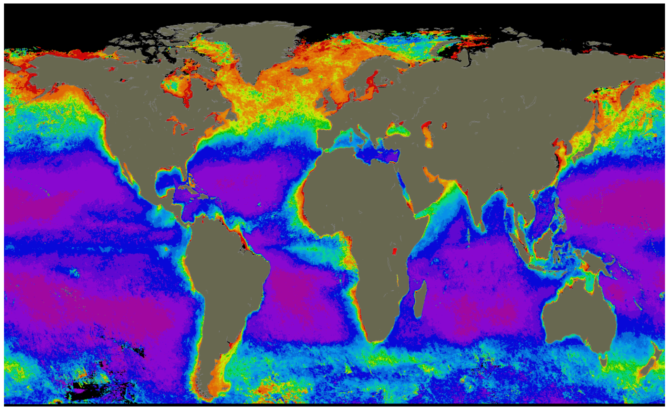
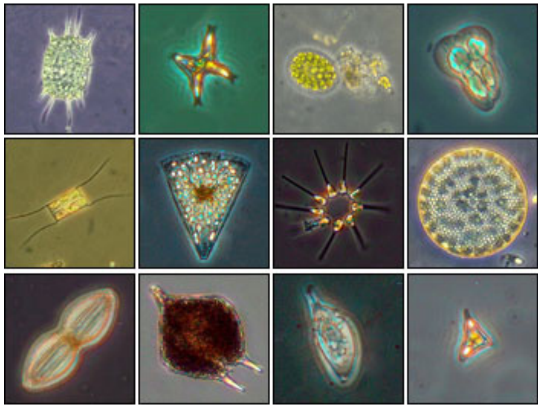


SeaWIFS primary production

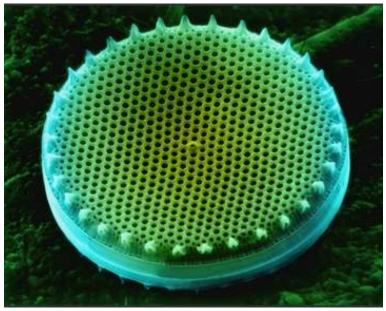
cyanobacterial cultures



Diverse phytoplankton

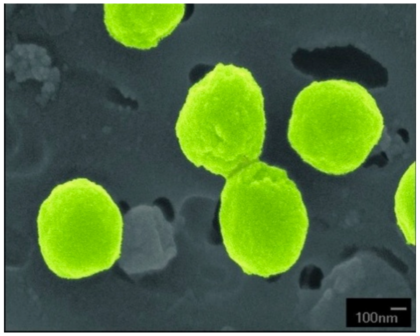
The Carbon Cycle from the Microbial Perspective, Part 1: Autotrophy

Nitrosopumilis maritimus
Ng et al 2013



Dennis Kunkel

Diatom



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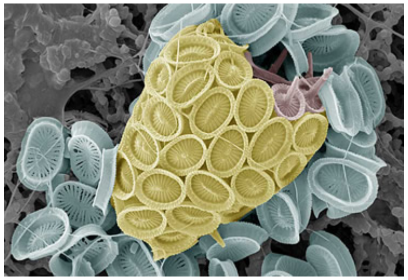
Prochlorococcus marinus



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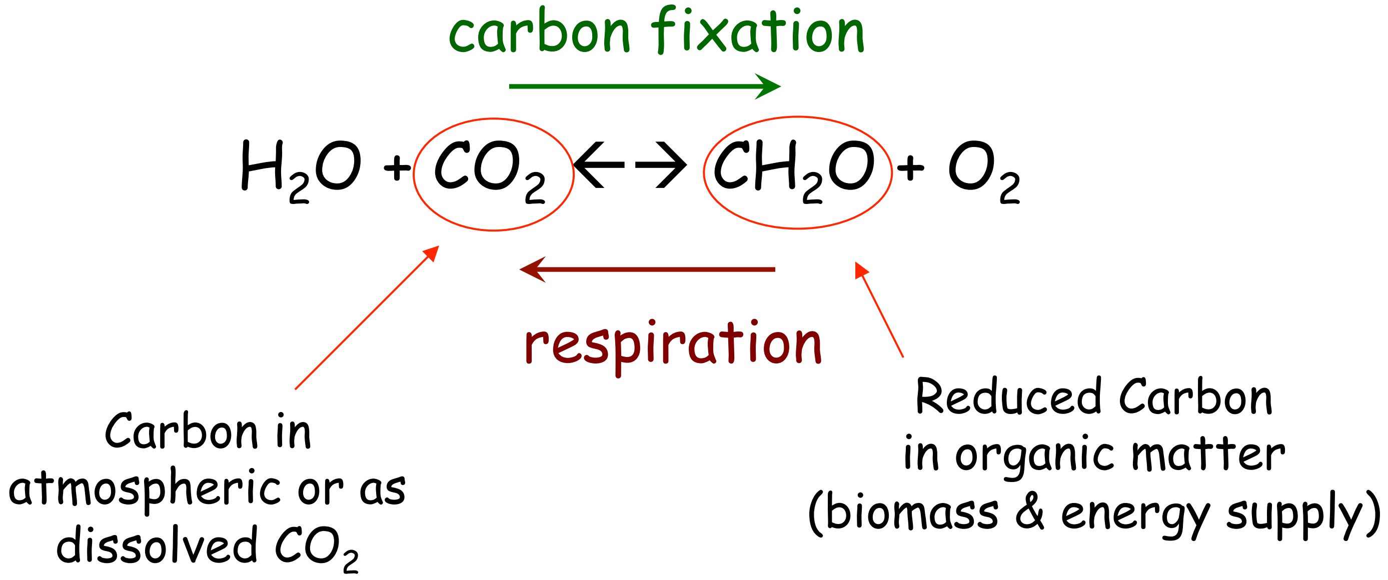
Coccolithophore

With some material from Drs. Raina Maier, Scott Saleska (U of Az), Gene Tyson (U of Queensland, Australia) and Kostas Konstantinidis (Georgia Tech)

“Carbon is the currency of life”

- Scott Saleska, biogeochemist, EEB Dept.



carbon fixation

$$H_2O + CO_2 \leftrightarrow CH_2O + O_2$$

respiration

Carbon in
atmospheric or as
dissolved CO_2

Reduced Carbon
in organic matter
(biomass & energy supply)

How do microbes make a living?

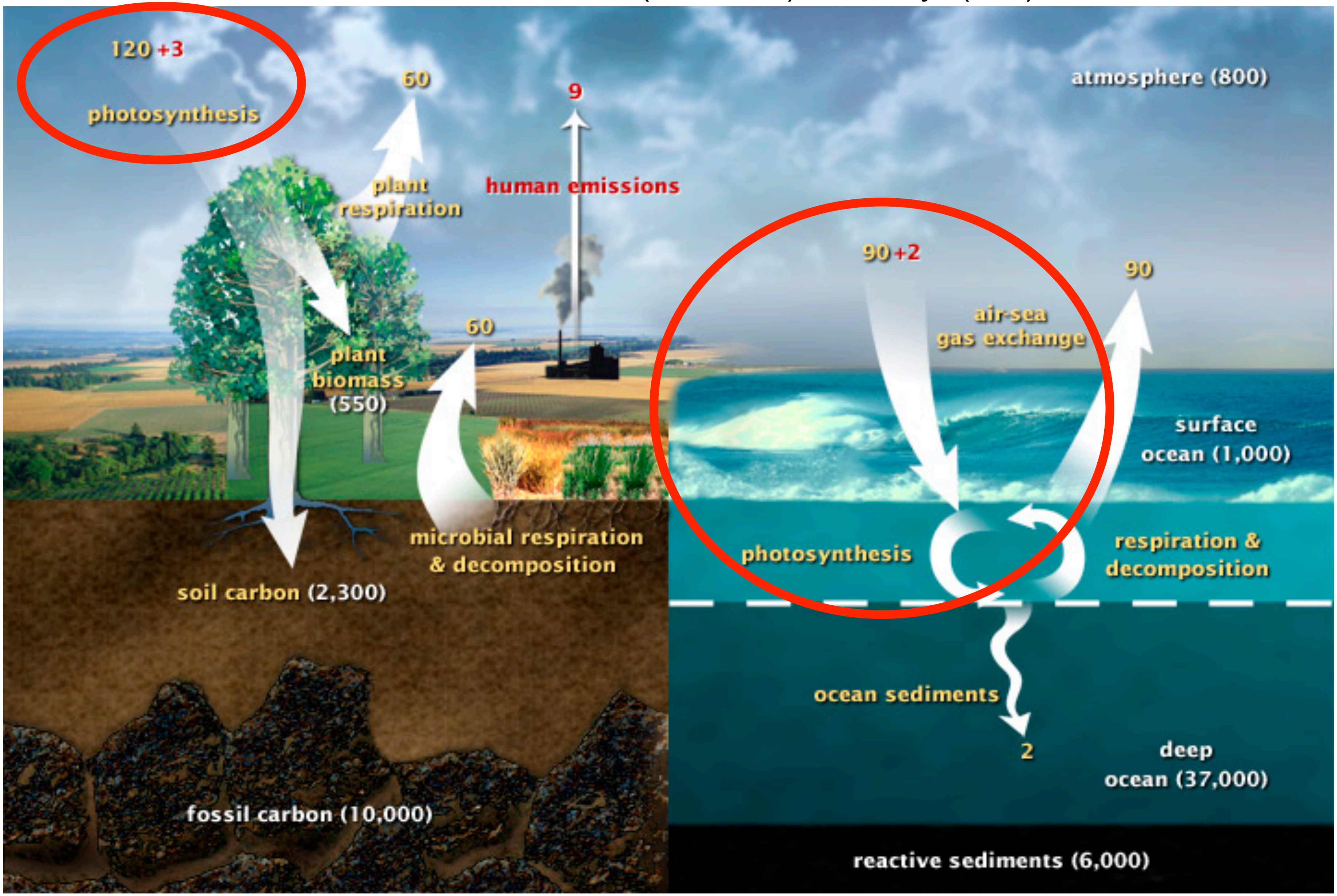
What do microbes – indeed all cells – need to make a living?

1. CARBON for bulk of biomass
2. NUTRIENTS (N,P, S) and micronutrients for proteins, nucleic acids, etc.
3. WATER as a solvent (and a reactant in biomass production)
4. ENERGY to allow them to work against entropy
5. ELECTRONS to transfer energy via redox reactions, and perform chemical transformations – so a *source* and a *sink* for electrons

Global C Cycle.

Values in yellow are natural, values in red are anthropogenic.

Values are in GtC (reservoir) or GtC/yr (flux)

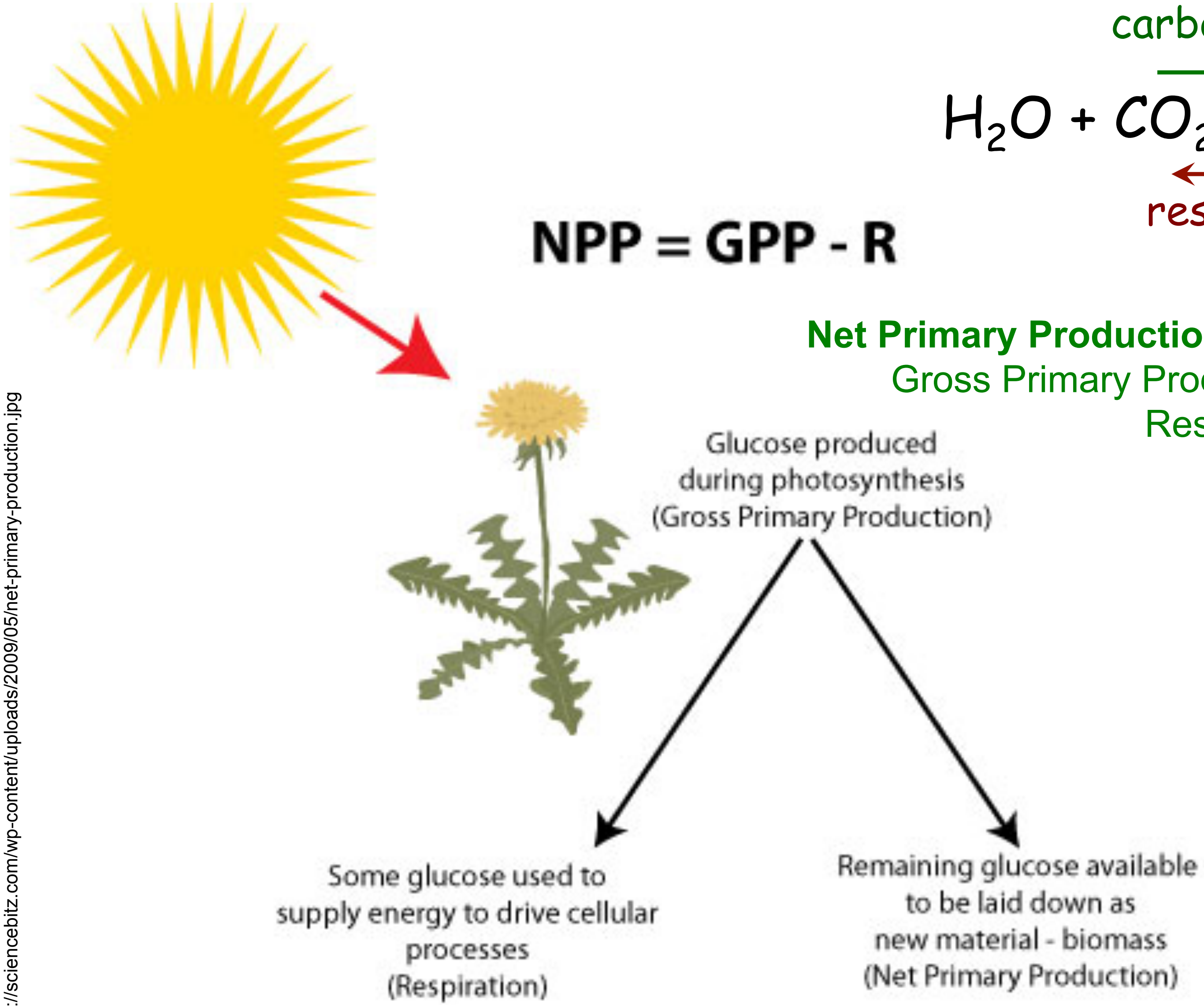


dynamicscience.com.au

Concept of Net Primary Production,

which defines the fixed C available in a system to do stuff…

$$H_2O + CO_2 \underset{\text{respiration}}{\overset{\text{carbon fixation}}{\longleftrightarrow}} CH_2O + O_2$$



NPP = GPP - R

Glucose produced during photosynthesis (Gross Primary Production)

Some glucose used to supply energy to drive cellular processes (Respiration)

Remaining glucose available to be laid down as new material - biomass (Net Primary Production)

Net Primary Production (CO_2 fixed) =
Gross Primary Production (CO_2 fixed) –
Respiration (CO_2 respired)

= biomass made, ie what's created to feed the rest of the food chain…

http://sciencebitz.com/wp-content/uploads/2009/05/net-primary-production.jpg

To most people, global primary production ≅ photoautotrophy

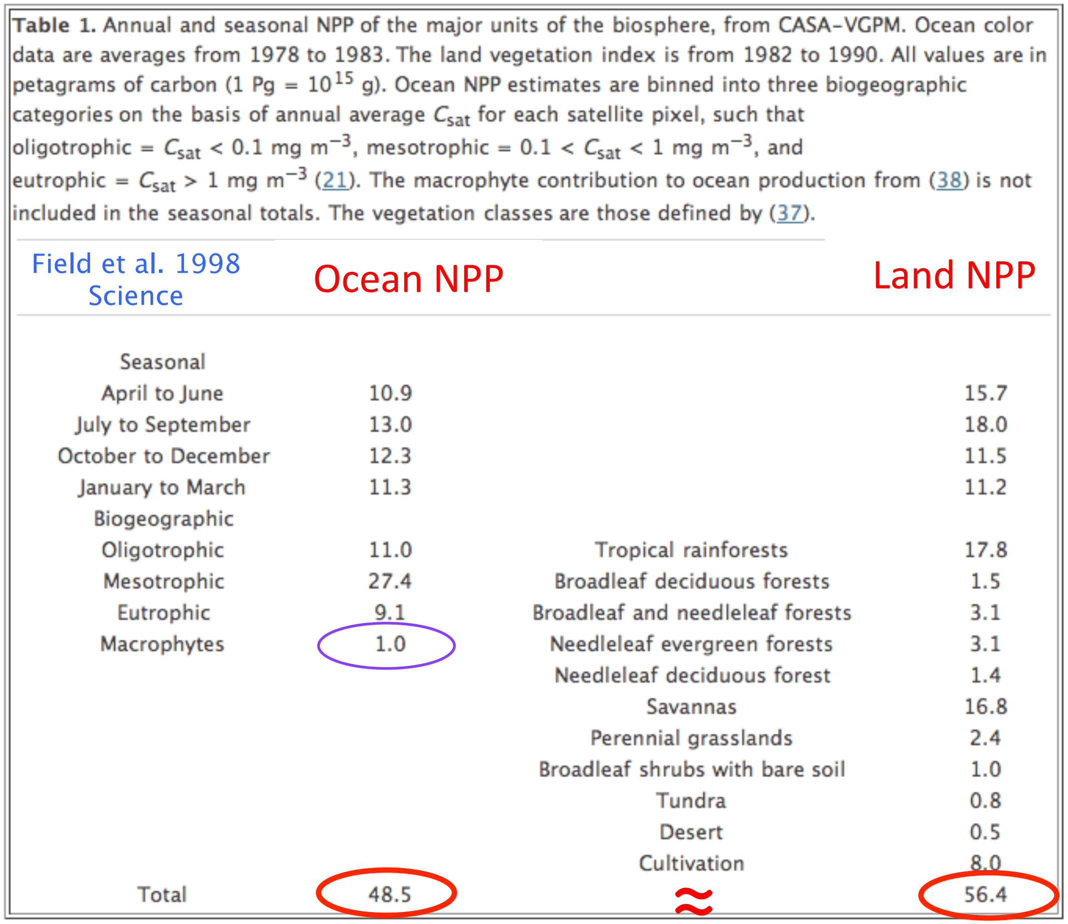
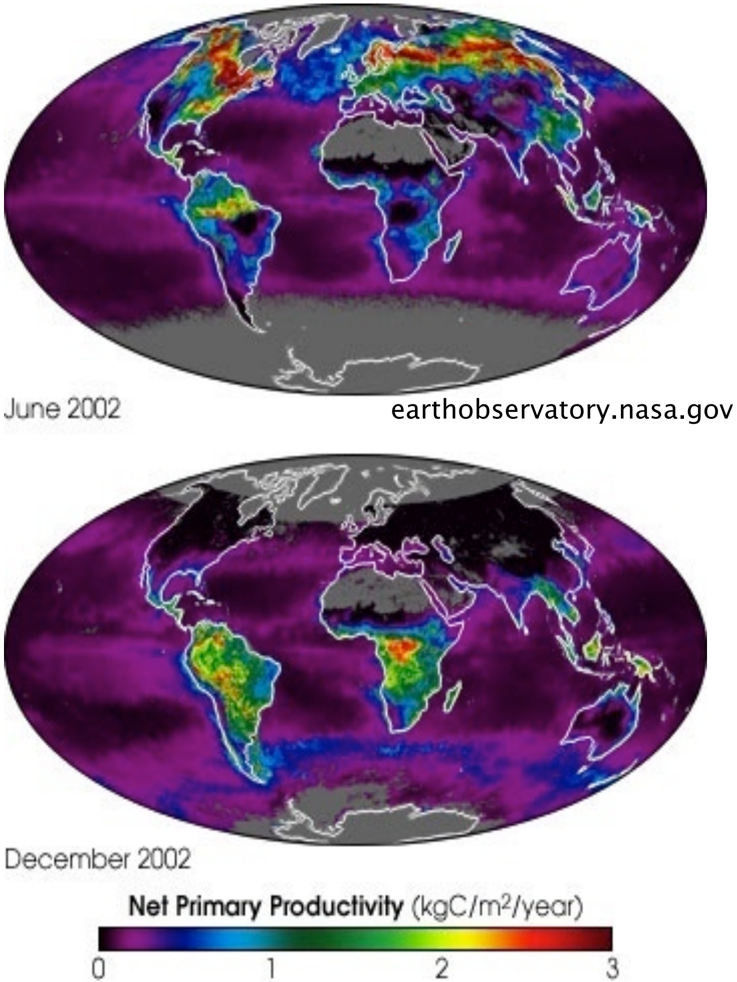


Table 1. Annual and seasonal NPP of the major units of the biosphere, from CASA-VGPM. Ocean color data are averages from 1978 to 1983. The land vegetation index is from 1982 to 1990. All values are in petagrams of carbon (1 Pg = 10^{15} g). Ocean NPP estimates are binned into three biogeographic categories on the basis of annual average C_{sat} for each satellite pixel, such that oligotrophic = $C_{sat} < 0.1$ mg m^{-3}, mesotrophic = $0.1 < C_{sat} < 1$ mg m^{-3}, and eutrophic = $C_{sat} > 1$ mg m^{-3} (21). The macrophyte contribution to ocean production from (38) is not included in the seasonal totals. The vegetation classes are those defined by (37).

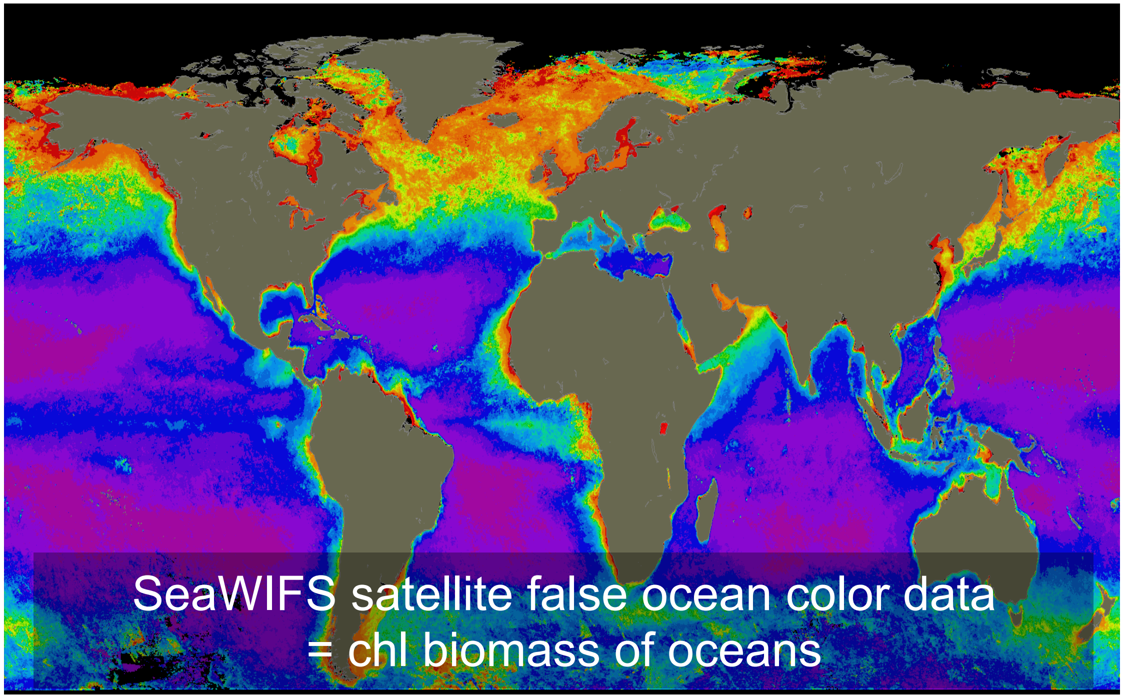
Field et al. 1998 Science	Ocean NPP		Land NPP
Seasonal			
April to June	10.9		15.7
July to September	13.0		18.0
October to December	12.3		11.5
January to March	11.3		11.2
Biogeographic			
Oligotrophic	11.0	Tropical rainforests	17.8
Mesotrophic	27.4	Broadleaf deciduous forests	1.5
Eutrophic	9.1	Broadleaf and needleleaf forests	3.1
Macrophytes	1.0	Needleleaf evergreen forests	3.1
		Needleleaf deciduous forest	1.4
		Savannas	16.8
		Perennial grasslands	2.4
		Broadleaf shrubs with bare soil	1.0
		Tundra	0.8
		Desert	0.5
		Cultivation	8.0
Total	48.5	≈	56.4



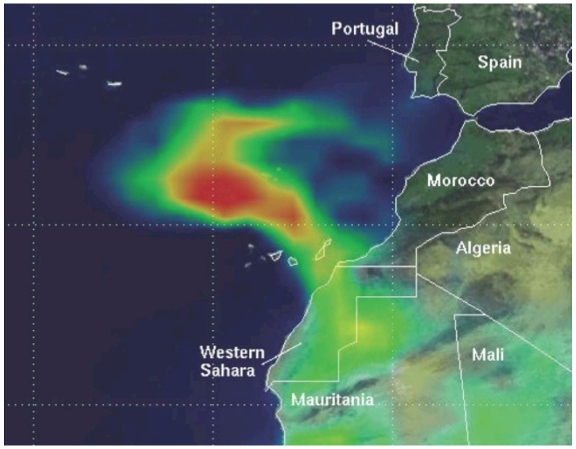
earthobservatory.nasa.gov

- Ocean NPP ~ land NPP. Much sparser biomass, so why?
- The oceans cover a lot of territory (~71% of the earth's surface)
- Not a lot of multi-cellular primary producers in the oceans – sea grasses & most seaweeds limited to coasts, etc. – so it's all about the microbes

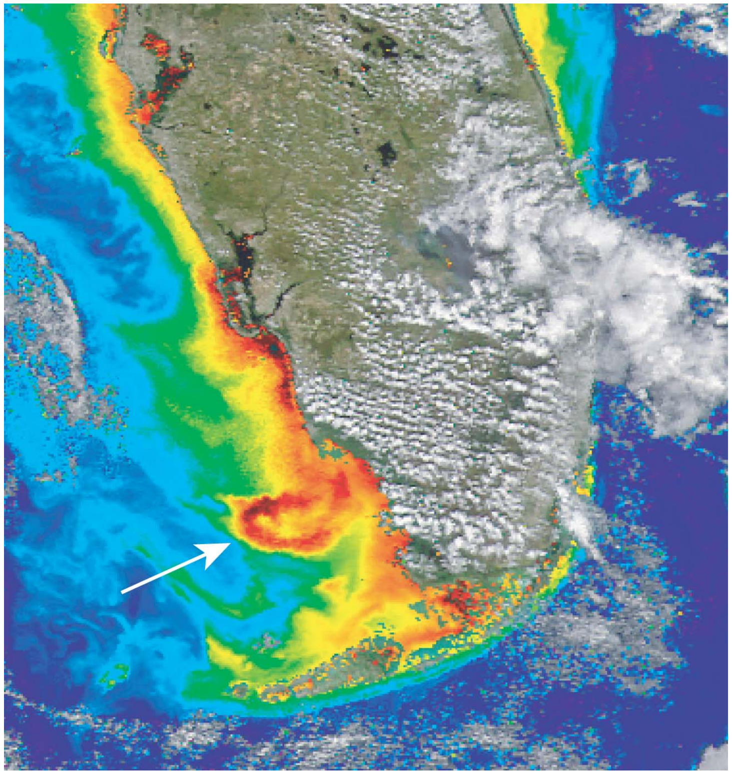
Satellites “see” primary production



SeaWIFS satellite false ocean color data
= chl biomass of oceans



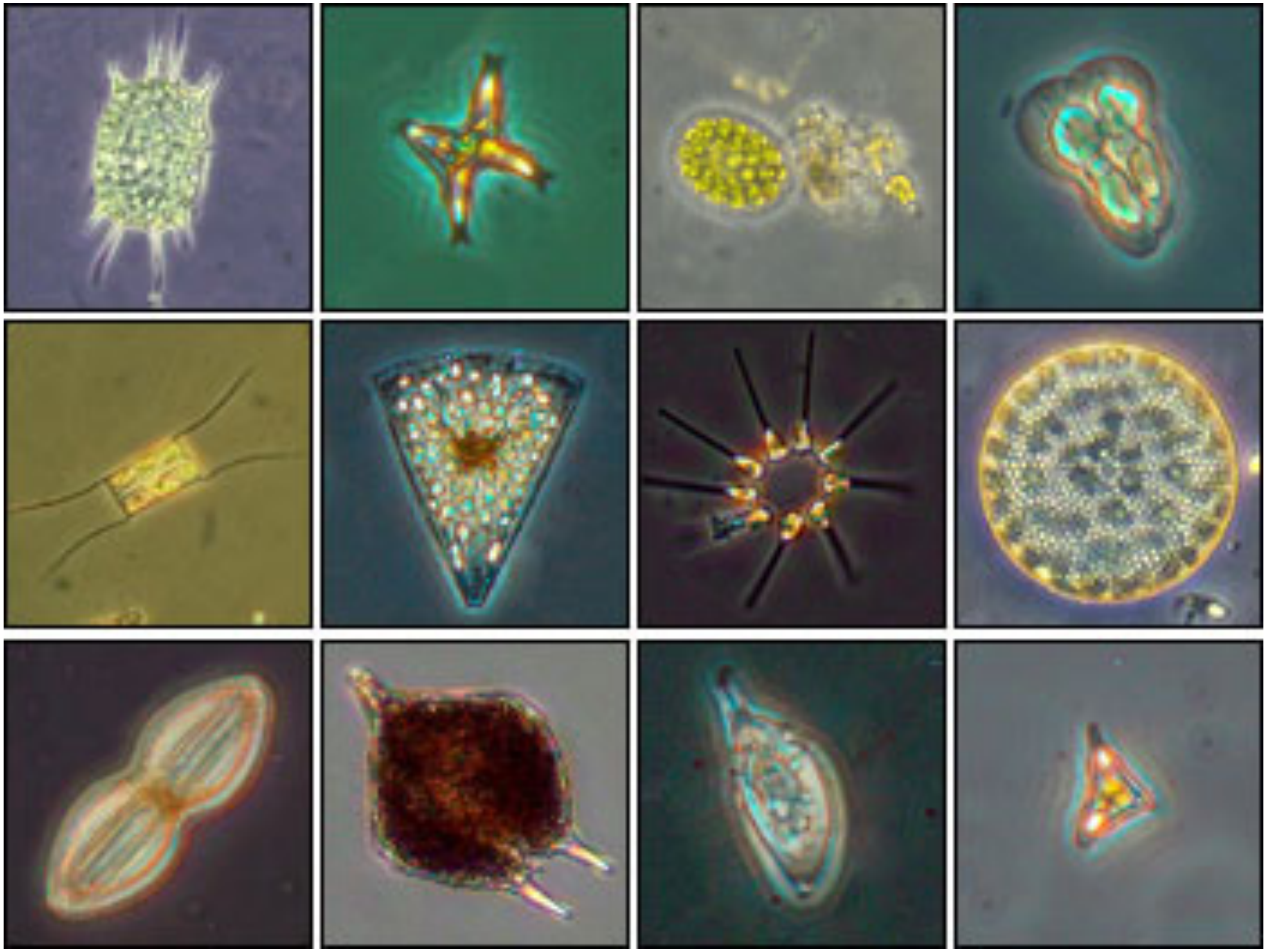
Dust storm off
Africa =
source of Fe,
P, other
nutrients



Red tide bloom off FL,
unknown causative species

TINY BUT MIGHTY

Ocean phytoplankton: half of global PP

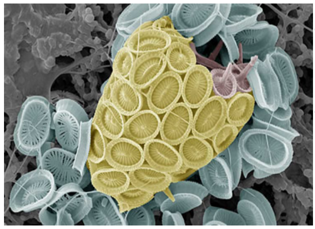


http://earthobservatory.nasa.gov

Eukaryotic phytoplankton

Coccolithophores: *"round stone-bearers"*

- $CaCO_3$ coverings "coccoliths" cover surface
- small (<5%?) but significant global PPers
- Form blooms (dominant in Sargasso Sea, and Gulf of Alaska), and settle into chalk layers; formed cliffs of Dover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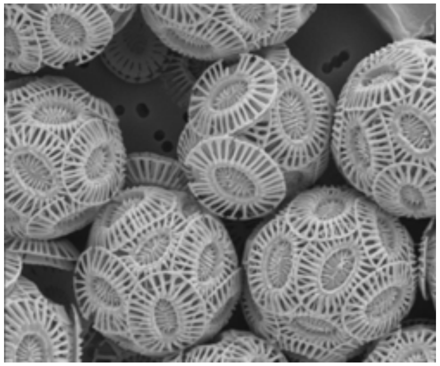
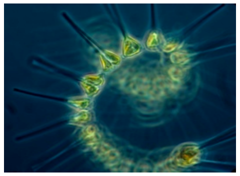
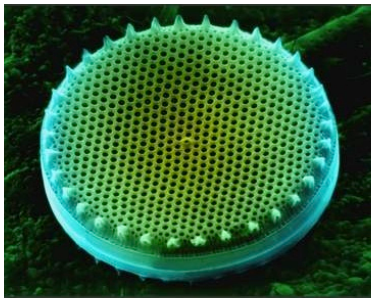


Diatoms:

- 2-valved extracellular skeleton (frustule) made of silica: silica = 4-50% of dry weight of the cell
- abundant, ~20% global PP
- unicellular/chains
- 15-1000µm, bloom-former



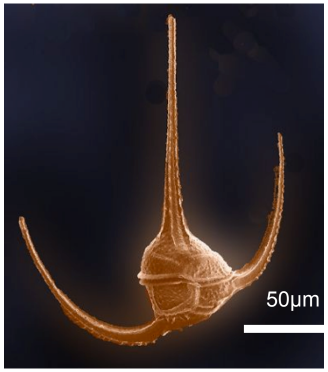

Dennis Kunkel

http://www.photolib.noaa.gov/bigs/fish1880.JPG

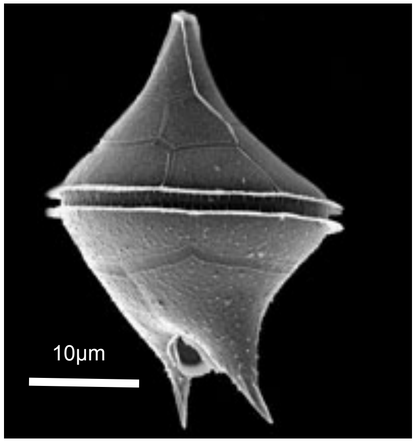

Thalassosira sp. (1st genome)

Dinoflagellates:

- auto-, hetero-, mixotrophic
- can form cysts
- bloom post-diatoms
- diel vertical migration
- associated with toxin production



Ceratium



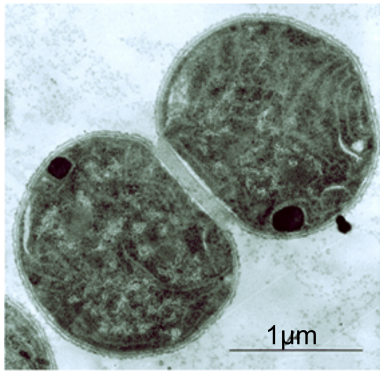
Protoperidinium

Cyanobacteria

- ~25% global primary production
- prokaryote (no chloroplast)
- unicellular or colonial
- all C-fixers (autotrophs), some are N-fixers

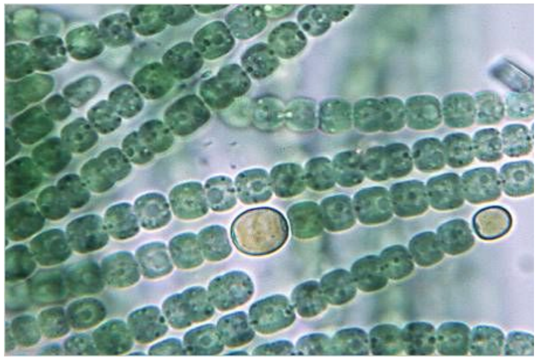
N-fixing cyanobacteria:

Crocosphaera



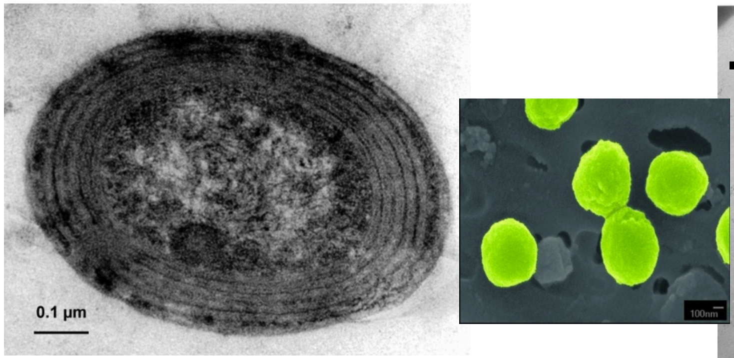
- 2-5 μm in size, 10^3 cells ml^{-1}
- recently discovered widespread

Anabaena



heterocysts

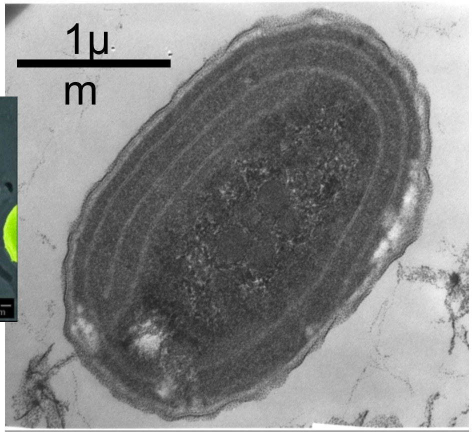
Prochlorococcus



- open oceans - discovered 1988
- **the numerically dominant photosynthetic cells on the planet**

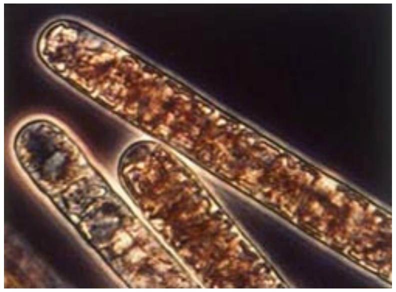
(up to 10^6 cells ml^{-1})

Synechococcus

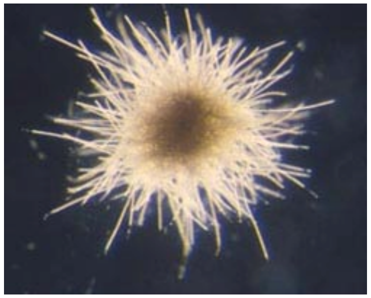


- coastal + open oceans

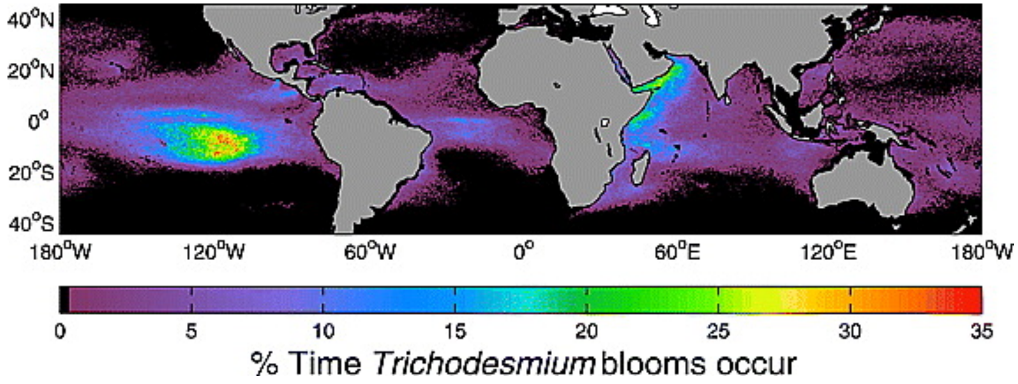
Trichodesmium



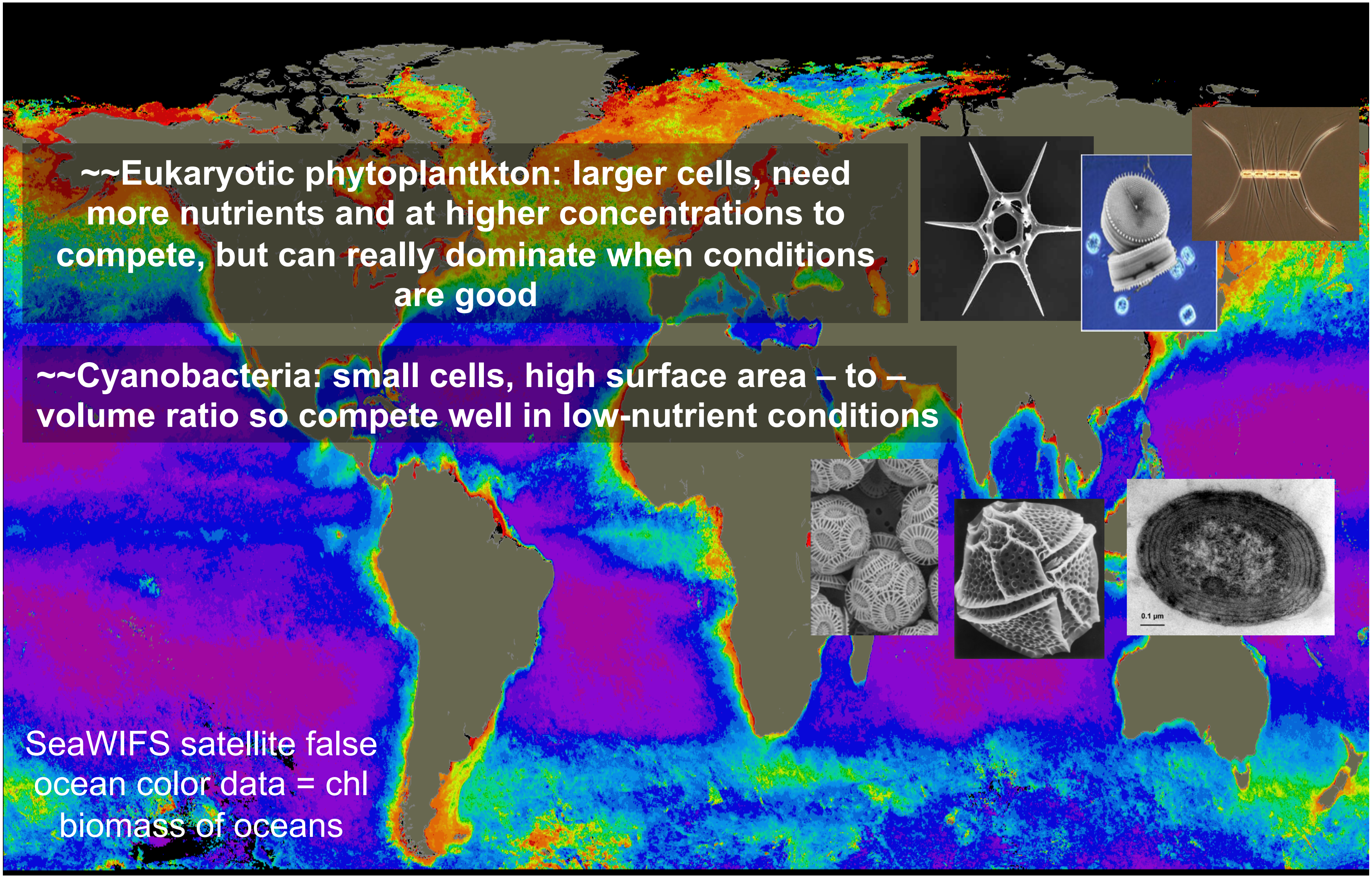
single trichomes



colonial



Distribution of marine chlorophyll (here e.g. July) and phytoplankton types

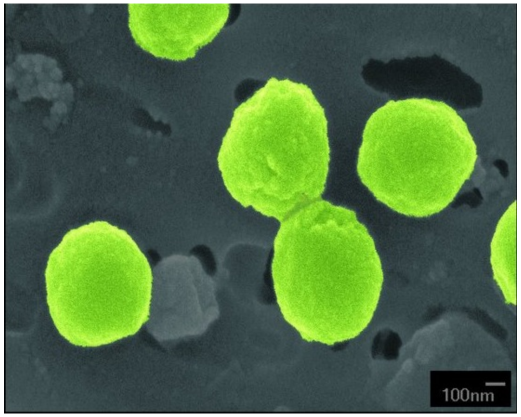


~~Eukaryotic phytoplantkton: larger cells, need more nutrients and at higher concentrations to compete, but can really dominate when conditions are good

~~Cyanobacteria: small cells, high surface area – to – volume ratio so compete well in low-nutrient conditions

SeaWIFS satellite false ocean color data = chl biomass of oceans

Recap: who is doing this marine photoautotrophy?



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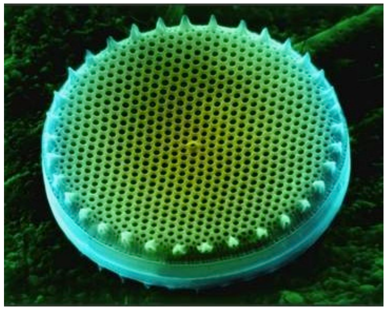
CYANOBACTERIA

(e.g. Prochlorococcus marinus)

~1/2 of ocean primary production

EUKARYOTIC PHYTOPLANKTON

~1/2 of ocean primary production



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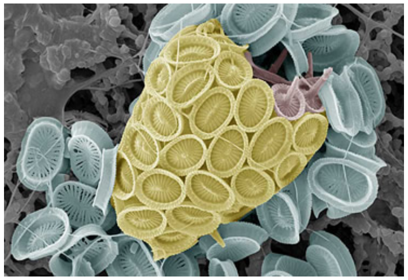
Diatom



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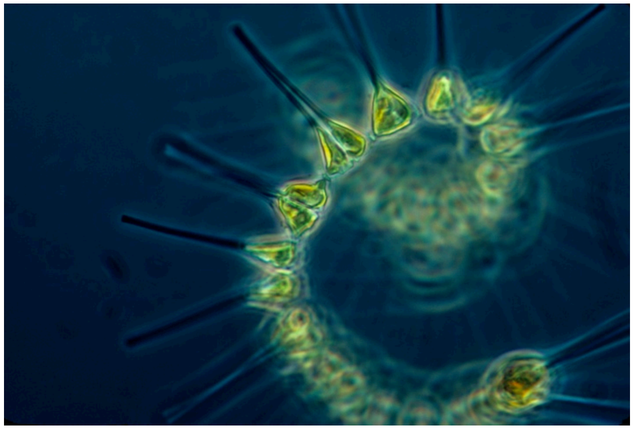
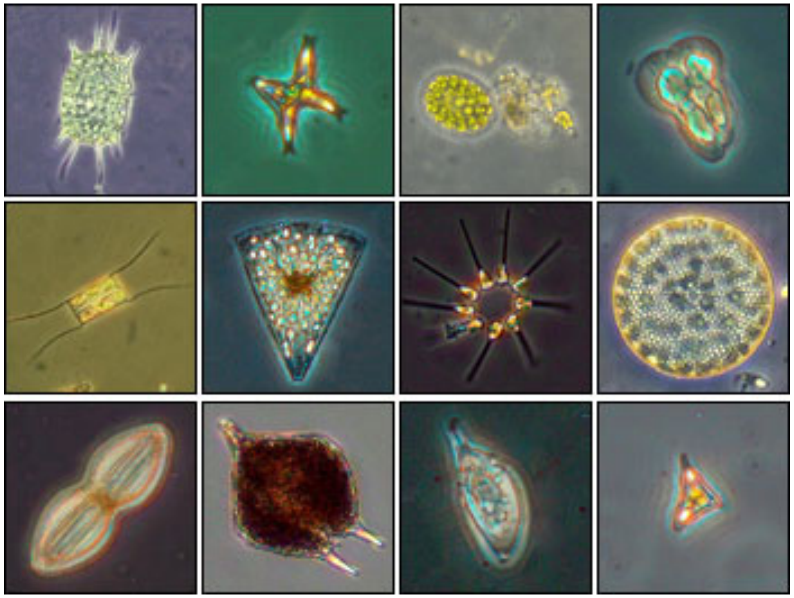
Coccolithophore



http://www.photolib.noaa.gov/bigs/fish1880.JPG



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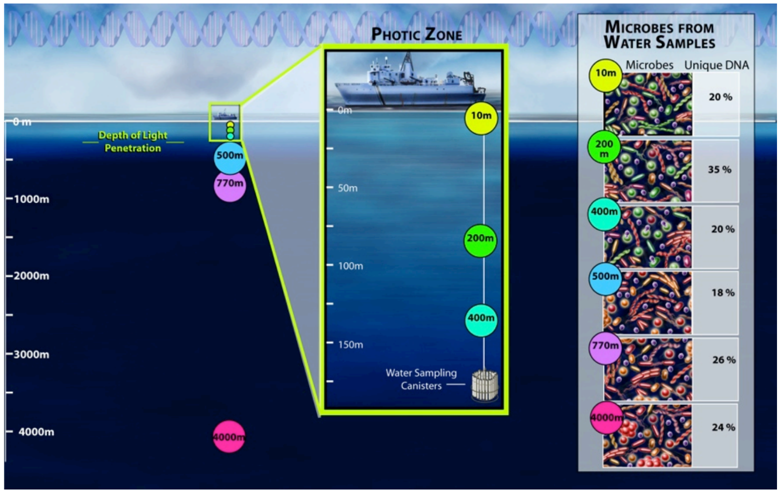
When phytoplankton go bad…
Harmful Algal Blooms

	Organism	*Common name*	*Mechanism of harm (to fish or shellfish)*
	*Pfisteria piscicida*	Pfisteria	Unknown, likely irritation of gills + possible toxicity (not confirmed)
	*Heterosigma akashiwo*	Brown tide	unknown
	*Chaetocerous convolutus*	---	Long spines irritate fish gills
	*Aureococcus anophagefferens*	Brown tide	Mucopolysaccharide clogs filter feeder gills (e.g., LI scallops)

But that's just *photo*autotrophy… what about *chemo*autrophy?

occurs in:

- soil
- wetlands, bogs, marshes and estuaries
- deep subsurface
- high organic-matter coastal zone waters,
- oxygen minimum zones (low O_2-horizontal stretches of the oceans, predicted to expand under climate change. "Dead zones" are an extreme anthropogenic type),
- hydrothermal vent systems,
- marine sediments,
- marine basalts,
- the water column of the open ocean,
- ….



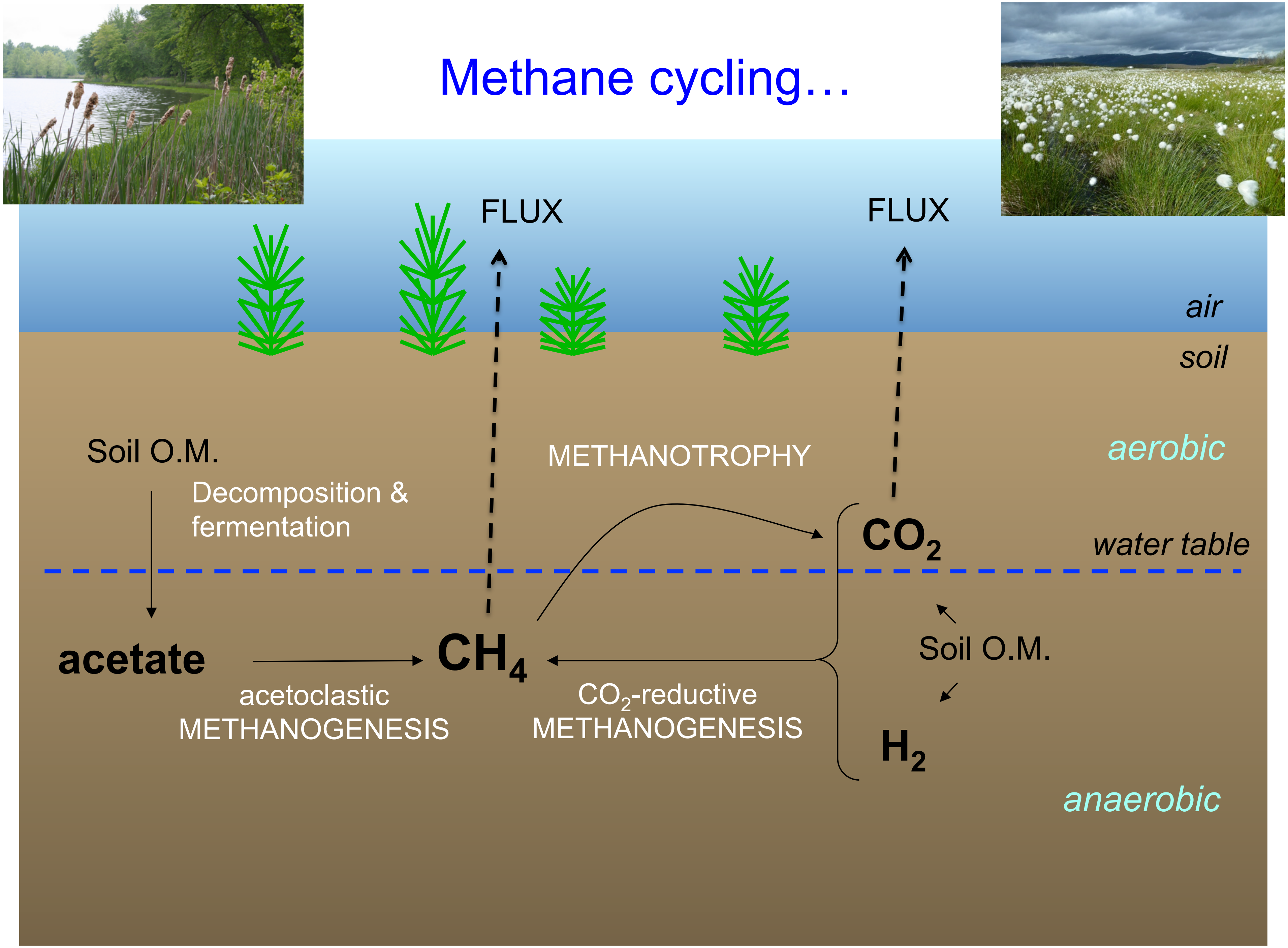
NSF press release for DeLong et al 2006 Science

Basically ***everywhere*** *we look, to varying degrees*

Chemoautotrophy Example 1: The special case of **Methanogens**

- Methanogenesis is central to carbon cycling in anoxic environments
- Can be **autotrophic** (fixing CO_2 into biomass) or **heterotrophic** (using acetate)
- CH_4 is **potent greenhouse gas** (33 x CO_2 over 100 years); controls on its production and consumption thus critical for understanding global change feedbacks
- Produced in numerous human-related endeavors…
- Methanogens often team up with hosts &/or microbial partners (syntrophs) that supply them with necessary substrates

Methane cycling…



FLUX

FLUX

air

soil

Soil O.M.

Decomposition & fermentation

METHANOTROPHY

aerobic

CO_2

water table

acetate

CH_4

Soil O.M.

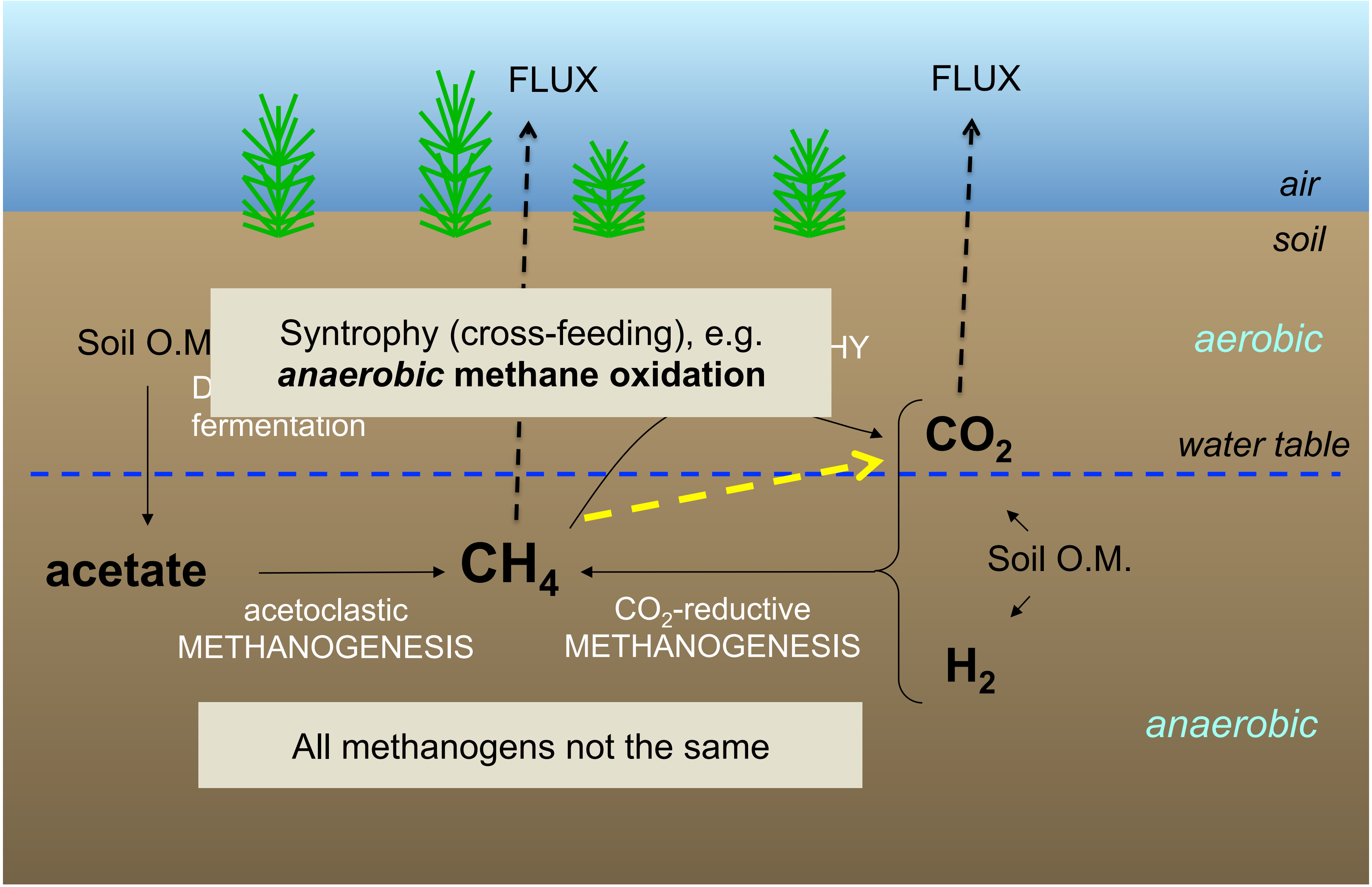
acetoclastic METHANOGENESIS

CO_2-reductive METHANOGENESIS

H_2

anaerobic

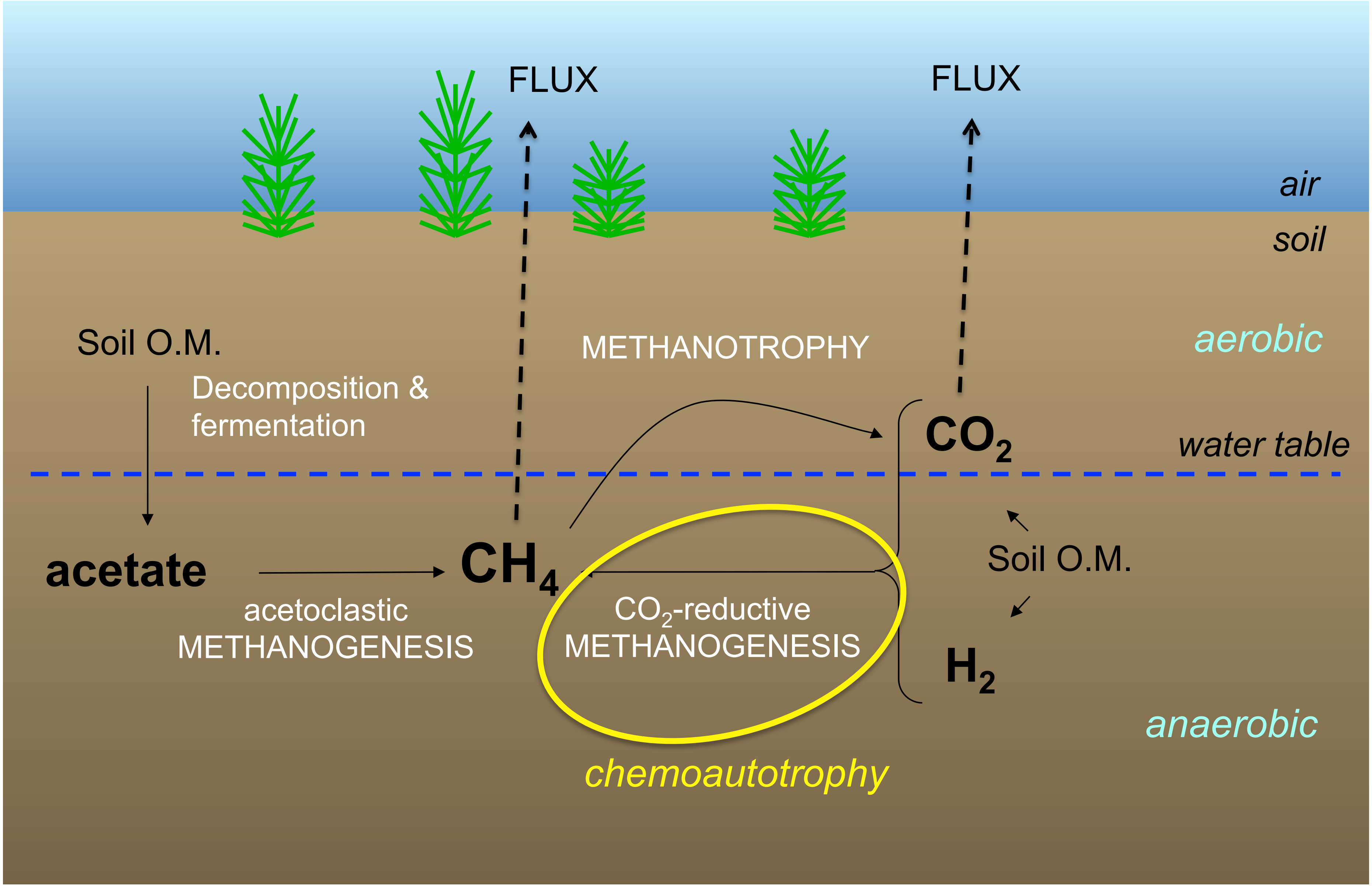
Diverse players, complex consortia



Syntrophy (cross-feeding), e.g. ***anaerobic* methane oxidation**

All methanogens not the same

Diverse players, complex consortia



FLUX

FLUX

air

soil

Soil O.M.

Decomposition &
fermentation

METHANOTROPHY

aerobic

CO_2

water table

acetate

CH_4

Soil O.M.

acetoclastic
METHANOGENESIS

CO_2-reductive
METHANOGENESIS

H_2

anaerobic

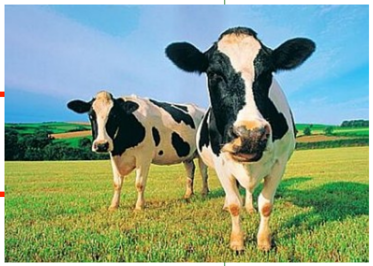
chemoautotrophy

Microbial sources in the global methane budget

Table 7.6 *Sources, sinks and atmospheric budgets of CH_4 ($Tg(CH_4)\ yr^{-1}$).*[a]

References	**Indicative ^{13}C, ‰[b]**	**Hein et al., 1997[c]**	**Houweling et al., 2000[c]**	**Olivier et al., 2005**	**Wuebbles and Hayhoe, 2002**	**Scheehle et al., 2002**	**J. Wang et al., 2004[c]**	**Mikaloff Fletcher et al., 2004a[c]**	**Chen and Prinn, 2006[c]**		
Base year		1983–1989		2000		1990	1994	1999	1996–2001		
Natural sources			**222**		**145**		**200**	**260**	**168**		
Wetlands	–58	231	163		100		176	231	145		
Termites	–70		20		20		20	29	23		
Ocean	–60		15		4						
Hydrates	–60				5		4				
Geological sources	–40		4		14						
Wild animals	–60		15								
Wildfires	–25		5		2						
Anthropogenic sources		**361**		**320**	**358**	**264**	**307**	**350**	**428**		
Energy						74	77				
Coal mining	–37	32		34	46			30	48[d]		
Gas, oil, industry	–44	68		64	60			52	36[e]		
Landfills & waste	–55	43		66	61	69	49	35			
Ruminants	–60	92		80	81	76	83	91	189[f]		
Rice agriculture	–63	83		39	60	31	57	54	112		
Biomass burning	–25	43			50	14	41	88	43[e]		
C3 vegetation	–25			27							
C4 vegetation	–12			9							
Total sources		**592**			**503**		**507**	**610**	**596**	**598**	**582**
Imbalance		+33								+22	+1
Sinks											
Soils	–18	26			30		34	30		30	30[g]
Tropospheric OH	–3.9	488			445		428	507		506	511[g]
Stratospheric loss		45			40		30	40		40	40[g]
Total sink		**559**			**515**		**492**	**577**		**576**	**581[g]**

Brock 2008



Notes:

[a] Table shows the best estimate values.

[b] Indicative ^{13}C values for sources are taken mainly from Mikaloff Fletcher et al. (2004a). Entries for sinks are the fractionation, (k_{13}/k_{12}–1) where k_n is the removal rate of $^nCH_4$; the fractionation for Saueressig et al. (2001) and that for the soil sink from Snover and Quay (2000) as the most recent determinations.

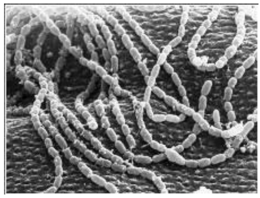
[c] Estimates from global inverse modelling (top-down method).

[d] Includes natural gas emissions.

[e] Biofuel emissions are included under Industry.

[f] Includes emissions from landfills and wastes.

[g] Numbers are increased by 1% from the TAR according to recalibration described in Chapter 2.



Graeme Attwood

IPCC 2007 Ch7

Microbial sources in the global methane budget

Table 7.6 *Sources, sinks and atmospheric budgets*

Average for natural sources = 199 Tg CH_4/yr

of which microbes drive an estimated 92%

Natural sources

References	Indicative ^{13}C, ‰^{b}	Hei									
Base year		198									
			222		145		200	260	168		
Wetlands	–58	231	163		100		176	231	145		
Termites	–70		20		20		20	29	23		
Ocean	–60		15		4						
Hydrates											
Geological sources											
Wild animals											
Wildfires											
		361		320	358	264	307				
Energy											
Coal mining	–37	32		34							
Gas, oil, industry	–44	68									
Landfills & waste											
Ruminants											
Rice agricultur								54	112		
Biomass burnir							41	88	43^{e}		
C3 vegetation											
C4 vegetation				9							
Total sources		**592**			**503**		**507**	**610**	**596**	**598**	**582**
Imbalance											+1
Soils	–18										30^{g}
Tropospheric OH	–3.9										511^{g}
Stratospheric loss											40^{g}
Total sink		**559**			**515**		**492**	**577**		**576**	**581^{g}**

Average for anthropogenic sources = 341

of which microbes drive an estimated 61%

Anthropogenic sources

All Microbial #s are Likely Underestimates

Sinks

Average for sinks = 550

of which microbes drive an estimated 5.5%

Notes:

[a] Table shows the best estimate values.

[b] Indicative ^{13}C values for sources are taken mainly from Mikaloff Fletcher et al. (2004a). Entries for sinks are the fractionation, $(k_{13}/k_{12}-1)$ where k_n is the removal rate of $^{n}CH_4$; the fractionation for Saueressig et al. (2001) and that for the soil sink from Snover and Quay (2000) as the most recent determinations.

[c] Estimates from global inverse modelling (top-down method).

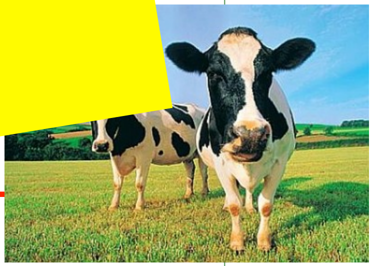
[d] Includes natural gas emissions.

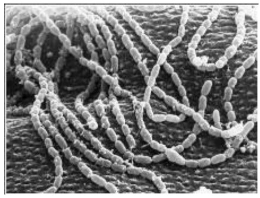
[e] Biofuel emissions are included under Industry.

[f] Includes emissions from landfills and wastes.

[g] Numbers are increased by 1% from the TAR according to recalibration described in Chapter 2.

Brock 2008





Graeme Attwood

IPCC 2007 Ch7

The Volta Experiment; aka the microbiologist’s party trick

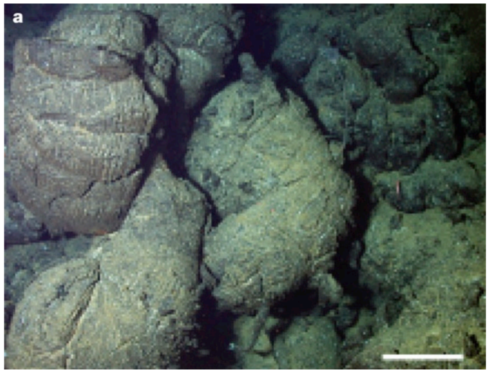
Brock 2008

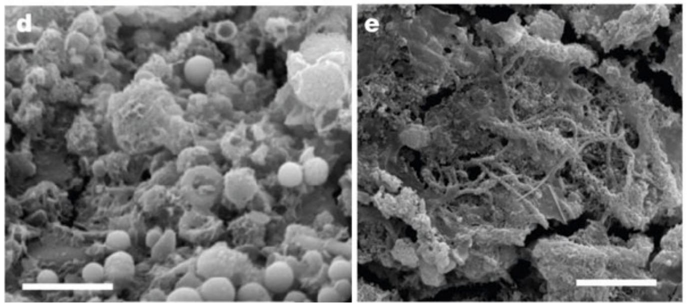
John A. Breznak

http://www.paranormal-encounters.com/wp/wp-content/uploads/2012/01/willothewisp3.jpg

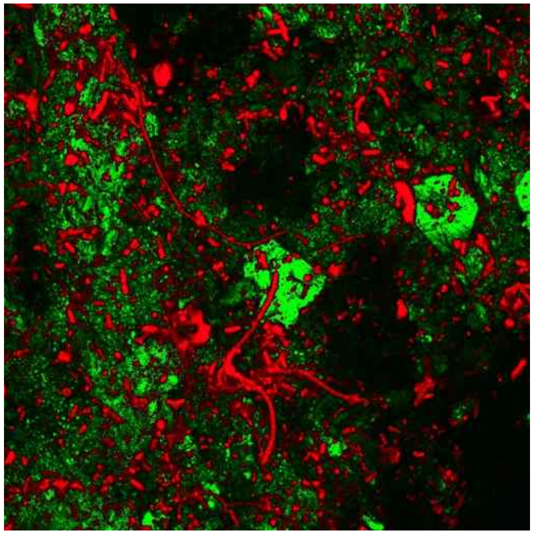
Historically, natural infrequent ignition of methane over bogs & marshes led to folktales of “willow-the-wisp” or “jack-o-the-lantern” to explain mysterious, shimmering lights

Chemoautotrophy Example 2: Iron and Manganese-oxidizing bacteria living on subseafloor basalt…



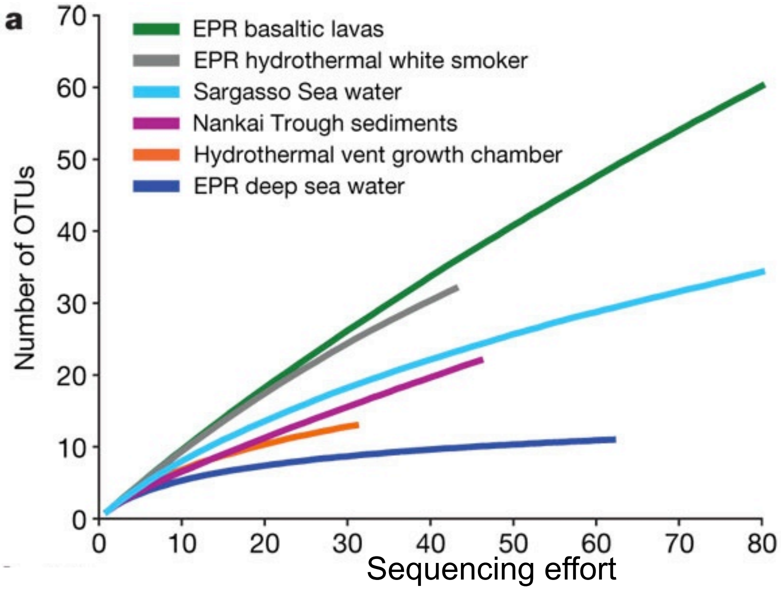


Santelli *et al*., 2008 Nature



Laser confocal micrograph of a biofilm attached to seafloor basalt from **1500 meters deep**.
Green = basalt surface
Red = Nile red–stained bacterial cells.”

Stevens & McKinley, 1995 Science.



Lifestyle: Fe- and Mn-oxidation

Eg: $Fe^{2+} + 0.25\ O_2 + H^+ \rightarrow Fe^{3+} + 0.5\ H_2O$

(so Fe^{2+} is e- donor, O_2 acceptor)

Subseafloor microbes = 10–30% of the total living biomass of Earth

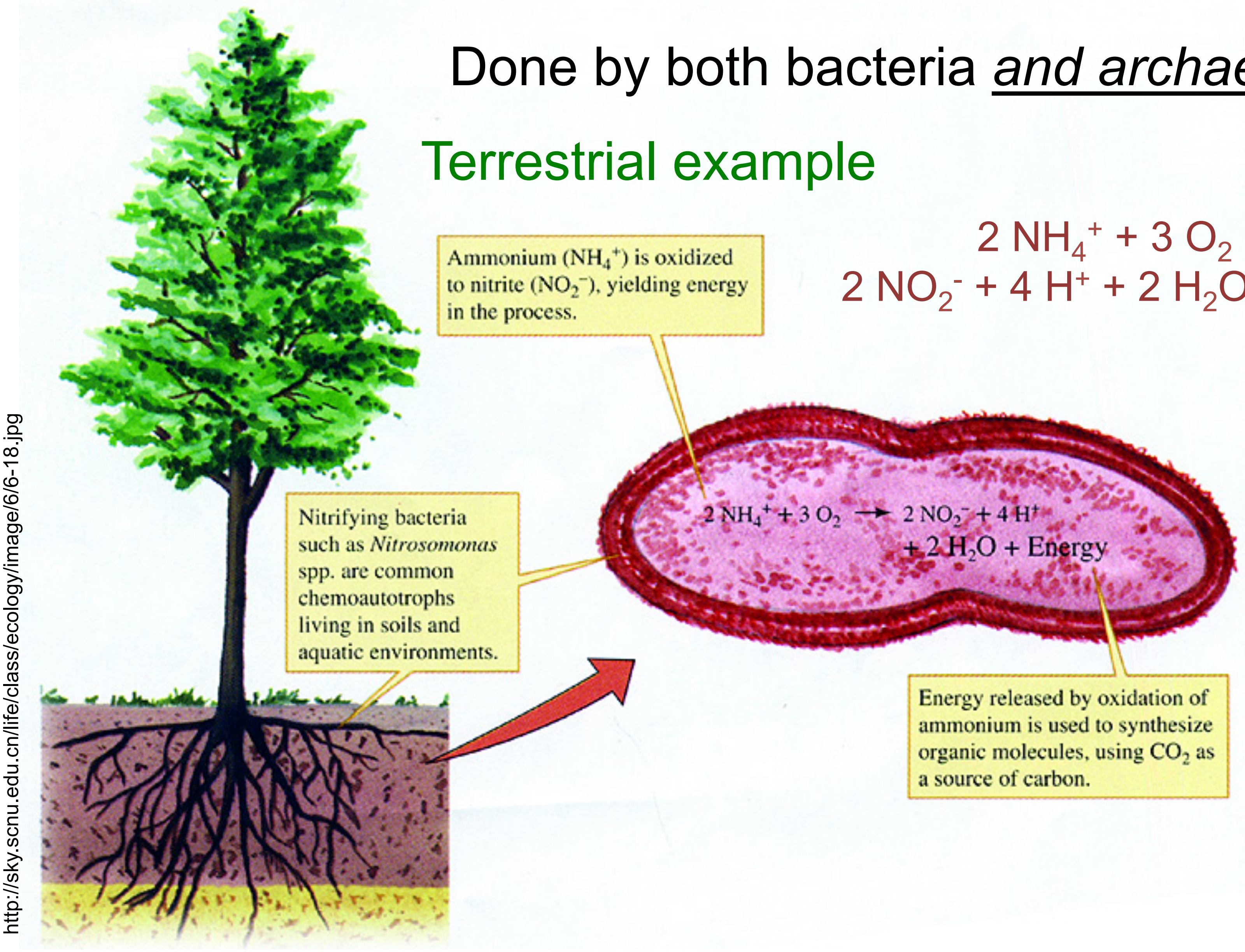
- Whitman *et al.* 1998 PNAS.

Chemoautotrophy Example 3: ammonia oxidation (the first step in nitrification)

Done by both bacteria ***and archaea***

Terrestrial example

$$2\ NH_4^+ + 3\ O_2 \rightarrow$$
$$2\ NO_2^- + 4\ H^+ + 2\ H_2O + \text{energy}$$



Ammonium (NH_4^+) is oxidized to nitrite (NO_2^-), yielding energy in the process.

Nitrifying bacteria such as *Nitrosomonas* spp. are common chemoautotrophs living in soils and aquatic environments.

$2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O + \text{Energy}$

Energy released by oxidation of ammonium is used to synthesize organic molecules, using CO_2 as a source of carbon.

This chemical bond-derived energy then used to fix CO_2 into biomass

http://sky.scnu.edu.cn/life/class/ecology/image/6/6-18.jpg

…& ammonia-oxidizing archaea in the dark expanses of the ocean

Elegant attempt to quantify amount of particular CO2 fixation in a deep-sea, low-carbon, open-ocean habitat:

Used carbon isotopes in microbial biomass to track autotrophy ("you are what you eat").

Quantifying archaeal community autotrophy in the mesopelagic ocean using natural radiocarbon

Anitra E. Ingalls*†‡, Sunita R. Shah*†, Roberta L. Hansman§, Lihini I. Aluwihare§, Guaciara M. Santos¶, Ellen R. M. Druffel¶, and Ann Pearson*‖

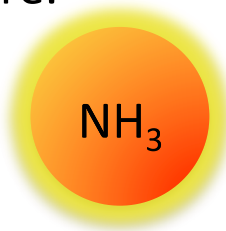
*Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138; §Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093; and ¶Department of Earth System Science, University of California, Irvine, CA 92697

Edited by John M. Hayes, Woods Hole Oceanographic Institution, Woods Hole, MA, and approved March 3, 2006 (received for review November 23, 2005)

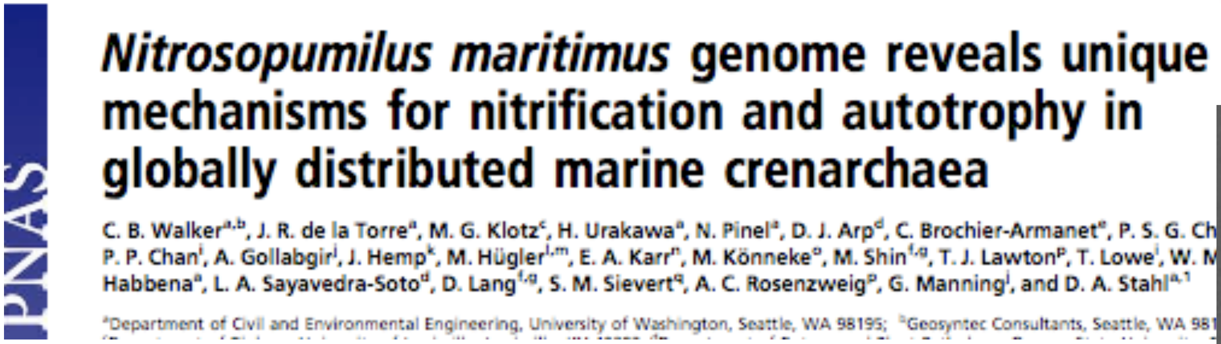
Ingalls *et al.*, 2006 PNAS

"Total [autotrophic] biomass production by archaea in deep waters is ... **1% of annual marine primary production...** of a magnitude significant to the global carbon cycle and greater than... that buried in marine sediments." (It's on scale of 1/10th annual human C addition to atmosphere.

What kind of chemoautotrophy?



nitrification, by ammonia-oxidizing archaea (ammonia is electron DONOR; O_2 is acceptor)



Nitrosopumilus maritimus **genome reveals unique mechanisms for nitrification and autotrophy in globally distributed marine crenarchaea**

C. B. Walker[a,b], J. R. de la Torre[a], M. G. Klotz[c], H. Urakawa[a], N. Pinel[a], D. J. Arp[d], C. Brochier-Armanet[e], P. S. G. Ch
P. P. Chan[i], A. Gollabgir[j], J. Hemp[k], M. Hügler[l,m], E. A. Karr[n], M. Könneke[o], M. Shin[f,g], T. J. Lawton[p], T. Lowe[i], W. M
Habbena[a], L. A. Sayavedra-Soto[d], D. Lang[f,g], S. M. Sievert[q], A. C. Rosenzweig[p], G. Manning[j], and D. A. Stahl[a,1]

[a]Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195; [b]Geosyntec Consultants, Seattle, WA 981

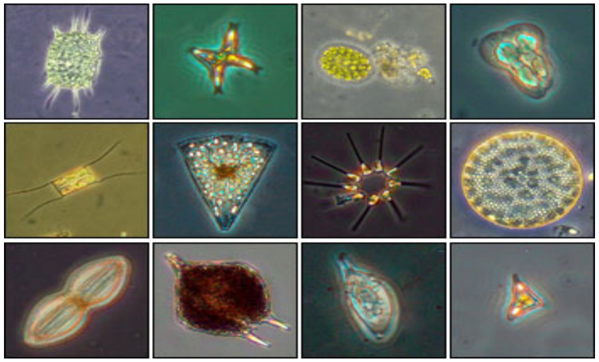
Walker *et al.*, 2010 PNAS

NH_4^+-oxidizing archaea *Nitrosopumilis maritimus*

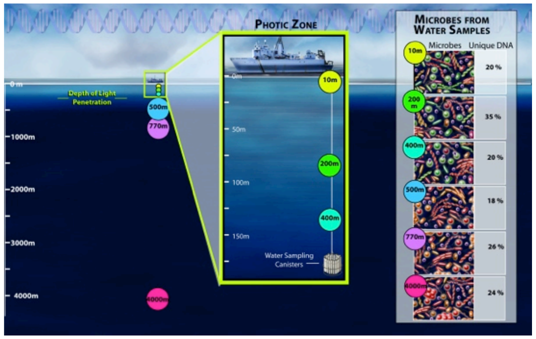
Ng et al 2013

Summary of microbial autotrophy

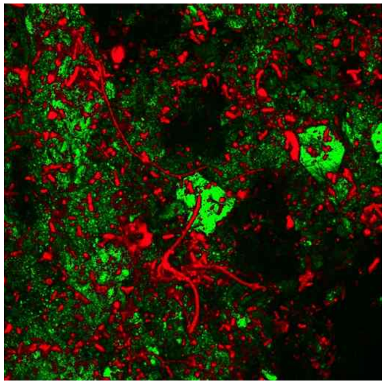
- Marine NPP
  - ~ terrestrial NPP
  - ~ microbial
  - cyanos + eukaryotic phytoplankton
- But wait, there's a lot of non-photic habitat on the planet
- **Chemoautrophs are abundant and diverse**
- Includes methanogens (some are autos, some are heteros)
- Unclear how much C chemoautotrophs may be fixing globally – but probably a LOT



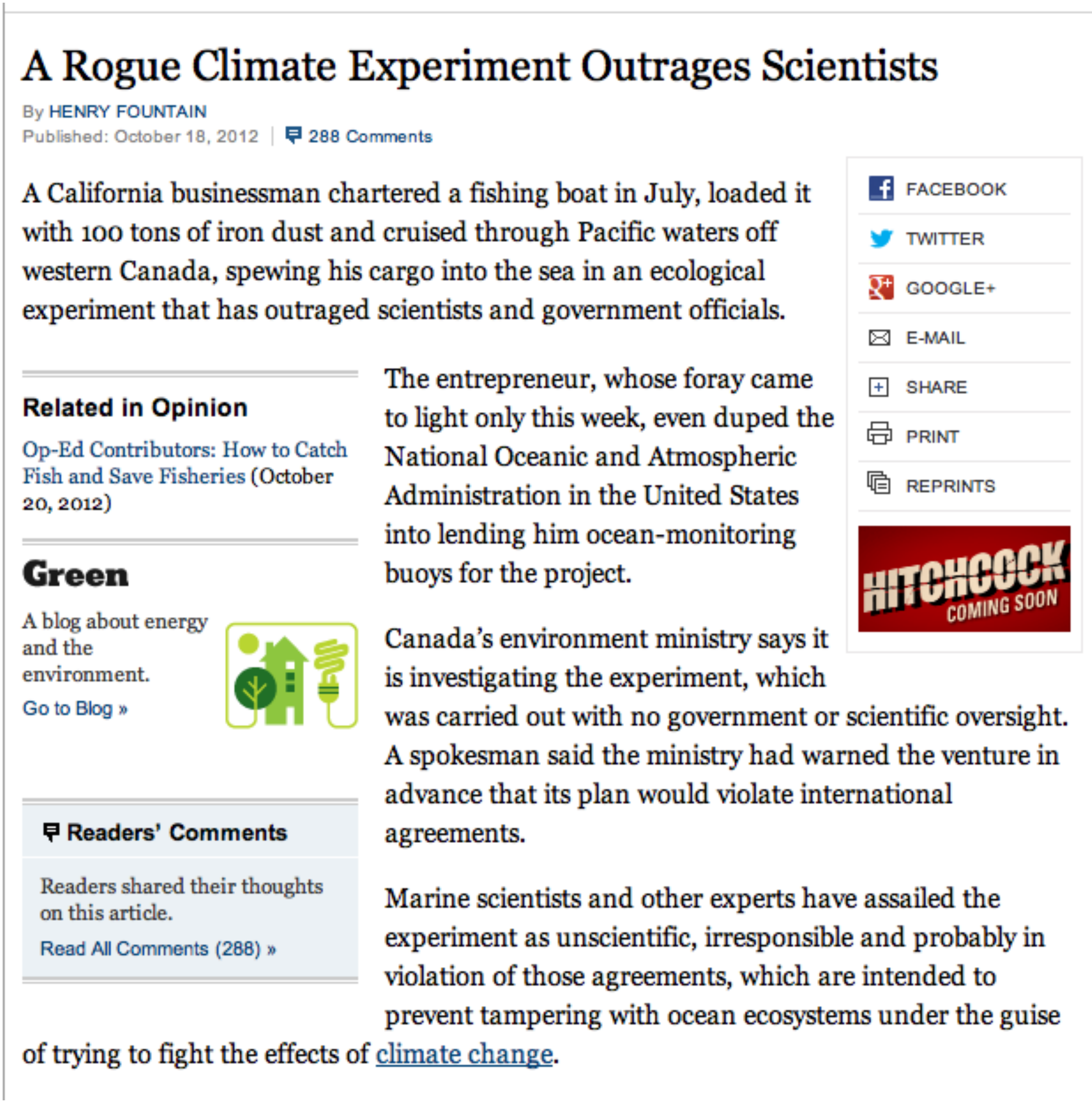
earthobservatory.nasa.gov



NSF for DeLong et al 2006



Stevens & McKinley, 1995.



A Rogue Climate Experiment Outrages Scientists

By HENRY FOUNTAIN

Published: October 18, 2012 | 288 Comments

A California businessman chartered a fishing boat in July, loaded it with 100 tons of iron dust and cruised through Pacific waters off western Canada, spewing his cargo into the sea in an ecological experiment that has outraged scientists and government officials.

The entrepreneur, whose foray came to light only this week, even duped the National Oceanic and Atmospheric Administration in the United States into lending him ocean-monitoring buoys for the project.

Canada's environment ministry says it is investigating the experiment, which was carried out with no government or scientific oversight. A spokesman said the ministry had warned the venture in advance that its plan would violate international agreements.

Marine scientists and other experts have assailed the experiment as unscientific, irresponsible and probably in violation of those agreements, which are intended to prevent tampering with ocean ecosystems under the guise of trying to fight the effects of climate change.

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A blog about energy and the environment.

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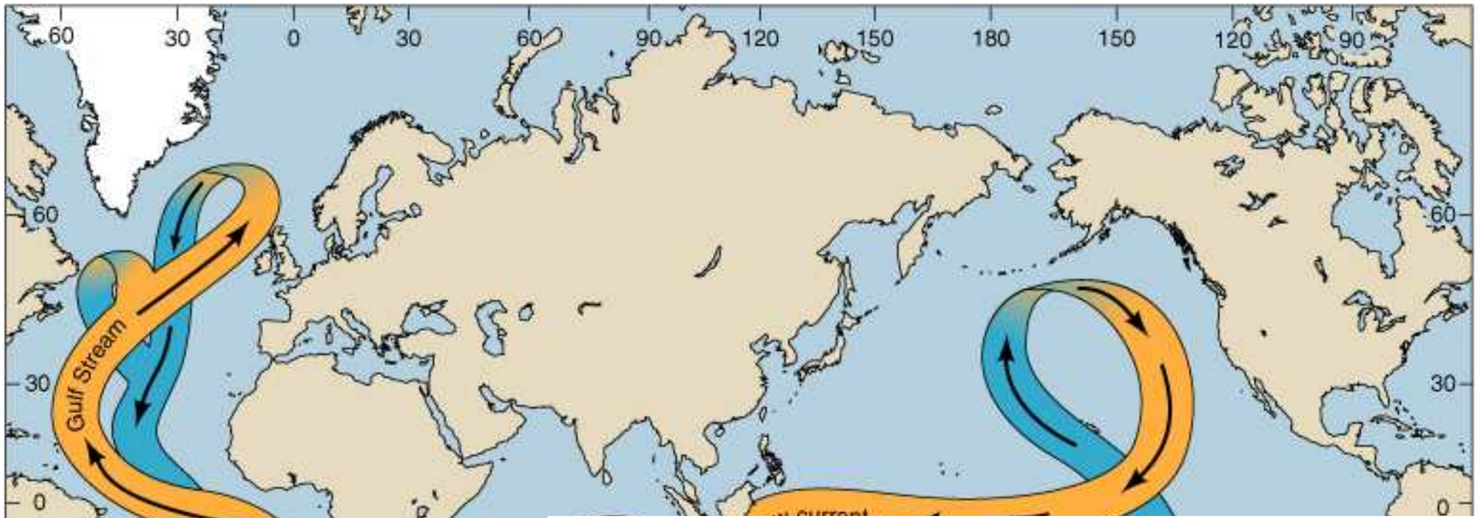
- 10X bigger than any previous ocean Fe-fertilization event
- done with funding from native Canadian group with goals of (a) aiding salmon fishery, and (b) test new revenue stream via carbon offset credits
- Unclear whether goals met…
- one-sided article but highlights complexity of these issues…



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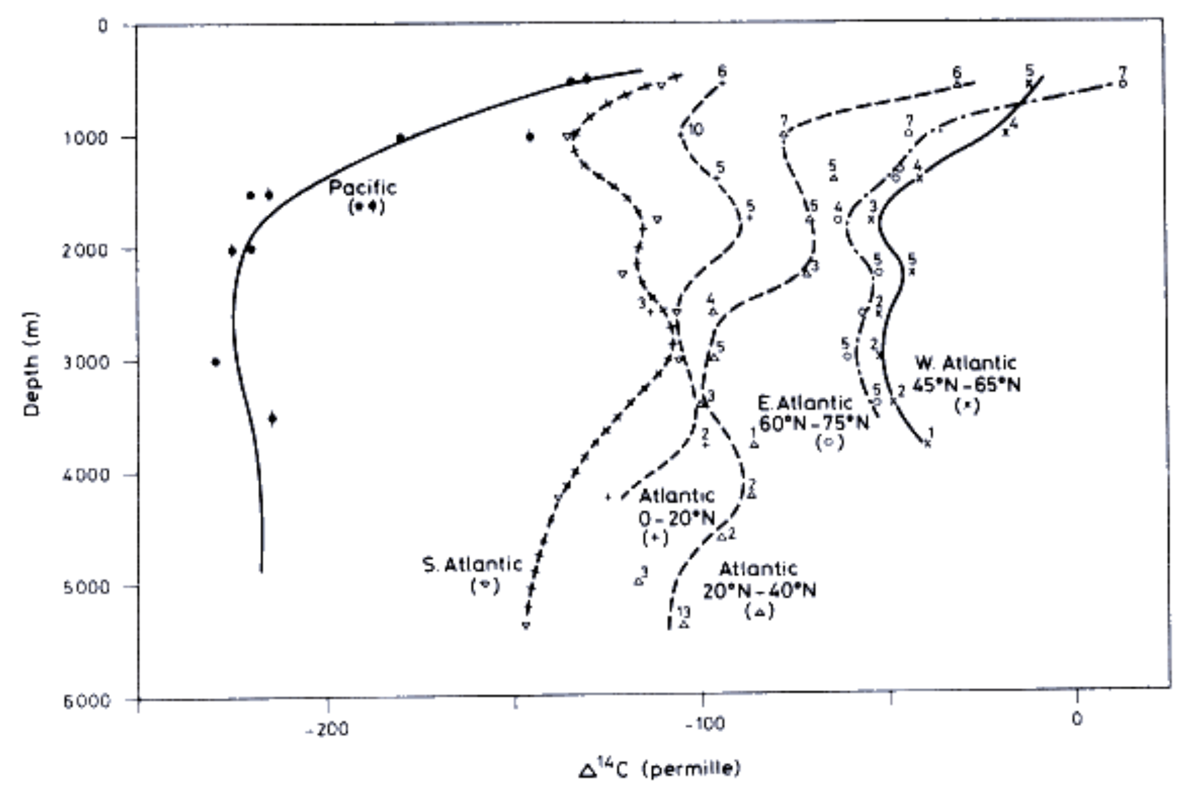

http://www.scopenvironment.org/downloadpubs/scope13/images/fig1.5.gif

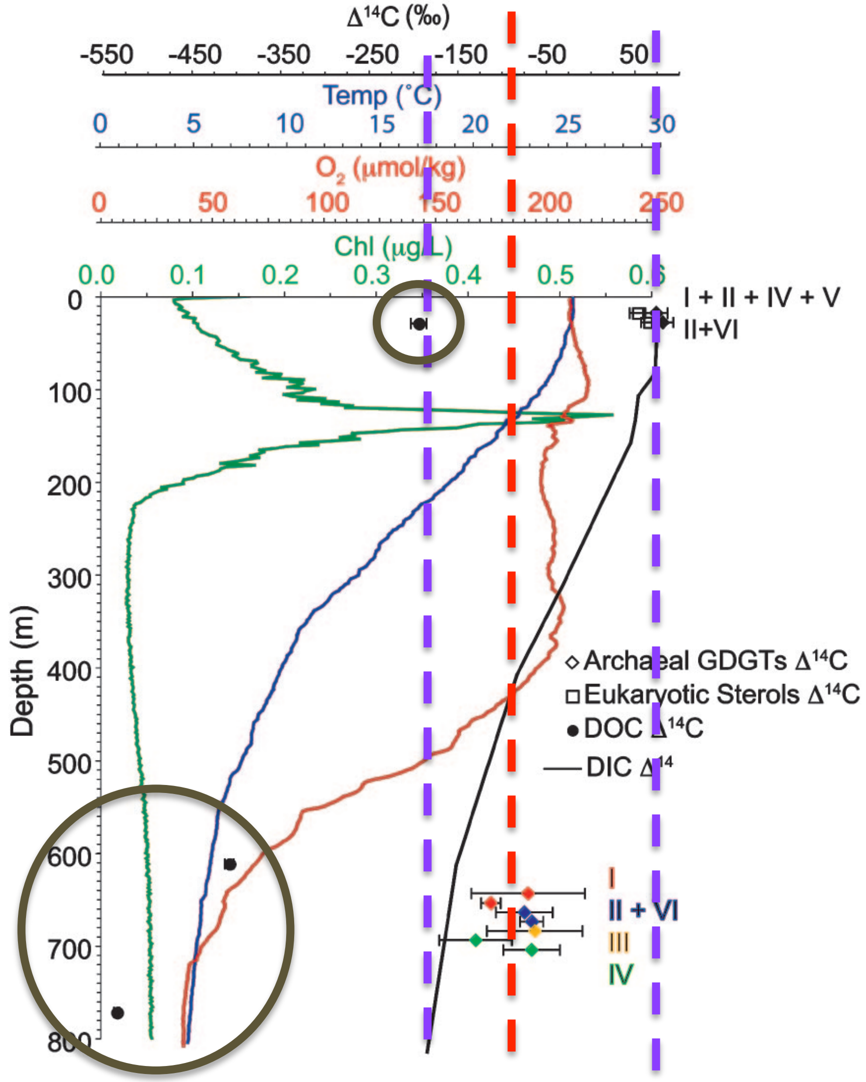

Fig. 2. Water column properties and Δ^{14}C values for DIC, DOC, sterols, and GDGTs. Chlorophyll, temperature, and dissolved oxygen data are from the Hawaii Ocean Time Series (HOTS) public data collected on May 19, 2004. DOC and DIC Δ^{14}C data are from refs. 24 and 46. Data points for individual compounds at 670 m have been separated for clarity.