L02b: Metabolic Diversity and Ecophysiology of Marine Microbes

0. Ethics in science, plagiarism and AI

1. Microbes in the Marine Environment

2. Metabolic Diversity and Ecophysiology of Marine Microbes

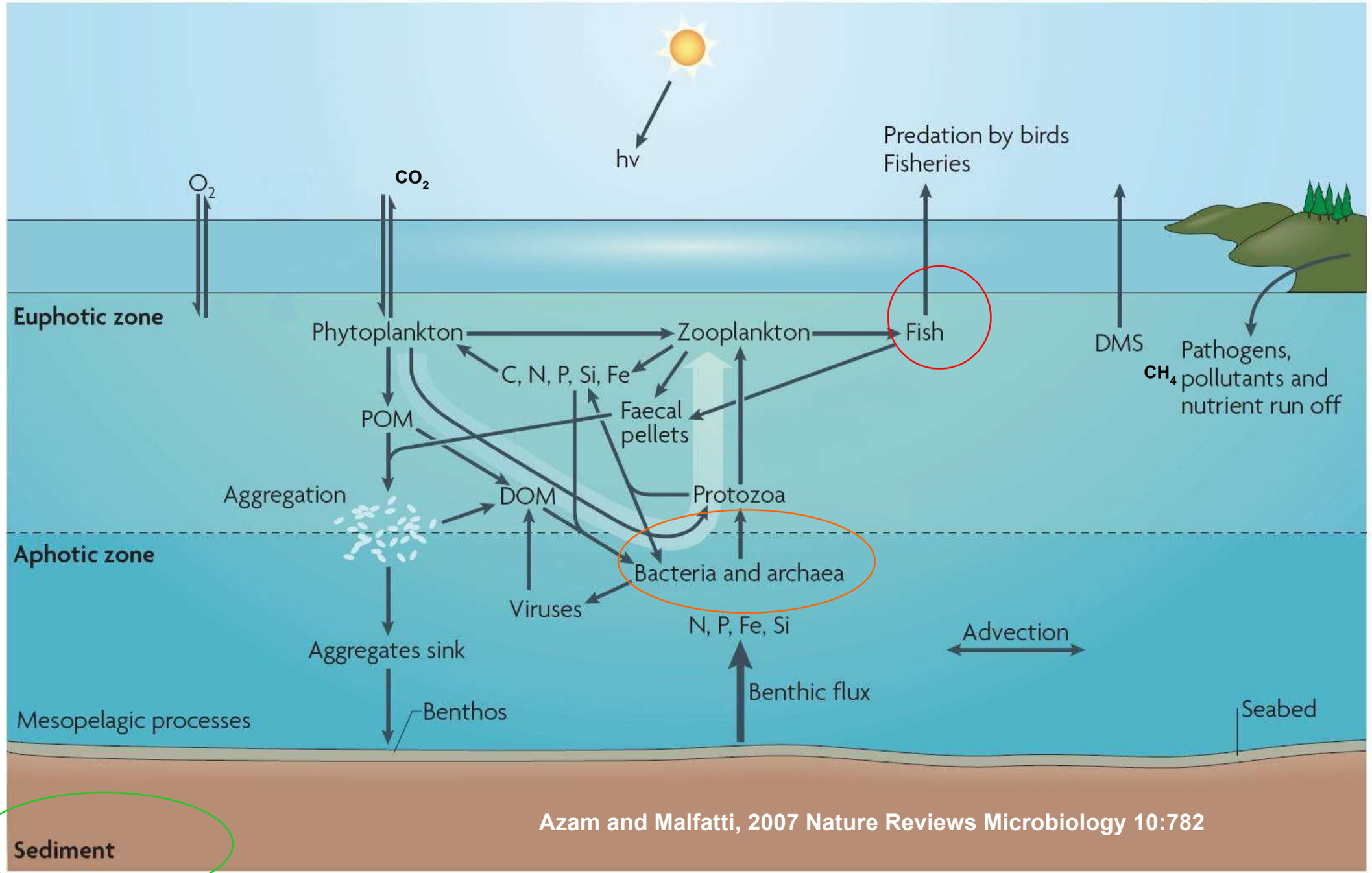
3. Diversity of Marine Bacteria, Archaea, Viruses and unicellular Eukaryotes

4. Microbes in Ocean Processes: Carbon and other nutrients

5. Marine Microbial Symbioses and Diseases

6. Marine Microbes, Climate and Society

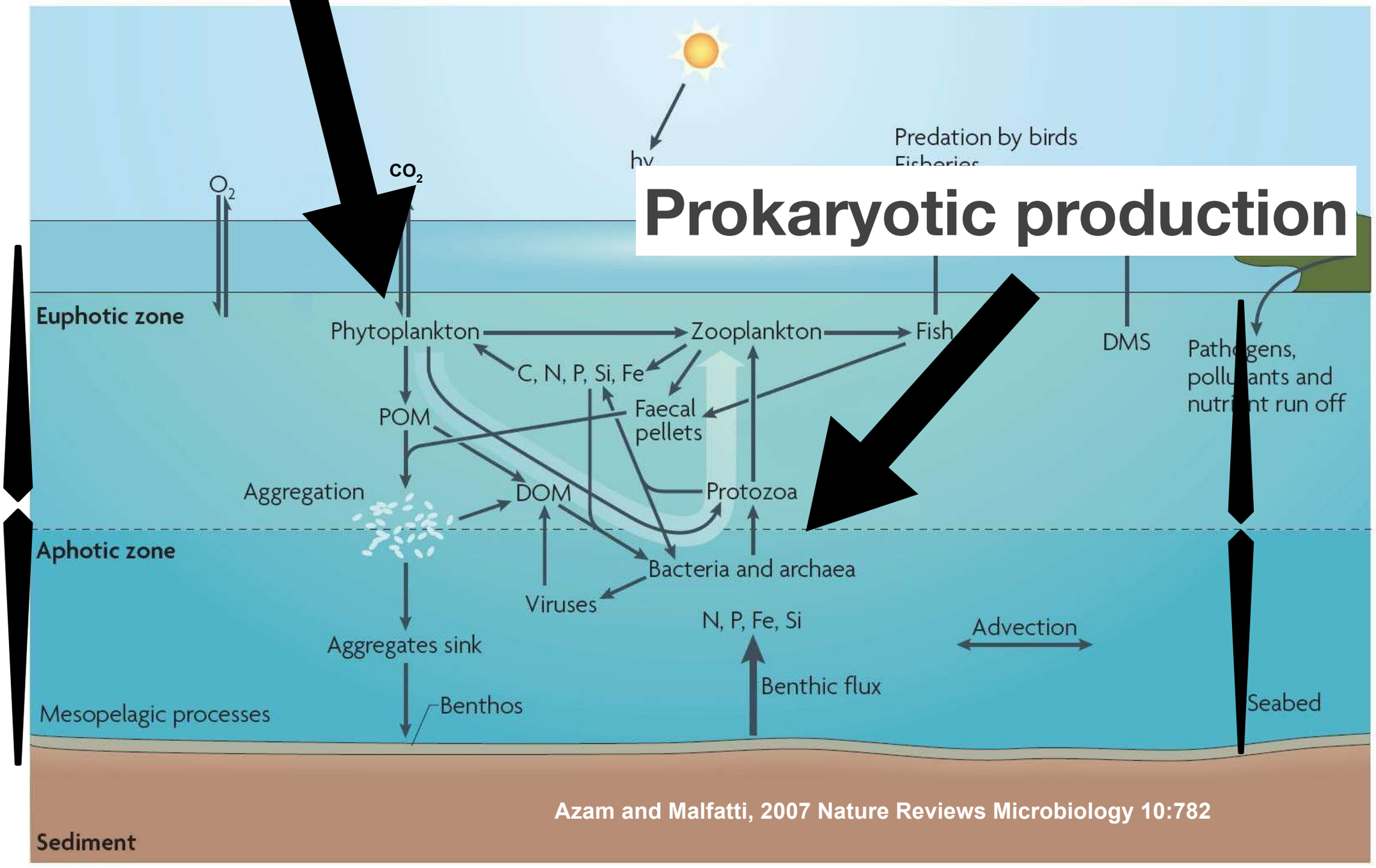
Marine Microbial Carbon Biogeochemical cycle



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

Primary production

Community Respiration



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

Dark Carbon fixation

Primary production method

https://www.nature.com/scitable/knowledge/library/the-biological-productivity-of-the-ocean-70631104/

^{14}C Primary production method

The ^{14}C method, originally devised by Steeman-Nielsen (1952), is used to estimate the uptake of DIC by photoautotrophic microorganisms in the water column. The method is based on the fact that the biological uptake of ^{14}C-labeled DIC is proportional to the biological uptake of ^{12}C-DIC. If one knows the initial concentration of DIC in a water sample, the DIC pool specific radioactivity ($^{14}C/^{12}C$), the ^{14}C retained in particulate matter (^{14}C-POC) at the end of the incubation and the metabolic discrimination between the two isotopes of carbon (i.e., 6% discrimination against the heavier ^{14}C isotope), then it is possible to estimate the total uptake of carbon from the following relationship:

$$C^{uptake} = \frac{DIC * {}^{14}C\text{-}POC * 1.06}{{}^{14}C\text{-}DIC \text{ added}}$$

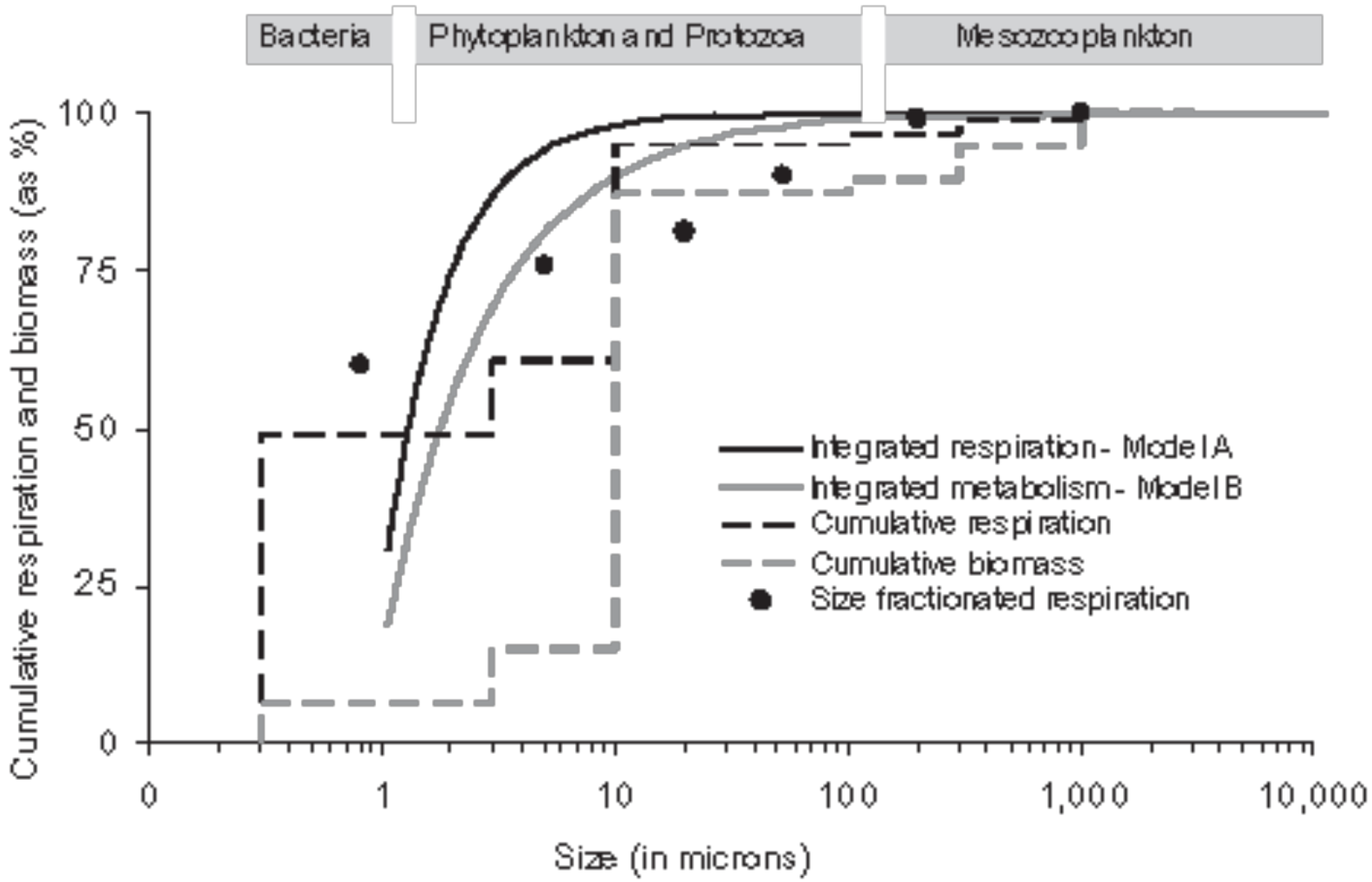
Result: carbon fixation rate, typically expressed as mg C m^{-3} h^{-1} or mg C m^{-3} d^{-1}.

https://hahana.soest.hawaii.edu/hot/protocols/chap14.html

Respiration method

https://kids.frontiersin.org/articles/10.3389/frym.2026.1578373

Figure 9.14 Size distribution of observed biomass and calculated and observed cumulative respiration. Integrated metabolism



The content of this slide may be subject to copyright: please see the slide notes for details.

Community Respiration at depth

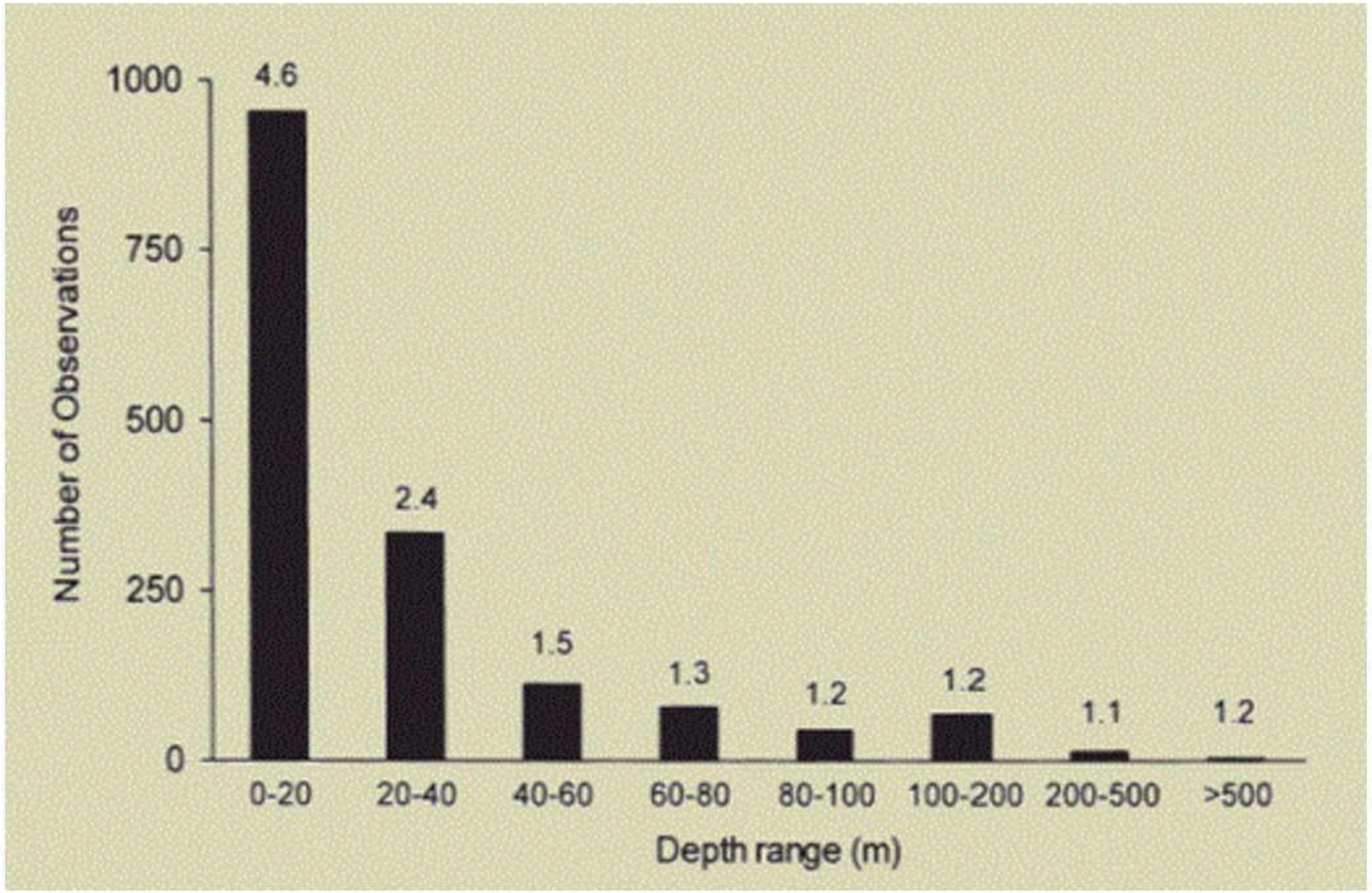


Figure 9.4 Depth distribution of the number of observations of volumetric rates of community respiration. The mean rate for each depth range (mmol O_2 m^{-3} d^{-1}) is shown above each histogram.

CHAPTER 9 Respiration and its measurement in surface marine waters in Respiration in Aquatic Ecosystems, https://doi.org/10.1093/acprof:oso/9780198527084.003.0009

The content of this slide may be subject to copyright: please see the slide notes for details.

OXFORD UNIVERSITY PRESS

Winkler titration for Oxygen in the dark over time

This approach is based on the measurement of the change of a reactant (e.g. oxygen) or product (e.g. carbon dioxide) of r**espiration over a period of time** (characteristically 12 or 24 h) in the dark.

The basic requirement is the ability to analyze the sample, a replicate or a representative body of water at point(s) during the incubation period.

The most common method is the *in vitro* dark bottle incubation, which was originally developed as a means of accounting for respiration during the determination of photosynthesis within the “light/dark” bottle protocol.

Dark incubations are necessary for the measurement of respiration via oxygen or carbon dioxide flux to eliminate concurrent counter fluxes of the same compounds by photosynthesis.

The dark bottles are incubated at *in situ* temperature, either deployed on an *in situ* rig (usually alongside samples incubated for determination of primary production), or held in temperature controlled incubators.

The DO method is based on the classic Winkler titration.

In this procedure, a divalent Mn solution ($MnCl_2$) and a strong base (NaOH) are added to a water sample resulting in the formation of a floc (equation 1). In the presence of O_2 the manganese (II) is oxidized to manganese (III) (equation 2). Following acidification in the presence of I^- ions (1<pH<2.5), the $Mn(OH)_3$ floc dissolves and iodine (I_2) is produced in stoichiometric proportion to the original O_2 concentration (equation 3). The I_2 , in the form of I_3^- (equation 4), is titrated with a standardized $S_2O_3^{2-}$ solution (equation 5), and the O_2 content is calculated from the concentration of $S_2O_3^{2-}$ consumed.

(1)	$Mn^{2+} + 2OH \longrightarrow Mn(OH)^2$
(2)	$2Mn(OH)_2 + ½O_2 + H_2O \longrightarrow 2Mn(OH)_3$
(3)	$2Mn(OH)_3 + 2I^- + 6H^+ \longrightarrow 2Mn_{2+} + I_2 + 6H_2O$
(4)	$I_2 + I^- \longrightarrow I_3^-$
(5)	$I_3^- + 2S_2O_3^{2-} \longrightarrow 3I^- + S_4O_6^{2-}$

https://hahana.soest.hawaii.edu/hot/protocols/#

Dark Carbon fixation method

DIC fixation is not only performed by photoautotrophs, but chemoautotrophs and heterotrophs incorporate CO2 via a wide range of carboxylation reactions (anaplerotic reactions and the synthesis of fatty acids, nucleotides and amino acids) that form part of their central and peripheral metabolic pathways

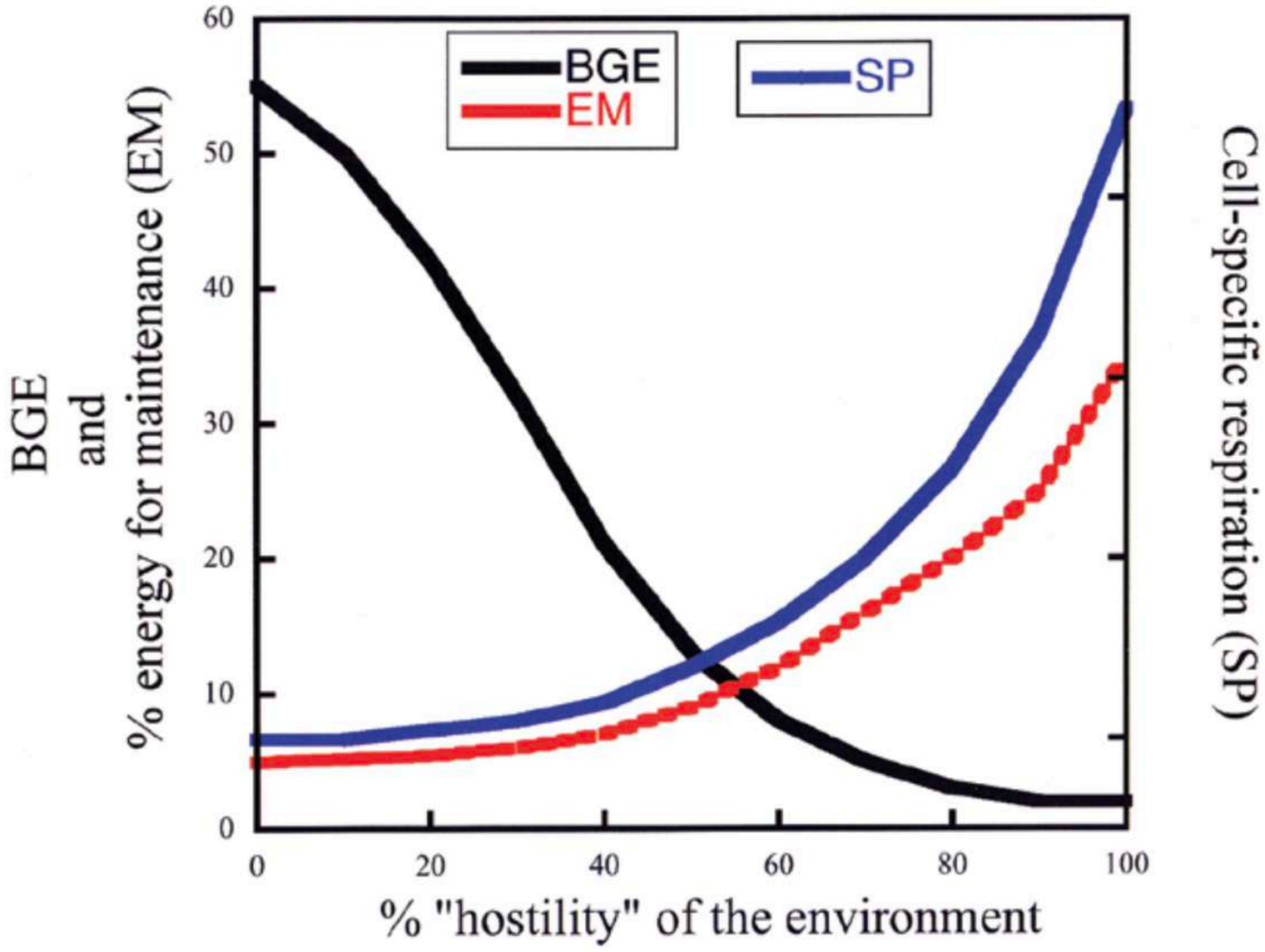
^{14}C method method

Integrated total primary production (PP) (i.e., light–dark DIC fixation), dark DIC fixation and percentage of dark to total PP at station ALOHA (0–175m) from 1989 to 2000 (11 years) and at station BATS (0–150m) from 1989 to 2017 (29 years).

ALOHA				
Depth range (m)	Total PP ($mg\,C\,m^{-2}\,d^{-1}$)	Dark DIC fixation ($mg\,C\,m^{-2}\,d^{-1}$)	% of dark to total PP	% of dark to total PP (calculated for daily 12 h dark fix)
0–65	289.1	10.7	3.7	1.8
65–175	117.5	10.1	8.6	4.3
0–175	406.6	20.8	5.1	2.5
Depth range (m)	Nitrification ($mmol\,NH_4^+\,m^{-2}\,d^{-1}$)	% dark DIC fixation from nitrification	% dark DIC fixation from other chemoautotrophic and anaplerotic reactions	
0–70	0.5	5.4	94.6	
70–150	1.1	12.5	87.5	
0–150	1.5	8.8	91.2	
BATS				
Depth range (m)	Total PP ($mg\,C\,m^{-2}\,d^{-1}$)	Dark DIC fixation ($mg\,C\,m^{-2}\,d^{-1}$)	% of dark to total PP	% of dark to total PP (calculated for daily 12 h dark fix)
0–70	314.2	54.3	17.3	8.6
70–150	103.8	37.9	36.5	18.2
0–150	418.0	92.2	22.1	11
Depth range (m)	Nitrification ($mmol\,NH_4^+\,m^{-2}\,d^{-1}$)	% of dark DIC fixation from nitrification	% of dark DIC fixation from other chemoautotrophic and anaplerotic processes	
0–70	0.7	1.5	98.5	
70–150	0.9	2.7	97.3	
0–150	1.6	2.0	98.0	

Prokaryotic production, respiration and growth efficiency and C demand

Microbial life is tough !



Carlson et al. 2007

Figure 3. Conceptual diagram demonstrating the relationship between environmental stressors or environmental "hostility" and the partitioning of energy within a bacterial cell, the resulting bacterial growth efficiency (BGE), and cell specific respiration. As environmental hostility increases, more energy is partitioned into maintenance energy (EM). Thus, bacterial growth efficiency decreases and cell-specific respiration (SP) increases. Some combination of both physical (temperature, pH, salinity) and chemical (toxins, substrate availability) factors contribute to environmental hostility

Definitions

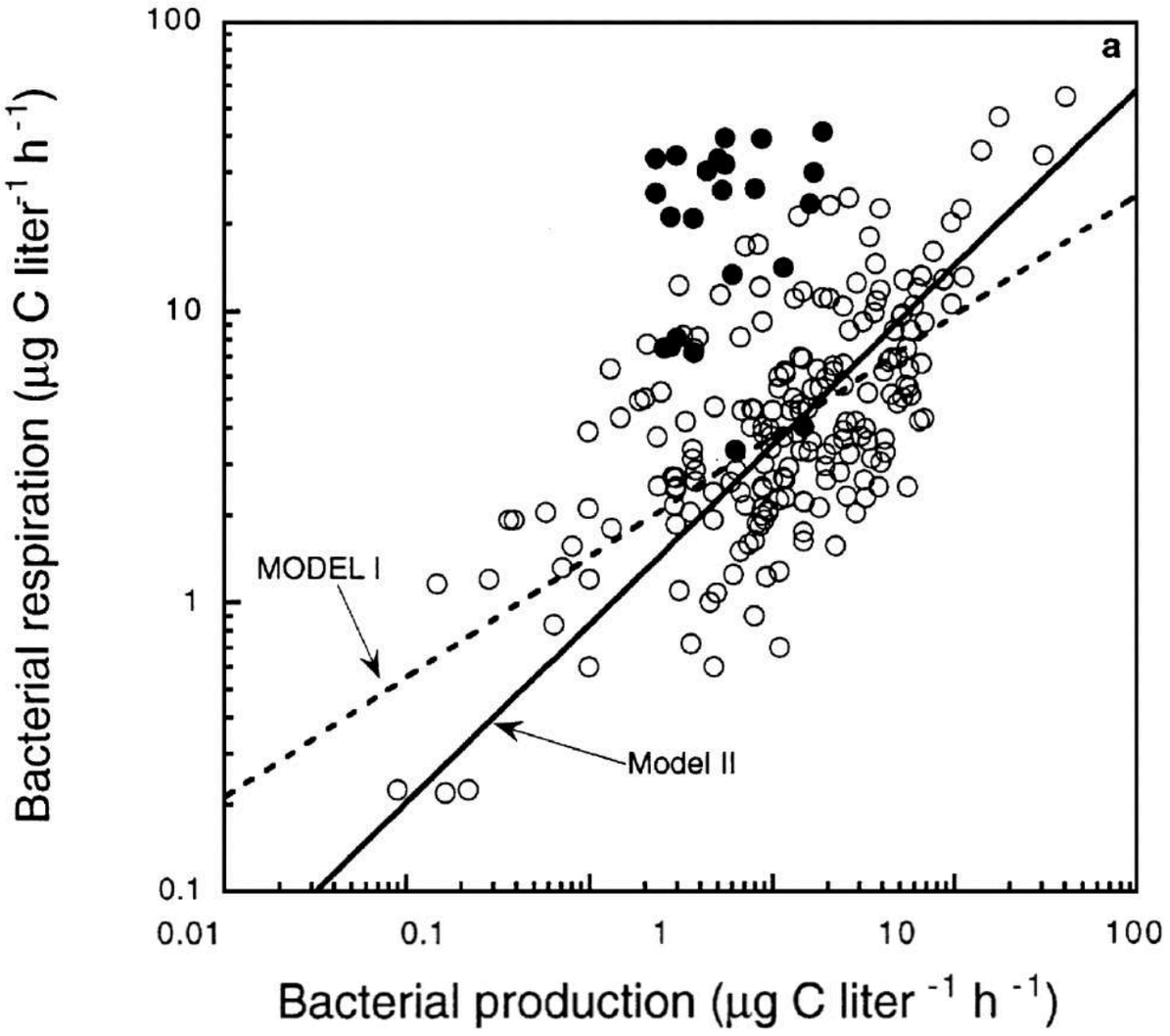
- The **amount of biomass produced per unit of organic C consumed is the bacterial growth efficiency (BGE)** (Sherr and Sherr, 1996; del Giorgio and Cole, 1998)

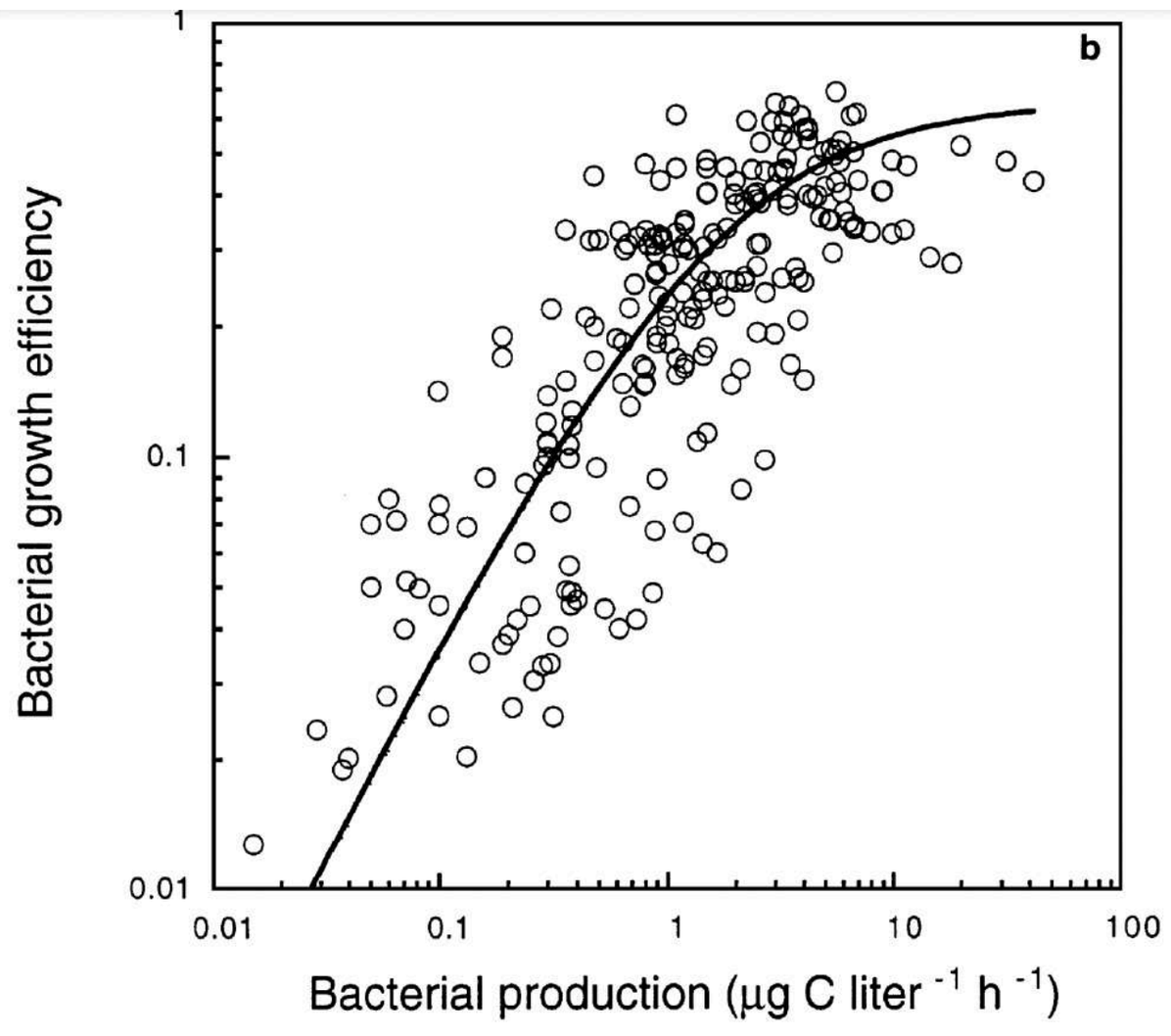
- BGE is a measure of the coupling between **catabolic (energy-yielding) reactions to anabolic (biosynthetic; energy requiring)** reactions and is expressed by the formula: **BGE = BP/(BP + BR)**

- **BP is bacterial production**
- **BR is bacterial respiration**

- **The flux of carbon needed to support a given estimate of BP is referred to as bacterial carbon demand (BCD).** It is possible to derive BCD, and thus total carbon consumption (BR plus BP), by combining measurements of BP with estimates of BGE, such that, **BCD = BP/ BGE**

BP, BR, BGE relationship





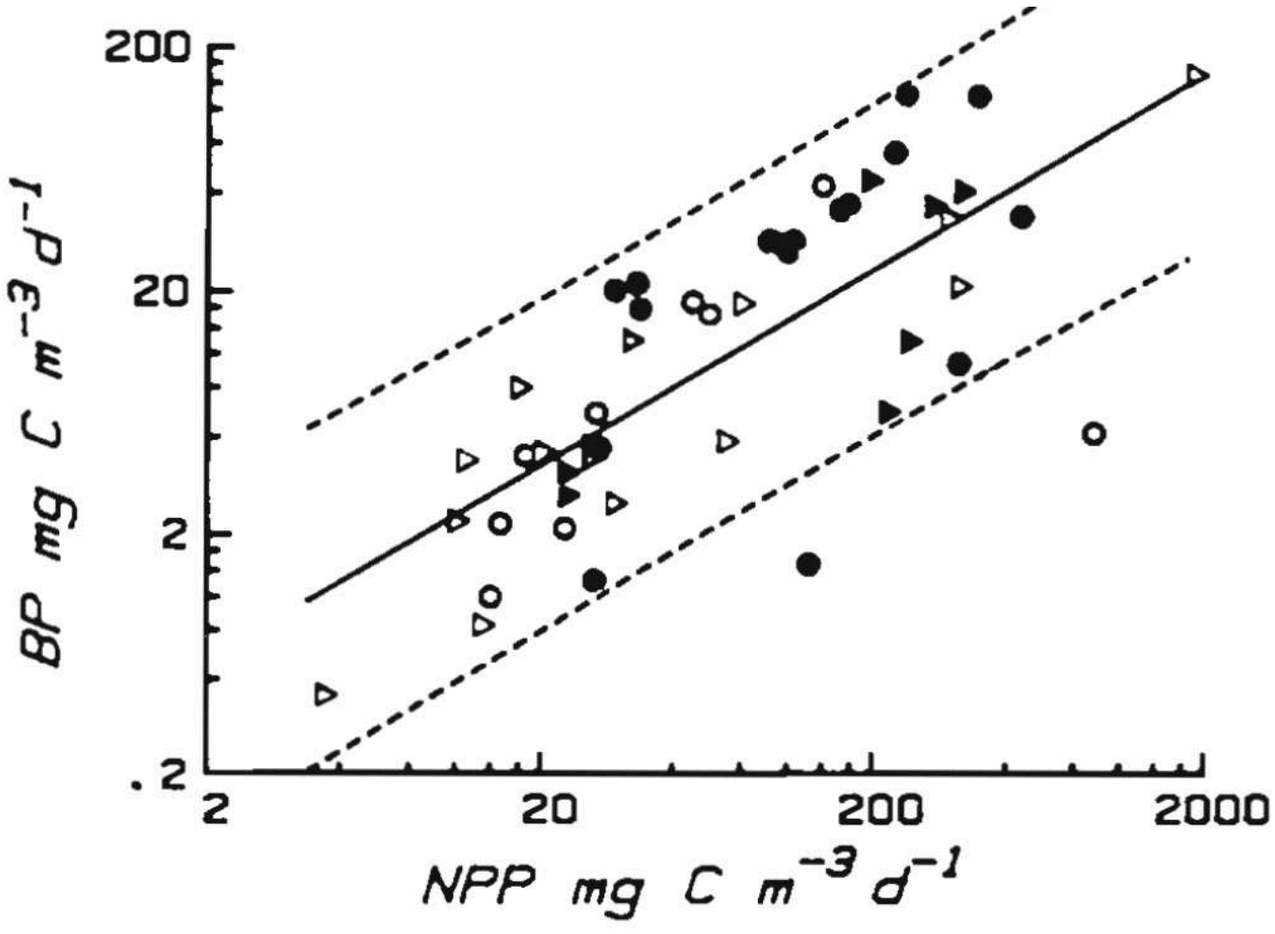
del Giorgio & Cole, 1989

Vol. 43: 1–10, 1988 | MARINE ECOLOGY – PROGRESS SERIES
Mar. Ecol. Prog. Ser. | Published March 24

Bacterial production in fresh and saltwater ecosystems: a cross-system overview

Jonathan J. Cole, Stuart Findlay, Michael L. Pace

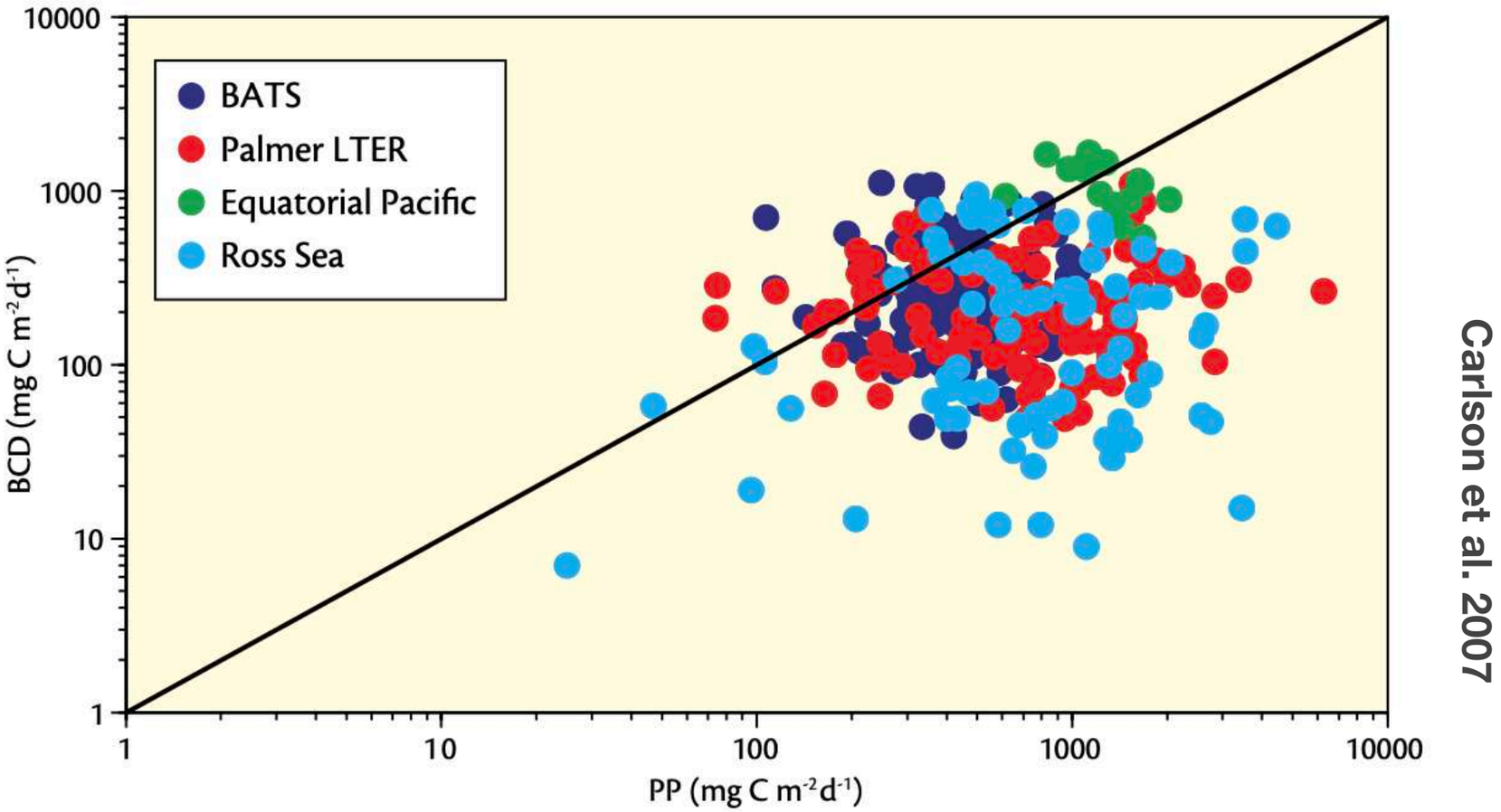
Institute of Ecosystem Studies, New York Botanical Garden, Mary Flagler Cary Arboretum, Millbrook, New York 12545, USA



- BP was positively and significantly correlated to primary production (PP) across a wide range of aquatic ecosystems, and concluded that net BP averaged about <20% - 30%-50% of PP

- **From cells to C per cell: 12.6 fg C cell^{-1}**

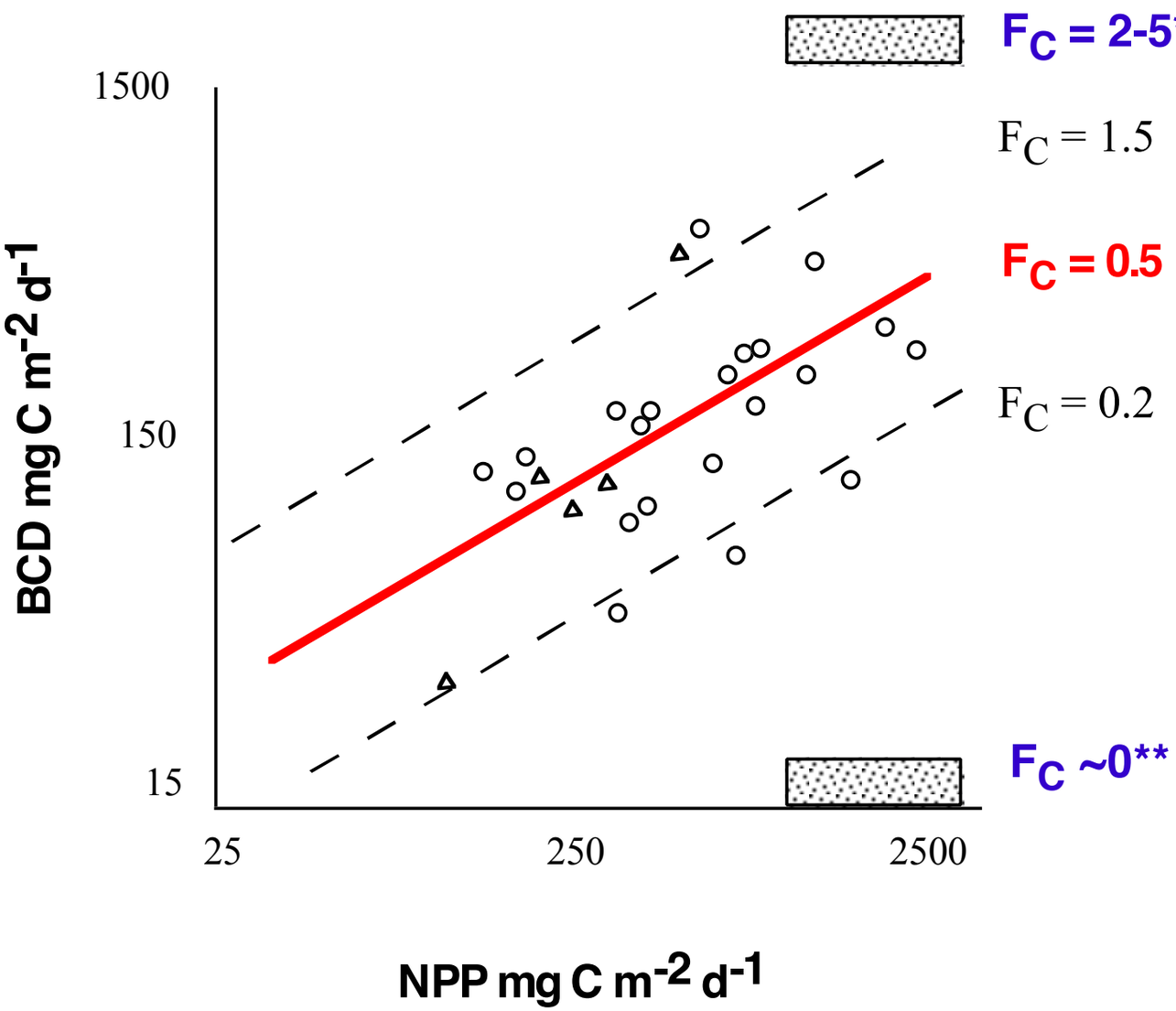
BCD and PP relationship



Carlson et al. 2007

Figure 4. Relationship between integrated bacterial carbon demand (BCD) and primary production (PP) within the euphotic zone of representative ocean sites. All data are derived from paired measurements of bacterial production and PP integrated within the euphotic zone from each study site. A common bacterial growth energy of 0.1 was used to estimate BCD. The black line represents the 1:1 line. Data points that lie above this line indicate that bacterial carbon demand was greater than local primary production at the time of sample collection. The Bermuda Atlantic Time-series Study (BATS) data represent monthly values from 1991–2003 (n = 155; see Steinberg et al., 2001 for details; data available at http://bats.bbsr.edu/). Paired BP and PP from the Equatorial Pacific (n=16) and Ross Sea, Antarctica, (n=77) were calculated according to Ducklow (1999) (data available at http://usjgofs.whoi.edu/jg/dir/jgofs/). All data from the Palmer Peninsula, Antarctica, (n=112) provided by H. Ducklow and the Palmer LTER program.

Bacterial Carbon Demand is a Major and Variable Flux Pathway



BCD=BCP + R

Modified from Cole et al, 1988 MEPS. 43: 1-10.

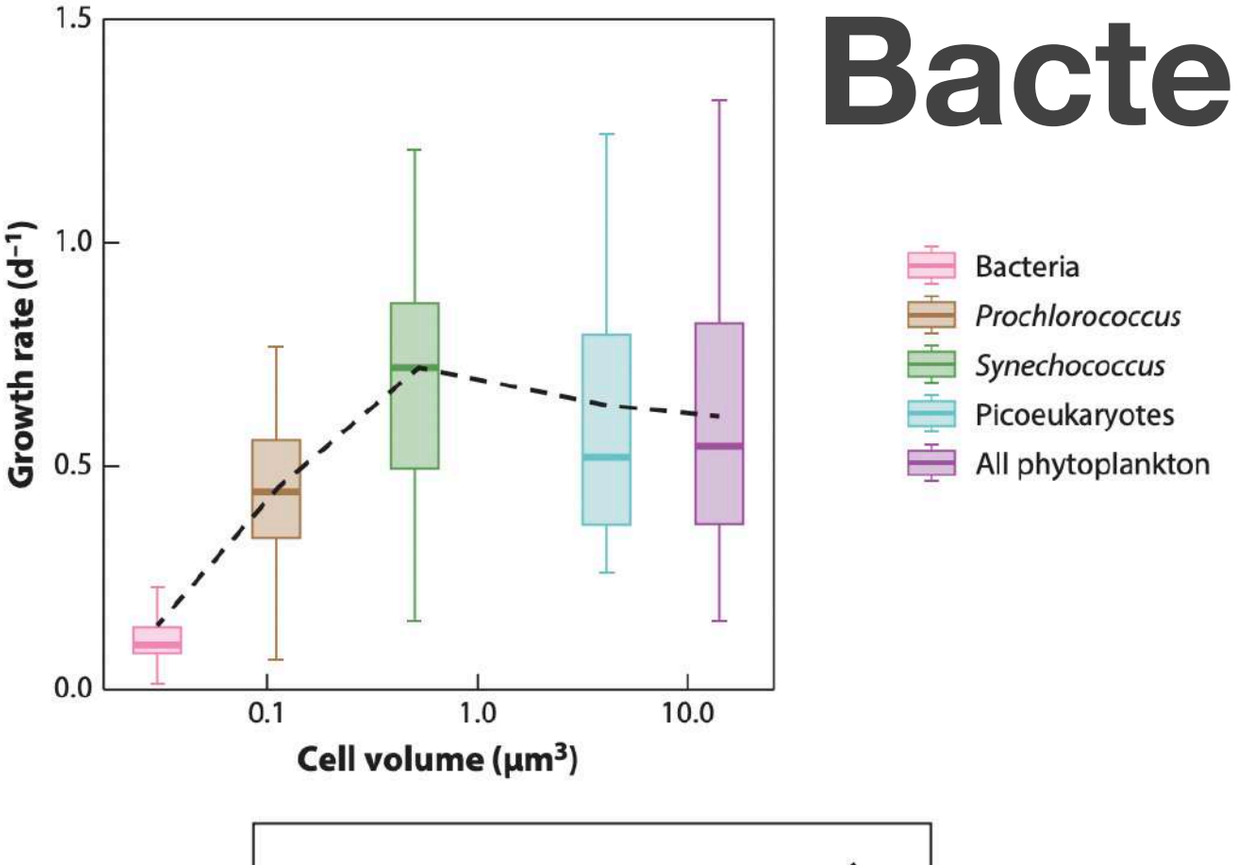
* Smith et al, 1995 (mesocosm bloom)

** Pomeroy & Deibel, 1986 (Newfoundland coast)

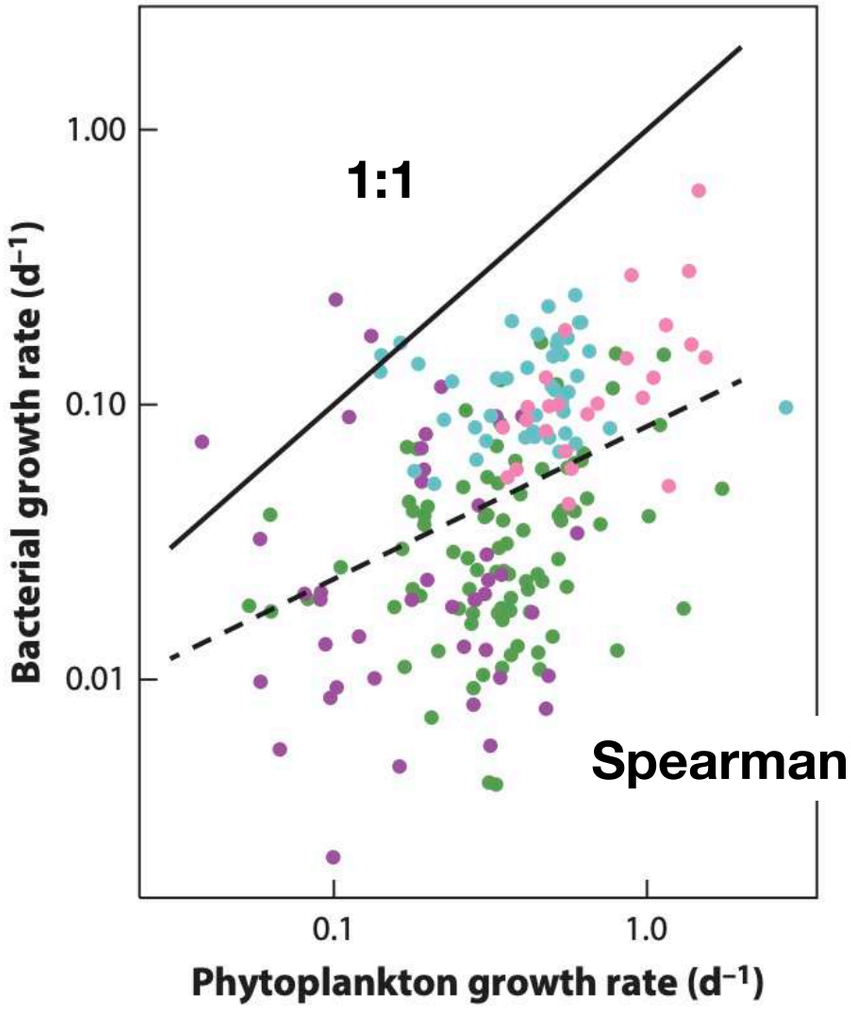
Turley et al, 1999 (E Med Fc=0.85)

From Farooq Azam

Bacteria-phytoplankton



- Heterotrophic bacteria μ < than Cyanobacteria and phytoplankton
- Bulk growth rate of the heterotrophic bacterial community is approximately 1/6 of the the phytoplankton community growth rate

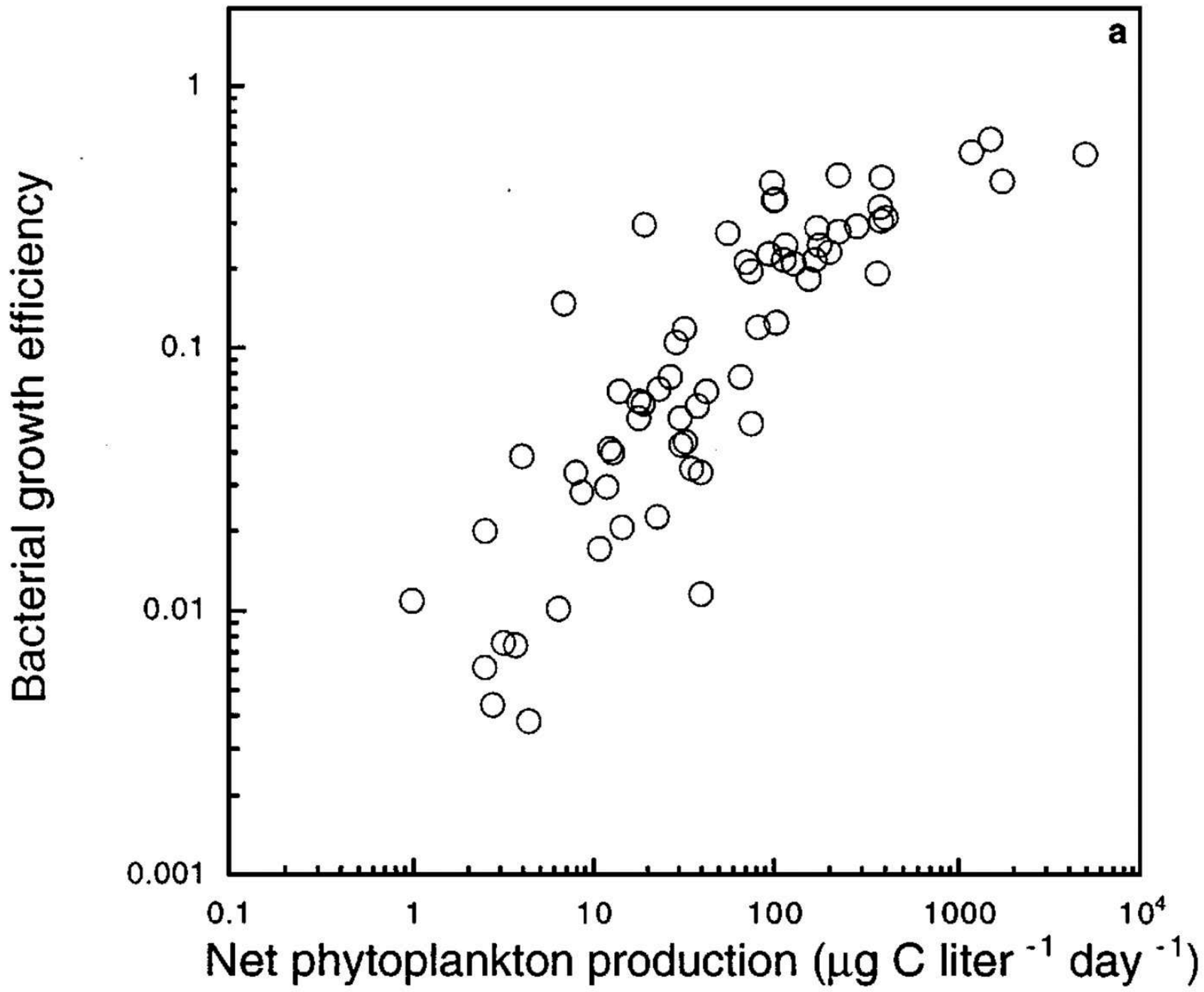


- Phytoplankton rates can constrain growth rates of heterotrophic bacteria
- Bacterial growth rate is correlated with phytoplankton growth rate

Spearman's ρ = 0.42, p < 0.001

Kirchman et al. 2015

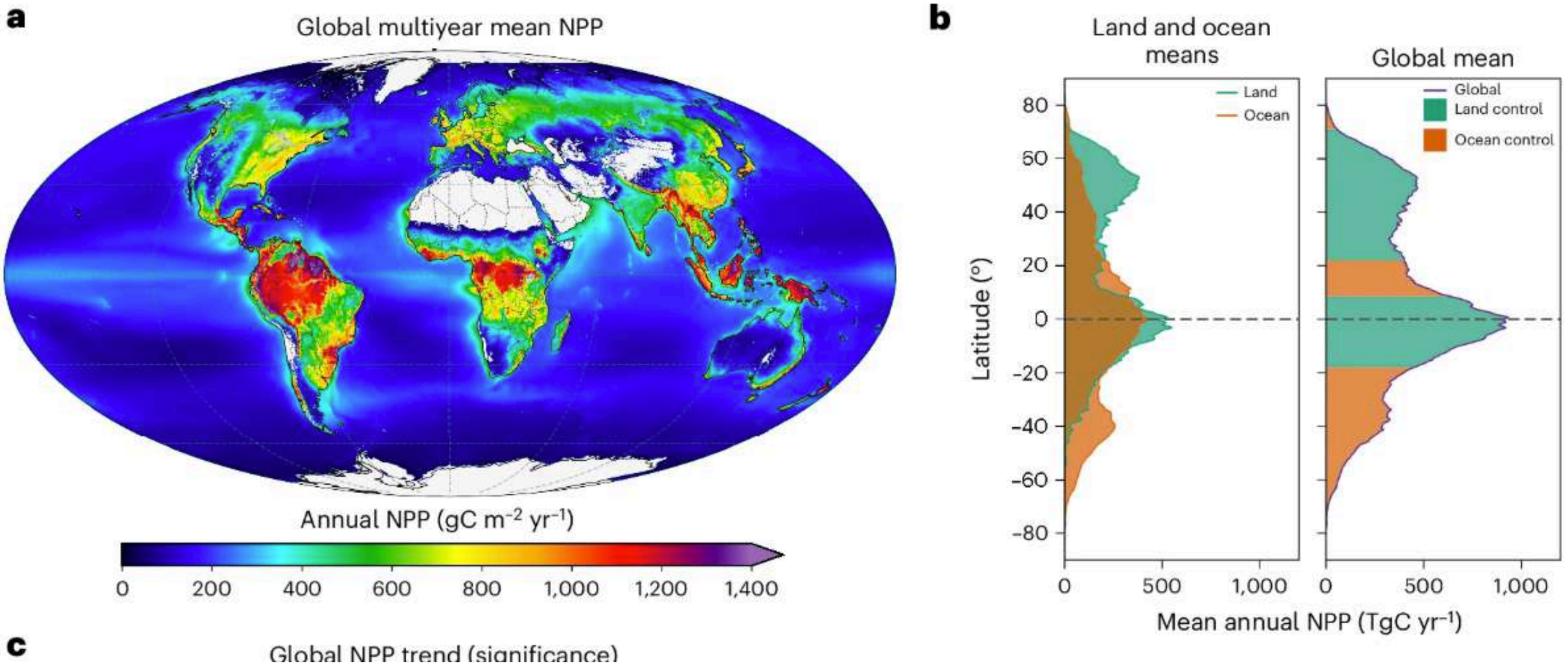
BGE and PP relationship



del Giorgio & Cole, 1989

Global Biological Productivity

From: Contrasting biological production trends over land and ocean



Net primary production

Zhang et al., 2025

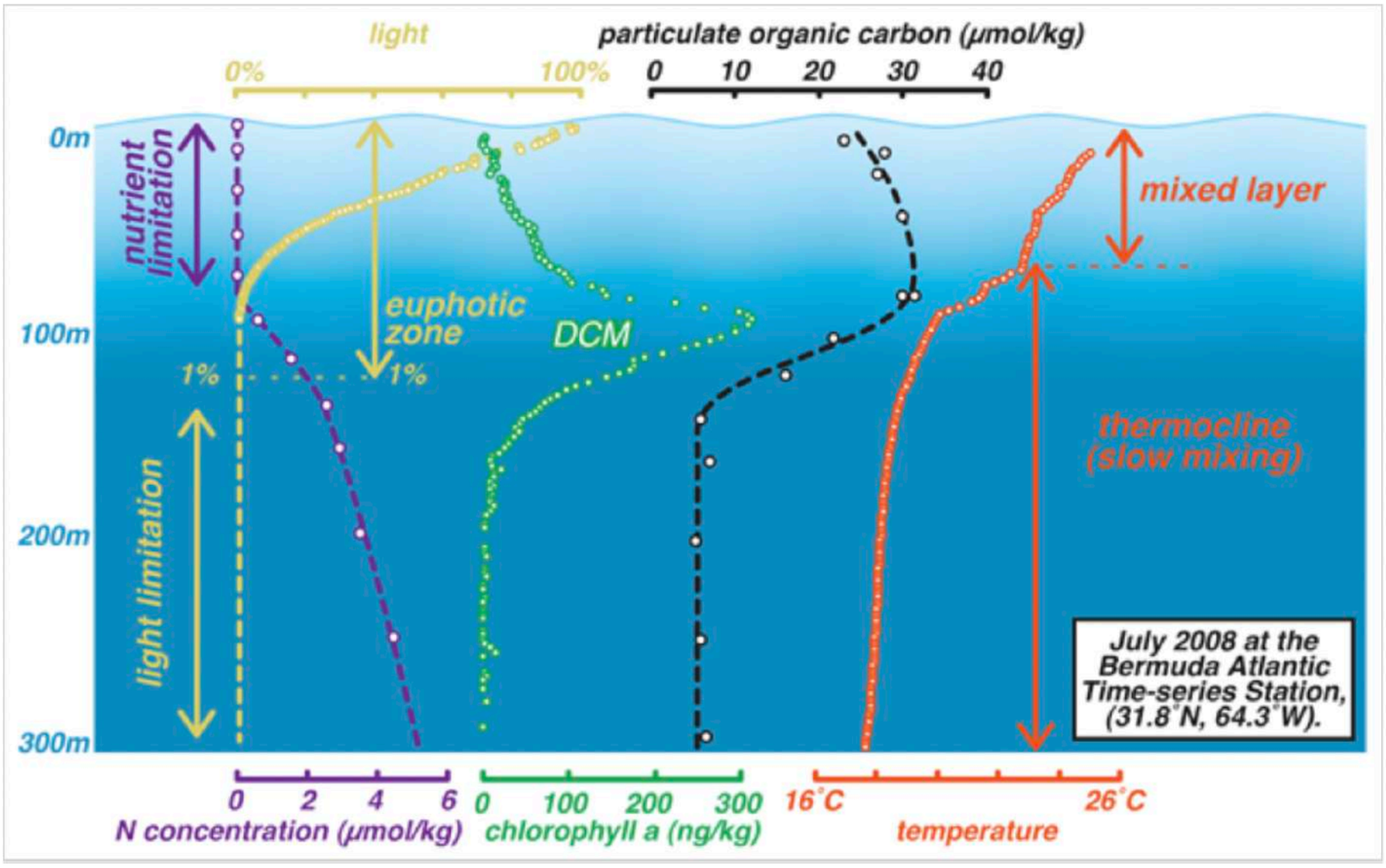
NPP represents the net accumulation of energy that sustains growth, reproduction and consumption by heterotrophs within an ecosystem

Gross vs Net PP

“**Gross** primary production" (**GPP**) refers to the **total** rate of **organic carbon** production by **autotrophs**, while "**respiration**" refers to the energy-yielding oxidation of **organic carbon** back to carbon dioxide

“**Net** primary production" (**NPP**) is **GPP minus** the **autotrophs'** own rate of **respiration**; NPP is the rate at which the full metabolism of **phytoplankton** produces biomass

The difference between plankton photosynthesis (P) and auto- plus heterotrophic respiration (R) is net community production (NCP), **the amount of photosynthetically fixed C available for sequestration to the deep ocean or for transfer up the marine food web**



Sigman & Hain, 2012
Bermuda Institute of Ocean Sciences (http://bats.bios.edu) and the
Bermuda Bio Optics Project (http://www.icess.ucsb.edu/bbop/)

The Biological Productivity of the Ocean

- **Primary productivity** is calculated by measuring the uptake of CO_2, or the output of O_2
- Production rates are expressed as grams of organic carbon per unit area per unit time: grams of carbon per meter squared per year: g Cm^{-2} yr^{-1}
- The annual primary productivity of the oceans is estimated to be approximately 50×10^{15} grams (50×10^{9} metric tons) of carbon per year, roughly half of the global total primary production
- The **energy** they produce is called **primary production**, and the **rate** at which they produce the energy is called **productivity**
- **Light**
- **Nutrient availability**
- **Temperature**
- **Predator and competitors**

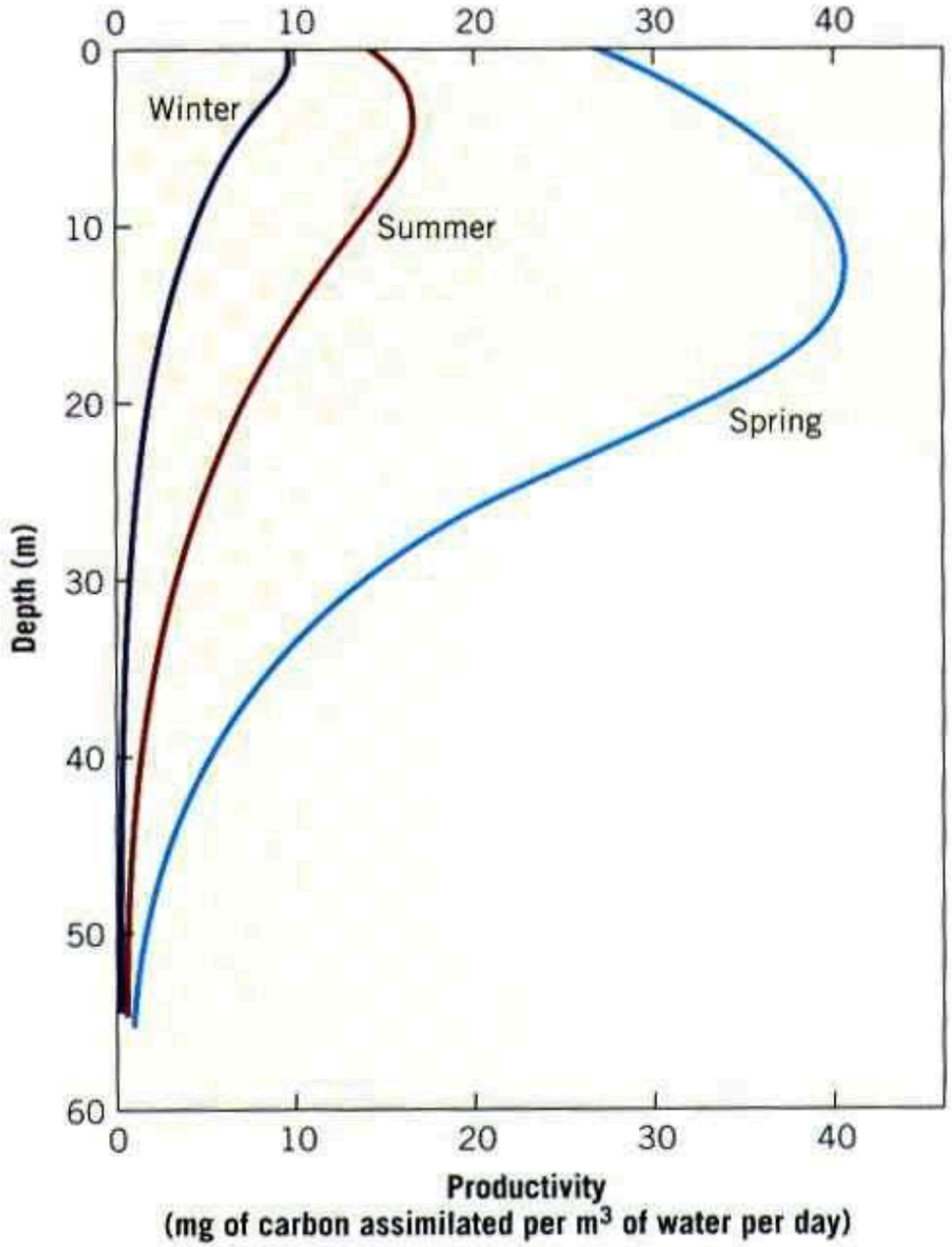
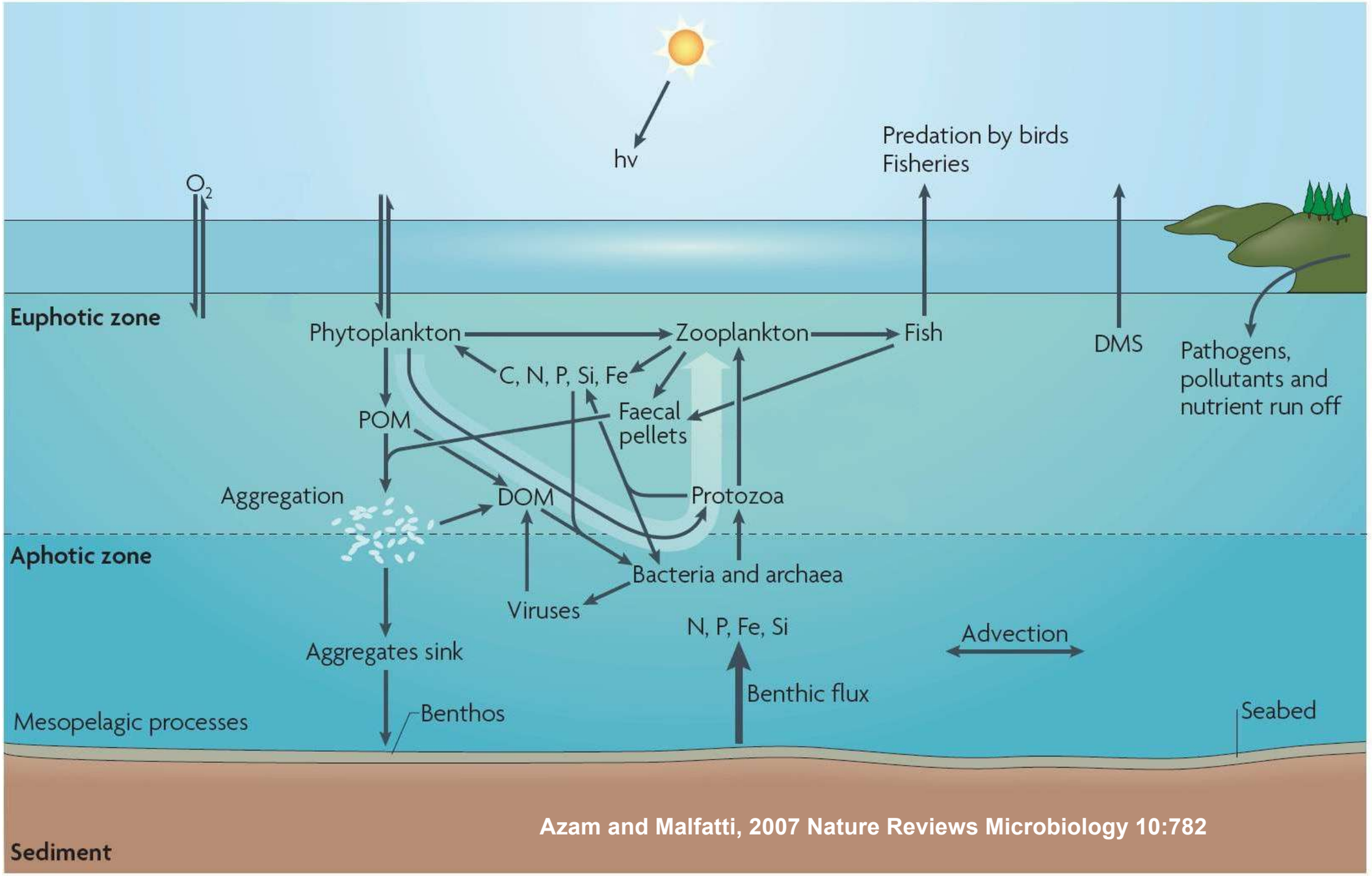


Figure 11.12

Typical variations in primary productivity with depth in the coastal waters of the Northeast Pacific Ocean. (Based on data from G. C. Anderson, 1964, *Limnology and Oceanography*. **9**; 294.)

From the ocean to….



Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

From the ocean to a mL ocean

Table 1. Carbon, abundance, and volume of the biota in surface seawater. Estimates are also given for particulate organic matter (POM) and dissolved organic matter (DOM). These estimates are not precise and show only the general order-of-magnitude reported in the literature.

	Amount ml^{-1} seawater		
Group	Carbon (ng)	Individuals	Volume (ml)
Algae	100	10^{3}	10^{-6}
Bacteria	10	10^{6}	10^{-7}
Microzooplankton	1	10^{2}	10^{-8}
Zooplankton	10	10^{-1}	10^{-7}
Larger Animals	<1	$<<10^{-1}$	$<<10^{-7}$
POM	10-100	10^{3}	10^{-7}-10^{-6}
DOM	1000	-	-

Azam & Ammerman, 1984