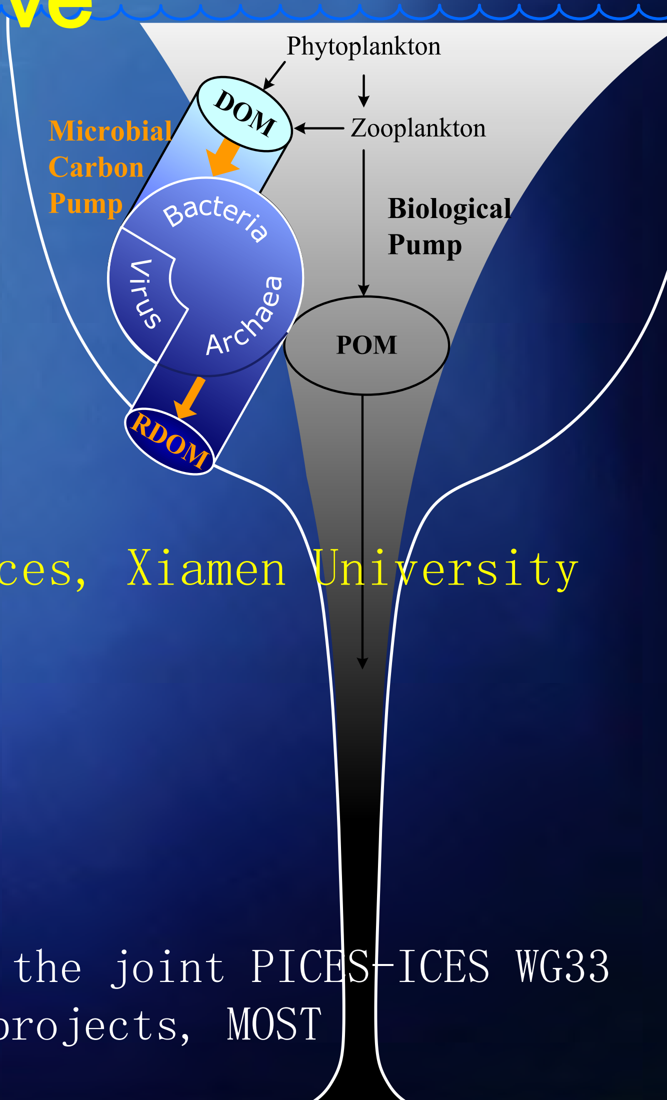
Biological mediated carbon cycling and sequestration in the ocean and climate change: A new dimension and perspective



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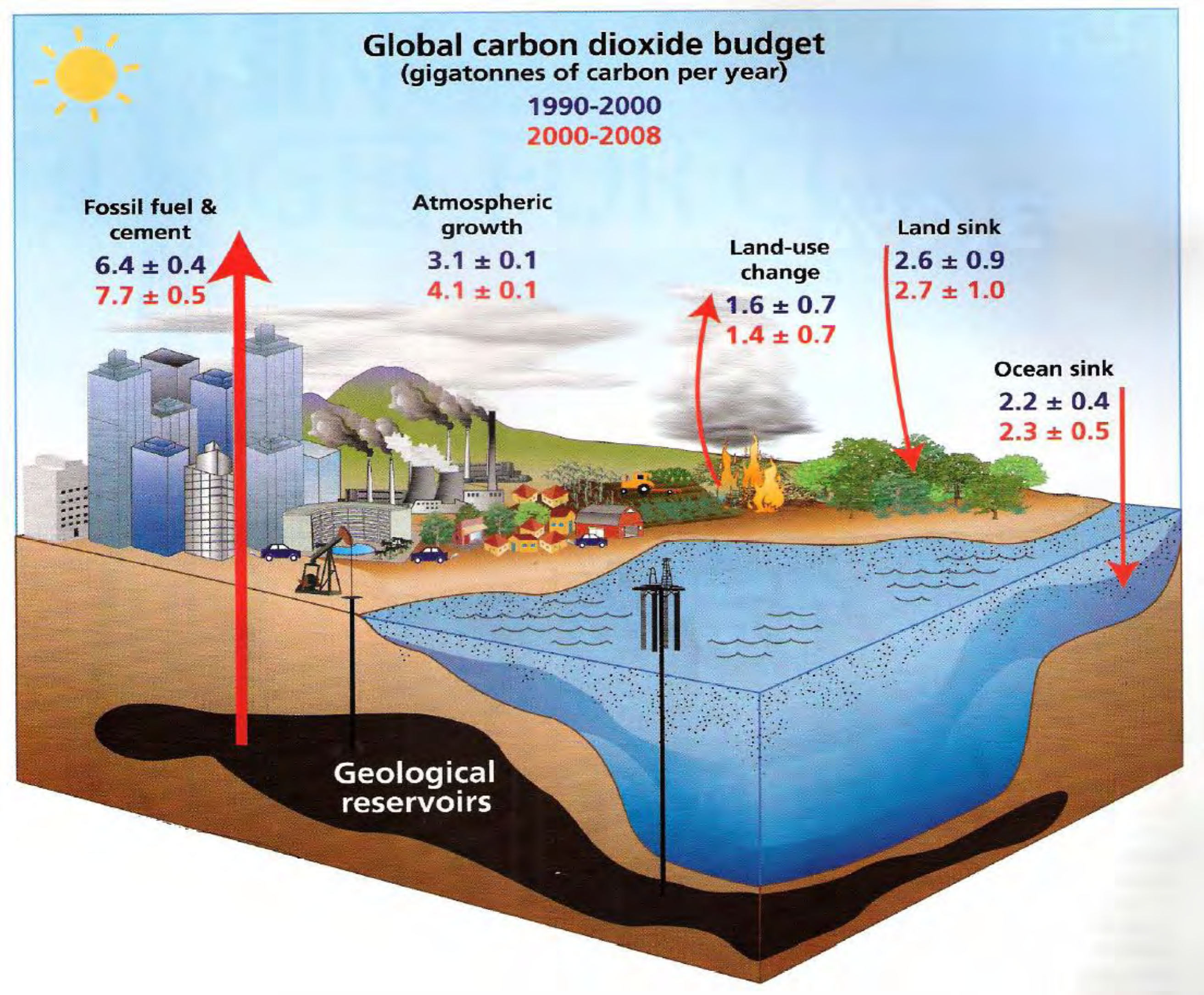
Acknowledgements

Members of the WG on the MCP, SCOR; Members of the joint PICES-ICES WG33
Members of the IME, XMU; Members of the 973 MCP projects, MOST

Outlines

1) Framework of Microbial Carbon Pump (MCP)
2) Impacts of MCP on climate change
3) Current status of the MCP studies
4) Future applications

Ocean Carbon: ~ 20x Land, 50x Atmospheric C
Play a significant role in climate changes



C. Le Quéré, et al., 2015

The Ocean is the largest carbon reservoir

Atmosphere
700 GT

Land
1,900 GT

Ocean
40,000 GT

uptake ~ 1/3 anthropogenic CO_2

Biological Pump Diagram

Chisholm 2000

Microbial Carbon Pump （MCP）

Jiao et al., 2010

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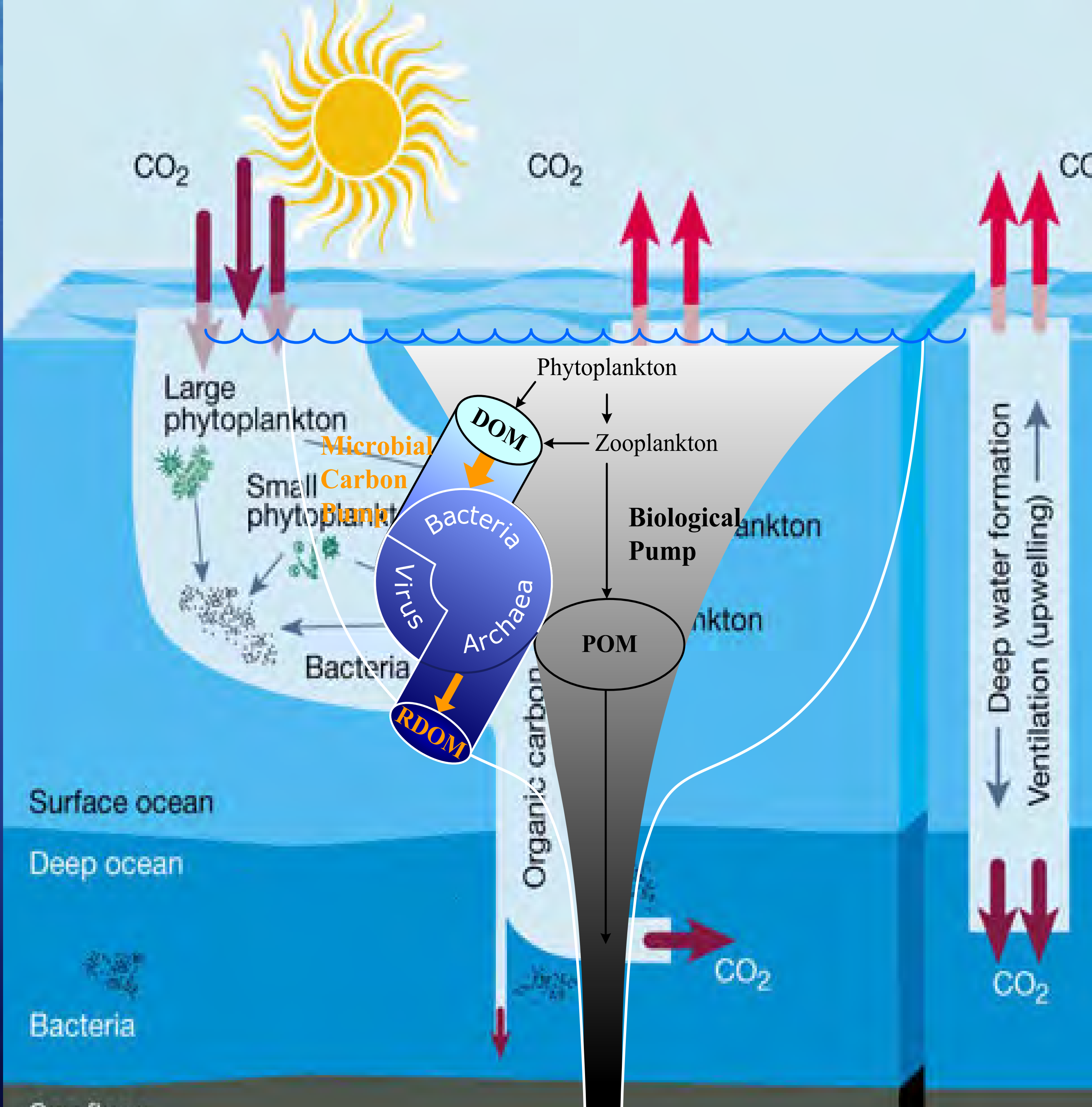


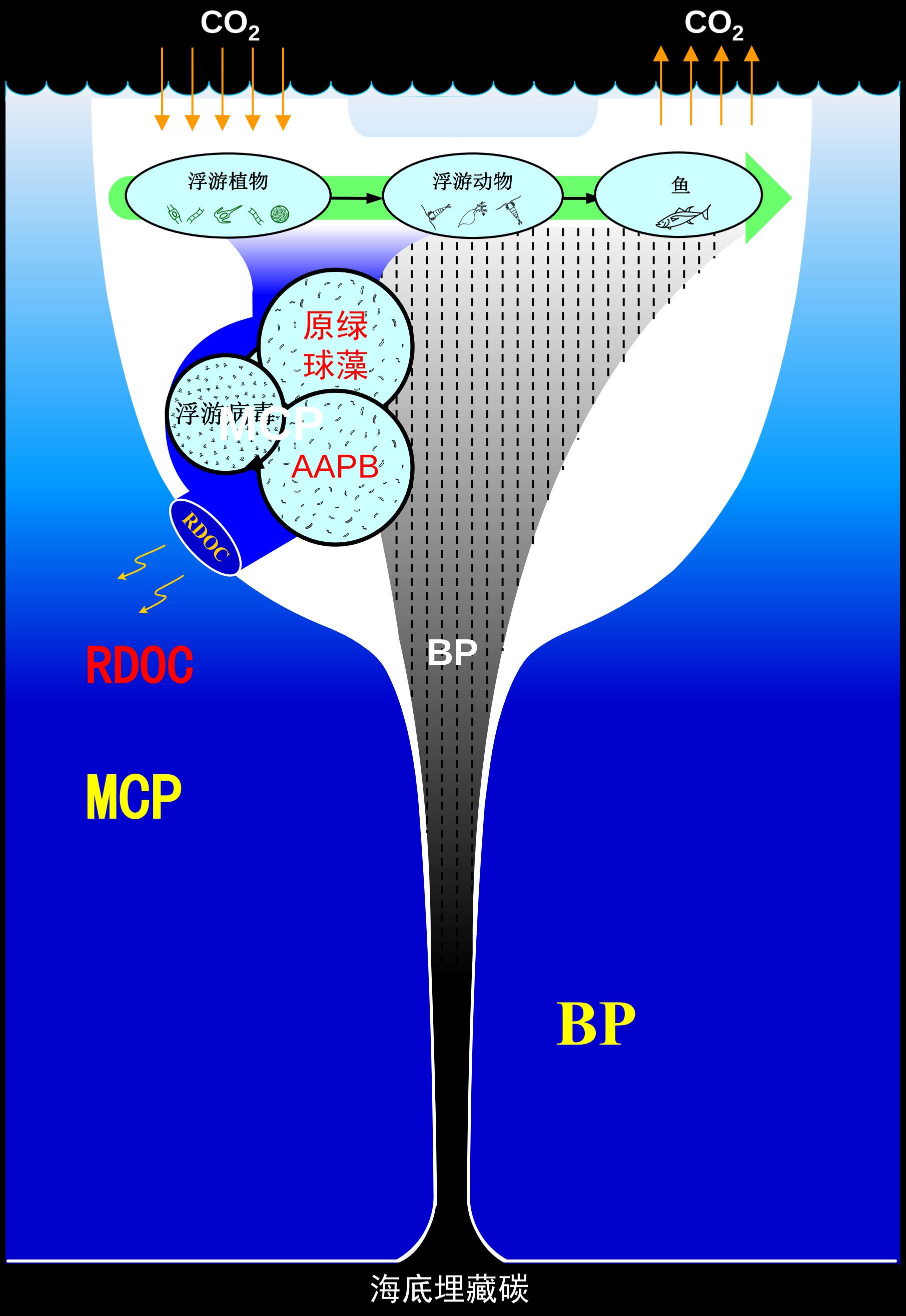
Microbial carbon pump (MCP) vs Biological pump (BP)

BP is based on physical transportation

MCP is based on microbial transformation

BP depends on vertical transport to depths

MCP is independent of water depth



Outlines

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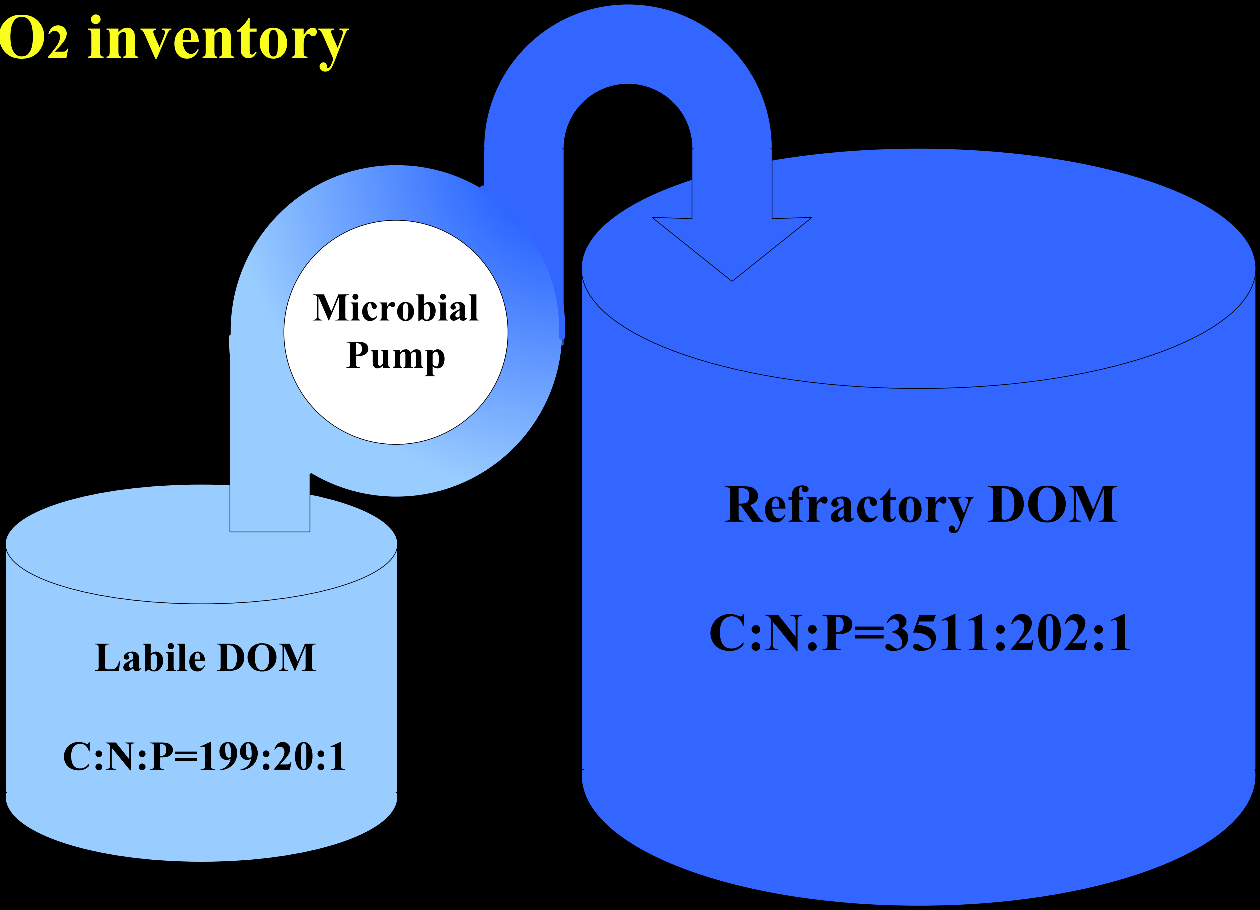
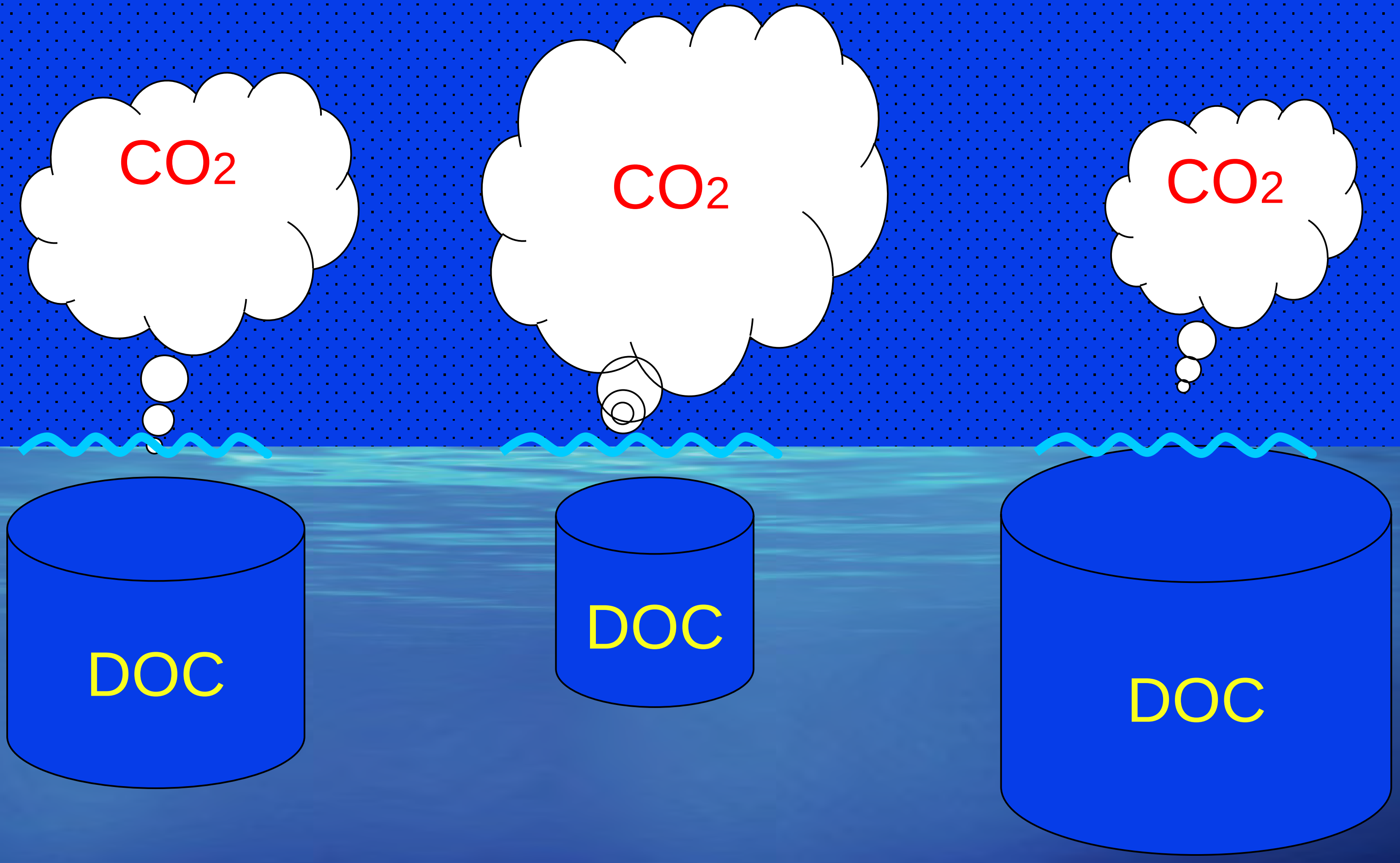
Since resistant to decomposition, RDOC accumulate

> 95% of marine OC is DOC ;
> 95% of DOC is RDOC

DOC = CO_2 inventory





Equivalent

Global warming

Global cooling

CO_2

CO_2

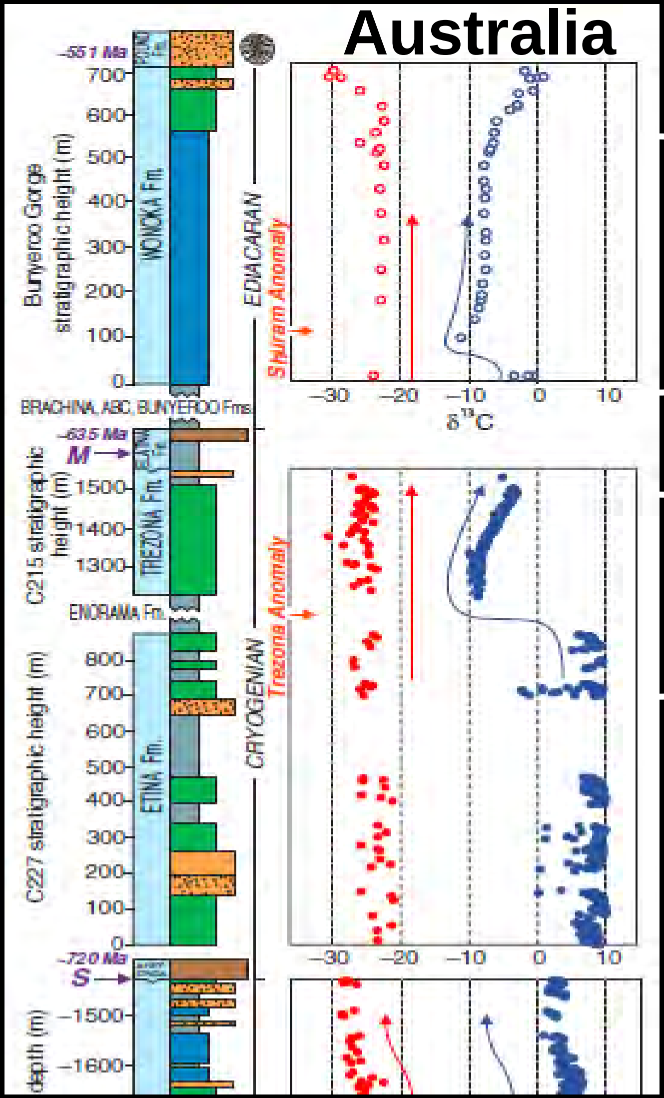
CO_2

DOC

DOC

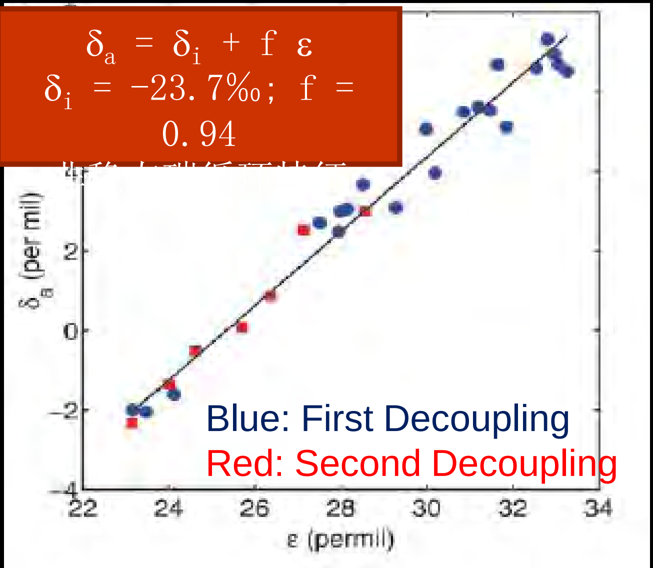
DOC

Evidence from the Proterozoic time



Second Decoupling

First Decoupling



$\delta_a = \delta_i + f\,\varepsilon$

$\delta_i = -23.7‰$; $f = 0.94$

Size ≥ 10^2-10^3 times of modern DOC

Turn-over Time ≥ 10^4 years

Metazoan were not evolved yet

no grazing impacts

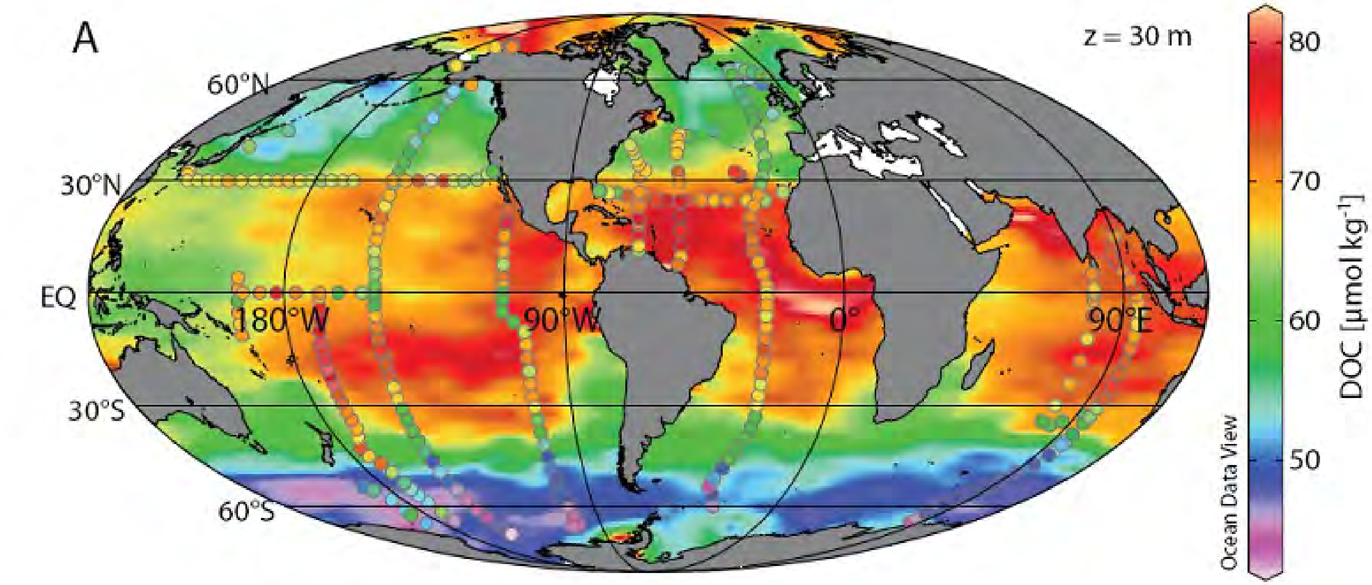
→ microbial C accumulated→ Viral lysis

→ tremendous DOC pool

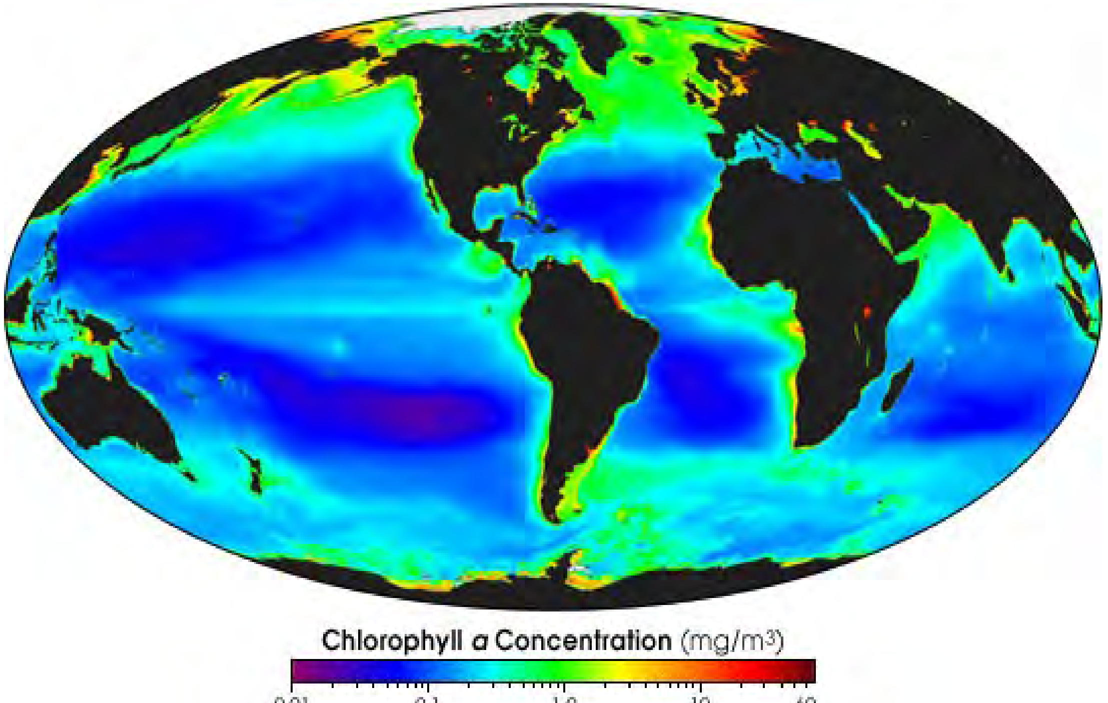
Macdonald et al. (2010), Science ;

Rothman et al. (2003), PNAS

Evidence in the current ocean



Hansell et al. 2009



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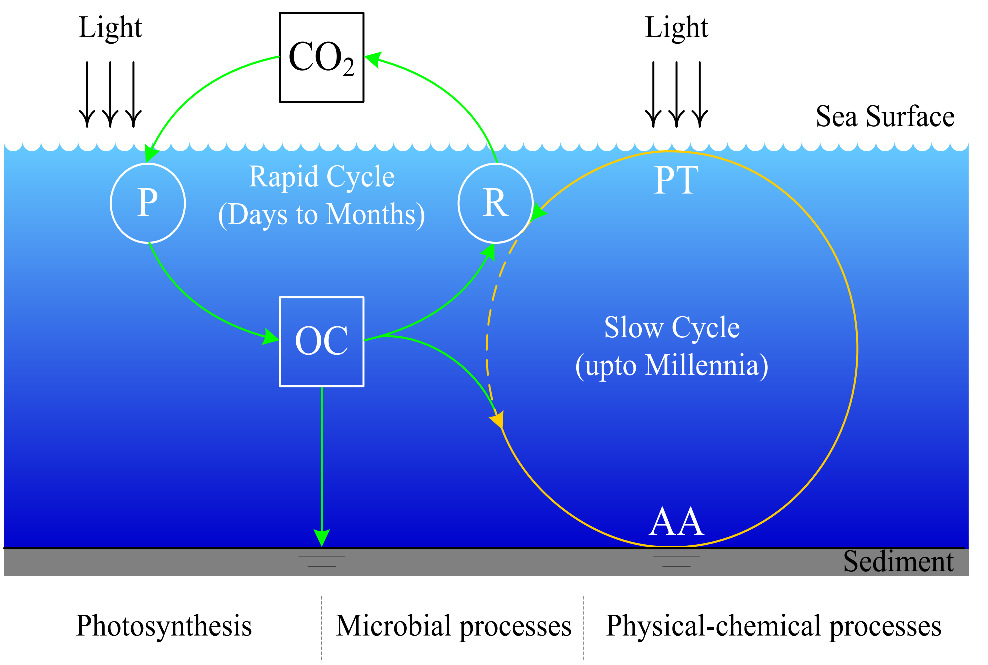
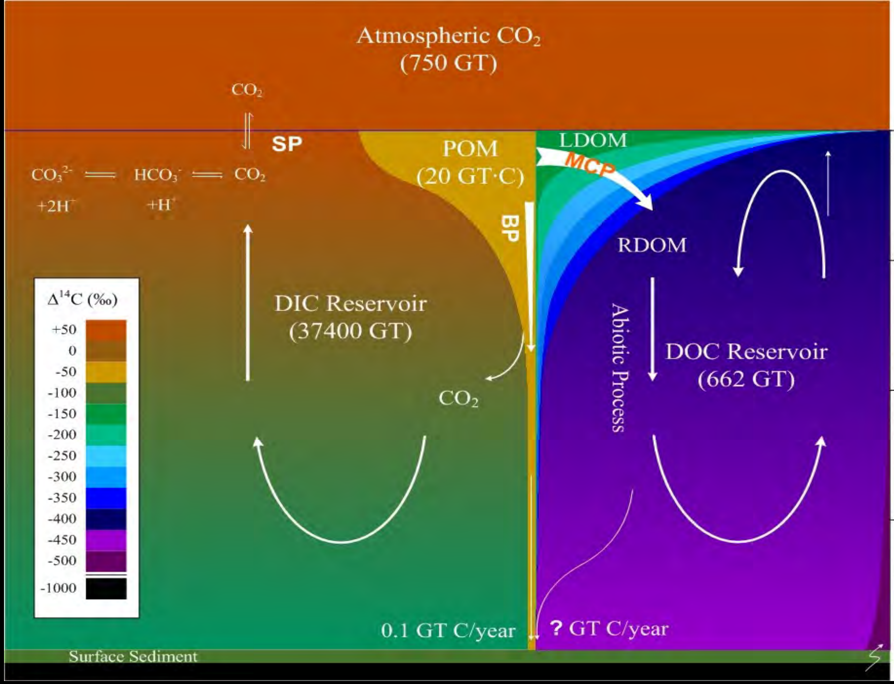
“微型生物碳泵”储碳新机制

nature REVIEWS MICROBIOLOGY

Jiao et al., 2010





“海洋微型生物碳泵”；RDOC的产生机制

Jiao et al., 2010

Nature Reviews Microbiology 作为其 **featured Article**

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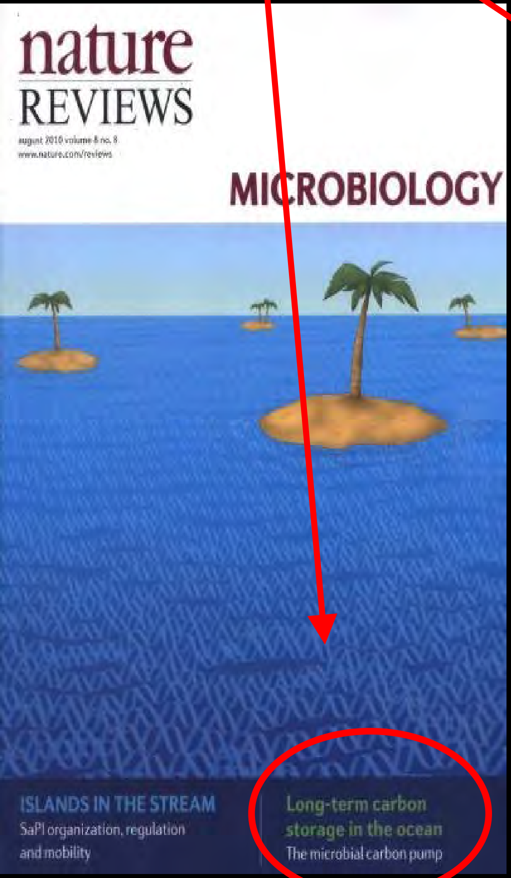

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ISLANDS IN THE STREAM
SaPI organization, regulation and mobility

Long-term carbon storage in the ocean
The microbial carbon pump

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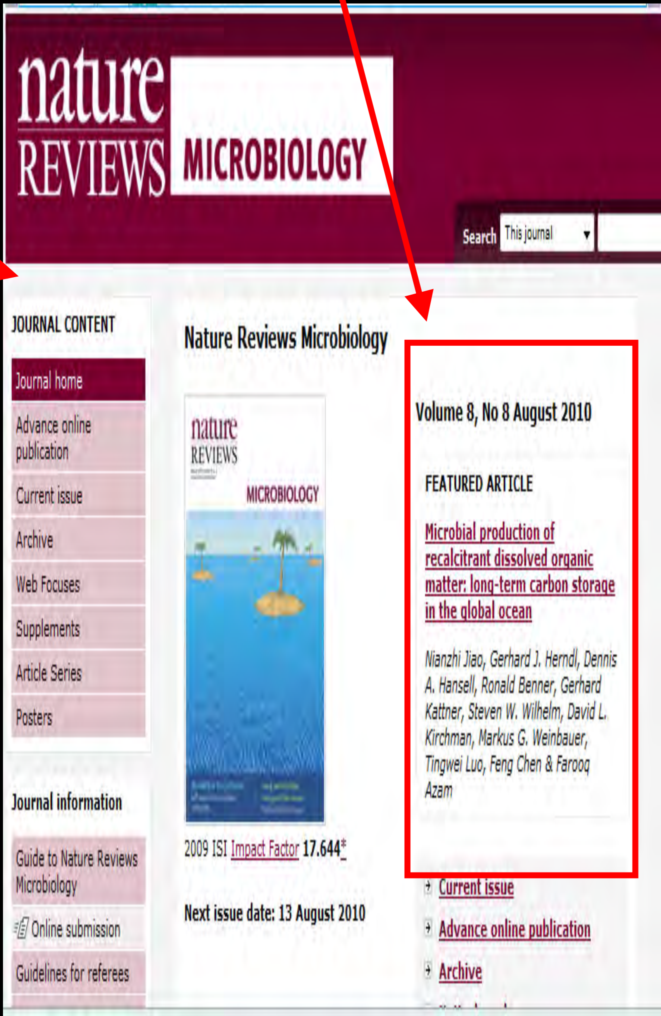

JOURNAL CONTENT

Journal information

Nature Reviews Microbiology

2009 ISI Impact Factor 17.644*

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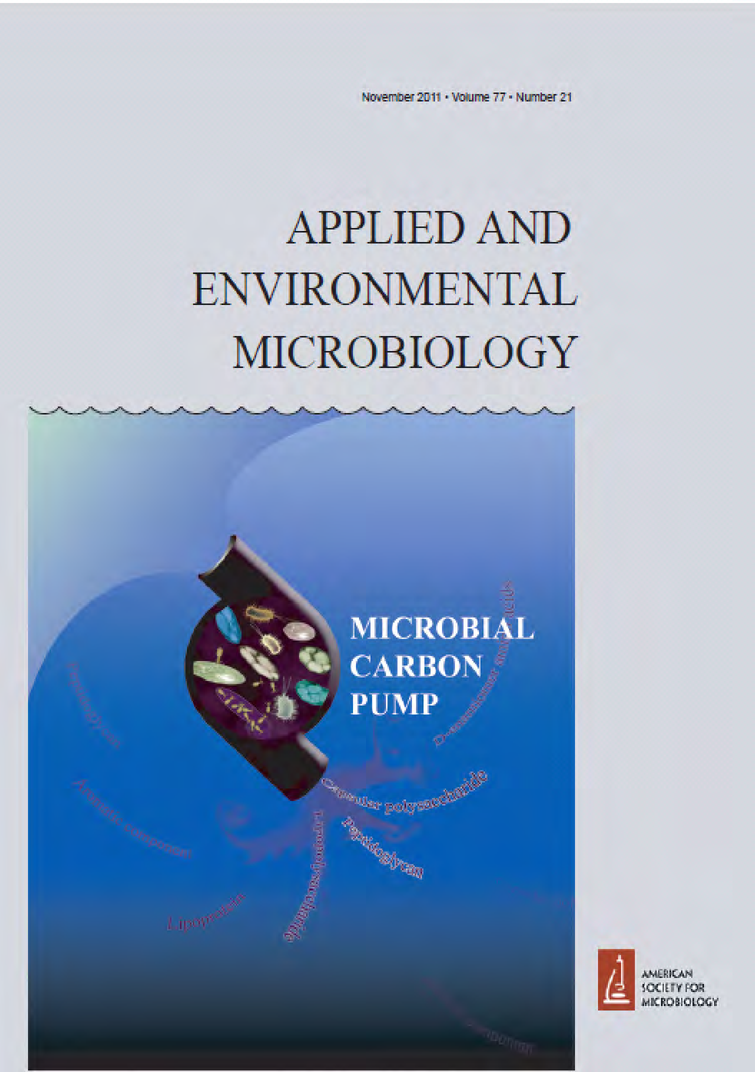
Volume 8, No 8 August 2010

FEATURED ARTICLE

Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean

Nianzhi Jiao, Gerhard J. Herndl, Dennis A. Hansell, Ronald Benner, Gerhard Kattner, Steven W. Wilhelm, David L. Kirchman, Markus G. Weinbauer, Tingwei Luo, Feng Chen & Farooq Azam

MCP special issues



November 2011 • Volume 77 • Number 21

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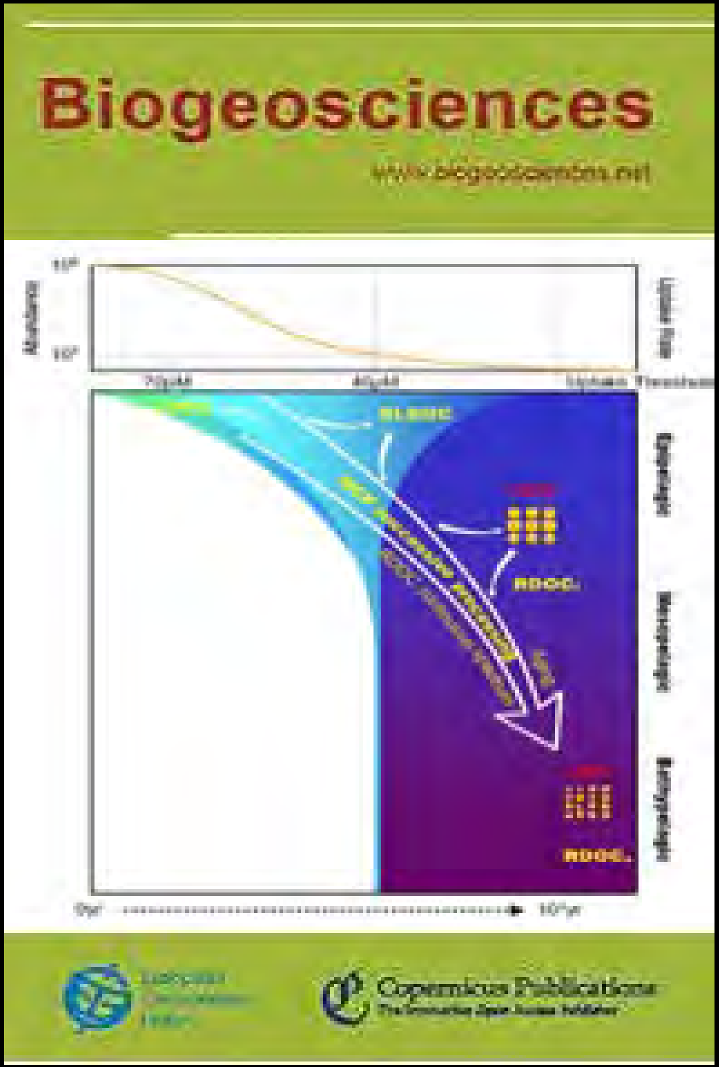

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MARINE BIOGEOCHEMISTRY

The Invisible Hand Behind A Vast Carbon Reservoir

A key element of the carbon cycle is the microbial conversion of dissolved organic carbon into inedible forms. Can it also serve to sequester CO_2?

Science 评论MCP为 “巨大碳库的幕后推手”

Azam and others credit Jiao with a key insight: the recognition that microbes play a dominant role in "pumping" bioavailable carbon into a pool of relatively inert compounds. Some refractory DOC hangs in the upper water column, while some gets shunted to the deep ocean interior via the biological pump. The MCP "may act as one of the conveyor belts that transport and store carbon in the deep oceans," says Chen-Tung "Arthur" Chen, an ocean carbonate chemist at National Sun Yat-sen University in Kaohsiung, Taiwan. The MCP also appears to function in deep waters, where bacteria adapted to the high-pressure environment may have "a special capacity" to degrade refractory DOC, says Christian Tamburini, a microbiologist at the Centre d'Océanologie de Marseille in France.

It took sharp sleuthing to uncover the microbial connection with refractory DOC. In a landmark paper in 2001, Hiroshi Ogawa of the University of Tokyo and colleagues showed that marine microbes are able to convert bioavailable DOC to refractory DOC (*Science*, 4 May 2001, p. 917). Then a month later, Zbigniew Kolber, now at the Monterey Bay Aquarium Research Institute in Moss Landing, California, and colleagues reported that in the upper open ocean, an unusual class of photosynthetic bacteria called AAPB accounts for 11% of the total microbial community (*Science*, 29 June 2001, p. 2492). AAPBs seemed to be plentiful everywhere, according to measurements of infrared fluorescence from the microbe's light-absorbing pigments.

It turned out, though, that other organisms were throwing the AAPB estimates way off the mark. Using a new technique, Jiao's group determined that the fluorescent glow of phytoplankton was masking the glow of the target microbes. "Just like when the moon is bright, less stars are visible," Jiao says. He put the new approach through its paces in 2005, when China's *Ocean 1* research vessel conducted campaigns to mark the 600th anniversary of Admiral He Zheng's historic voyages. The observations "turned things upside down," Jiao says. His group found that AAPBs are more abundant in nutrient-rich waters than in the open ocean, indicating that AAPB population levels are linked with DOC, not light.

Next, Jiao found that AAPBs are prone to viral infection, and he isolated the first phage that's specific for these bacteria. Phages rip apart their hosts, spilling their guts, including organic carbon, into the water. This viral shunt acting on many marine bacteria "may be a significant player in the accumulation of refractory DOC compounds" in the water column, says Steven Wilhelm, a microbiologist at the University of Tennessee, Knoxville. Pulling together several strands—the ubiquity of AAPBs, their low abundance but high turnover rate, the tight link to DOC, and their susceptibility to infection—Jiao proposed that AAPBs and other microbes are a key mechanism for the conversion of bioavailable DOC to refractory DOC. That may seem counterintuitive, as microbes do not set out to produce refractory DOC; rather, the compounds are a byproduct of their demise. "This process is not beneficial to the cell," says Simon.

Because the buildup of refractory DOC in the water column is accidental, it will be a challenge to coax microbes to sequester more carbon. For decades, researchers have been tinkering with the biological pump to store more carbon in the deep ocean by seeding seas with iron fertilizer. The iron triggers phytoplankton blooms that suck more CO_2 from the air. That should also drive more carbon into the refractory pool, Koblizek says.

Even tweaking the MCP could have a profound effect. The water column holds on average 35 to 40 micromoles of carbon from refractory DOC per liter. An increase of a mere 2 to 3 micromoles per liter would sock away several billion tons of carbon, says Nagappa Ramaiah, a marine microbial ecologist at the National Institute of Oceanography in Goa, India. "We have to investigate any and all means to help sink the excess carbon," he says.

Two billion years ago, when bacteria ruled Earth, the oceans held 500 times as much DOC as today, most likely generated by the MCP, Jiao says. Ecosystem dynamics have changed immensely since then, but the microbial sequestration potential could still be huge, he argues. No chemical equilibrium would limit conversion of bioavailable DOC to refractory DOC, which in turn would not exacerbate ocean acidification, says Jiao, who is planning pilot experiments this summer. Ramaiah, meanwhile, says he is looking for enhanced sequestration potential in select marine bacteria strains.

There's no simple recipe—and some scientists are not convinced that it's feasible or even safe. "I do not think it is possible to enhance carbon sequestration by the MCP. We have no handle on any controls" of how refractory DOC is generated, says Simon. With the present knowledge, any sequestration effort, argues Weinbauer, "could come back like a boomerang and worsen the problem." At the same time, humans may already be "inadvertently stimulating the MCP," says Salgado. Global warming is increasing stratification, reducing deep convection, and stimulating microbial respiration—all of which favor the MCP, he says.

The MCP concept should help address critical issues, such as whether ocean acidification and warming will significantly alter carbon flux into refractory DOC, says Azam, who with Jiao chairs the Scientific Committee on Oceanic Research's new working group on the role of MCP in carbon biogeochemistry. The upcoming research cruises should fill in more details of how the MCP governs carbon cycling and how it may respond to climate change. As Wilhelm notes, "We are just at the dawn of developing this understanding."

–RICHARD STONE

Double-barrel pump. Each year, the biological pump deposits some 300 million tons of carbon in the deep ocean sink. Even more massive amounts are suspended in the water columns as dissolved organic carbon, much of which is converted into refractory forms by the microbial carbon pump.

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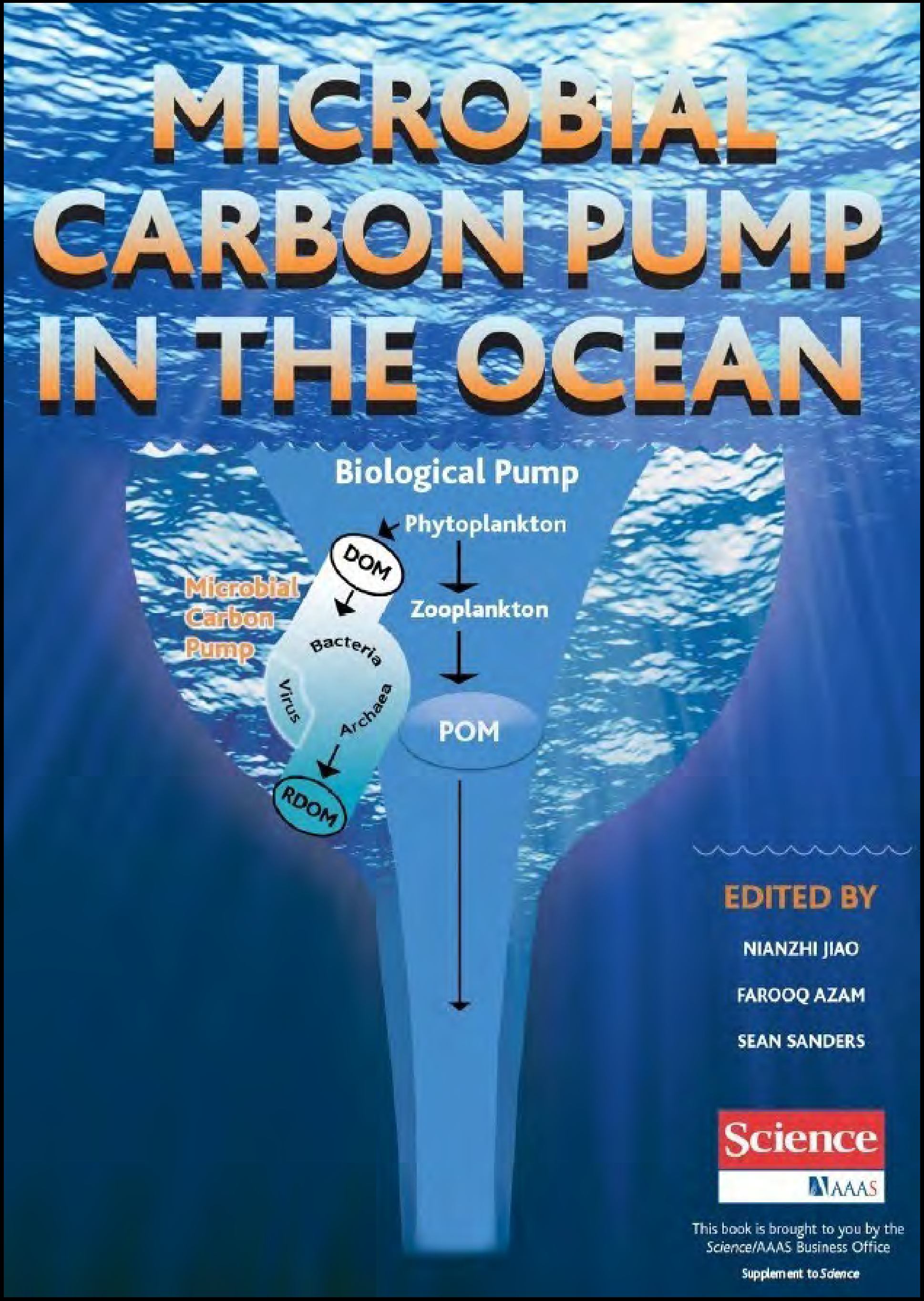

Supplement to *Science*,
May 13,2011.

Editors: Nianzhi Jiao,
Farooq Azam,
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Correspondences

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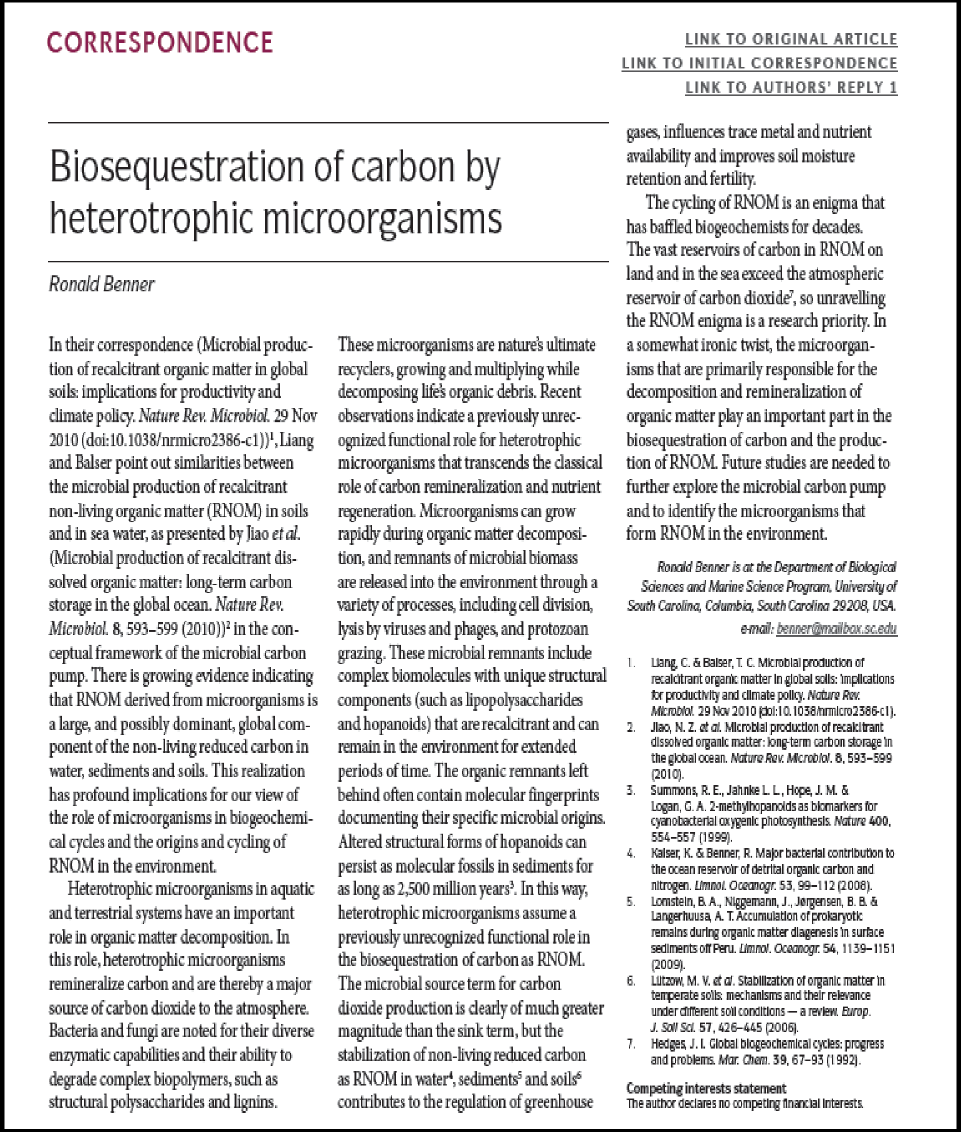
MCP

is applicable to terrestrial environments



CORRESPONDENCE

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LINK TO AUTHORS' REPLY 1

Biosequestration of carbon by heterotrophic microorganisms

Ronald Benner

In their correspondence (Microbial production of recalcitrant organic matter in global soils: implications for productivity and climate policy. *Nature Rev. Microbiol.* 29 Nov 2010 (doi:10.1038/nrmicro2386-c1))[1], Liang and Balser point out similarities between the microbial production of recalcitrant non-living organic matter (RNOM) in soils and in sea water, as presented by Jiao *et al.* (Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Rev. Microbiol.* 8, 593–599 (2010))[2] in the conceptual framework of the microbial carbon pump. There is growing evidence indicating that RNOM derived from microorganisms is a large, and possibly dominant, global component of the non-living reduced carbon in water, sediments and soils. This realization has profound implications for our view of the role of microorganisms in biogeochemical cycles and the origins and cycling of RNOM in the environment.

Heterotrophic microorganisms in aquatic and terrestrial systems have an important role in organic matter decomposition. In this role, heterotrophic microorganisms remineralize carbon and are thereby a major source of carbon dioxide to the atmosphere. Bacteria and fungi are noted for their diverse enzymatic capabilities and their ability to degrade complex biopolymers, such as structural polysaccharides and lignins. These microorganisms are nature's ultimate recyclers, growing and multiplying while decomposing life's organic debris. Recent observations indicate a previously unrecognized functional role for heterotrophic microorganisms that transcends the classical role of carbon remineralization and nutrient regeneration. Microorganisms can grow rapidly during organic matter decomposition, and remnants of microbial biomass are released into the environment through a variety of processes, including cell division, lysis by viruses and phages, and protozoan grazing. These microbial remnants include complex biomolecules with unique structural components (such as lipopolysaccharides and hopanoids) that are recalcitrant and can remain in the environment for extended periods of time. The organic remnants left behind often contain molecular fingerprints documenting their specific microbial origins. Altered structural forms of hopanoids can persist as molecular fossils in sediments for as long as 2,500 million years[3]. In this way, heterotrophic microorganisms assume a previously unrecognized functional role in the biosequestration of carbon as RNOM. The microbial source term for carbon dioxide production is clearly of much greater magnitude than the sink term, but the stabilization of non-living reduced carbon as RNOM in water[4], sediments[5] and soils[6] contributes to the regulation of greenhouse gases, influences trace metal and nutrient availability and improves soil moisture retention and fertility.

The cycling of RNOM is an enigma that has baffled biogeochemists for decades. The vast reservoirs of carbon in RNOM on land and in the sea exceed the atmospheric reservoir of carbon dioxide[7], so unravelling the RNOM enigma is a research priority. In a somewhat ironic twist, the microorganisms that are primarily responsible for the decomposition and remineralization of organic matter play an important part in the biosequestration of carbon and the production of RNOM. Future studies are needed to further explore the microbial carbon pump and to identify the microorganisms that form RNOM in the environment.

Ronald Benner is at the Department of Biological Sciences and Marine Science Program, University of South Carolina, Columbia, South Carolina 29208, USA.
e-mail: benner@mailbox.sc.edu

1. Liang, C. & Balser, T. C. Microbial production of recalcitrant organic matter in global soils: implications for productivity and climate policy. *Nature Rev. Microbiol.* 29 Nov 2010 (doi:10.1038/nrmicro2386-c1).
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6. Lützow, M. V. *et al.* Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions — a review. *Europ. J. Soil Sci.* 57, 426–445 (2006).
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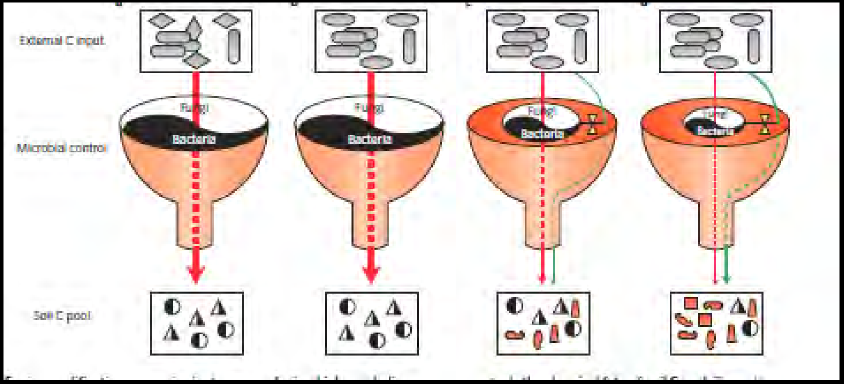
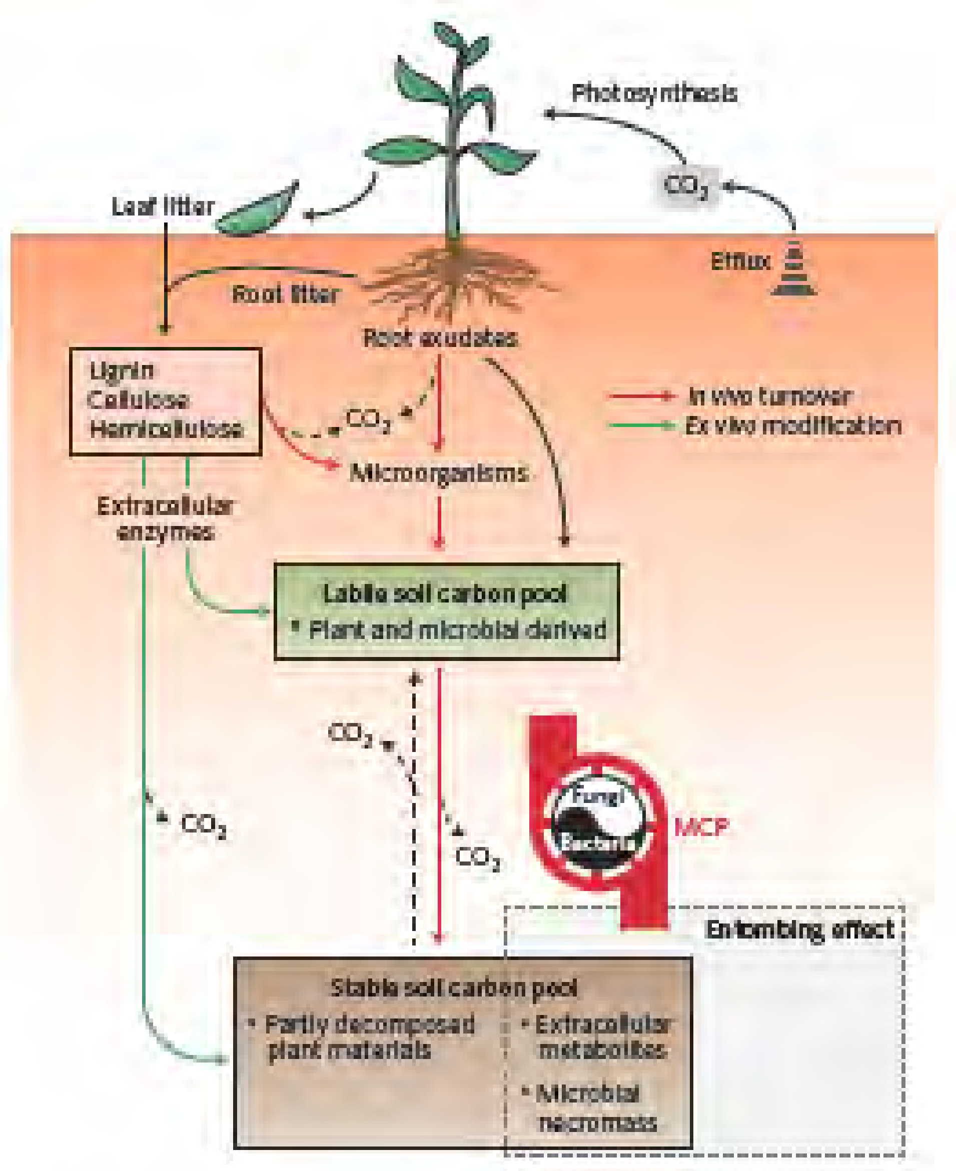
Competing interests statement
The author declares no competing financial interests.

nature microbiology

Chao Liang[1*], Joshua P. Schimel[2] and Julie D. Jastrow[3]

MCP in Soil





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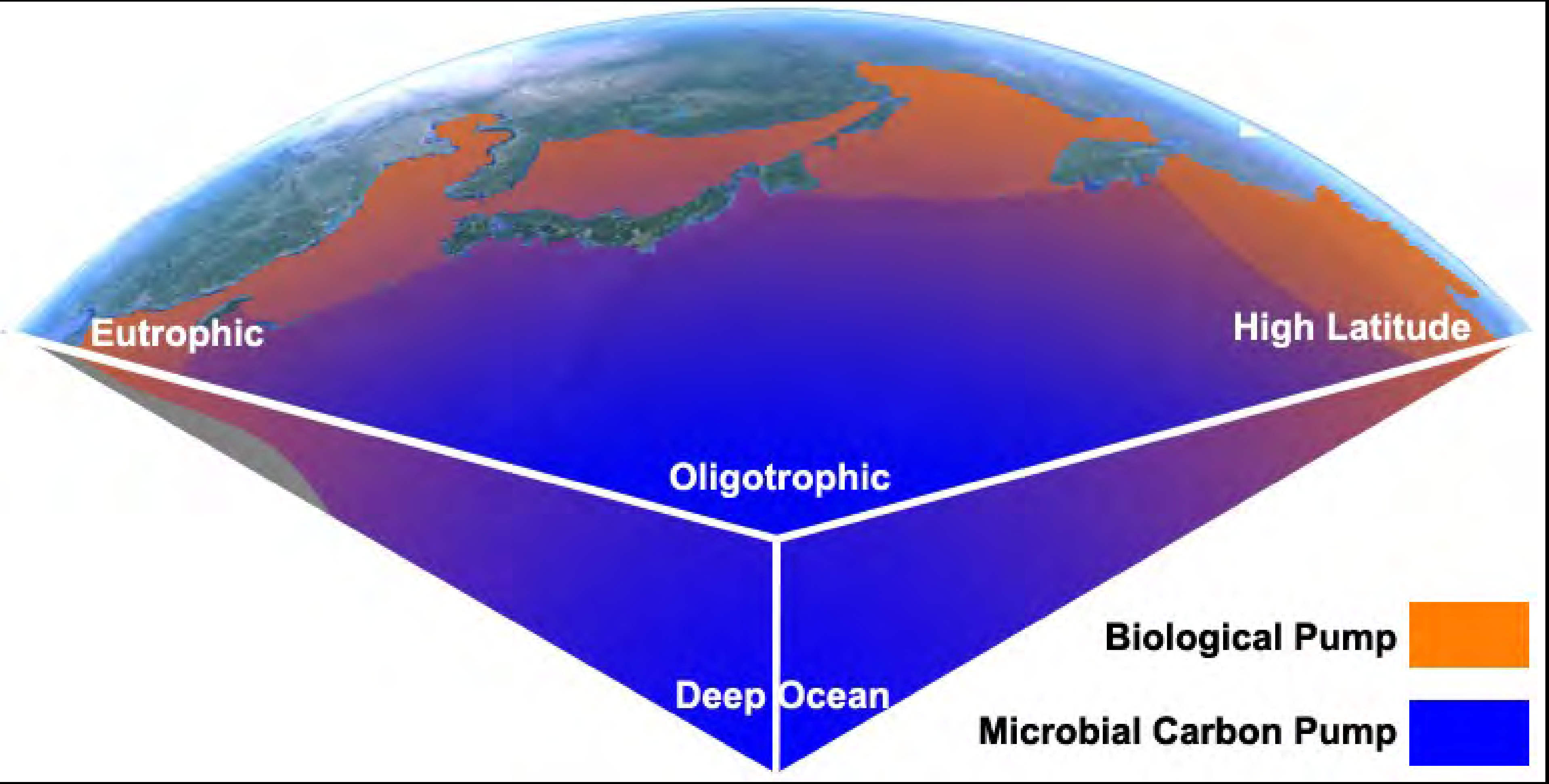
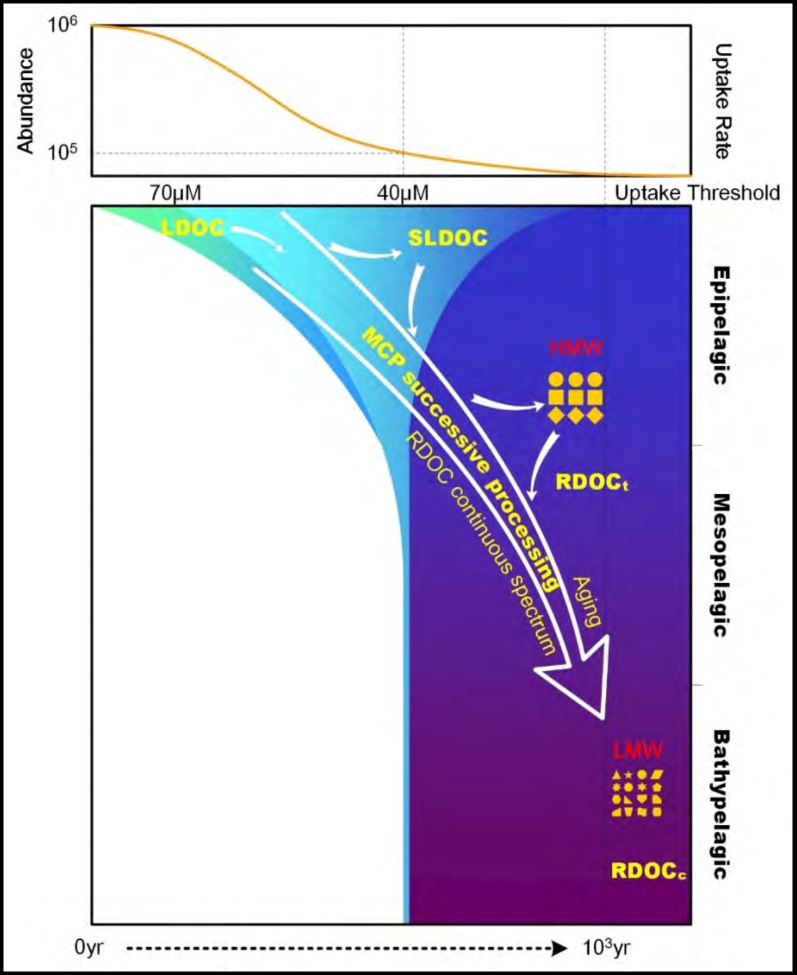
Trends in relative dominance of the BP and the MCP along environmental gradients



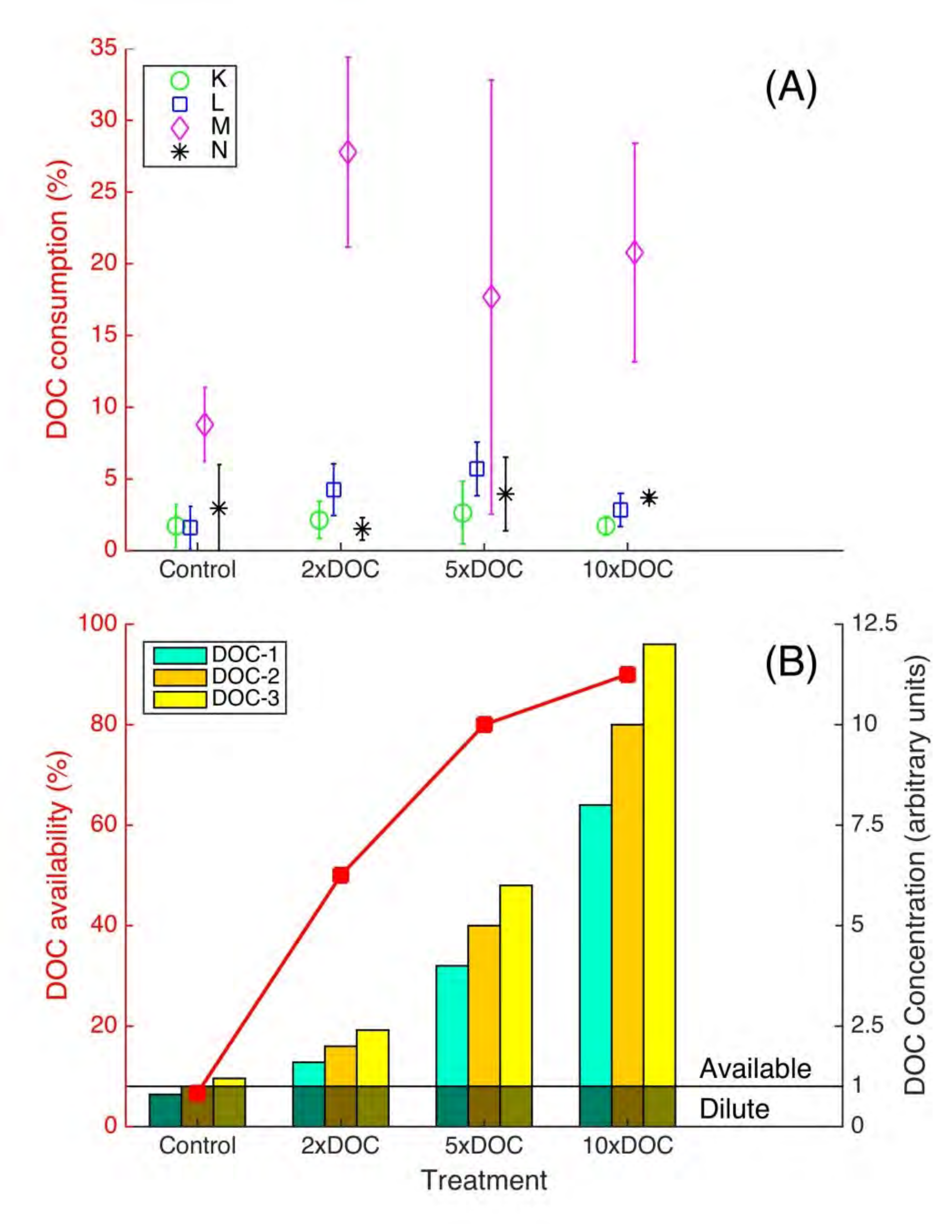
RDOCt vs RDOCc

Why deep ocean DOC can hold in the presence of hungry microbes ?

- **RDOCt** _Rcalcitrance of the RDOC under certain environmental conditions
- **RDOCc** _RDOC compounds are very diverse. There are thousands of different molecules generated from the successive microbial processing of organic matter. Each individual molecule could be at extremely low concentration which is below the microbial uptake threshold..
-



Jiao et al., 2014 Biogeoscience



Jiao *et al.*, *Science* 2015,

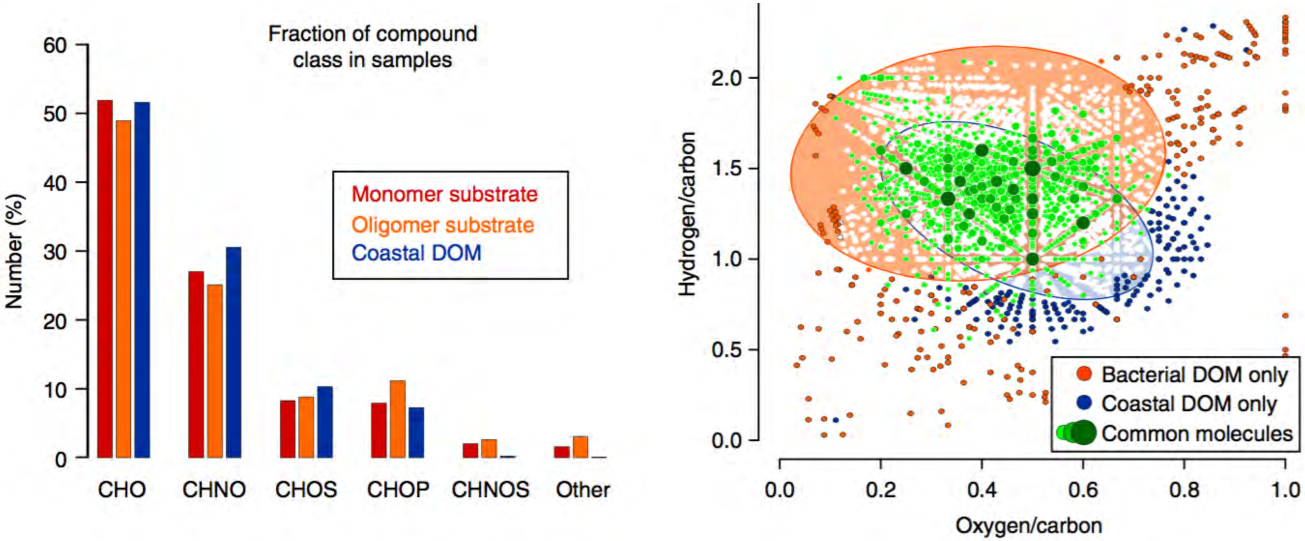
Science

RDOC t rather than RDOCc
is the majority of
deep-sea RDOC pool

Nauture Communication

Lechtenfeld et al., 2015)

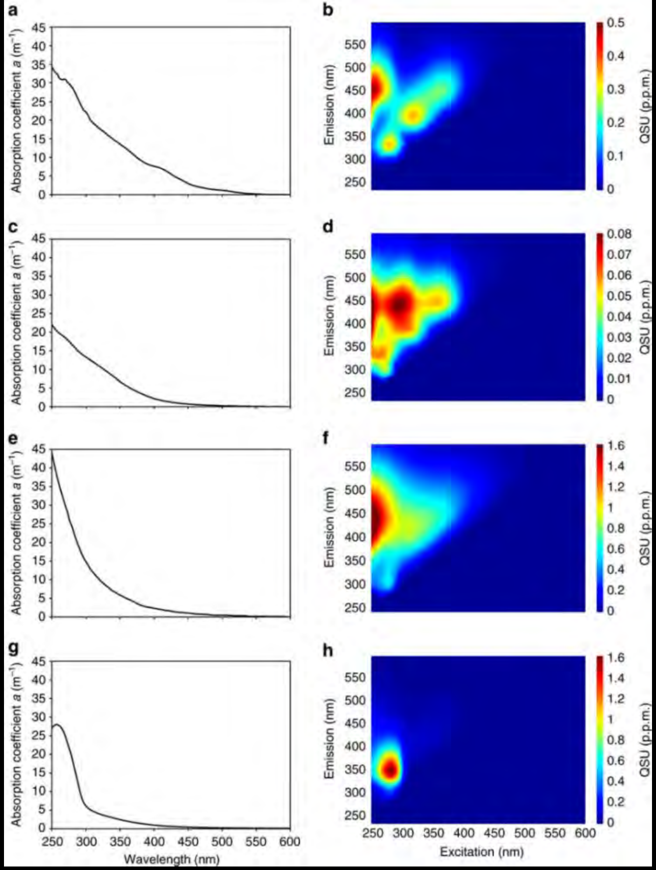
Marine sequestration of carbon in bacterial metabolites



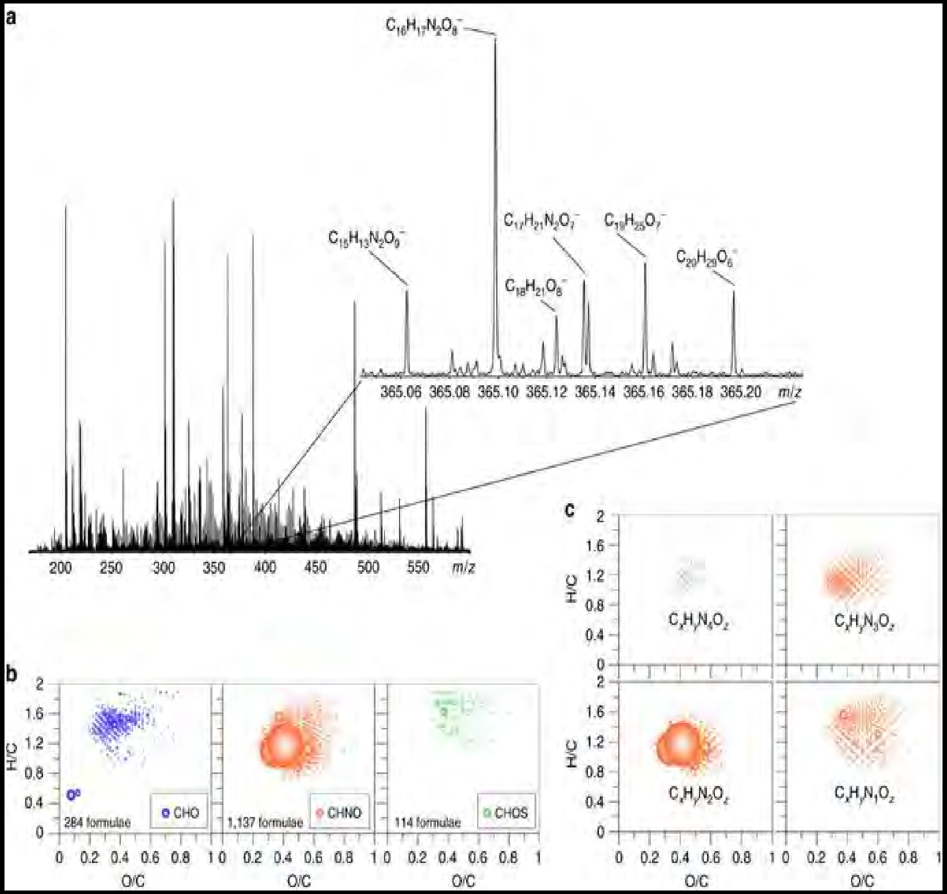
- An appreciable fraction of bacterial DOM has molecular and structural properties that are consistent with those of refractory molecules in the ocean, indicating a dominant role for bacteria in shaping the refractory nature of marine DOM. The rapid production of chemically complex and persistent molecules from simple biochemicals demonstrates a positive feedback between primary production and refractory DOM formation. It appears that carbon sequestration in diverse and structurally complex dissolved molecules that persist in the environment is largely driven by bacteria.

Nauture Communication

Zhao et al., 2017



Ultraviolet–Vis absorption and EEM fluorescence spectra of (a,b) Synechococcus-derived SPE-DOM, (c,d) Prochlorococcus-derived SPE-DOM, (e,f) SPE-DOM collected from the Sargasso Sea (BATS at 4,530 m depth) in August 2013 and (g,h) heterotrophic bacterium R. pomeroyi-derived SPE-DOM. Note: cell density was different in each culture and preclude a direct comparison of fluorescence intensity, and hence the given ultraviolet–Vis and EEM data are only intended to compare peak shapes



(a) Fourier transform ion cyclotron resonance mass spectrum of Synechococcus SPE-DOM, (b) van Krevelen diagram of all assigned molecular formulas of Synechococcus (CB0101) SPE-DOM and (c) van Krevelen diagrams of the distribution of CHNO formulas. Note: size of bubbles

Gordon Research Conferences

First meeting of "Ocean Biogeochemistry" on Biological driven carbon pumps

HK, China

2016.6.12-17

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2) Impacts of MCP on climate change
3) Current status of the MCP studies
4) Applications and future direction

MCP is applicable to different environments

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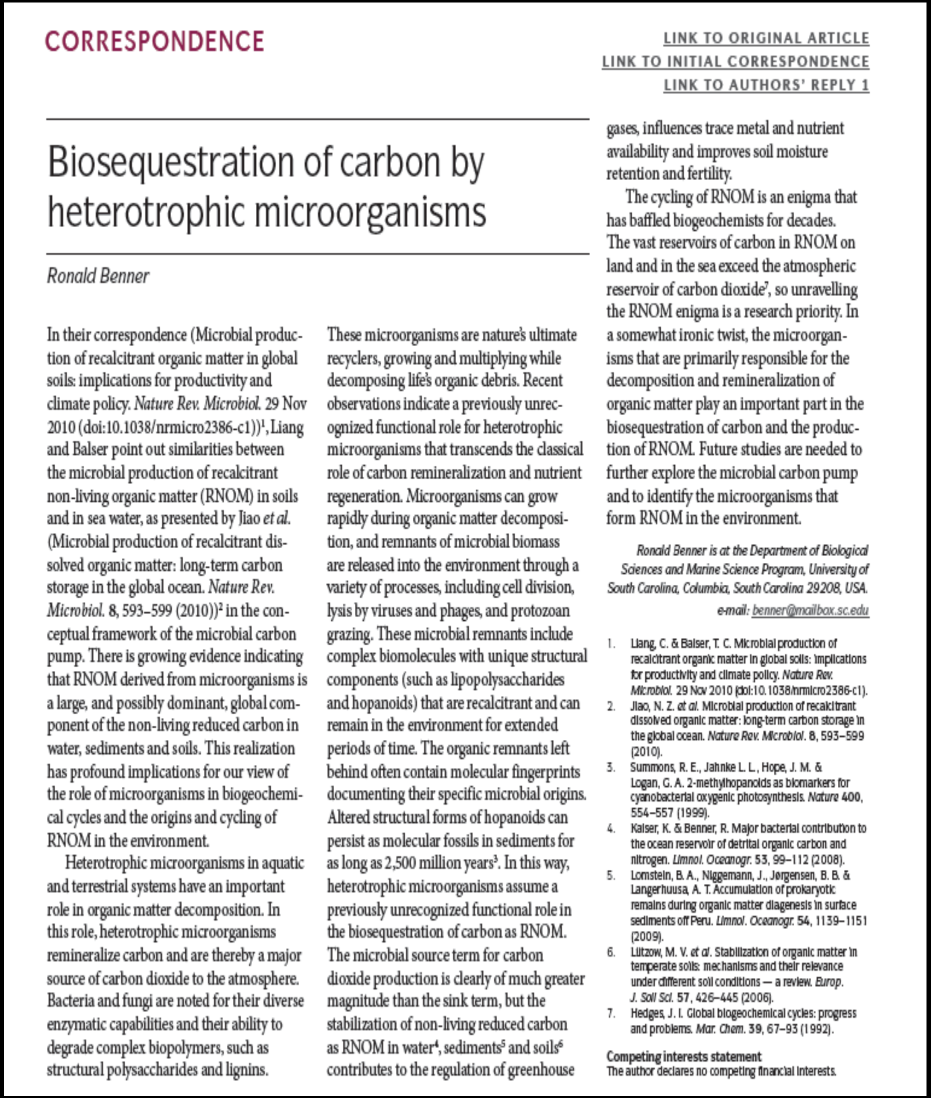
Implication for policy



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Heterotrophic microorganisms in aquatic and terrestrial systems have an important role in organic matter decomposition. In this role, heterotrophic microorganisms remineralize carbon and are thereby a major source of carbon dioxide to the atmosphere. Bacteria and fungi are noted for their diverse enzymatic capabilities and their ability to degrade complex biopolymers, such as structural polysaccharides and lignins. These microorganisms are nature's ultimate recyclers, growing and multiplying while decomposing life's organic debris. Recent observations indicate a previously unrecognized functional role for heterotrophic microorganisms that transcends the classical role of carbon remineralization and nutrient regeneration. Microorganisms can grow rapidly during organic matter decomposition, and remnants of microbial biomass are released into the environment through a variety of processes, including cell division, lysis by viruses and phages, and protozoan grazing. These microbial remnants include complex biomolecules with unique structural components (such as lipopolysaccharides and hopanoids) that are recalcitrant and can remain in the environment for extended periods of time. The organic remnants left behind often contain molecular fingerprints documenting their specific microbial origins. Altered structural forms of hopanoids can persist as molecular fossils in sediments for as long as 2,500 million years[3]. In this way, heterotrophic microorganisms assume a previously unrecognized functional role in the biosequestration of carbon as RNOM. The microbial source term for carbon dioxide production is clearly of much greater magnitude than the sink term, but the stabilization of non-living reduced carbon as RNOM in water[4], sediments[5] and soils[6] contributes to the regulation of greenhouse gases, influences trace metal and nutrient availability and improves soil moisture retention and fertility.

The cycling of RNOM is an enigma that has baffled biogeochemists for decades. The vast reservoirs of carbon in RNOM on land and in the sea exceed the atmospheric reservoir of carbon dioxide[7], so unravelling the RNOM enigma is a research priority. In a somewhat ironic twist, the microorganisms that are primarily responsible for the decomposition and remineralization of organic matter play an important part in the biosequestration of carbon and the production of RNOM. Future studies are needed to further explore the microbial carbon pump and to identify the microorganisms that form RNOM in the environment.

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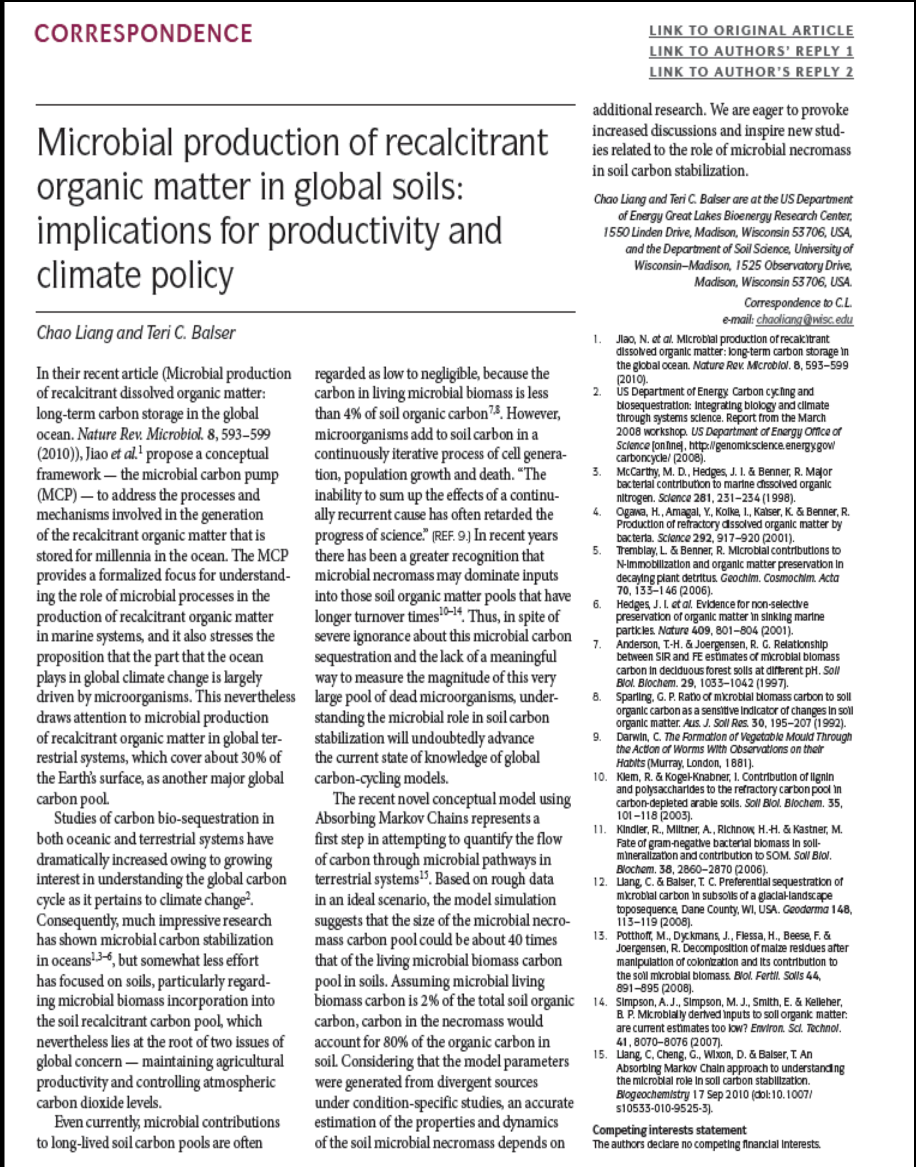
Competing interests statement
The author declares no competing financial interests.



CORRESPONDENCE

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LINK TO AUTHORS' REPLY 1
LINK TO AUTHOR'S REPLY 2

Microbial production of recalcitrant organic matter in global soils: implications for productivity and climate policy

Chao Liang and Teri C. Balser

In their recent article (Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Rev. Microbiol.* 8, 593–599 (2010)), Jiao *et al.*[1] propose a conceptual framework — the microbial carbon pump (MCP) — to address the processes and mechanisms involved in the generation of the recalcitrant organic matter that is stored for millennia in the ocean. The MCP provides a formalized focus for understanding the role of microbial processes in the production of recalcitrant organic matter in marine systems, and it also stresses the proposition that the part that the ocean plays in global climate change is largely driven by microorganisms. This nevertheless draws attention to microbial production of recalcitrant organic matter in global terrestrial systems, which cover about 30% of the Earth's surface, as another major global carbon pool.

Studies of carbon bio-sequestration in both oceanic and terrestrial systems have dramatically increased owing to growing interest in understanding the global carbon cycle as it pertains to climate change[2]. Consequently, much impressive research has shown microbial carbon stabilization in oceans[1,3–6], but somewhat less effort has focused on soils, particularly regarding microbial biomass incorporation into the soil recalcitrant carbon pool, which nevertheless lies at the root of two issues of global concern — maintaining agricultural productivity and controlling atmospheric carbon dioxide levels.

Even currently, microbial contributions to long-lived soil carbon pools are often regarded as low to negligible, because the carbon in living microbial biomass is less than 4% of soil organic carbon[7,8]. However, microorganisms add to soil carbon in a continuously iterative process of cell generation, population growth and death. "The inability to sum up the effects of a continually recurrent cause has often retarded the progress of science." (REF. 9.) In recent years there has been a greater recognition that microbial necromass may dominate inputs into those soil organic matter pools that have longer turnover times[10–14]. Thus, in spite of severe ignorance about this microbial carbon sequestration and the lack of a meaningful way to measure the magnitude of this very large pool of dead microorganisms, understanding the microbial role in soil carbon stabilization will undoubtedly advance the current state of knowledge of global carbon-cycling models.

The recent novel conceptual model using Absorbing Markov Chains represents a first step in attempting to quantify the flow of carbon through microbial pathways in terrestrial systems[15]. Based on rough data in an ideal scenario, the model simulation suggests that the size of the microbial necromass carbon pool could be about 40 times that of the living microbial biomass carbon pool in soils. Assuming microbial living biomass carbon is 2% of the total soil organic carbon, carbon in the necromass would account for 80% of the organic carbon in soil. Considering that the model parameters were generated from divergent sources under condition-specific studies, an accurate estimation of the properties and dynamics of the soil microbial necromass depends on

additional research. We are eager to provoke increased discussions and inspire new studies related to the role of microbial necromass in soil carbon stabilization.

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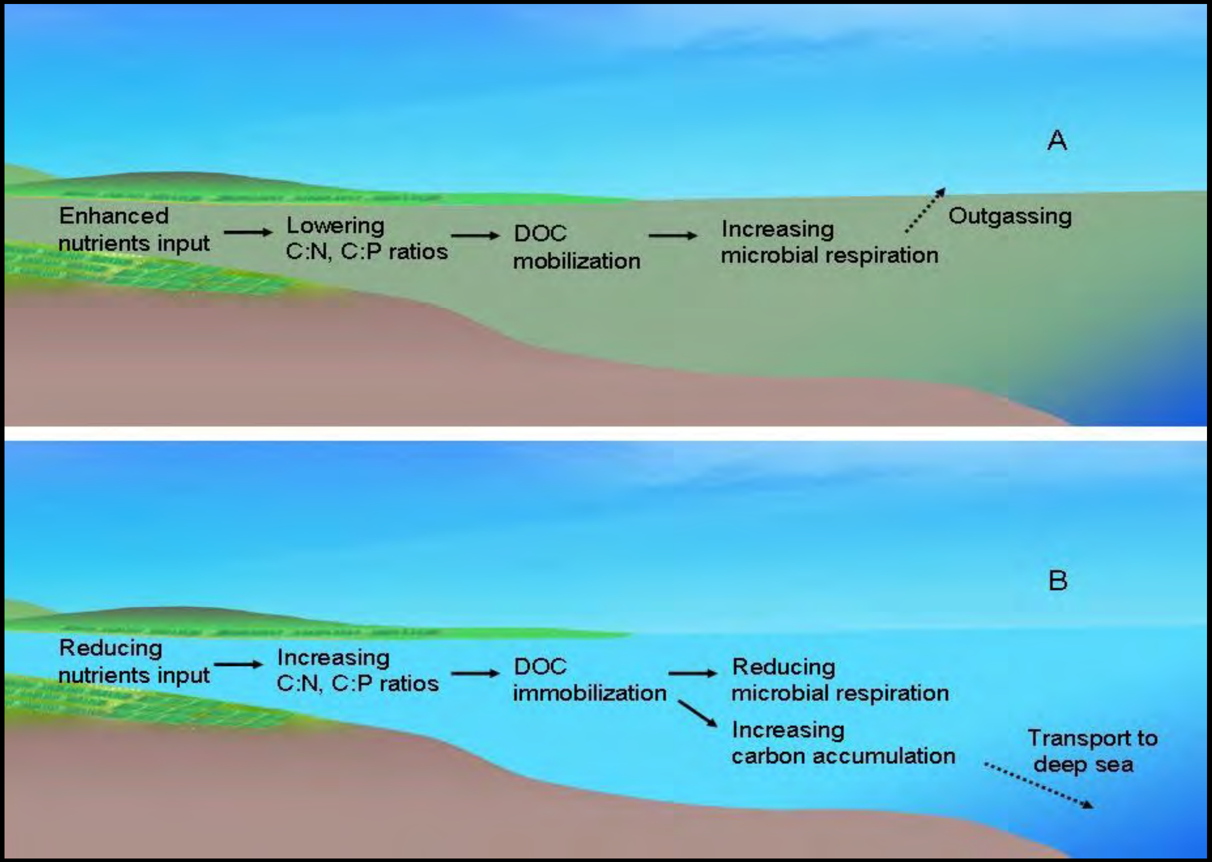
Competing interests statement
The authors declare no competing financial interests.

A proposal for practice:
Increase Carbon sequestration in the coastal water by reducing fertilization on the land

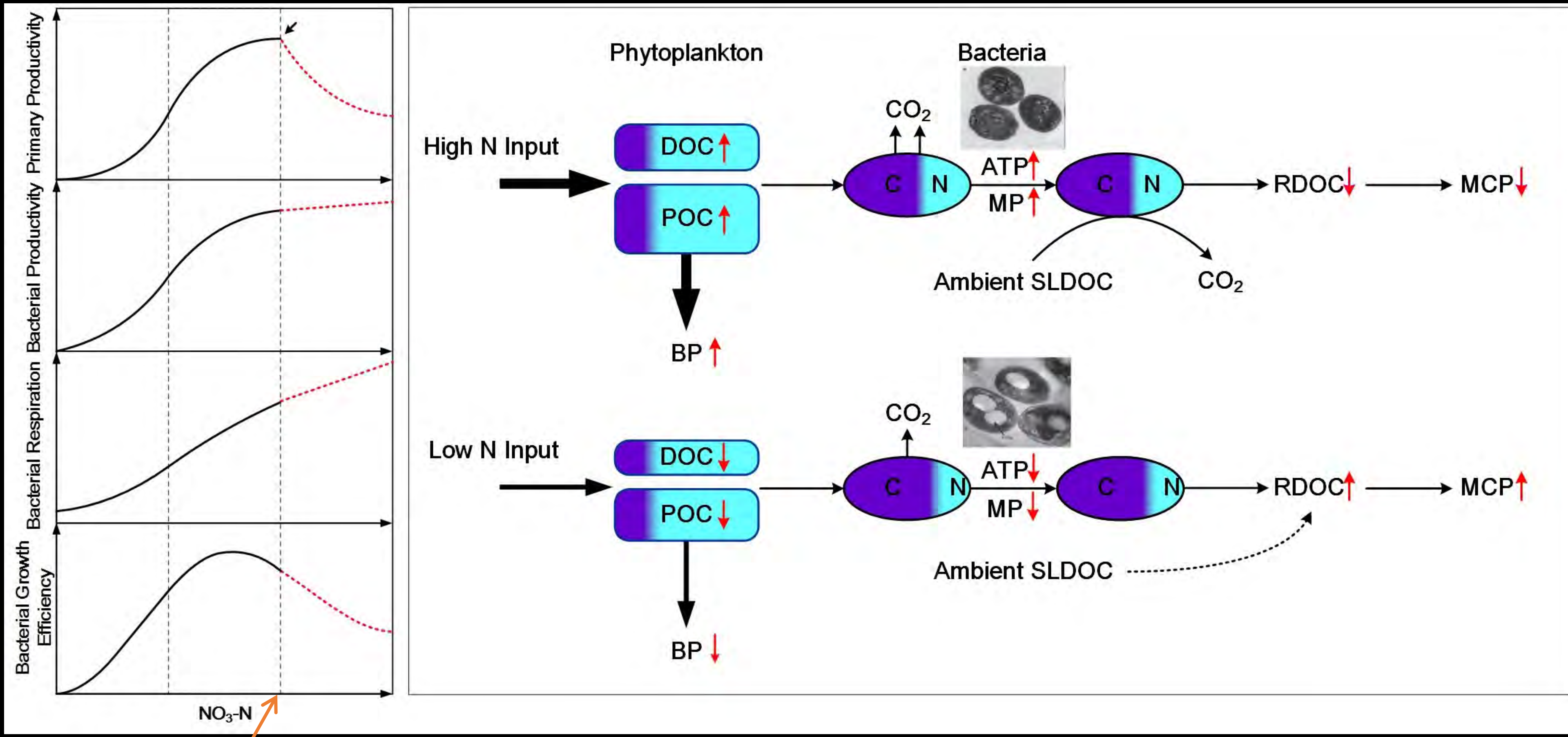


Jiao et al., 2010

nature REVIEWS MICROBIOLOGY

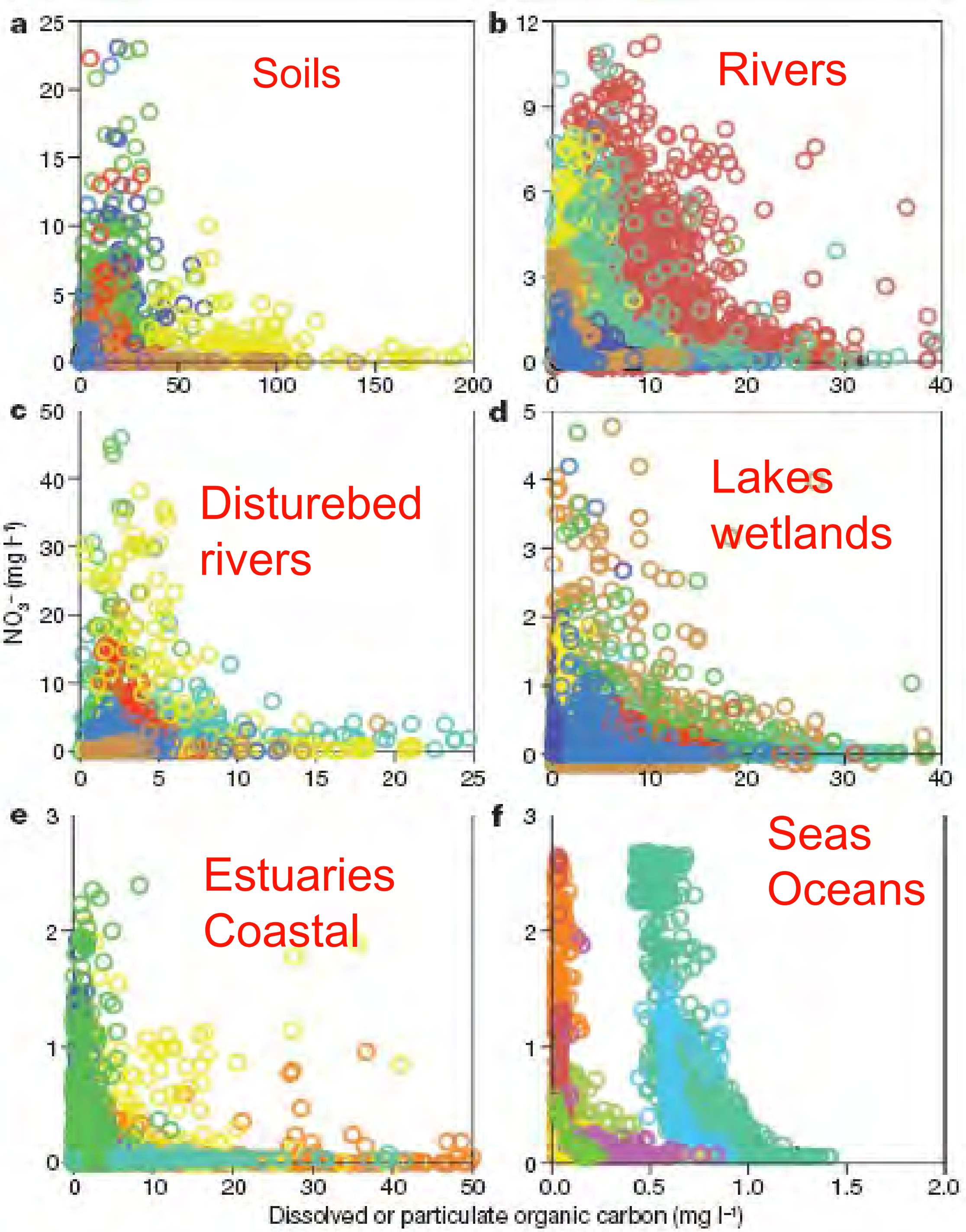
Nutrients can be a double edged sword

Maximum output of the sum of “BP+MCP” is the goal to achieve for carbon sequestration



tipping point

Jiao et al., 2014



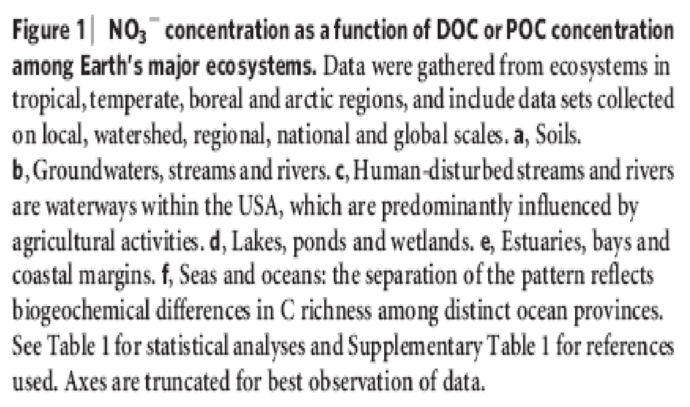


Figure 1 | NO$_3^-$ concentration as a function of DOC or POC concentration among Earth's major ecosystems. Data were gathered from ecosystems in tropical, temperate, boreal and arctic regions, and include data sets collected on local, watershed, regional, national and global scales. **a**, Soils. **b**, Groundwaters, streams and rivers. **c**, Human-disturbed streams and rivers are waterways within the USA, which are predominantly influenced by agricultural activities. **d**, Lakes, ponds and wetlands. **e**, Estuaries, bays and coastal margins. **f**, Seas and oceans: the separation of the pattern reflects biogeochemical differences in C richness among distinct ocean provinces. See Table 1 for statistical analyses and Supplementary Table 1 for references used. Axes are truncated for best observation of data.

- Taylor et al. *Nature*(2010)

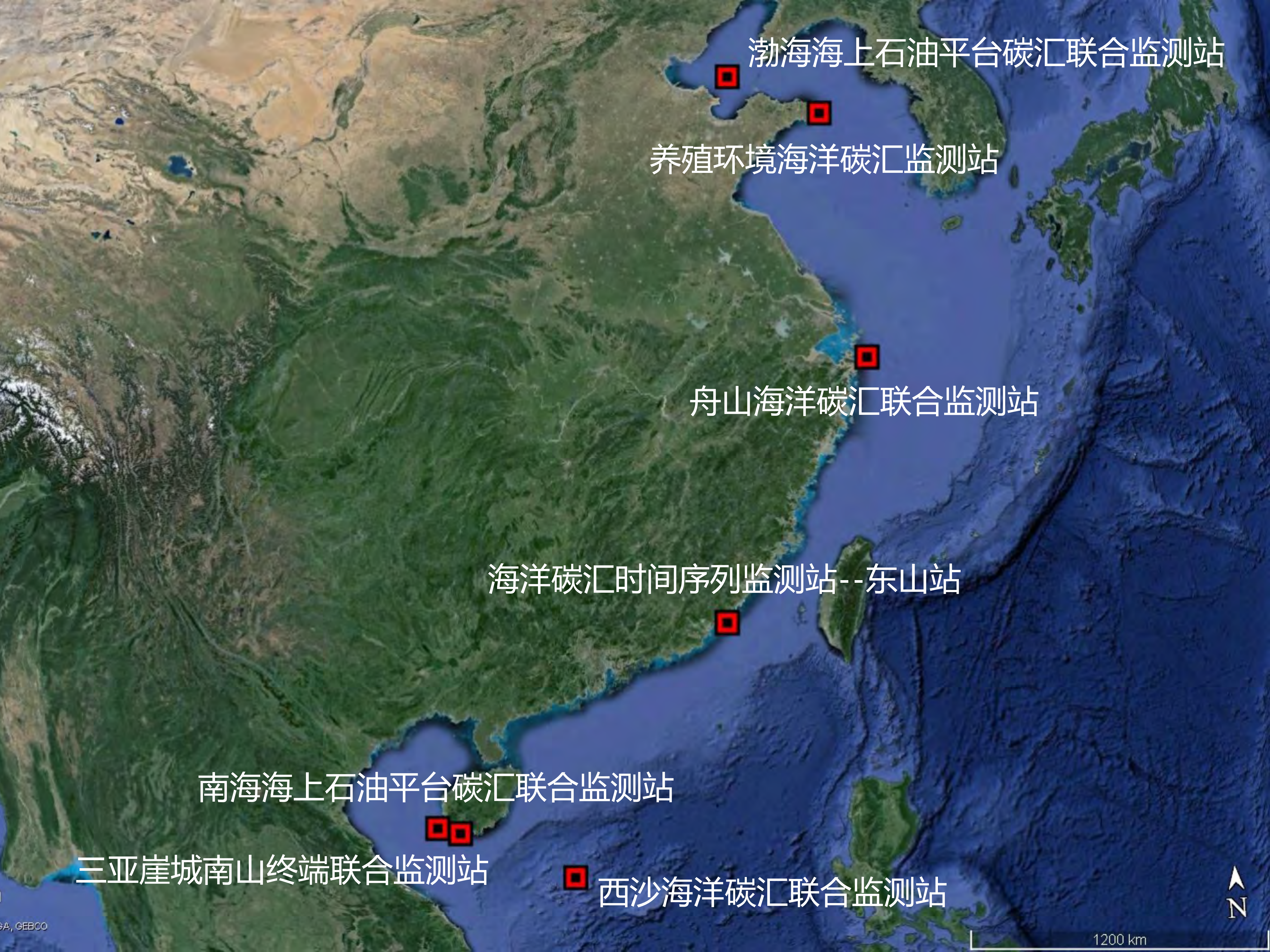
2013年 发起建立了全国海洋碳汇联盟
Pan China Ocean Carbon Alliance（COCA）

全国海洋碳汇联盟的徽标

徽标释义：COCA 是全国海洋碳汇联盟（Pan-China Ocean Carbon Alliance）的缩写。COCA 读音类似 Coke（可乐）。图案中央蓝色代表海洋，周边黑色半圆代表碳的元素符号 C，C 末端红色箭头指向海洋示意海洋储碳。【在远古碳通过海洋形成地下化石燃料，而今天人类活动将其释放到大气加剧了气候变化，人类应该把 C 再还给海洋】。

全国海洋碳汇联盟“产学研政用”各方代表揭牌仪式（2013 年 9 月 17 日，三亚）

全国30多个涉海单位的科技人员秉承“自发、自愿、贡献、分享”的原则共同组建的“全国海洋碳汇联盟（COCA）”于2013年9月17日在三亚揭牌成立。


渤海海上石油平台碳汇联合监测站
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舟山海洋碳汇联合监测站
海洋碳汇时间序列监测站--东山站
南海海上石油平台碳汇联合监测站
三亚崖城南山终端联合监测站
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1200 km
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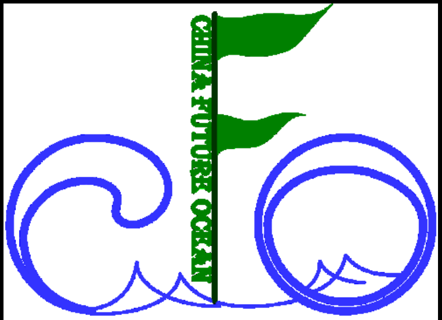
2014年　发起建立“China Future Alliance”



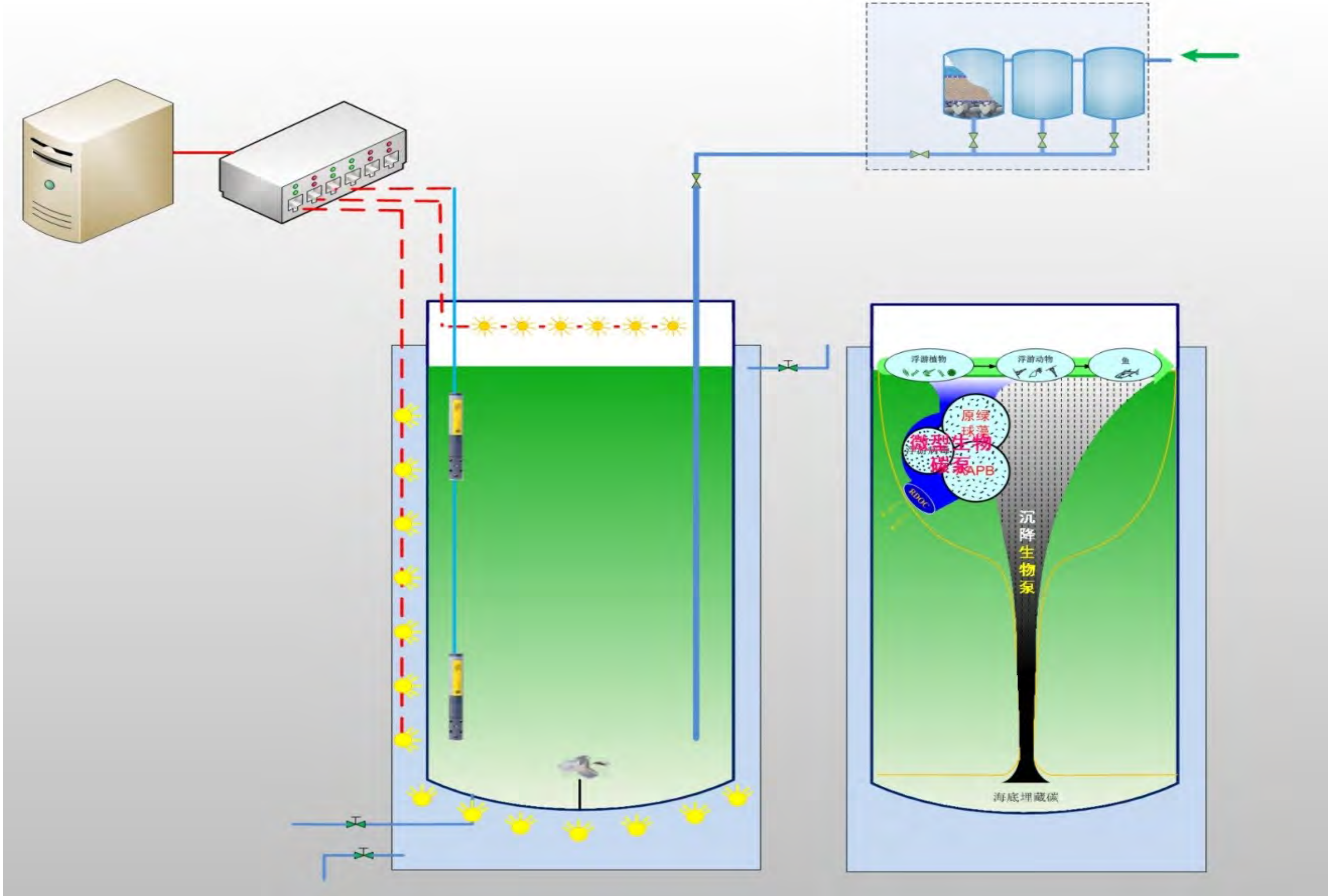
PICES --- FUTURE-China

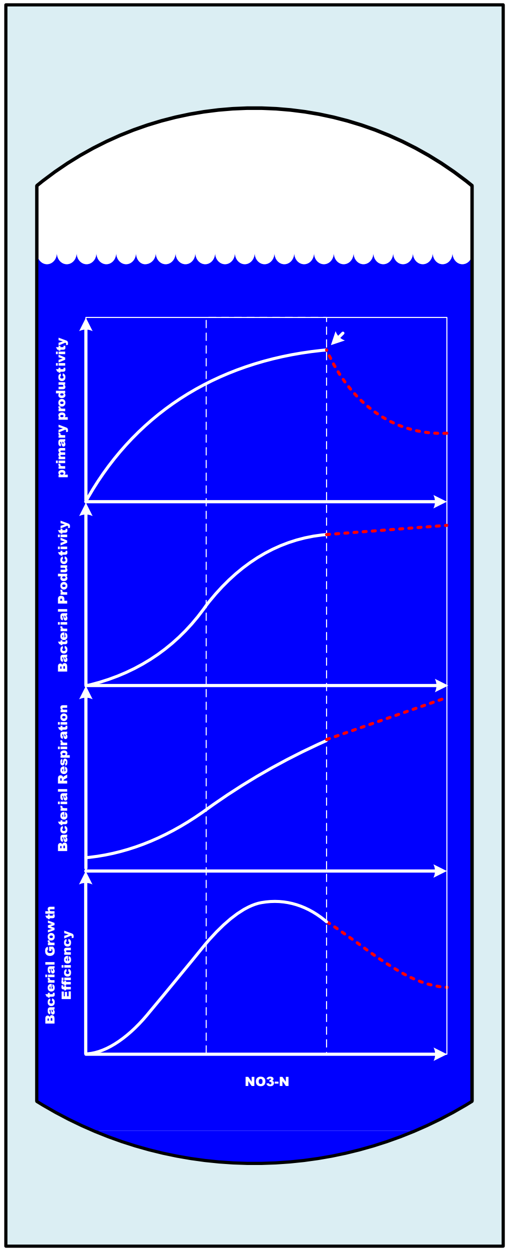
2015年10月

Marine Environmental Chamber System （ MECS ）

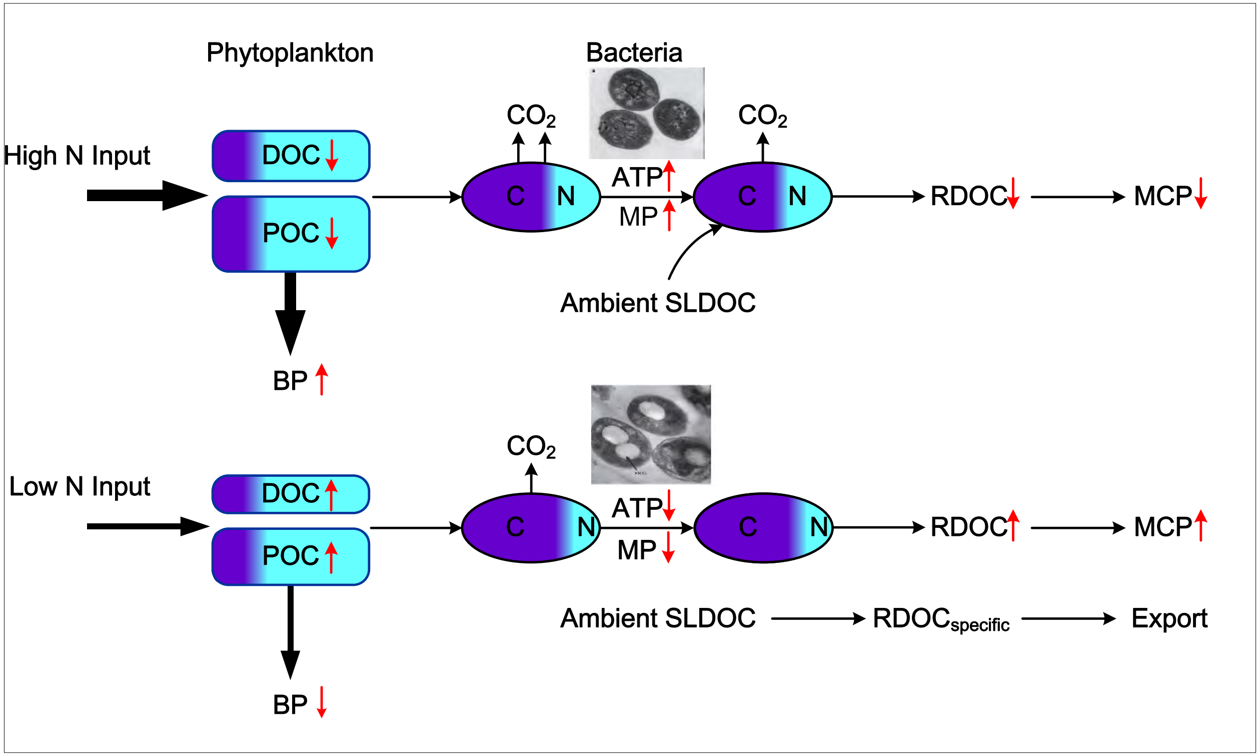
Mini MECS at Shandong University (Qingdao Campus)

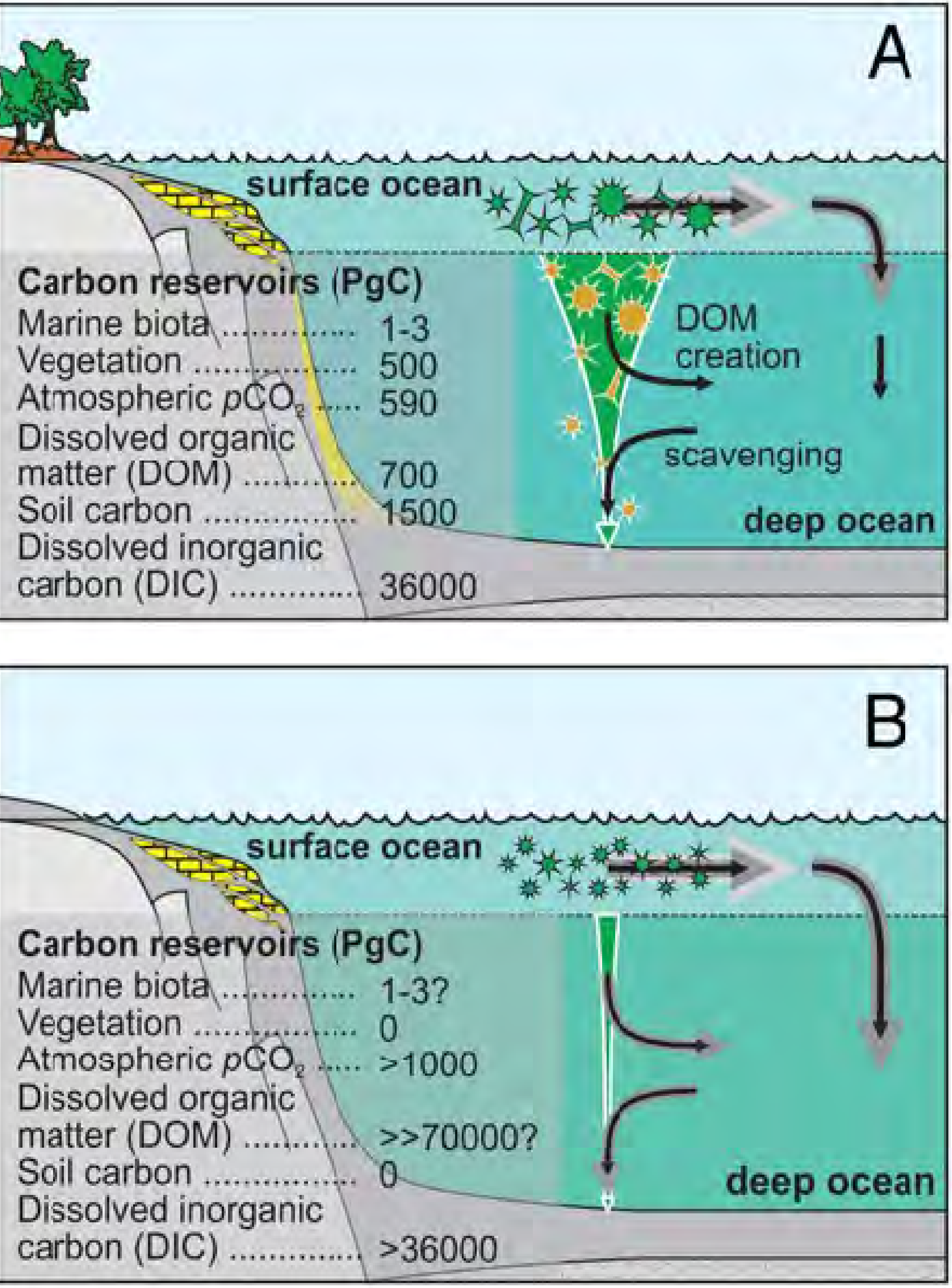
MECS for Ecosystem-level Scenario Studies Such as BP vs MCP at different conditions …





Seek optimum combined conditions for maximum output of the sum of "BP+MCP"





BP is very strong
in the current ocean
but was very weak
in the ancient ocean,

MCP was very strong
in ancient time resulting
in accumulation of DOM

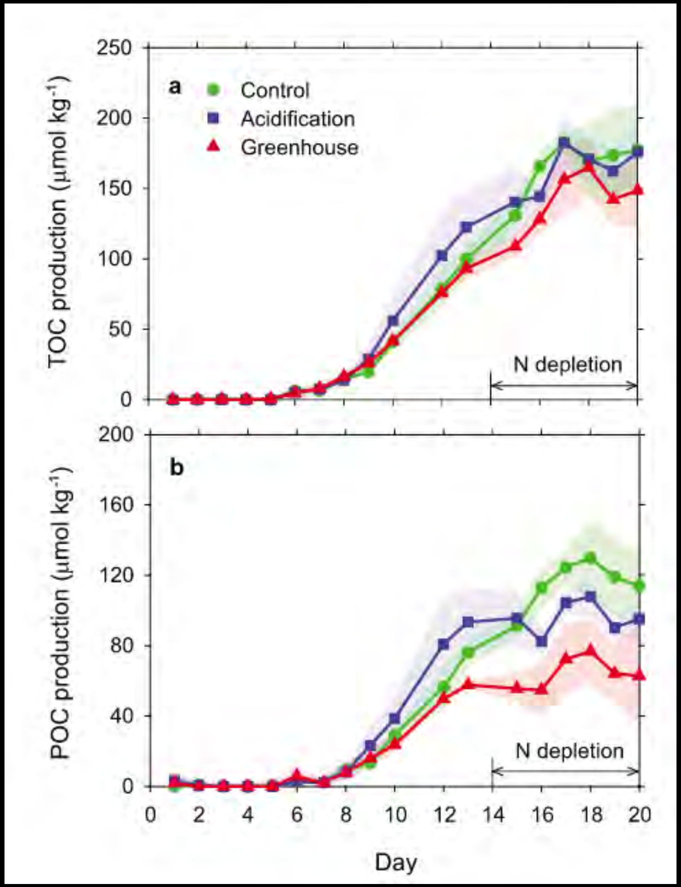
DOM reservoir is 100
times largen than the
current one

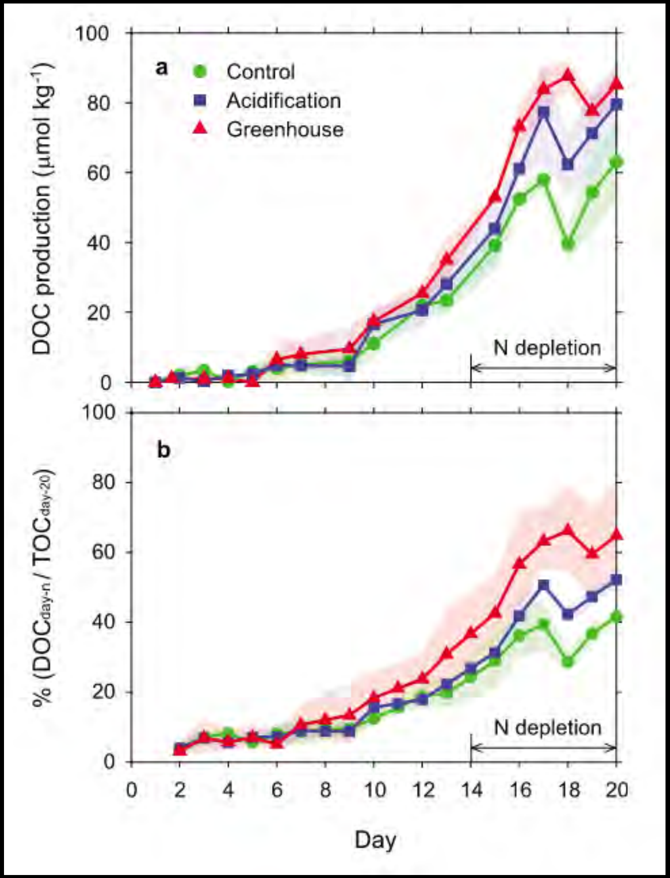
i.e.,
MCP plays a siginicant
role in climate change

（Ridgwell ，2011)

Shifts in biogenic carbon flow from particulate to dissolved forms under high carbon dioxide and warm ocean conditions

Kim et al., 2011, Geophysical Research Letters





BP

MCP

- Global cooling

global warming

Thanks for your attention !