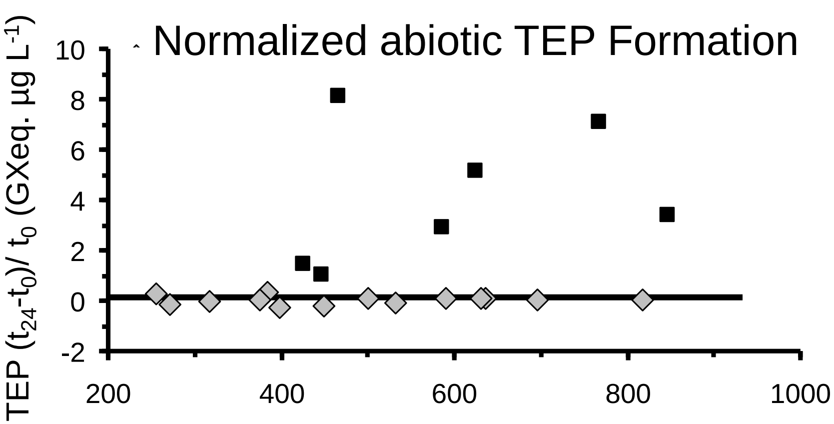


(9) Aggregation and Transparent Exopolymer Particles, TEP

Number of studies	Impact	Range
6 (3↑, 3→)	Inconsistent	Increase 20%

- **No change in abiotic TEP formation expected**
- **Possibly enhanced TEP formation due to increase in DOC exudation but not observed in PeECE II & III.**
- **Impact for aggregation or microbial dynamics are unclear**



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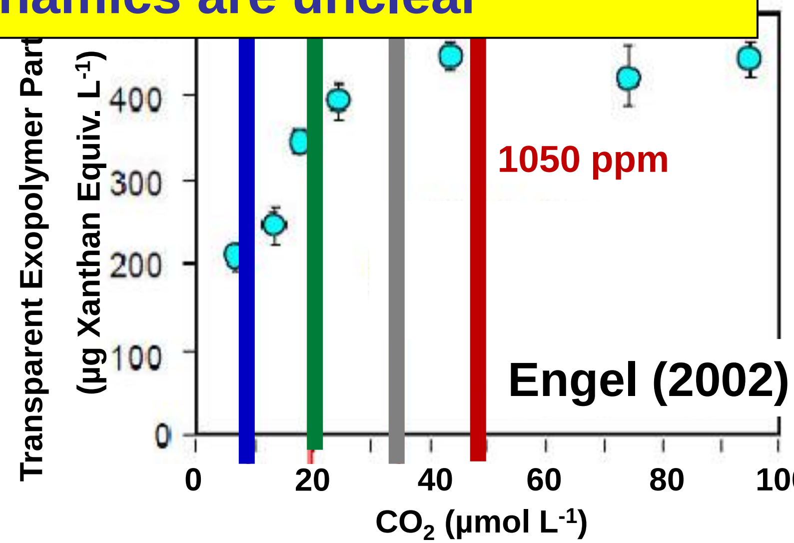
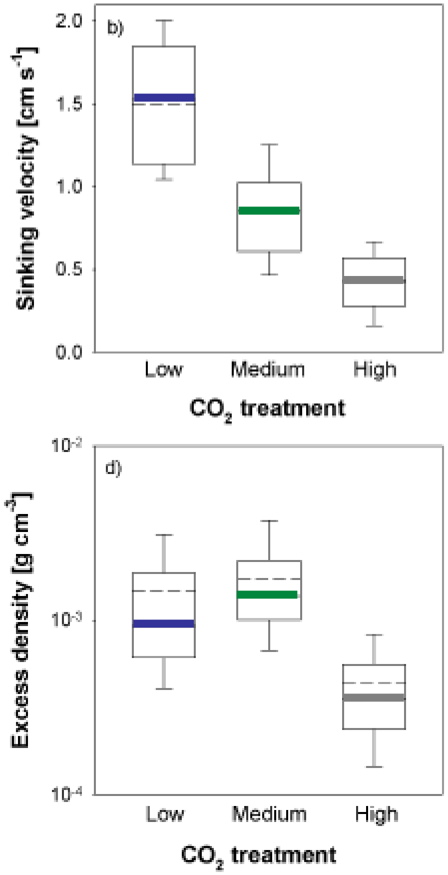


(9) Sinking velocity of aggregates

Number of studies	Impact	Range
2	Decrease	Decrease

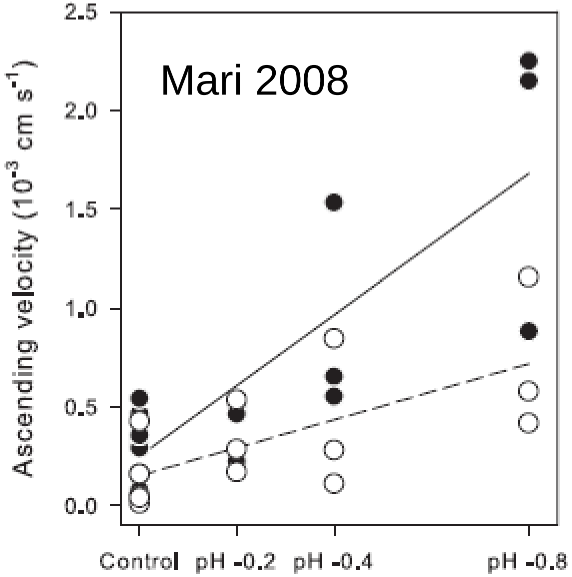
Ballasting: Aggregates of *E. hux.*



Biermann & Engel 2010

TEP Fraction:

Aggregates of TEP & beads



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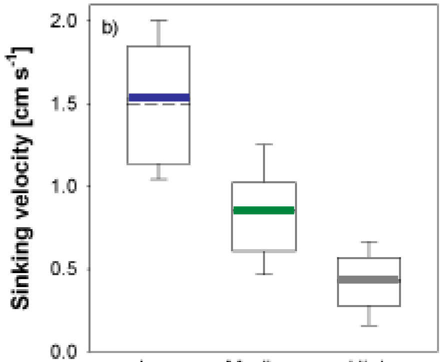
Ballasting: Aggregates of *E. hux.*



TEP Fraction:

Aggregates of TEP & beads

- **Lack of ballasting due reduction in calcification reduces sinking velocity**
- **Increase in the volume fraction of TEP in aggregates decreases sinking velocity**
- **Decrease of flux to deep sea in the future ocean → positive feed back**

CO_2 treatment

Biermann & Engel 2010

(9) Efficiency of Biological pump

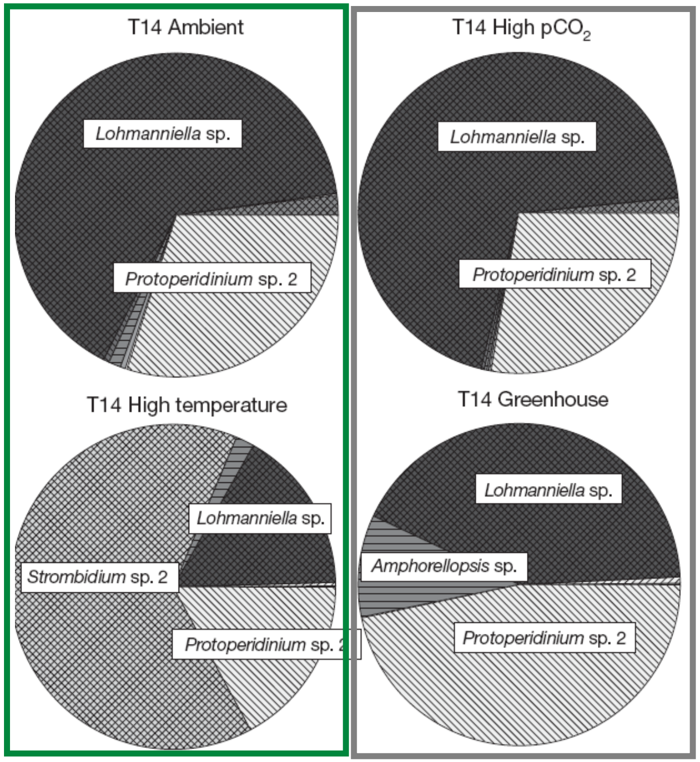
Number of studies	Impact	Range
3	Increase	PeECE III[Mes], ↓$CaCO_3$ Prod[Mod]., Salps vs krill[Theo,Field]

- **Overall effect on biological pump unknown (regionally different?) :**
- **Increase in efficiency (negative feed back):**
  - **C-overconsumption, TEP formation & sedimentation**
  - **Decrease in calcification**
  - **Increase in fraction of salps vs krill**
- **Decrease in efficiency (positive feed back):**
  - **Decrease in sinking velocity due to increase of TEP in aggregates**
  - **Decrease in sinking velocity due to lack of ballasting**
  - **Decrease in diatom abundance**

(10) Zooplankton

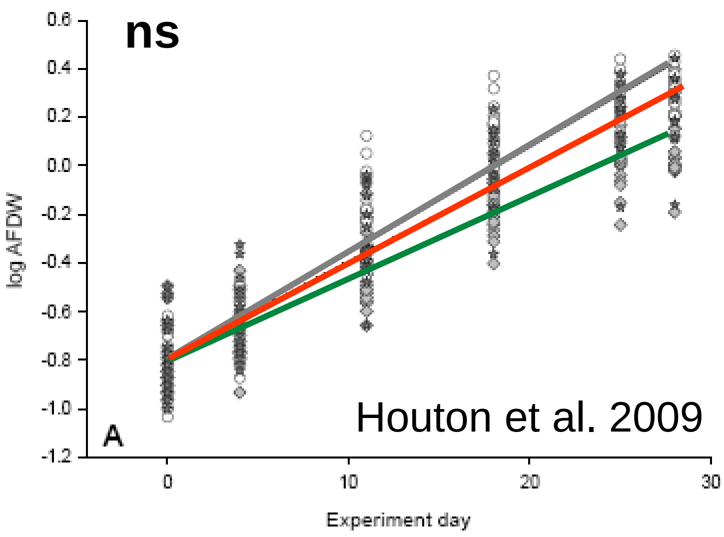
Number of studies	Impact	Range
3	Subtle	No change

Protozooplankton day 14



Rose et al. 2009

Growth rate of amphipod

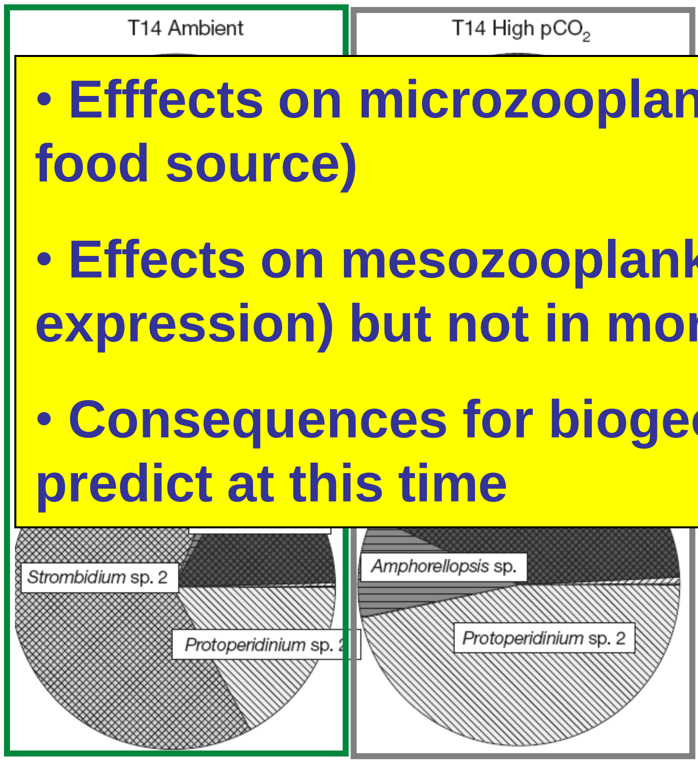


Effects on grazing rate & vertical migration

(10) Zooplankton

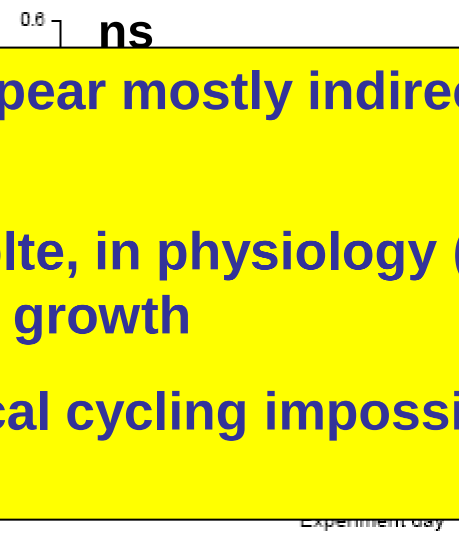
Number of studies	Impact	Range
3	Subtle	No change

Protozooplankton day 14



Rose et al. 2009

Growth rate of amphipod



- Efffects on microzooplankton appear mostly indirect (shift in food source)
- Effects on mesozooplankton sublte, in physiology (gene expression) but not in mortality or growth
- Consequences for biogeochemical cycling impossible to predict at this time

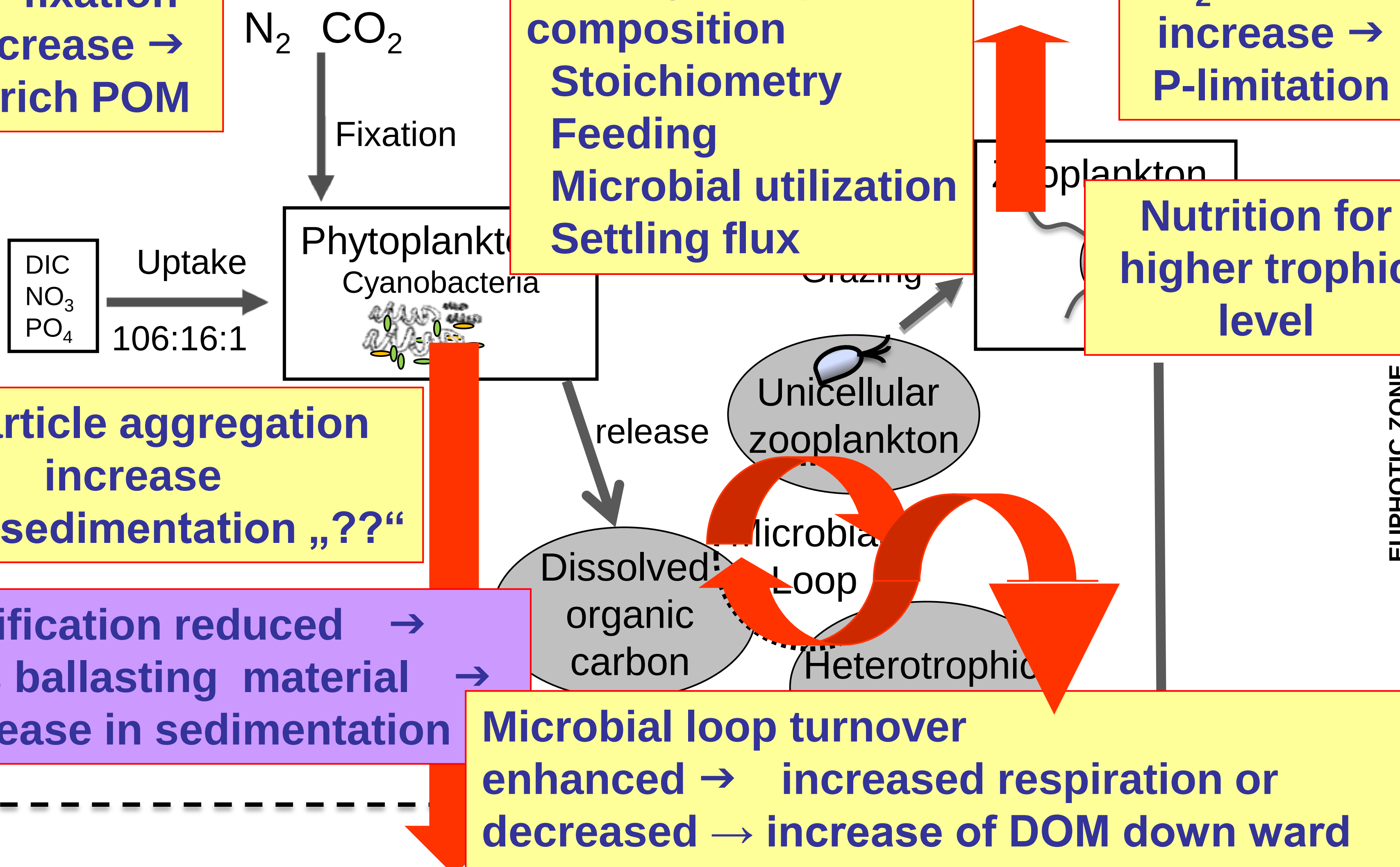
Effects on grazing rate & vertical migration

Effects on Biogeochemistry on Biological Timescales

C- fixation increase → C-rich POM

Change in species composition
- **Stoichiometry**
- **Feeding**
- **Microbial utilization**
- **Settling flux**

N_2 fixation increase → P-limitation



Nutrition for higher trophic level

Particle aggregation → increase in sedimentation „??“

Calcification reduced → Less ballasting material → decrease in sedimentation

Microbial loop turnover enhanced → increased respiration or decreased → increase of DOM down ward transport

Summary

- Number of available studies very limited considering the complexity of the problem
- Ocean acidification seems to significantly alter the environment of microbes
- Changes in phytoplankton and bacterial community structure and physiology are likely
- Changes in microbial processes and community structure impact biogeochemical cycles
- Magnitude and direction of impact presently unpredictable, because of its complexity
- Associated changes of climate add to the complexity → need for multifactorial experiments

Challenges

1. **The carbonate system structures the environment.**
   a) **Spatial and temporal fluctuations are large and *will become larger as OA progresses***
   b) **Feed-backs make changes in carbonate system partially unpredictable**
   c) **These effect organisms, populations, ecosystems and biogeochemical cycling**
   d) **Till recently ignored: Re-evaluate many "pre-OA" results**
2. **OA does not happen isolated – synergistic and antagonistic interactions with other parameters of major importance.**
3. **Ability of organisms to acclimatize and adapt unknown.**
4. **Empirical relationships (*Redfield* ratio, *Martin* curve) may not hold.**

Conclusions

Approaches

1. Autonomous CO_2 buoys – understand rate of change an variability

2. Process studies (laboratory or shipboard experiments) isolating individual processes and field surveys evaluating temporal or spatial gradients will give us information on the breadth of possible reactions

3. Explore combined influence of global change relevant parameters (light, nutrients, trace elements, temperature) in experiments. Test for parameter range in expected changes of specific regions.

4. Models could help predict regional specific expected changes of these parameter combinations (tighter collaboration between modelers and experimentalists).

5. Proxy evaluation to utilize past data for analysis of long-term trends.

6. “Evolutionary” Experiments

7. Mesocosm studies look at community level net effects (black box for individual processes)

8. Model processes and feed-backs, e.g. sedimentation – ballasting,


Thank you!