Allometric scaling of community metabolism in estuaries and large oceanic provinces

Nick Nidzieko
UC Santa Barbara

Willie Haskell
MBARI

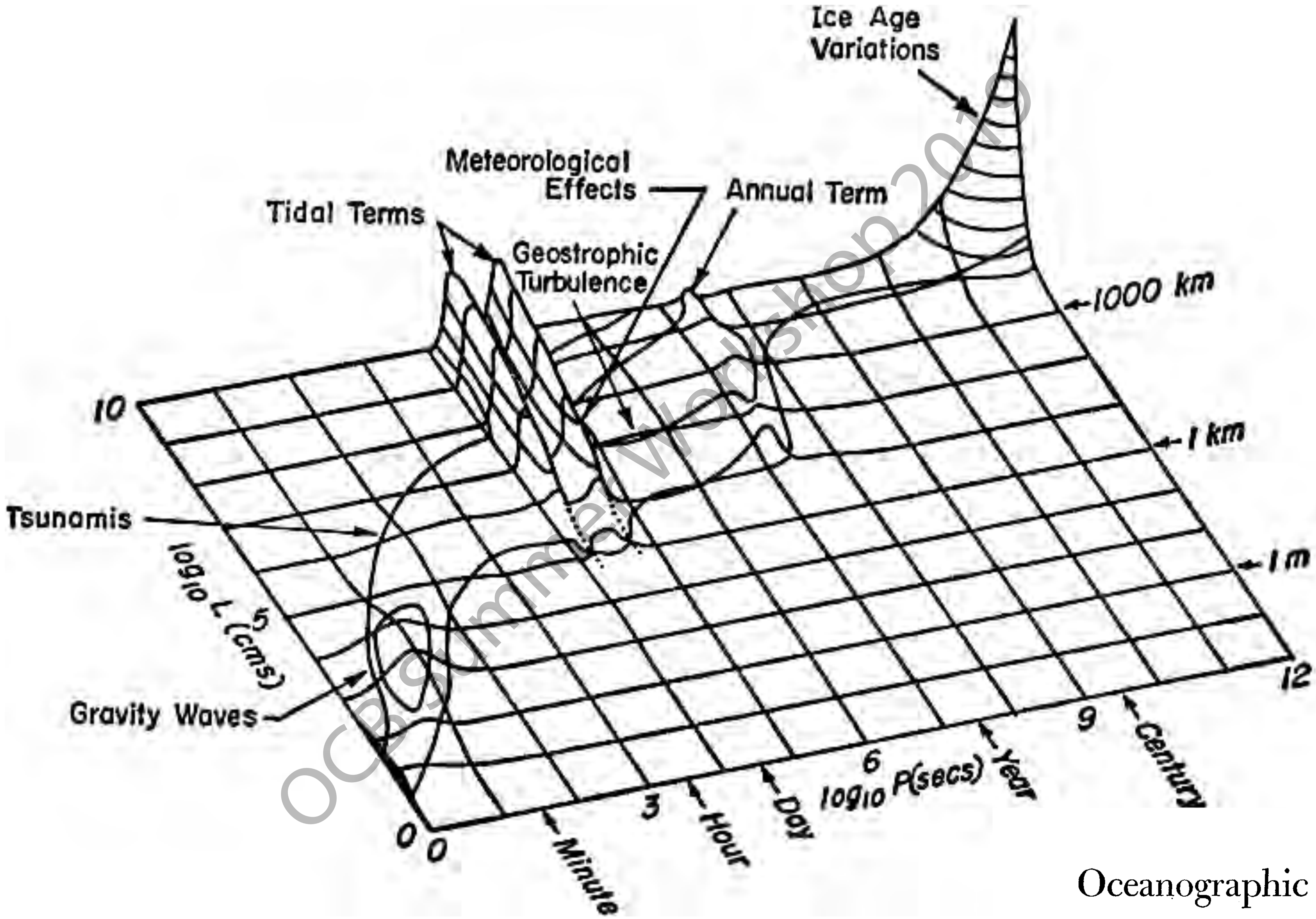
ucsbcoastlab.org

Each day as the sun rises and retires
the beautiful green bays like great creatures
breathe in and out.

Odum & Hoskins, 1958

OCB Summer Workshop June 27, 2019

As oceanographers, we are interested in processes that span many orders of magnitude in space and time



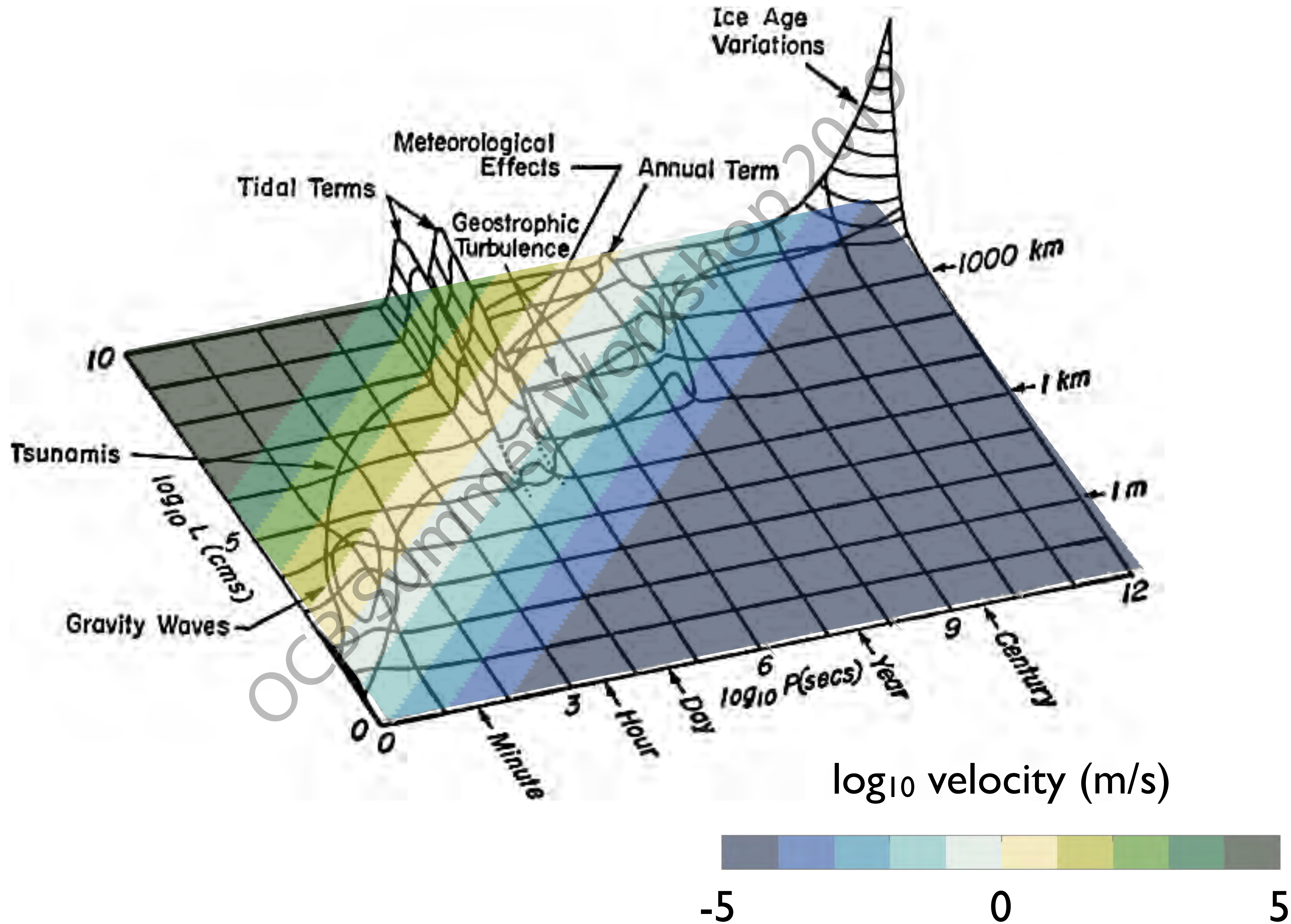
Varieties of Oceanographic Experience

The ocean can be investigated as a hydrodynamical phenomenon as well as explored geographically.

Henry Stommel

15 FEBRUARY 1963 SCIENCE, VOL. 139

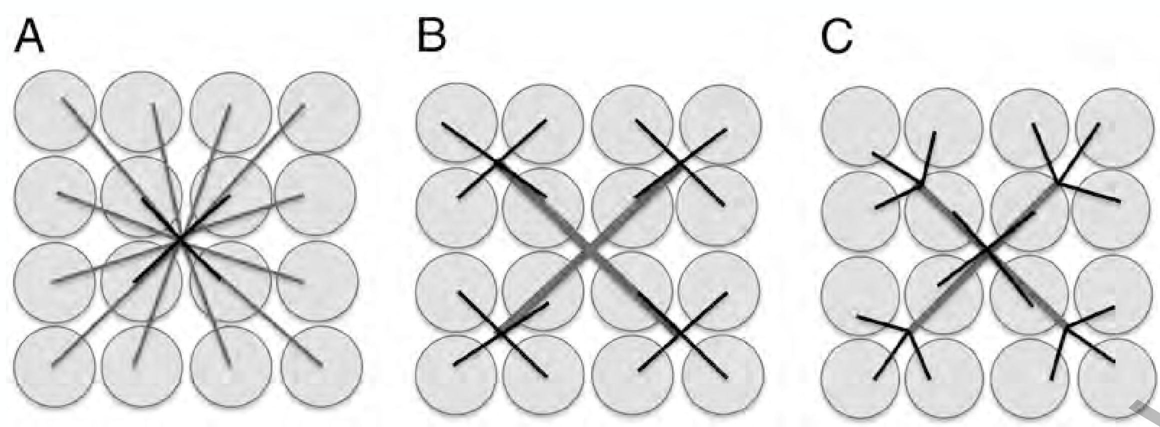
But velocities of interest only span a few orders of magnitude

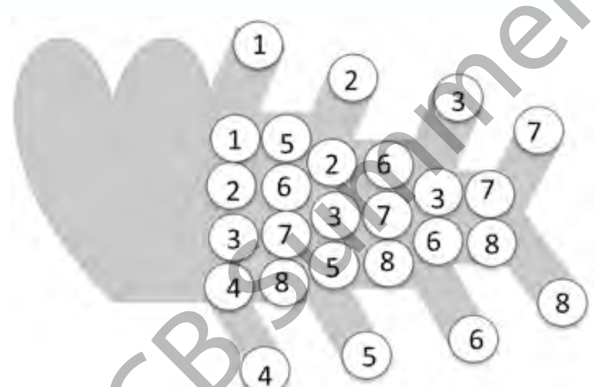


How velocity scales with size is a fundamental aspect of organismal biology

A general basis for quarter-power scaling in animals

Jayanth R. Banavar[a], Melanie E. Moses[b,c,1], James H. Brown[c,d,1], John Damuth[e], Andrea Rinaldo[f], Richard M. Sibly[g], and Amos Maritan[h]

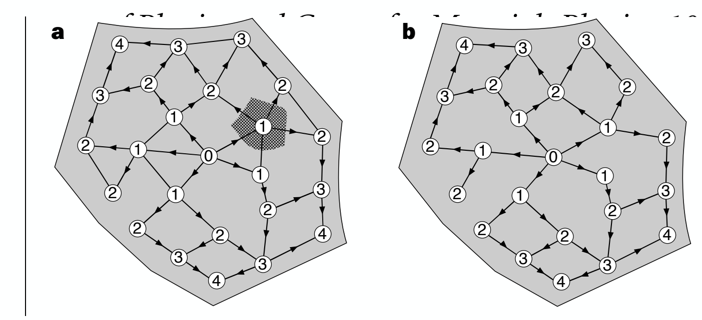




letters to nature

Size and form in efficient transportation networks

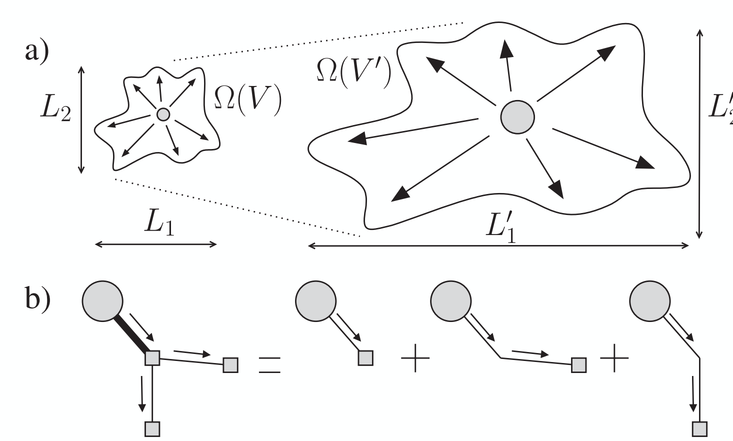
Jayanth R. Banavar*, Amos Maritan† & Andrea Rinaldo‡



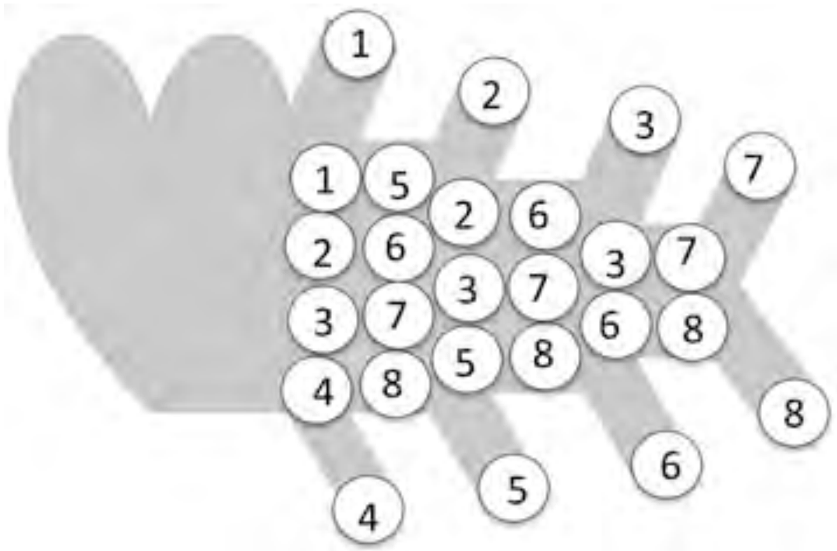
PRL 104, 048702 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

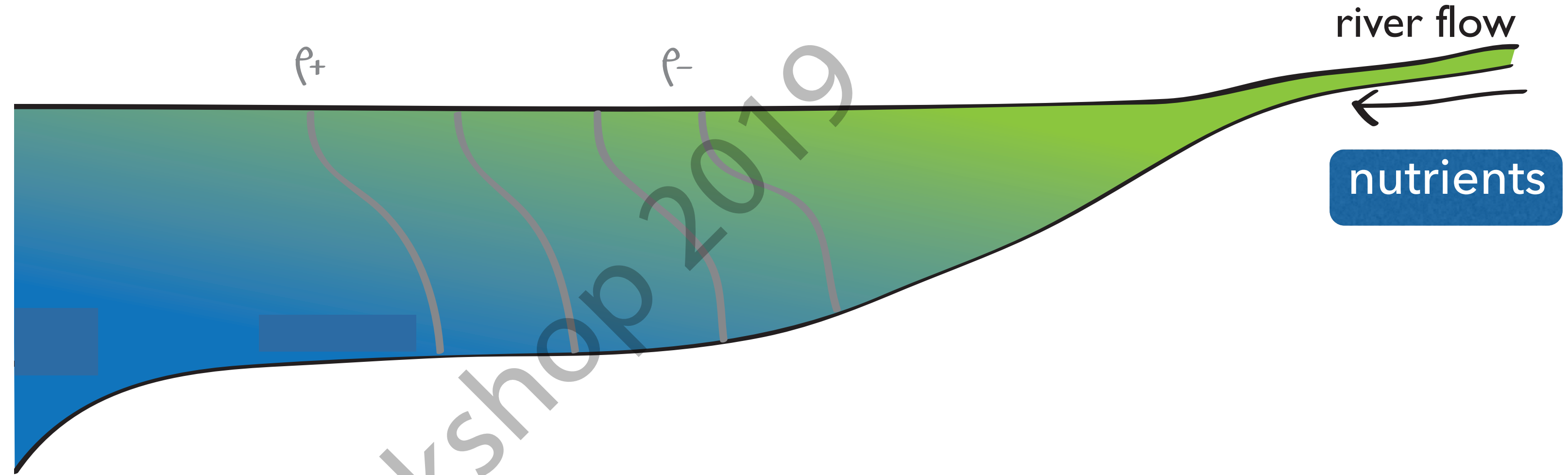
Optimal Form of Branching Supply and Collection Networks

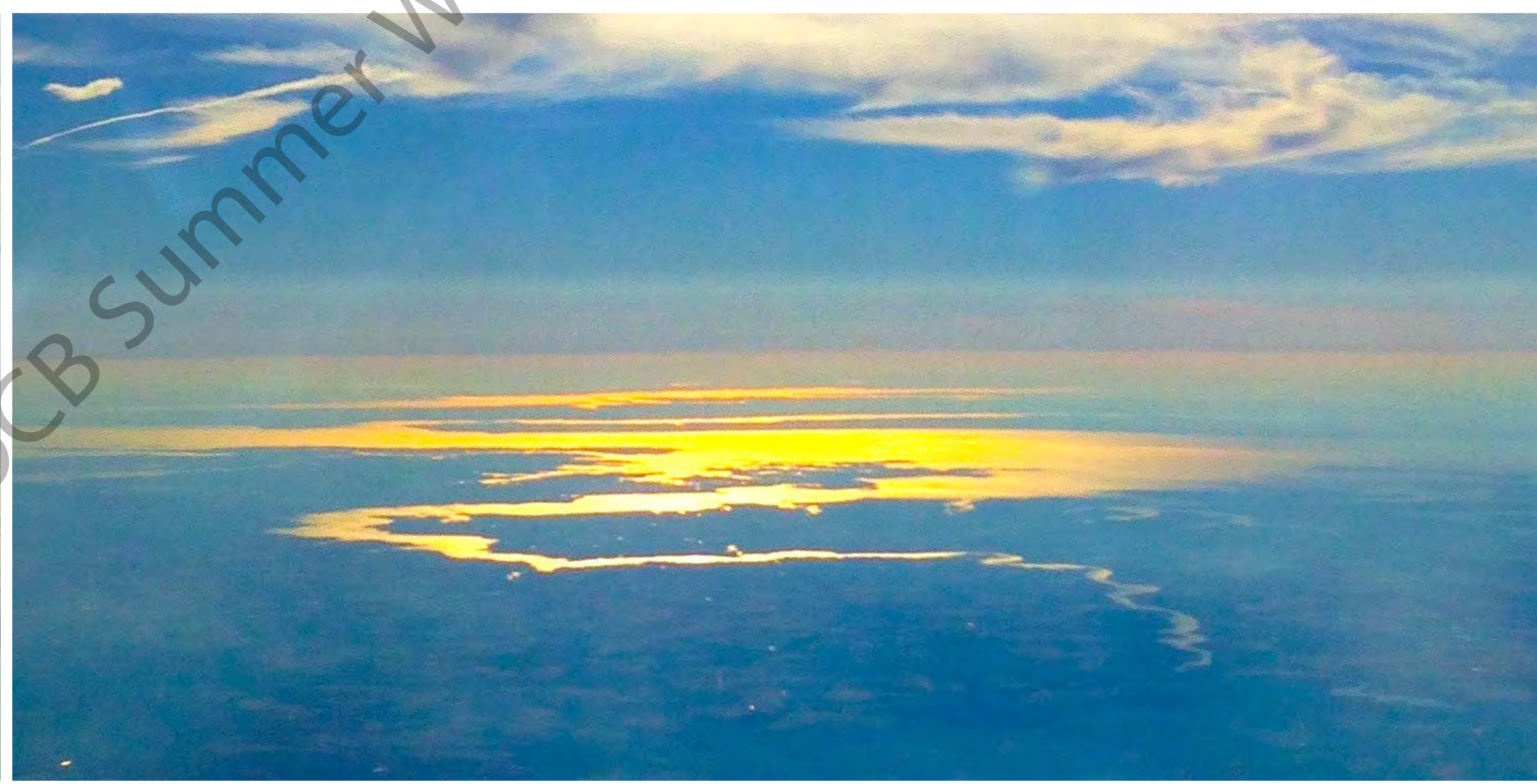
Peter Sheridan Dodds*



In this talk, we'll apply ideas from the metabolic theory of ecology to marine ecosystems





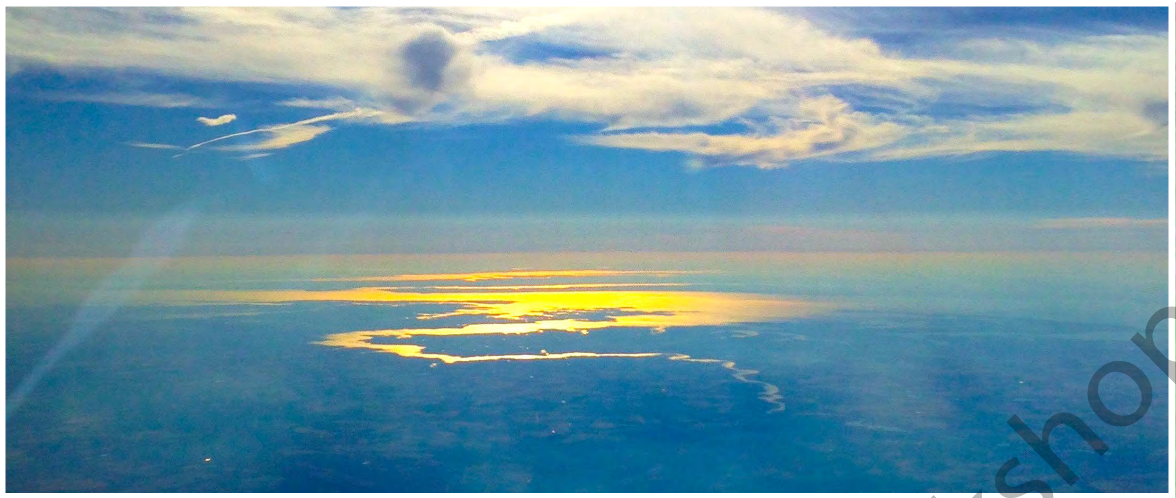


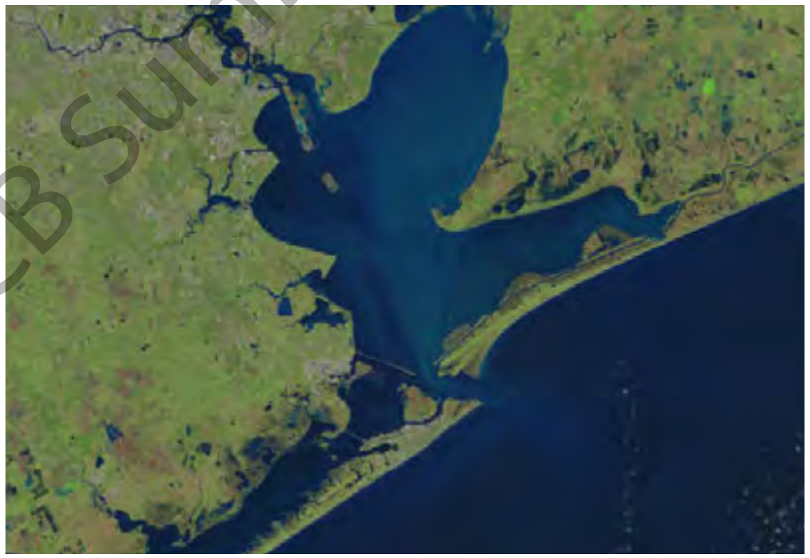
Basic Idea

Use biology to measure physical processes

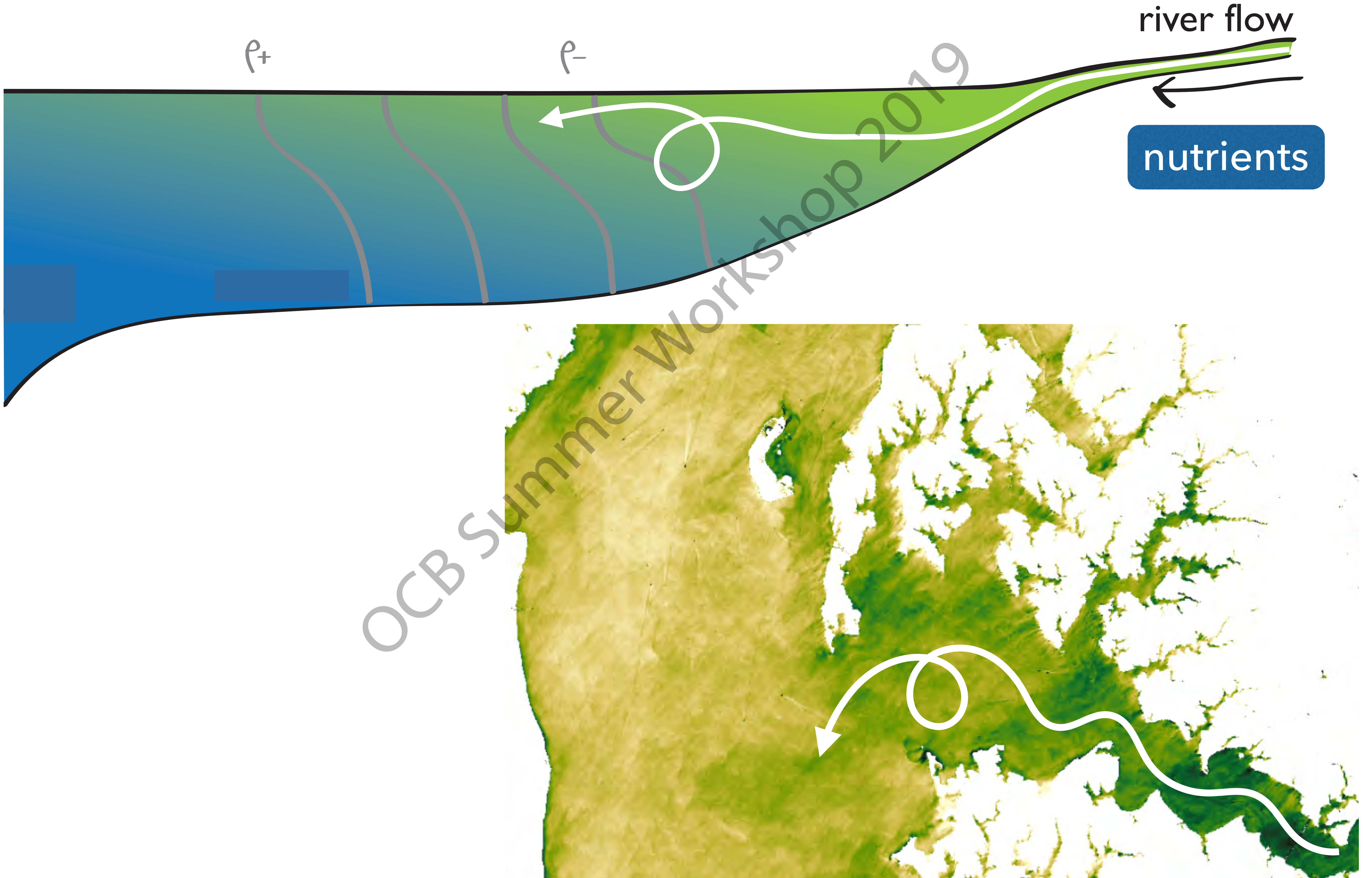
Goal/motivation

To understand mixing across seemingly diverse systems

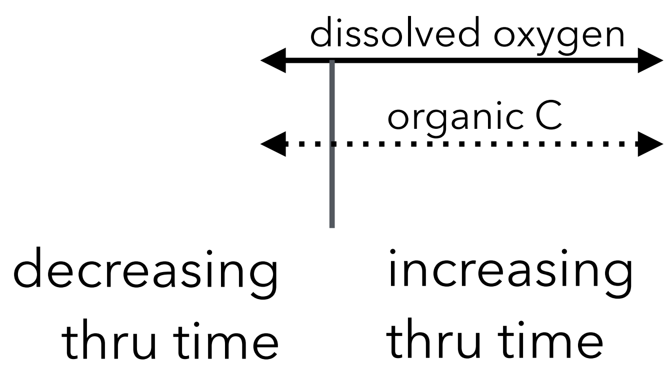



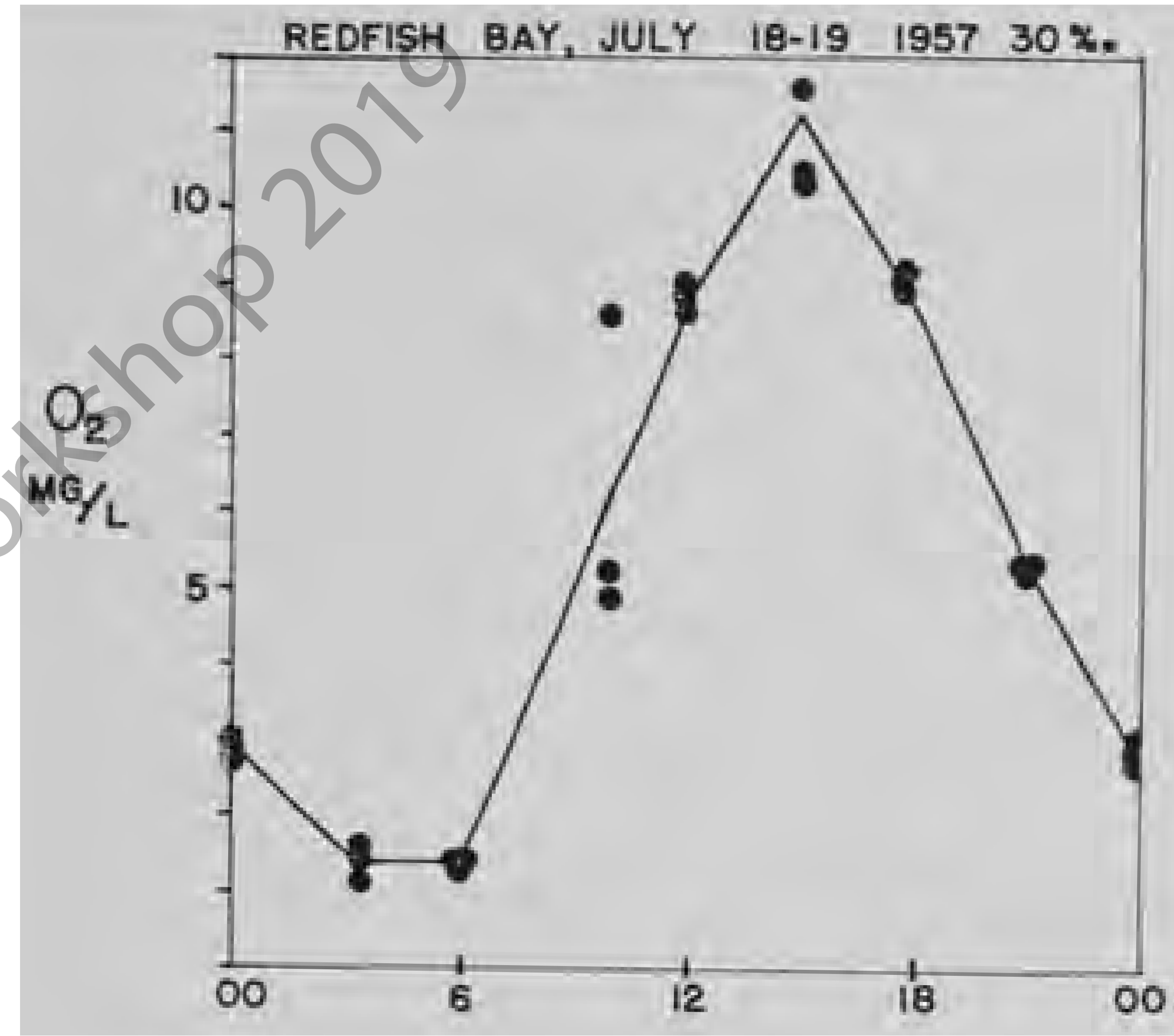

Rationale Primary producers reflect the integrated result of nutrient mixing & transport



Approach Measure ecosystem metabolism – the sum of metabolic processes of resident organisms

Measurements

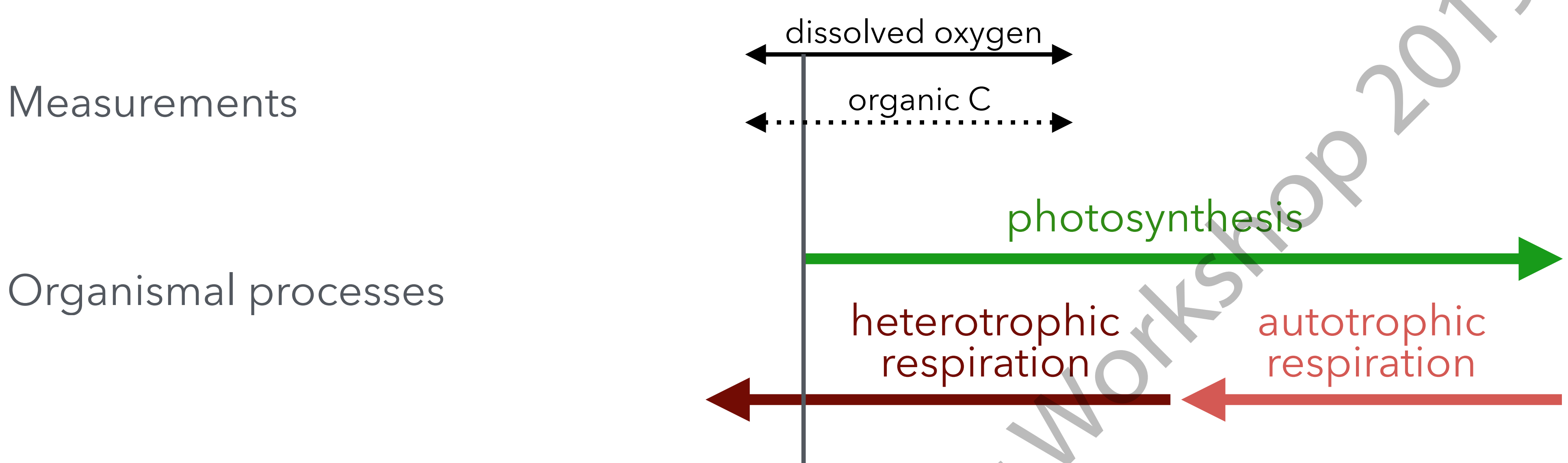




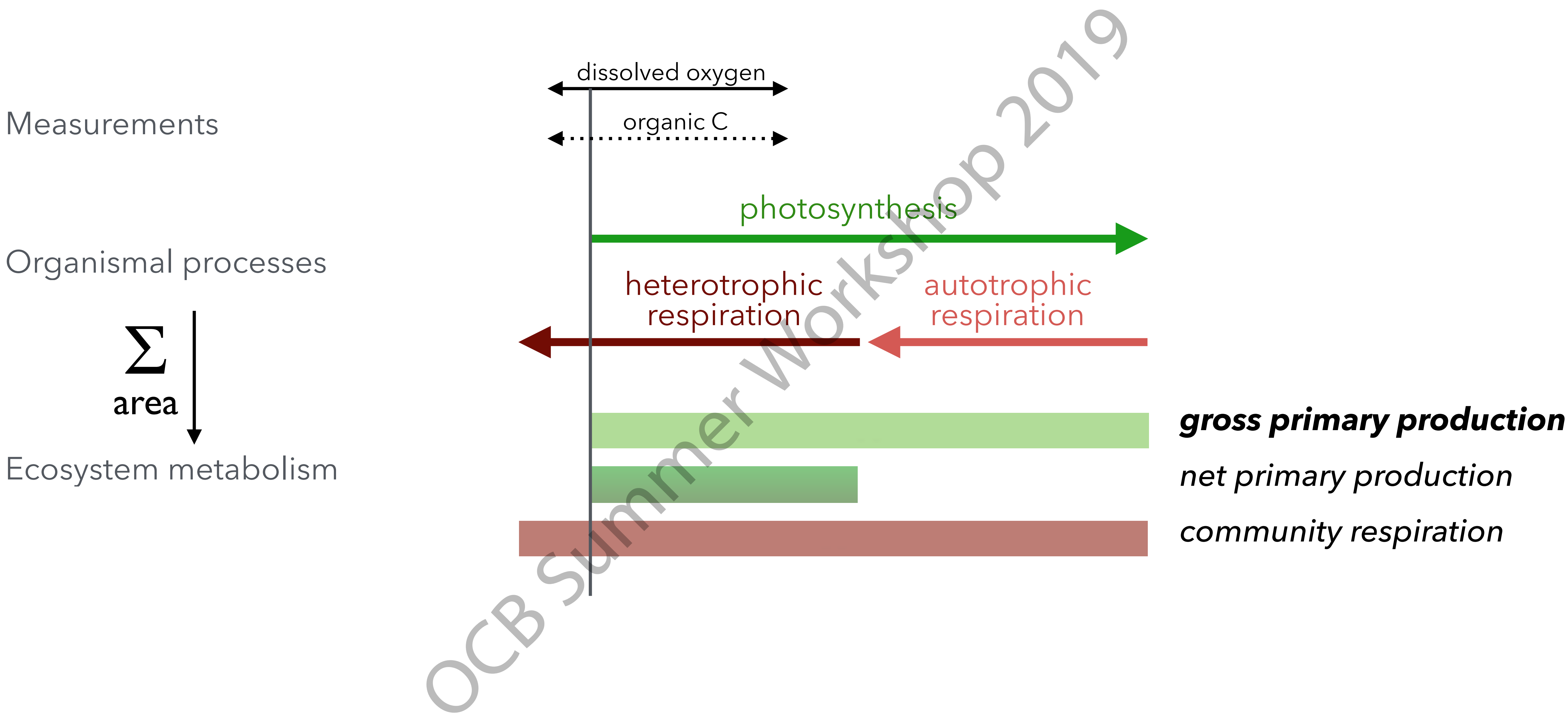
Comparative Studies on the Metabolism of Marine Waters[1]

Howard T. Odum and Charles M. Hoskin
Institute of Marine Science
The University of Texas
Port Aransas, Texas

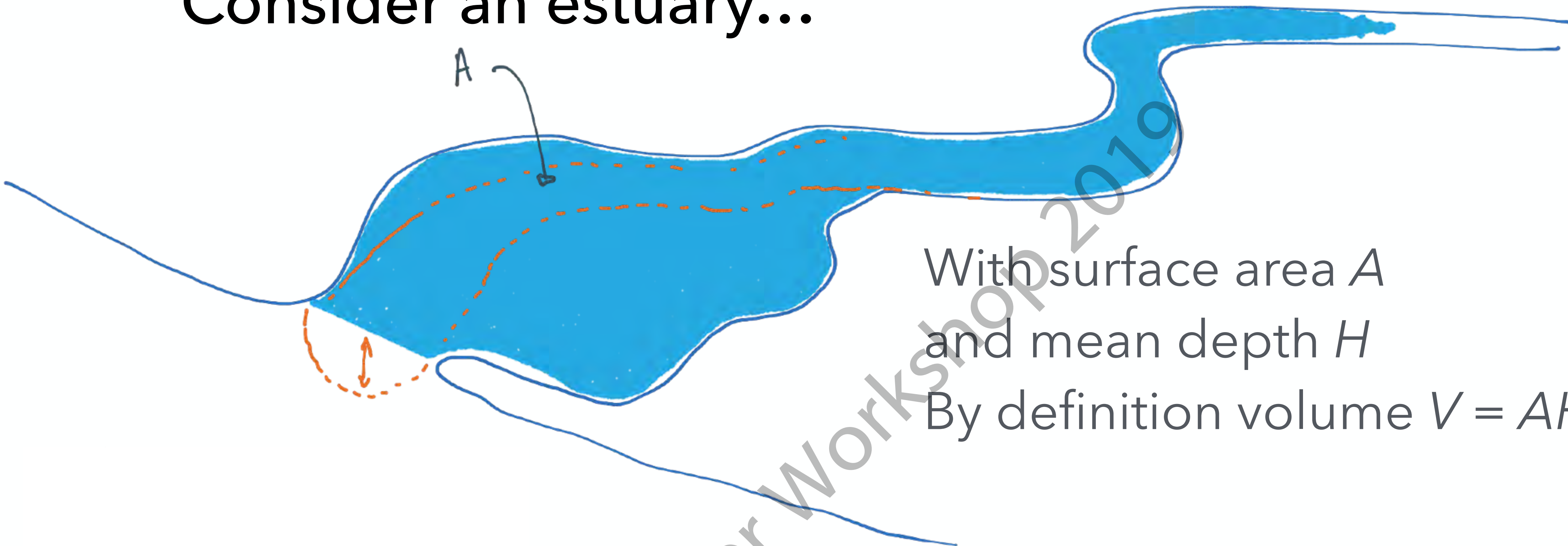
Approach Measure ecosystem metabolism – the sum of metabolic processes of resident organisms



Approach Measure ecosystem metabolism – the sum of metabolic processes of resident organisms

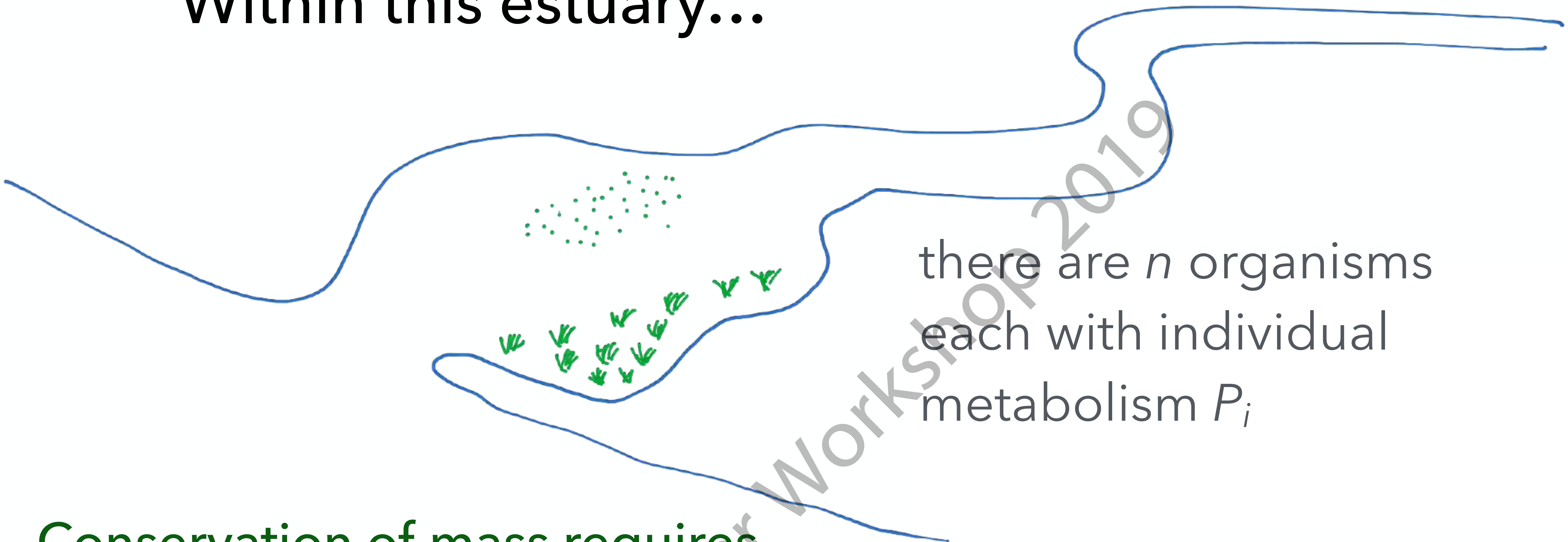


Consider an estuary…



With surface area A
and mean depth H
By definition volume $V = AH$

Within this estuary...

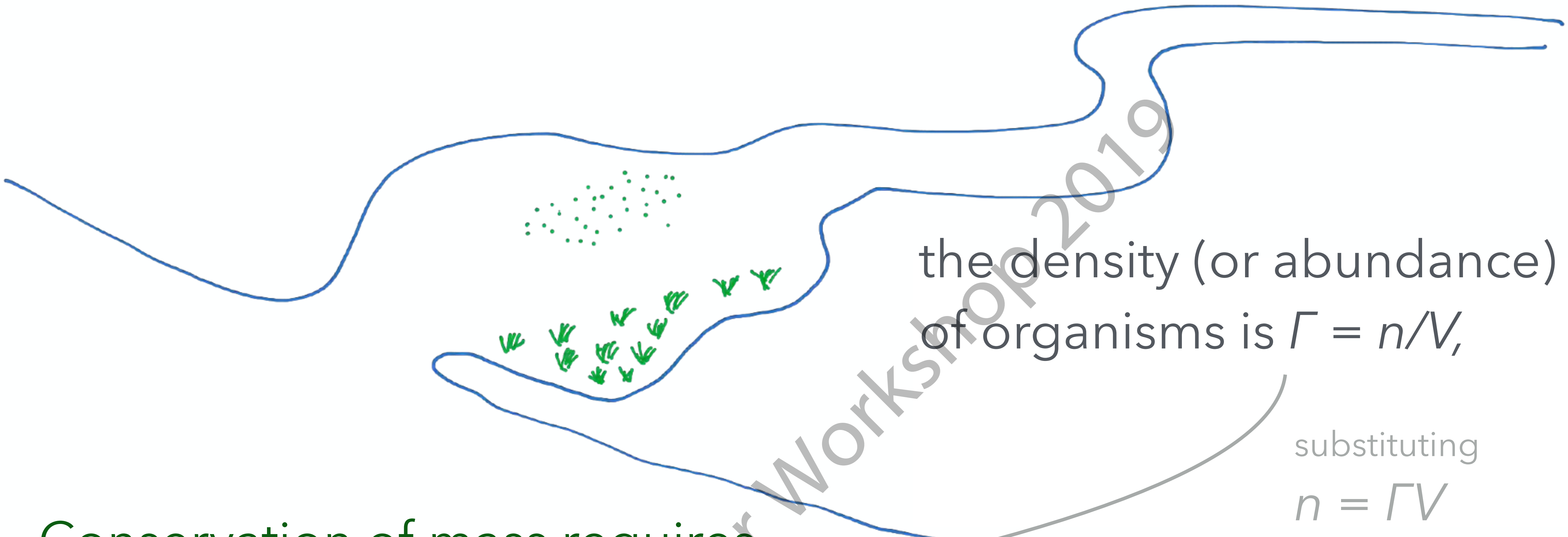


there are n organisms each with individual metabolism P_i

Conservation of mass requires

$$P = \sum_n P_i = n\langle P_i \rangle$$

Total productivity is the specific productivity times size



the density (or abundance) of organisms is $\Gamma = n/V$,

substituting

$n = \Gamma V$

Conservation of mass requires

$P = \sum_n P_i = n\langle P_i \rangle$

and defining

$E = \Gamma\langle P_i \rangle$

specific metabolism

Total Productivity: $P = EV$

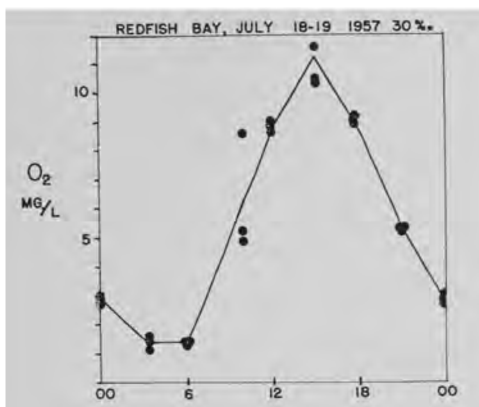
To investigate metabolism/size scaling, we compiled 134 published estimates of ecosystem metabolism

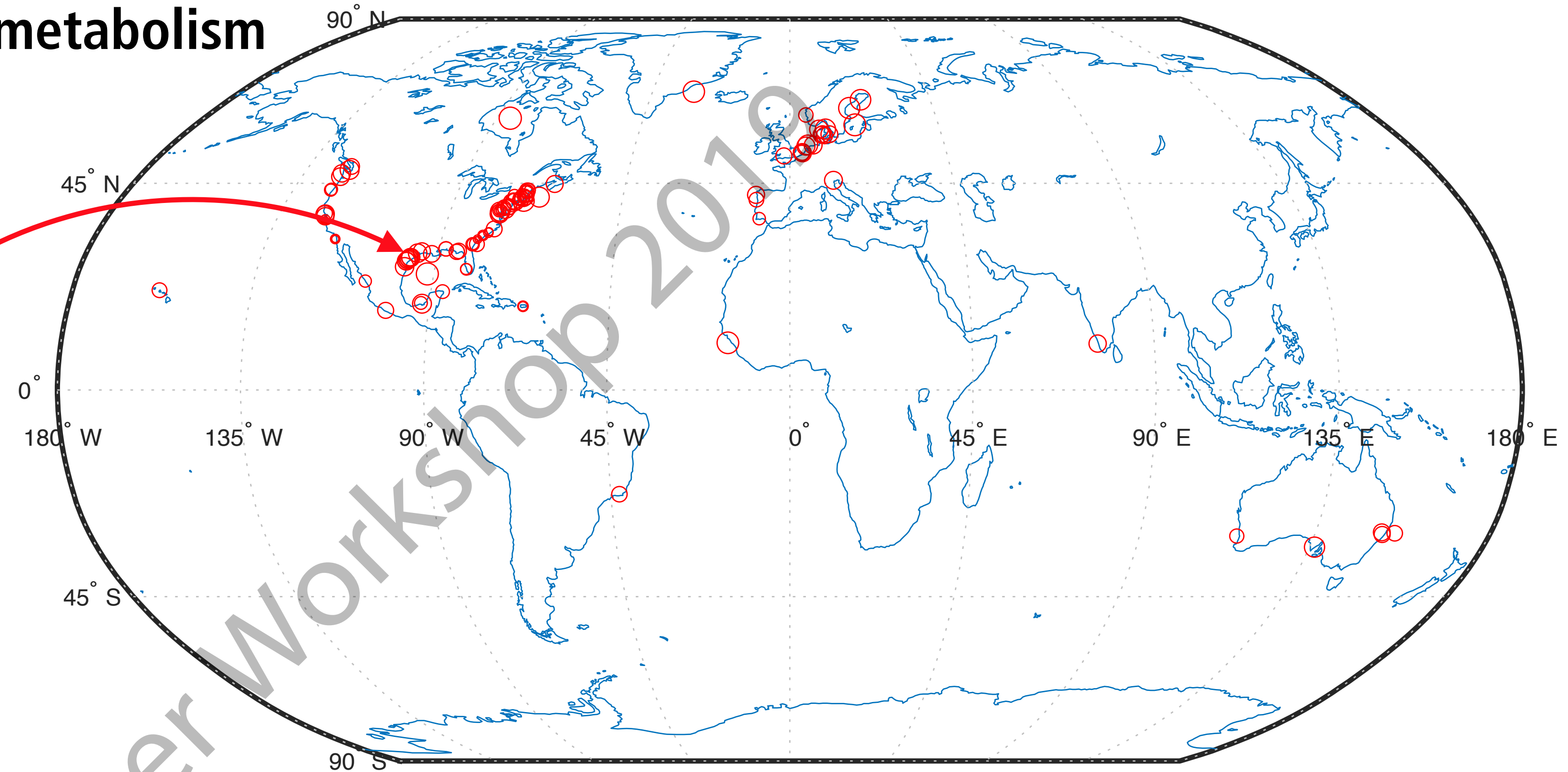
Allometric scaling of estuarine ecosystem metabolism

Nicholas J. Nidzieko[a,1]

[a]Department of Geography, University of California, Santa Barbara, CA 93106

PNAS | June 26, 2018 | vol. 115 | no. 26 | 6733–6738

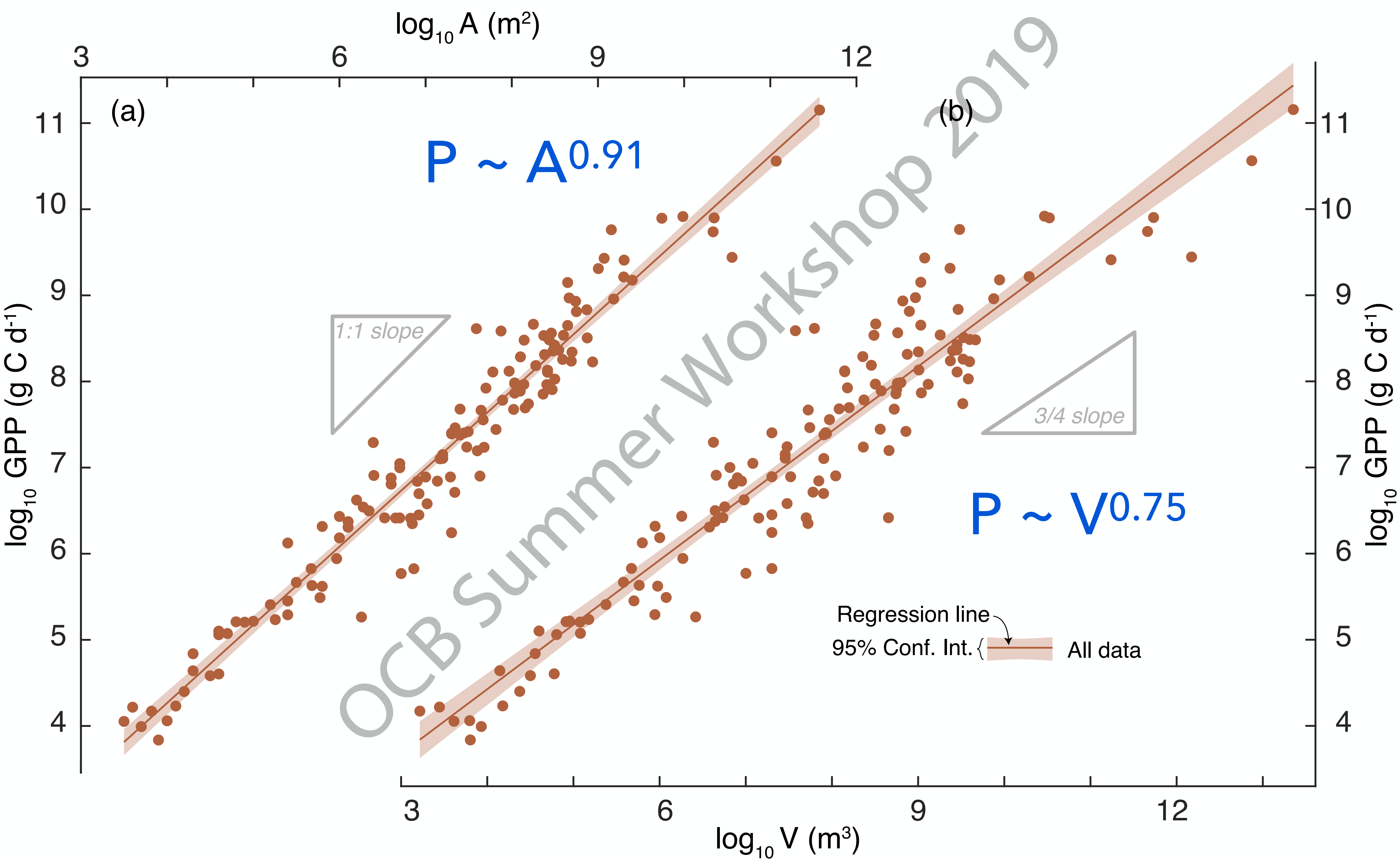




H A V P

Location			Geometry			Gross Primary Production			
	Lat. °N	Lon. °E	Depth m	Area $\log_{10}$ m^2	Volume $\log_{10}$ m^3	Benthic	Pelagic g C m^{-2} d^{-1}	Specific	Total $\log_{10}$ g C d^{-1}
Århus Bugt	56.093	10.191	12 *c*	8.50 [1]	9.58 [1]			0.34 [2]	8.03 *c*
Aabenraa Fjord	55.024	9.504	23 [3]	7.49 [4]	8.86 *c*			0.84 [2]	7.42 *c*
ACE Basin (Big Bay Creek)	32.494	-80.324	1.3 [5]	3.50 [5]	3.61 *c*			3.57 [5]	4.05 *c*
ACE Basin (St. Pierre)	32.523	-80.357	1.8 [5]	4.30 [5]	4.56 *c*			3.46 [5]	4.84 *c*
Alewife Cove	41.312	-72.100	0.8 [6]	5.26 [6]	5.18 *c*	0.51 [7]	0.44 [7]	0.95 [7]	5.23 *c*
Apalachicola Bay (Bottom)	29.786	-84.875	1.8 [5]	7.20 [5]	7.46 *c*			0.89 [5]	7.15 *c*
Apalachicola Bay (Surface)	29.786	-84.875	1.8 [5]	7.20 [5]	7.46 *c*			0.81 [5]	7.11 *c*
Augustenborg Fjord	54.945	9.831	5.1 *c*	7.14 [1]	7.85 [1]			0.51 [2]	6.84 *c*
Baltic Sea	58.000	20.000	60 [8]	11.57 [8, 9]	13.35 *c*	0.01 [7]	0.44 [7]	0.38 [8, 9]	11.15 *c*
Bissel Cove	41.548	-71.432	0.2 [6]	3.82 [6]	3.22 *c*	2.09 [7]	0.15 [7]	2.25 [7]	4.17 *c*
Bojorquez Lagoon	21.126	-86.758	1.7 [10]	6.39 [10]	6.62 *c*			7.91 [10, 11]	7.29 *c*
Boston Harbor	42.338	-70.985	5.8 [12]	8.03 [12]	8.80 *c*			0.89 [13, 14]	7.98 *c*
Bothnian Bay	64.000	23.000	41 [15]	10.56 [15]	12.17 *c*	0.01 [7]	0.07 [7]	0.08 [7]	9.44 *c*
Bothnian Sea	62.000	19.000	63 [15]	11.07 [15]	12.87 *c*	0.01 [7]	0.30 [7]	0.31 [7]	10.56 *c*

Result Ecosystem metabolism scales nonlinearly with ecosystem size



Allometric scaling of estuarine ecosystem metabolism

Nicholas J. Nidzieko[a,1]

[a]Department of Geography, University of California, Santa Barbara, CA 93106

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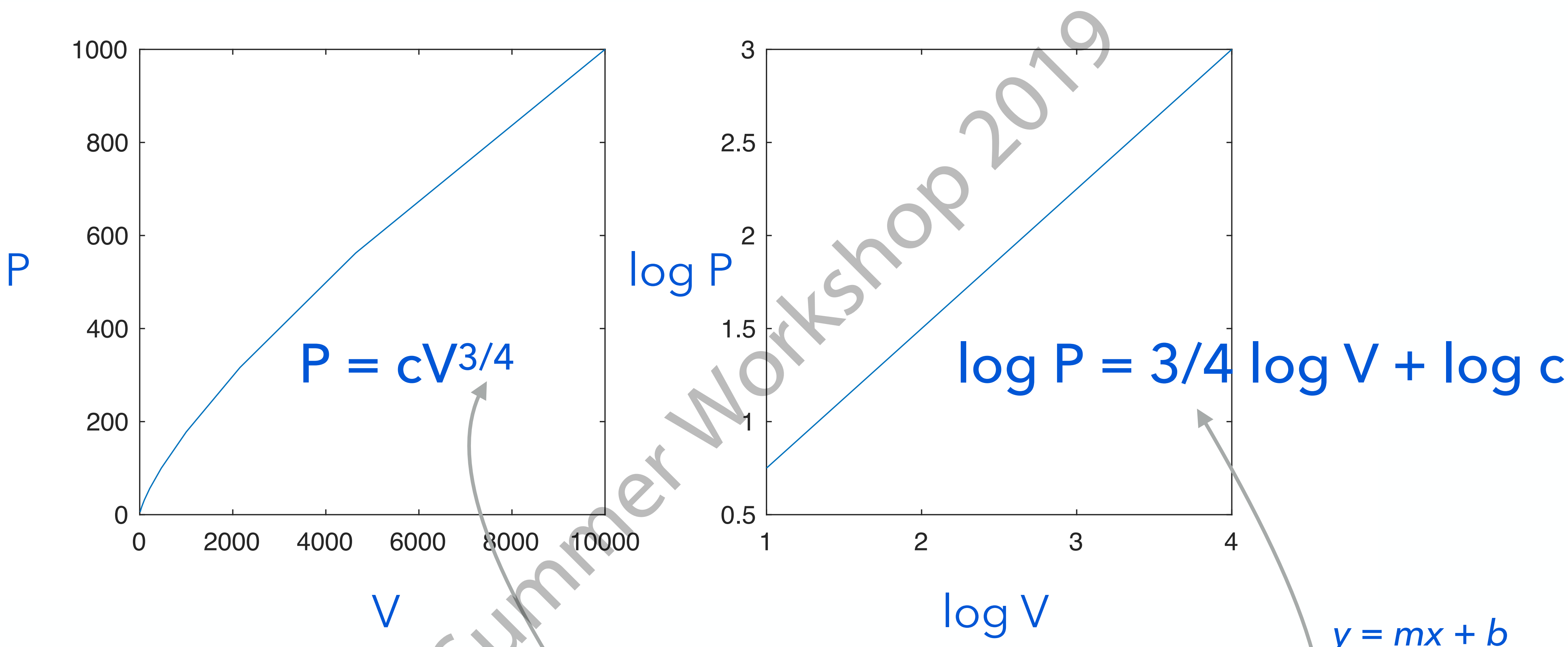
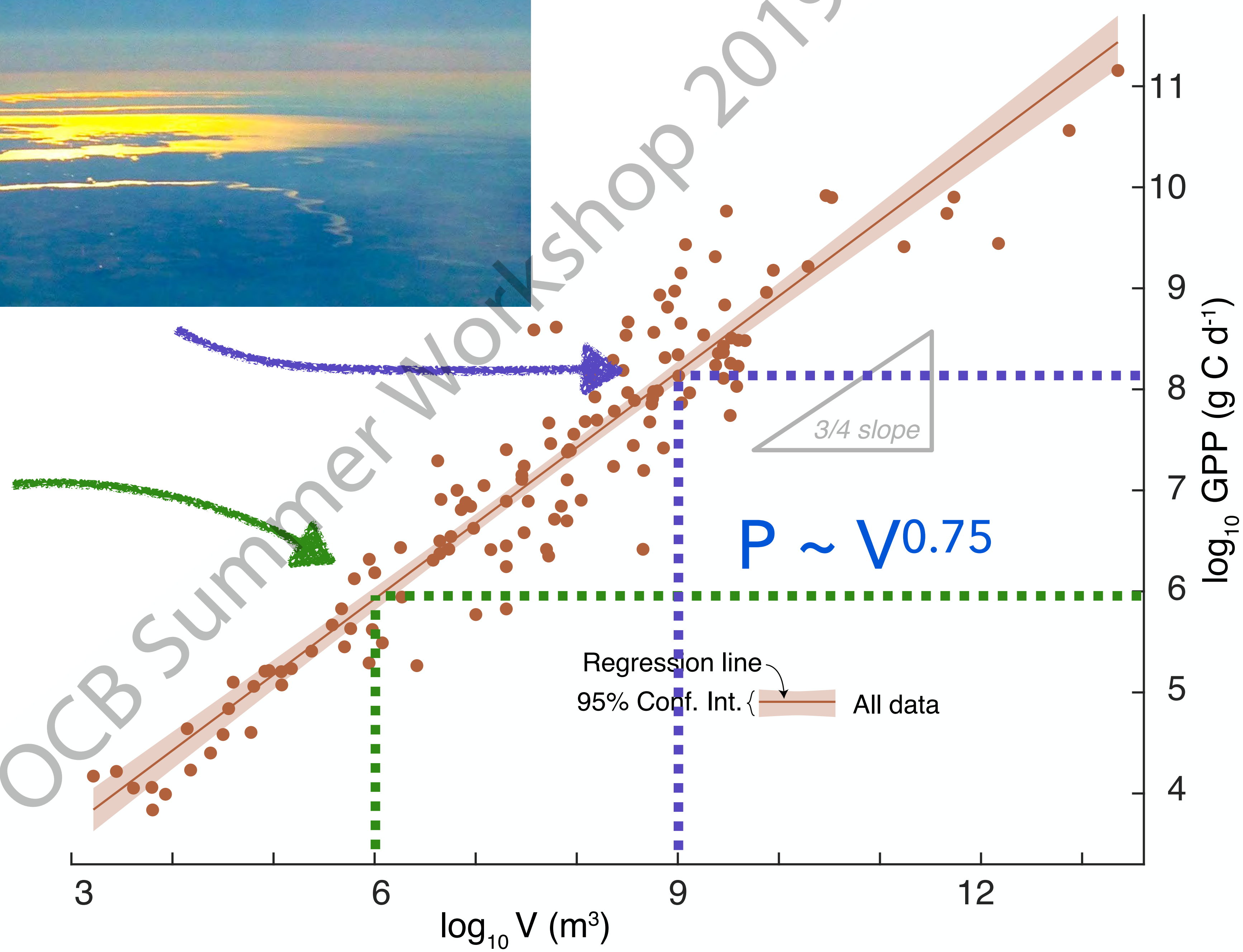
Recall from log laws that a slope not equal to 1 in log space indicates a nonlinear (allometric) relationship



scaling exponent = slope

Here, we might say "P scales with V to the 3/4ths"

Result An estuary that is 1000 times bigger is not necessarily 1000 times as productive



PNAS
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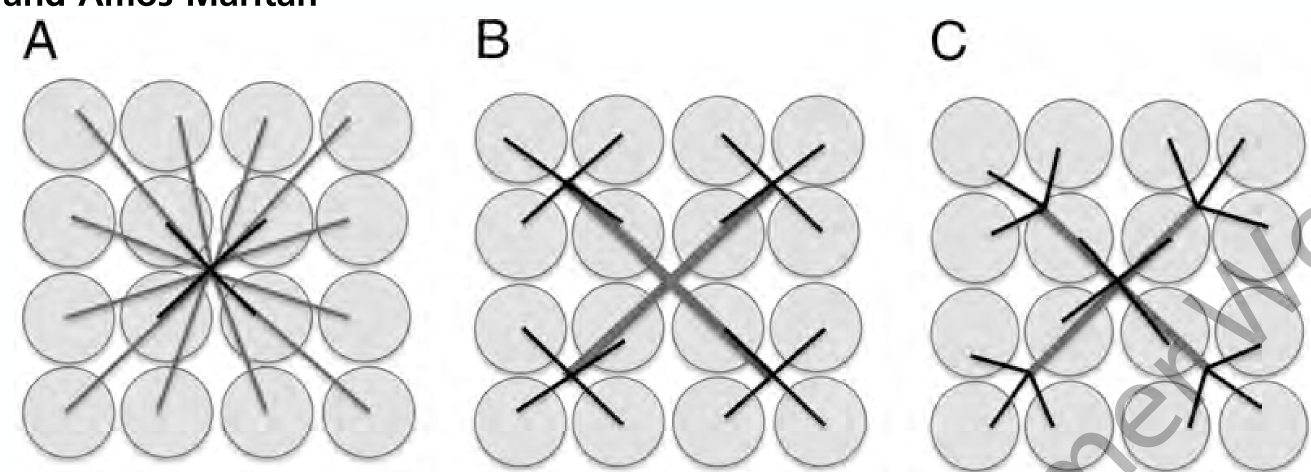
[a]Department of Geography, University of California, Santa Barbara, CA 93106
PNAS | June 26, 2018 | vol. 115 | no. 26 | 6733–6738

Quarter-power scaling is explained by theoretical arguments for organismal metabolism

A general basis for quarter-power scaling in animals

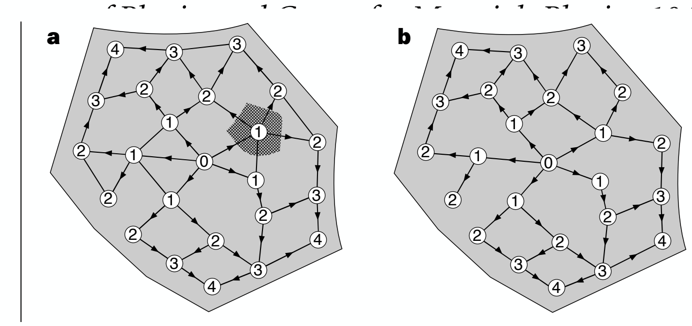
Jayanth R. Banavar[a], Melanie E. Moses[b,c,1], James H. Brown[c,d,1], John Damuth[e], Andrea Rinaldo[f], Richard M. Sibly[g], and Amos Maritan[h]



letters to nature

Size and form in efficient transportation networks

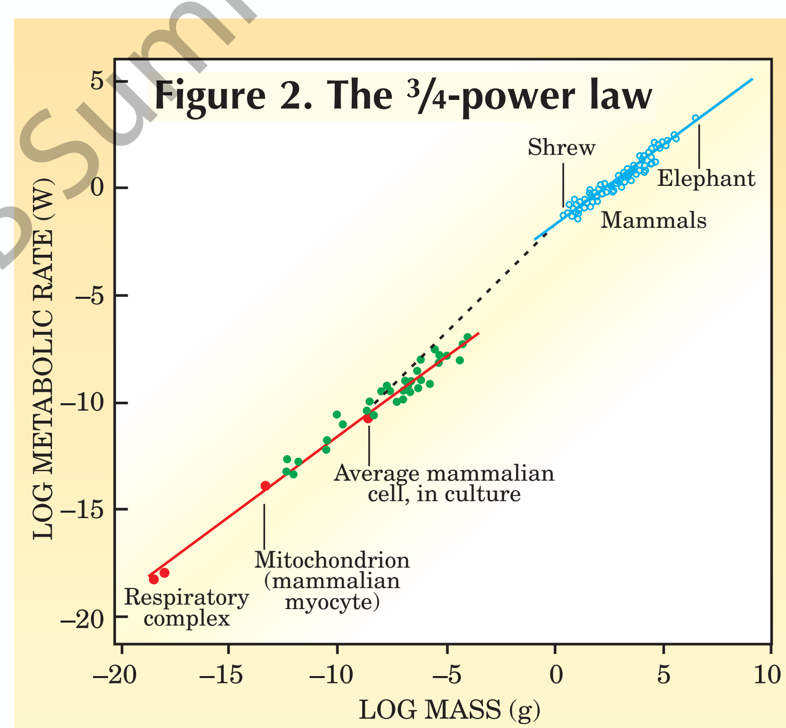
Jayanth R. Banavar*, Amos Maritan† & Andrea Rinaldo‡



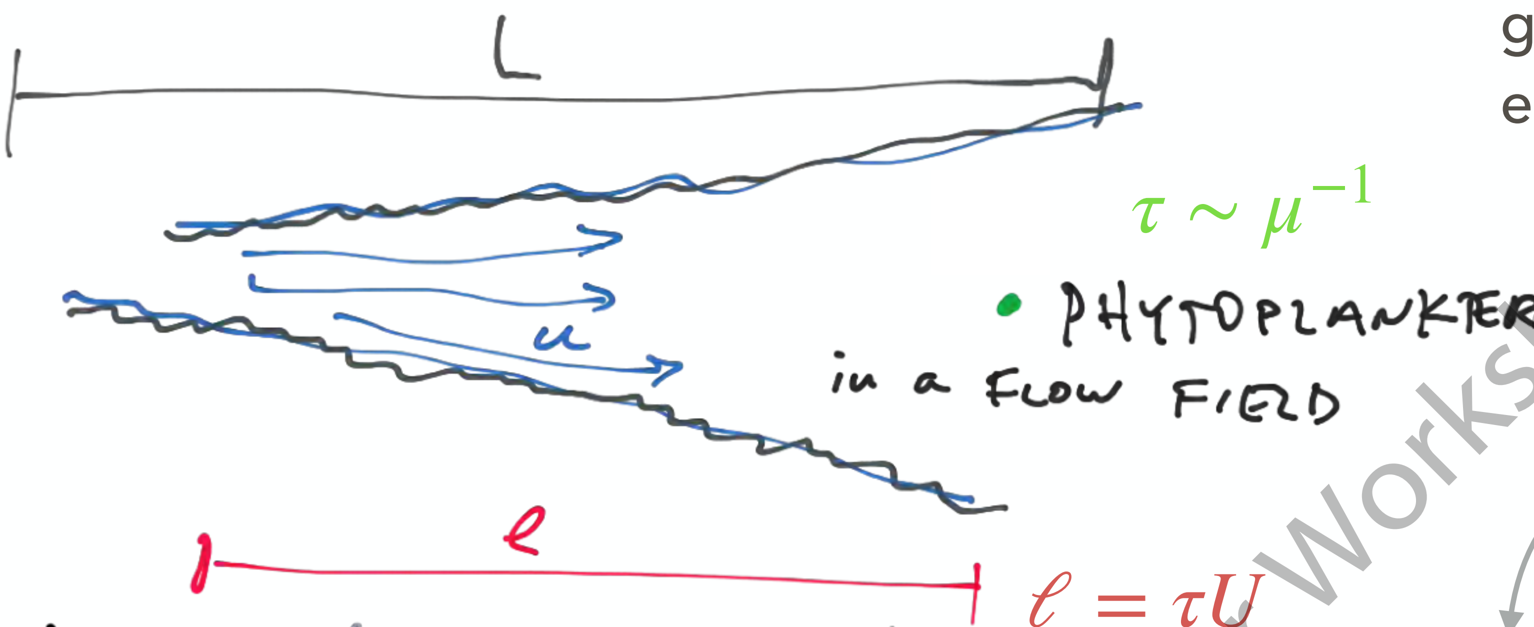
Life's Universal Scaling Laws

Geoffrey B. West and James H. Brown

September 2004 Physics Today



One insight from MTE theory: Ecosystem metabolism scales as a ratio of biological to physical rates



$\tau \sim \mu^{-1}$

$\ell = \tau U$

ℓ is a *length scale* proportional to the growth rate μ and independent of ecosystem size

$$E\ell^D \sim V^0$$

equivalently

$E \sim \ell^{-D}$

$$P = EV$$

$$P \sim \left(\frac{L}{\ell}\right)^D \sim \left(\frac{L\mu}{U}\right)^D \sim \left(\frac{T_R}{\tau}\right)^D$$

where

$T_R = L/U$

D is the dimensionality of the system

PNAS

A general basis for quarter-power scaling in animals

Jayanth R. Banavar[a], Melanie E. Moses[b,c,1], James H. Brown[c,d,1], John Damuth[e], Andrea Rinaldo[f], Richard M. Sibly[g], and Amos Maritan[h]

[a]Department of Physics, Pennsylvania State University, University Park, PA 16802; [b]Department of Computer Science, University of New Mexico, Albuquerque, NM 87131; [c]Department of Biology, University of New Mexico, Albuquerque, NM 87131; [d]Santa Fe Institute, Santa Fe, NM 87501; [e]Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, CA 93106; [f]Laboratory of Ecohydrology, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland; [g]School of Biological Sciences, University of Reading, Whiteknights, Reading RG6 6AS, United Kingdom; and [h]Dipartimento di Fisica, Università di Padova, Istituto Nazionale di Fisica Nucleare, sez. Padova, I-35131 Padua, Italy

Contributed by James H. Brown, July 9, 2010 (sent for review June 7, 2010)

Another insight: transport time scales differently for deep and shallow systems

Q is the size of the transport network (i.e., the estuary)

Equating

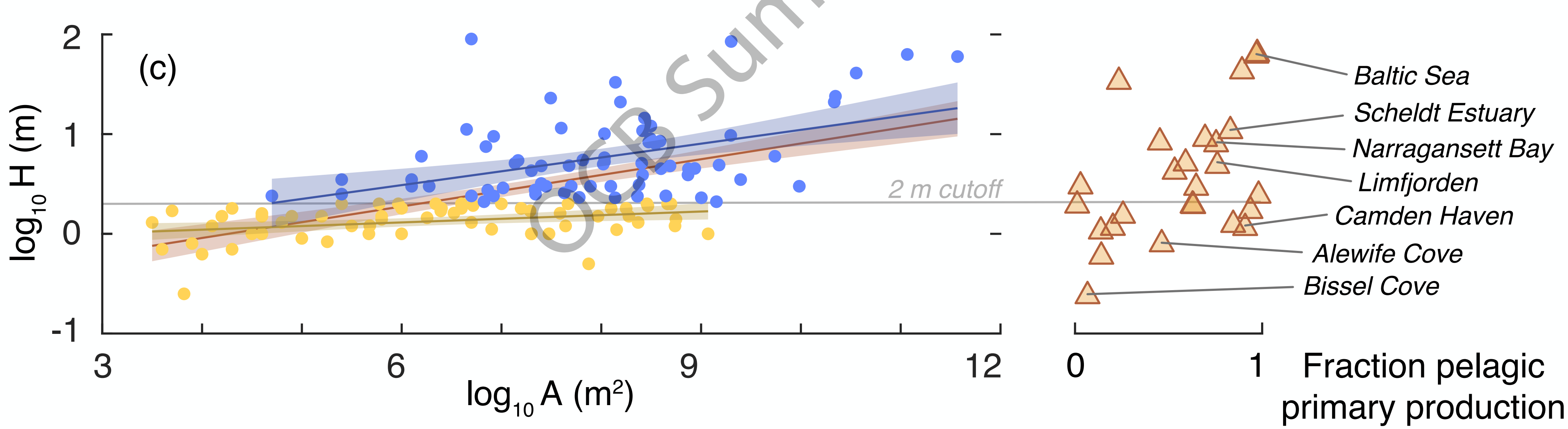
$$P \sim Q^{D/D+1} \quad \text{(network scaling)}$$

$$P \sim \left(\frac{T_R}{\tau}\right)^D \quad \text{(transport/growth)}$$

Transport time: $T_R \sim Q^{1/(D+1)}$

Noting that $Q \sim V \sim L^3$

shallow	$T_R \sim L$	$U \sim L^0$
deep	$T_R \sim L^{3/4}$	$U \sim L^{1/12}$



Allometric scaling of estuarine ecosystem metabolism

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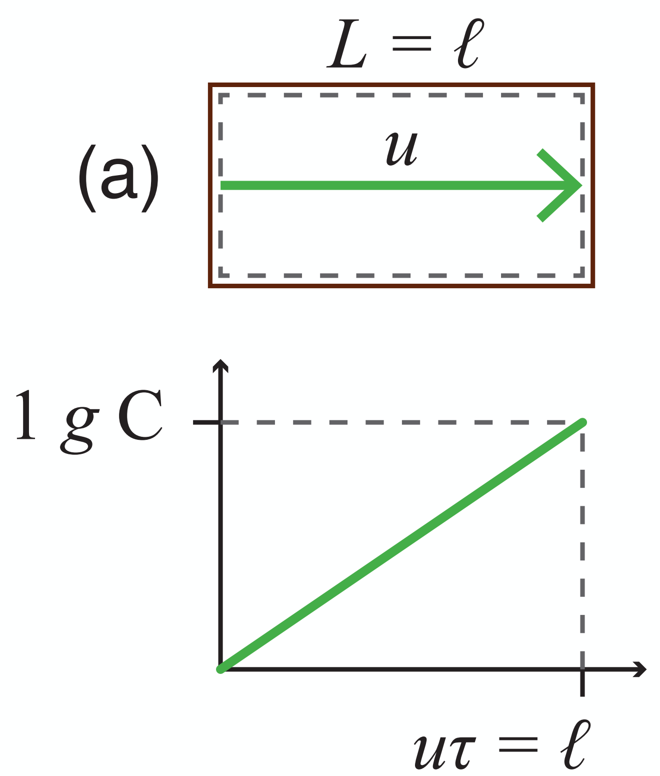
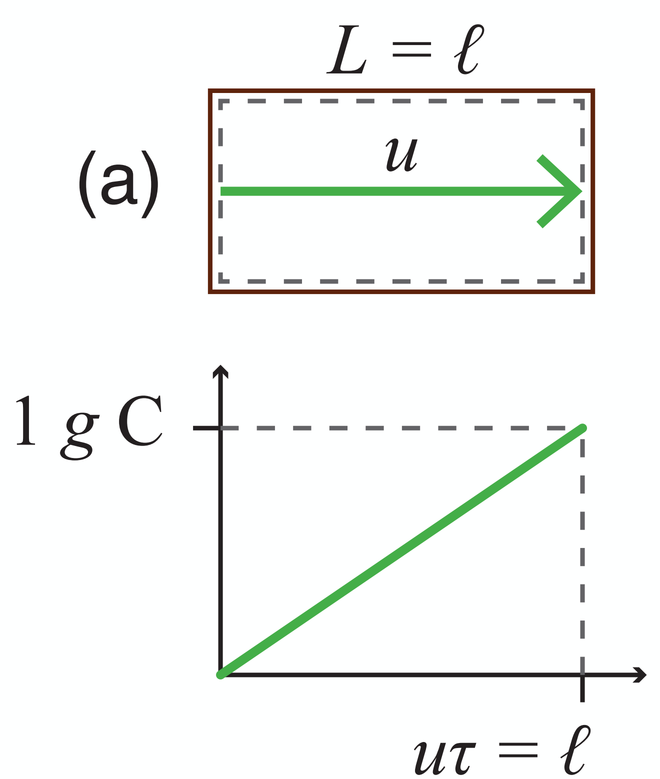
PNAS | June 26, 2018 | vol. 115 | no. 26 | 6733–6738

If the transport time increases nonlinearly with ecosystem size, then metabolism will vary nonlinearly across ecosystems, as we observe

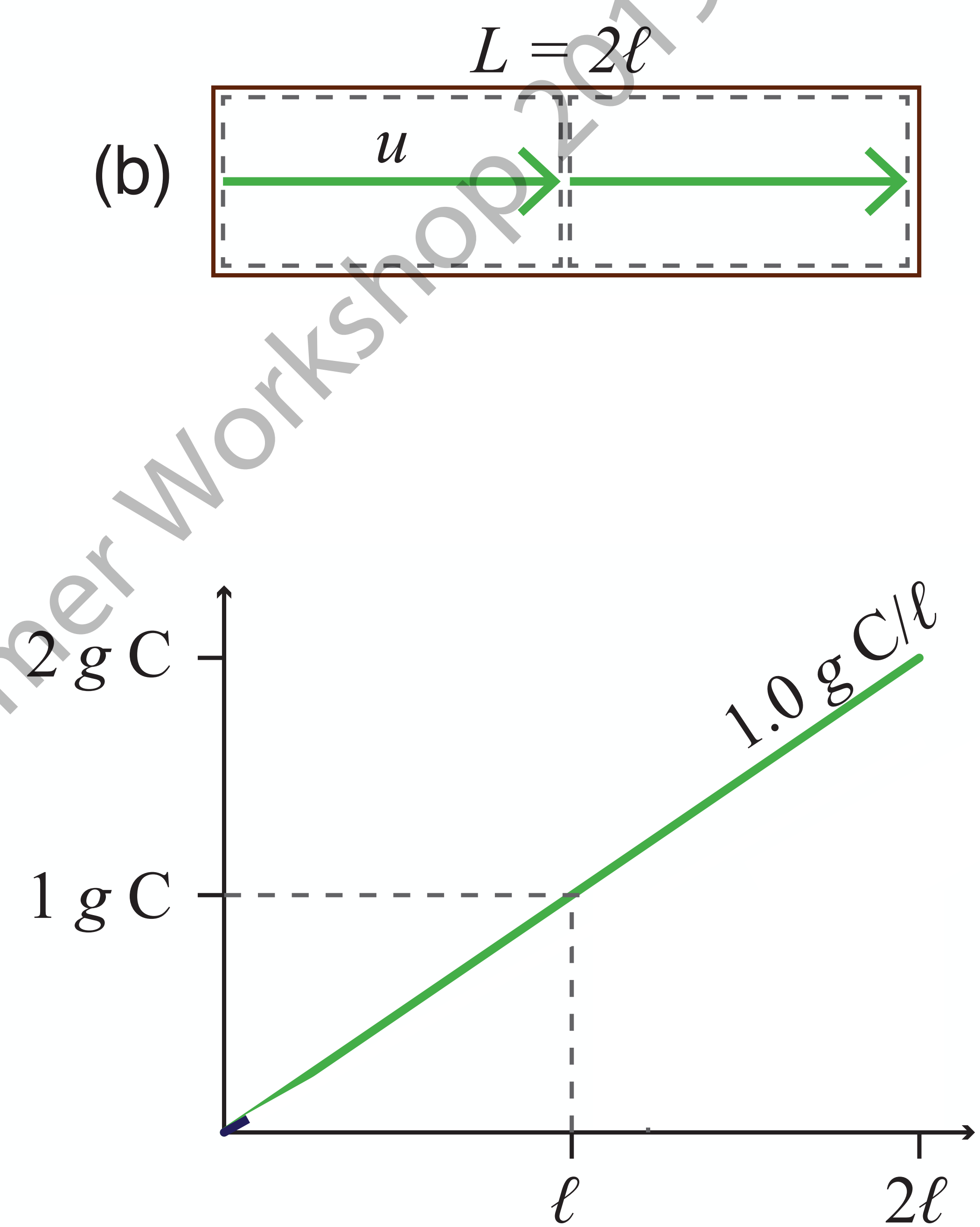


Imagine organic C is produced as a water parcel travels through the estuary

If the transport time increases nonlinearly with ecosystem size, then metabolism will vary nonlinearly across ecosystems, as we observe



Twice as much org C is produced in a system twice as big, if U doesn't change



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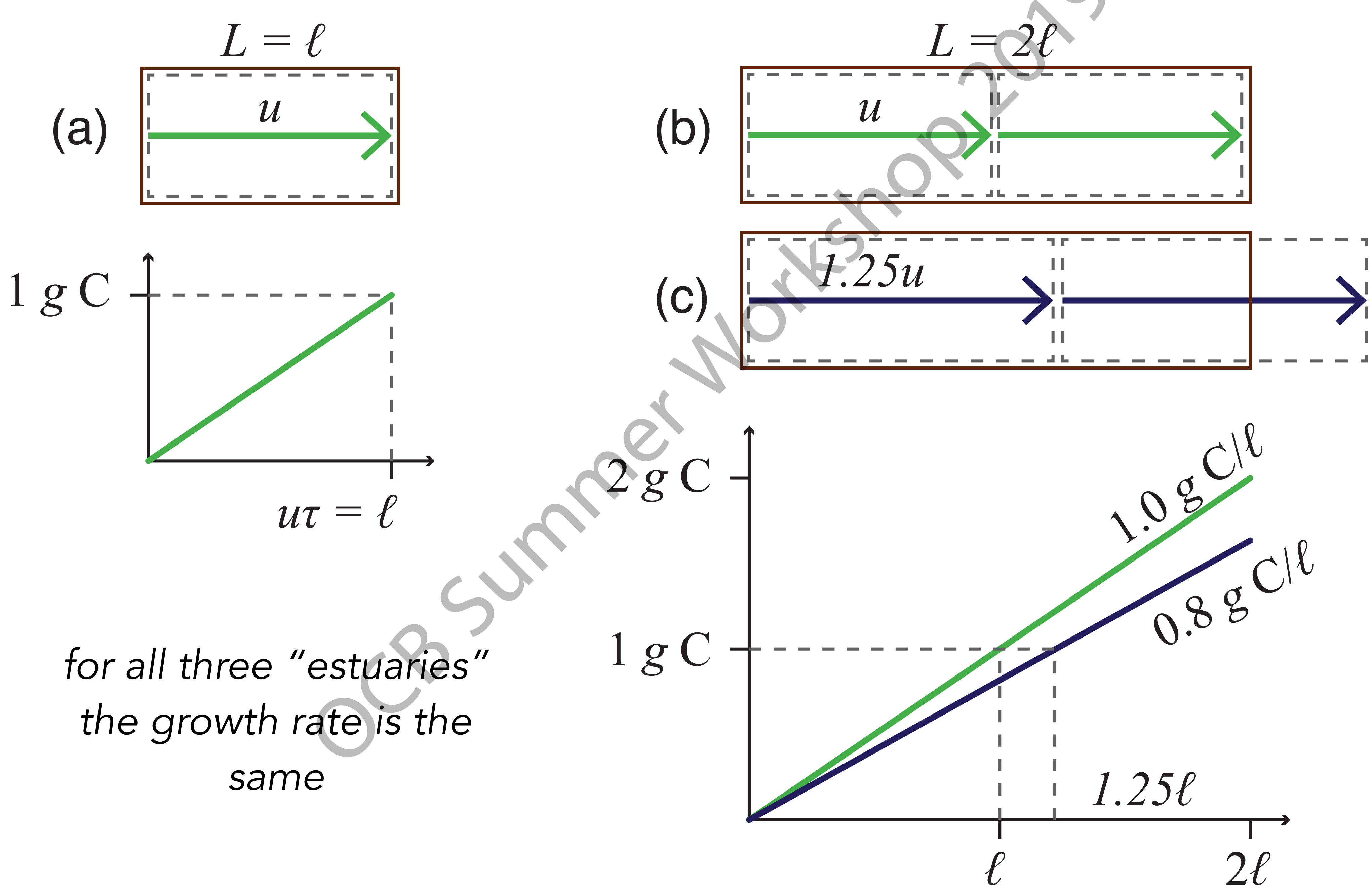
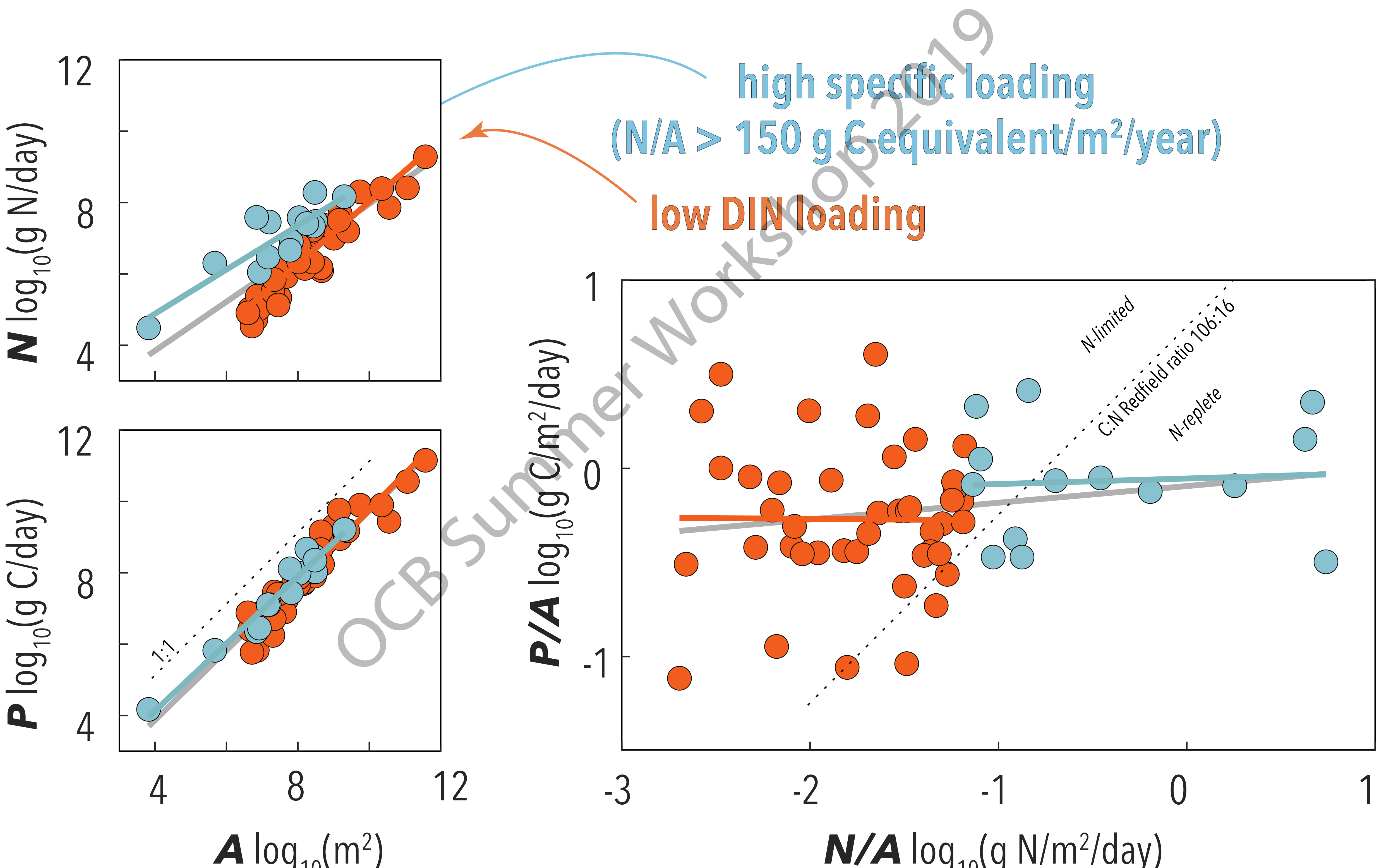
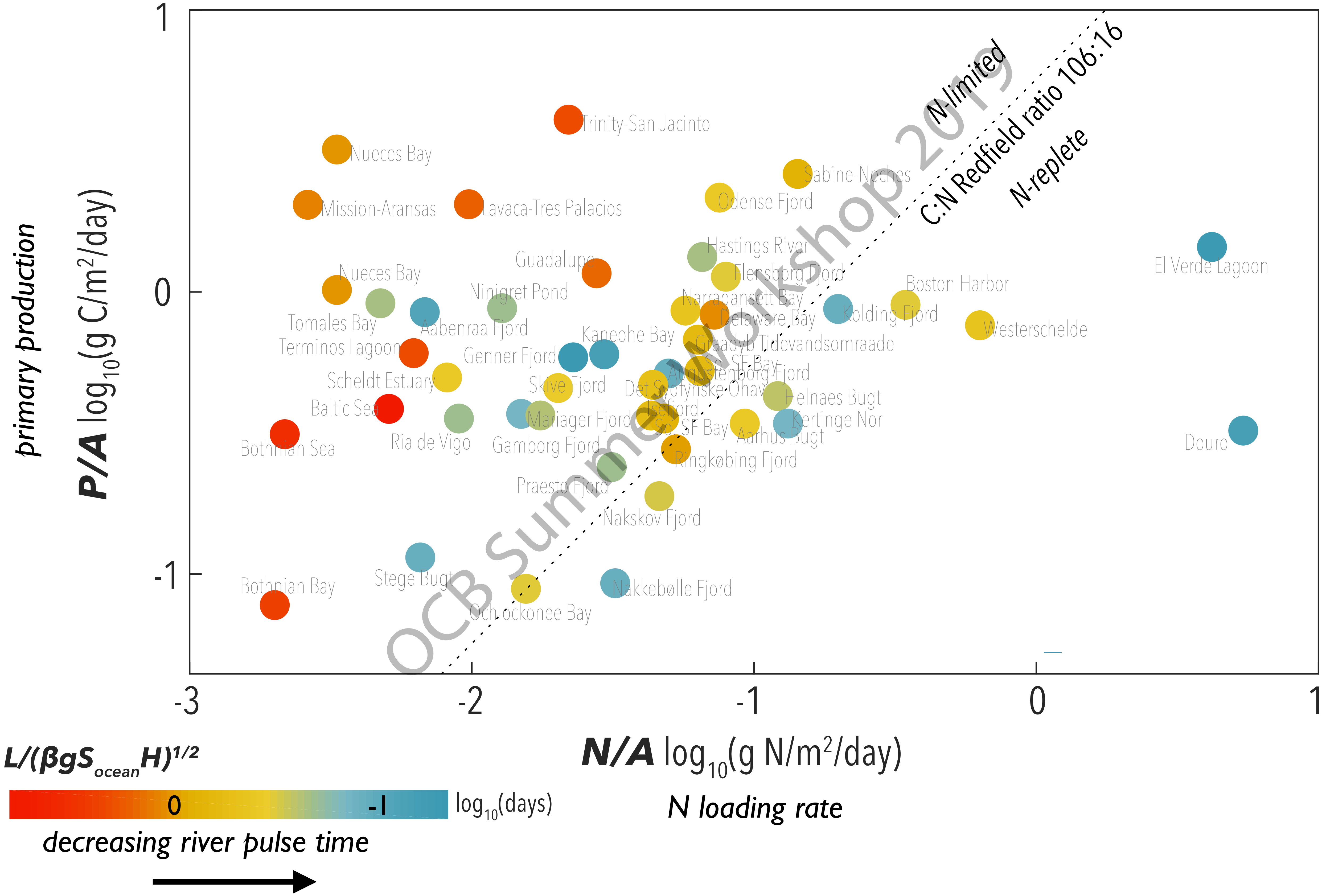


for all three "estuaries" the growth rate is the same

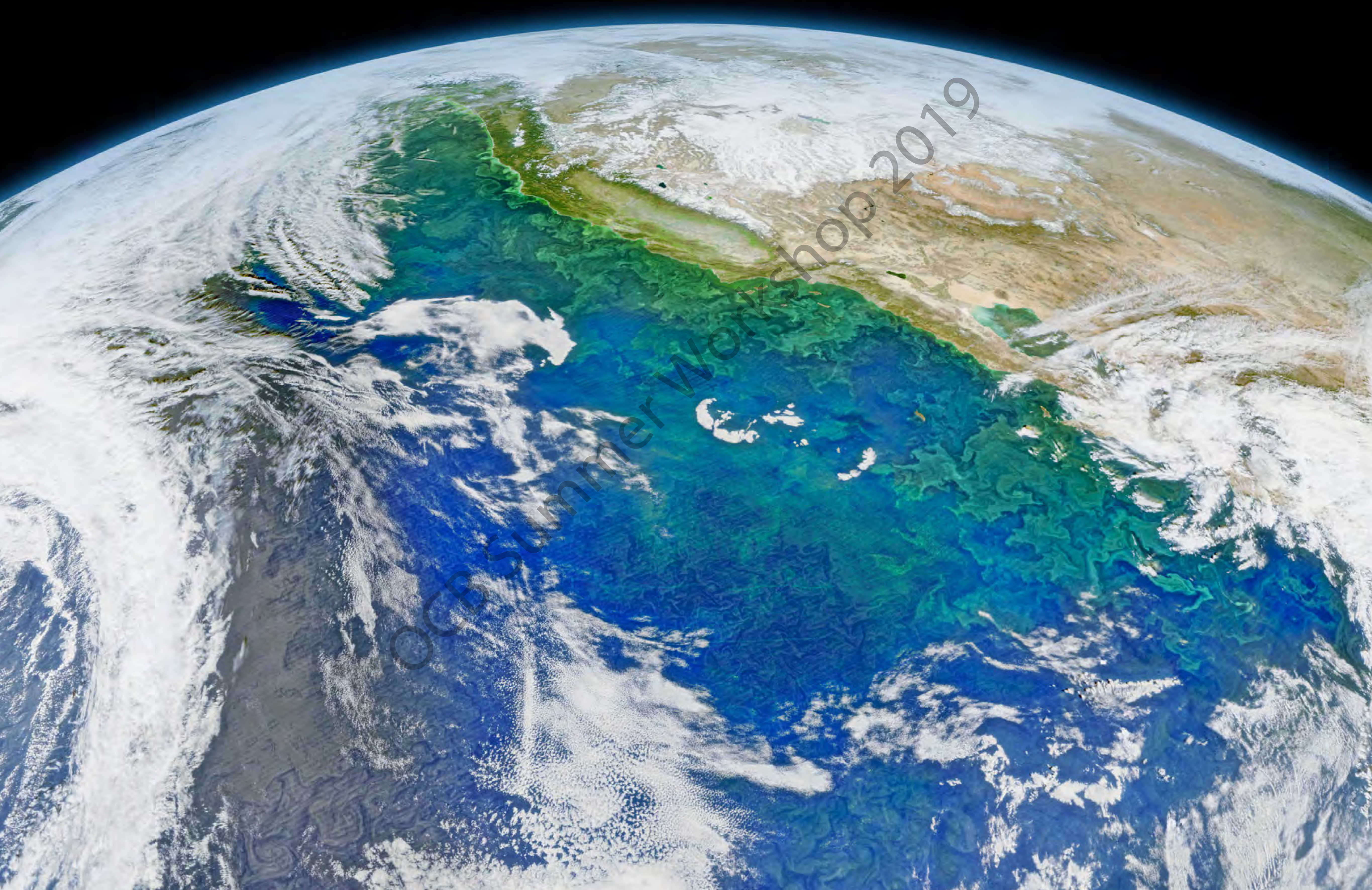
Larger estuaries have greater nitrogen loads, but higher specific loading doesn't increase specific productivity



One explanation may be the rate at which nutrient pulses move through an estuary



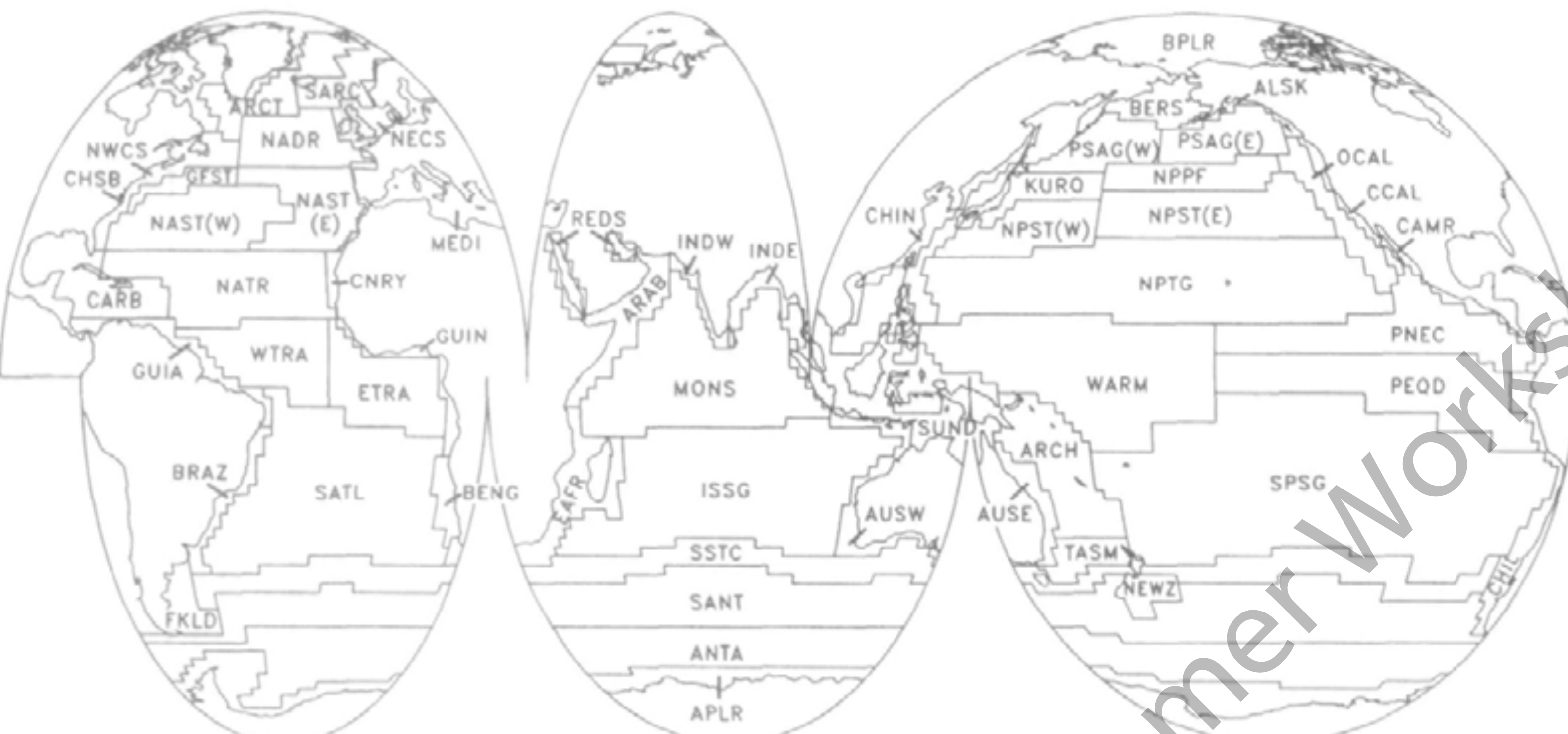
Does size scaling apply across the oceans?

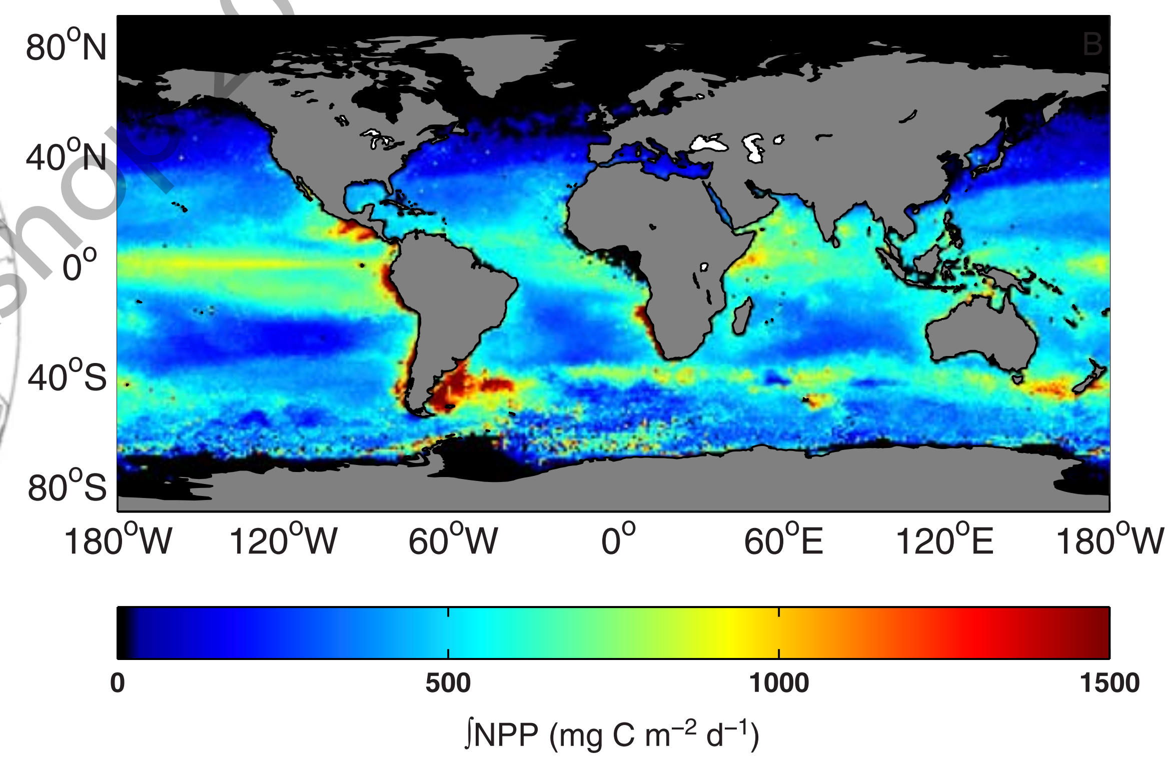


Willie Haskell (MBARI) aggregated net primary production into a variety of biogeographic provinces

Carbon-based primary productivity modeling with vertically resolved photoacclimation

T. Westberry,[1] M. J. Behrenfeld,[1] D. A. Siegel,[2] and E. Boss[3]





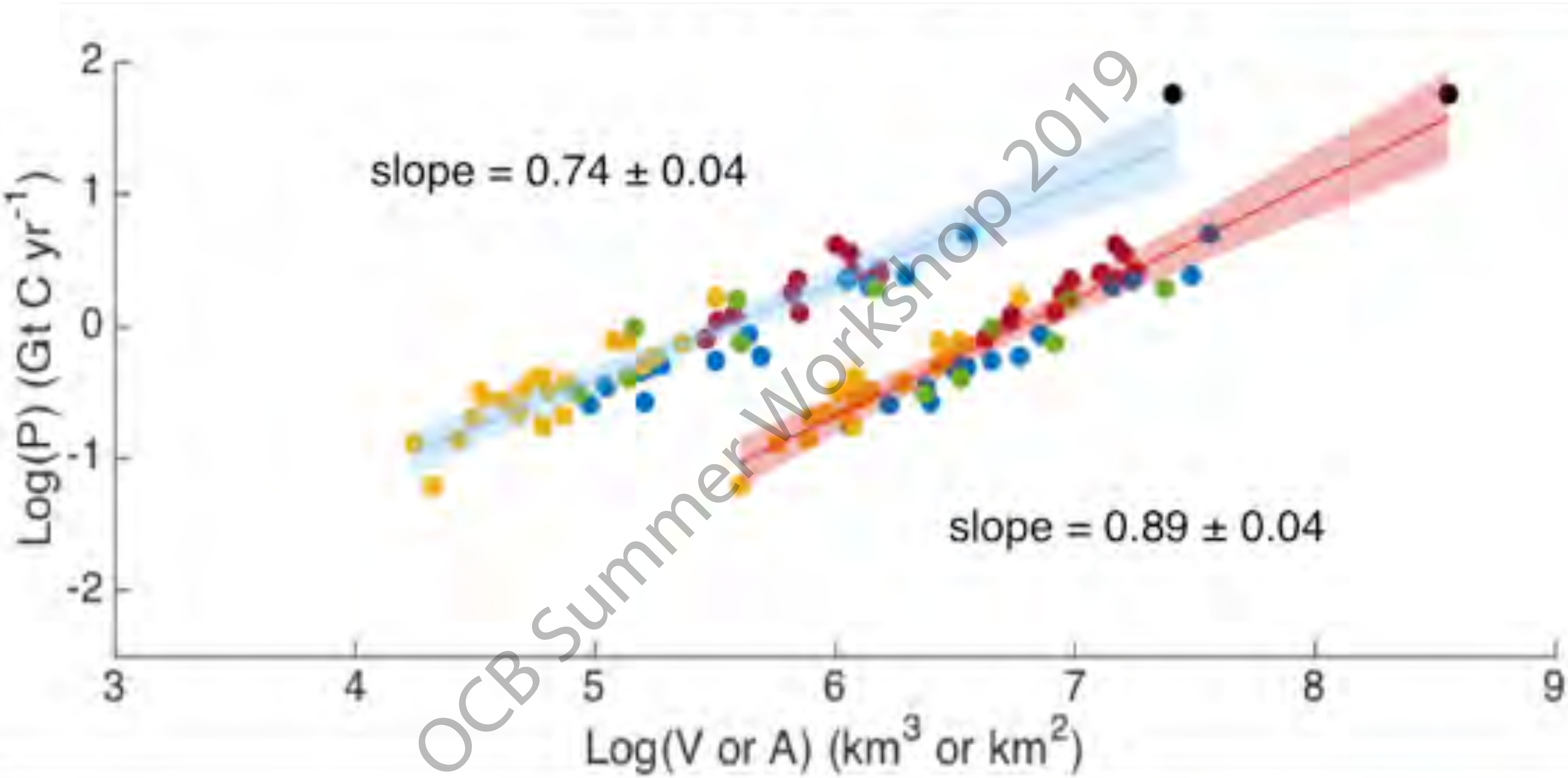
Journal of Plankton Research Vol.17 no.6 pp.1245–1271, 1995

An estimate of global primary production in the ocean from satellite radiometer data

Alan Longhurst, Shubha Sathyendranath[1], Trevor Platt and Carla Caverhill

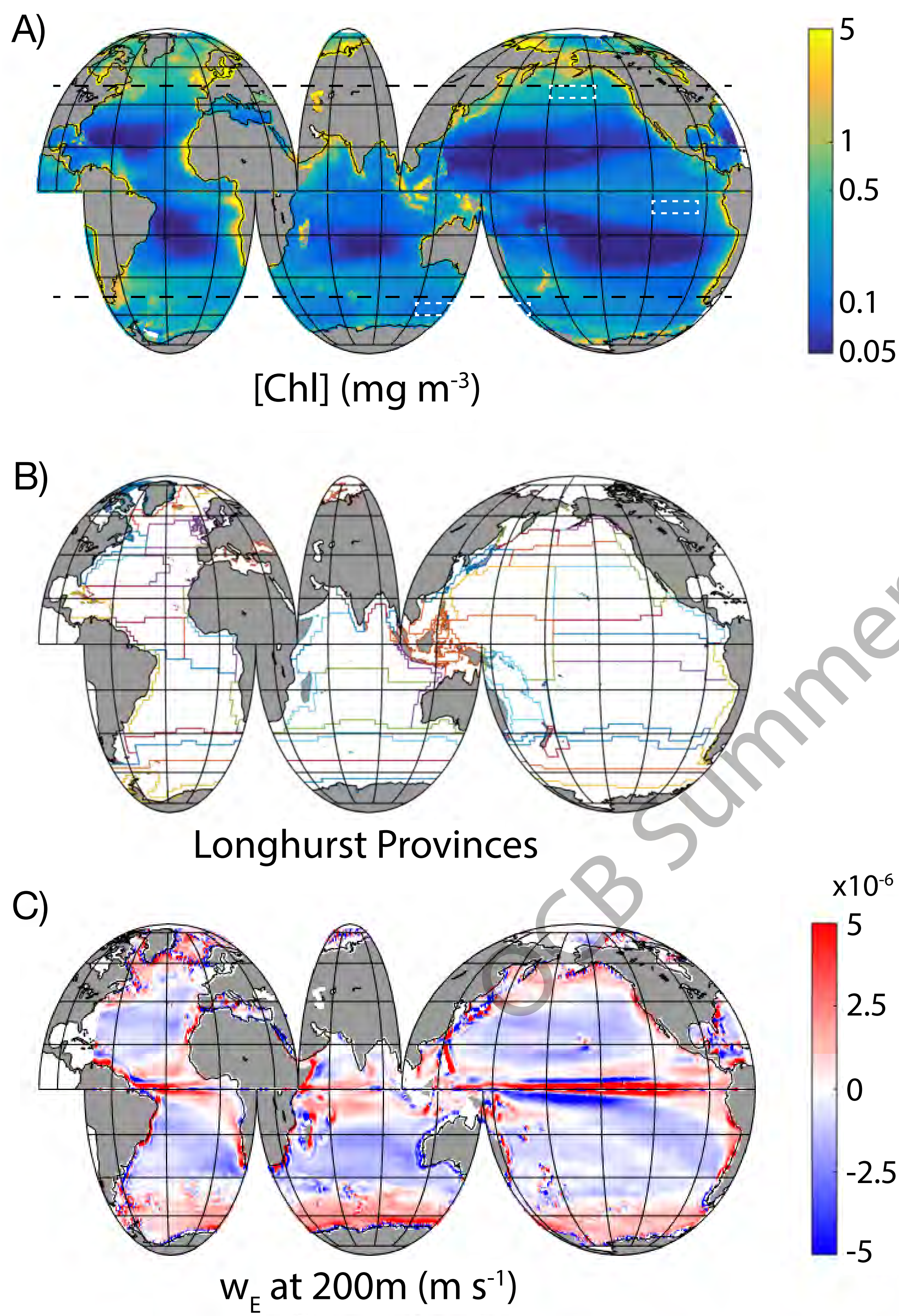
Willie Haskell, *in prep*

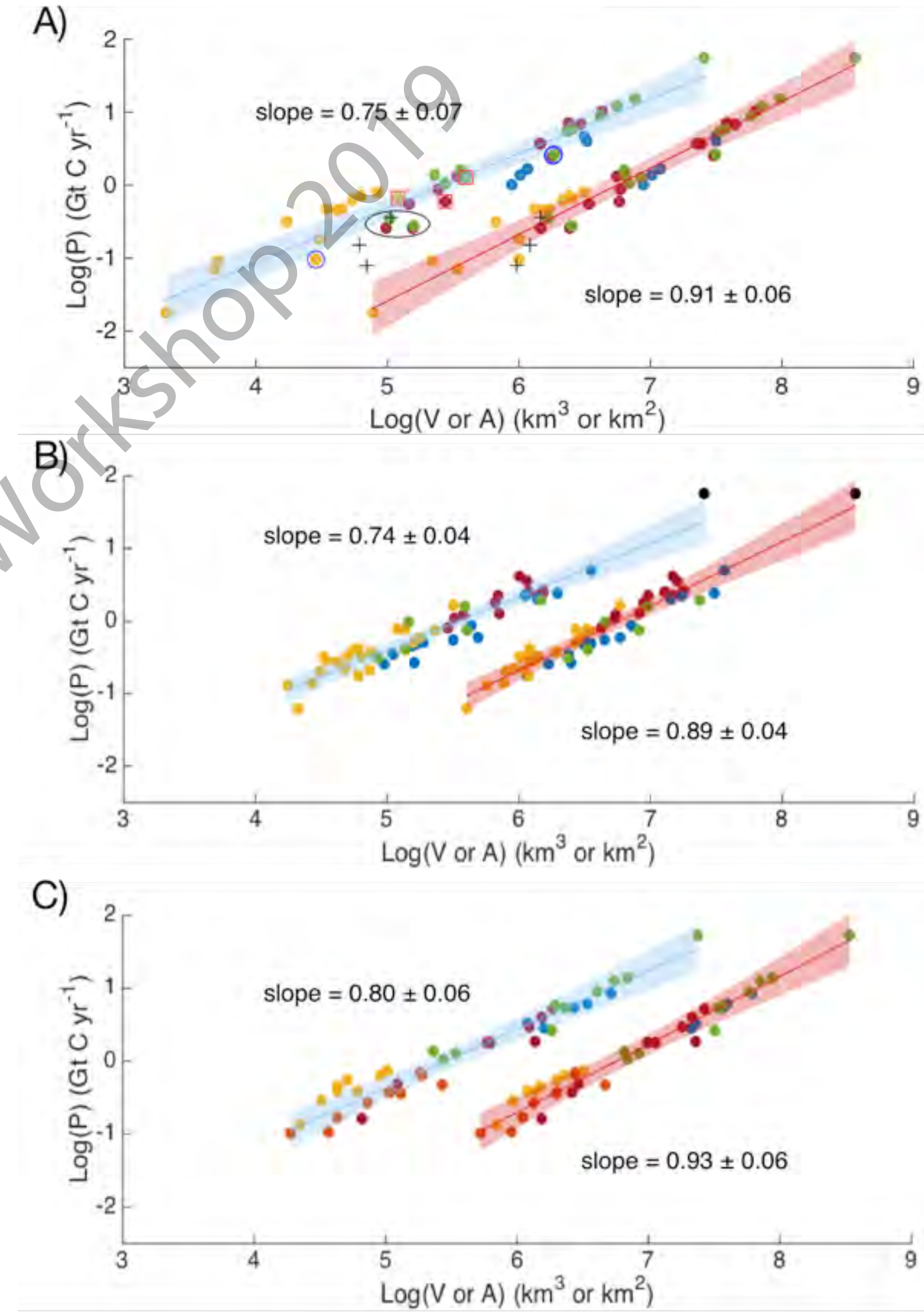
As with estuaries, community metabolism scales nonlinearly with ecosystem size



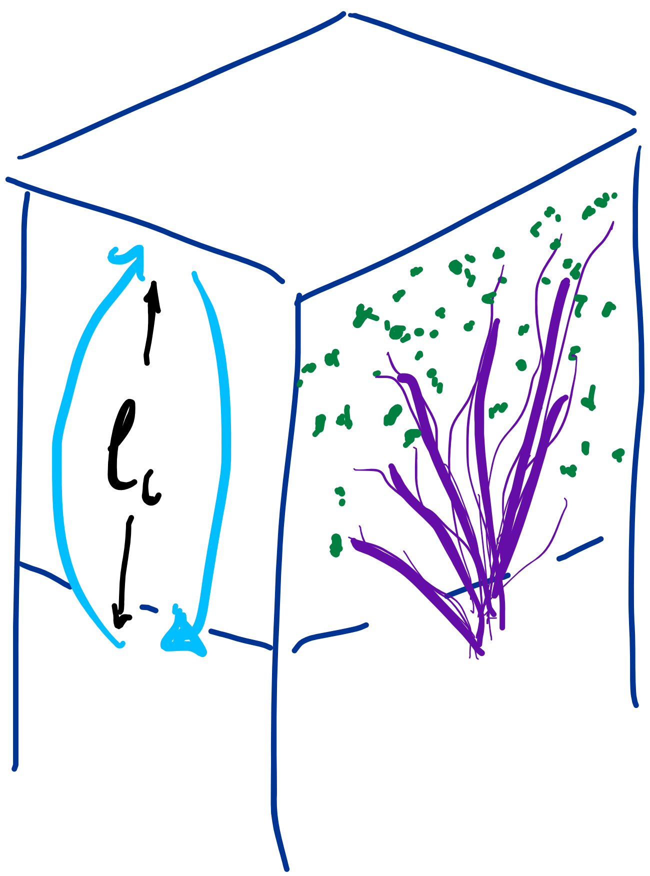
Oligotrophic (blue)
Mesotrophic (red)
Eutrophic (yellow)
Total basins/Global (green).

Similar scaling exponents emerge, regardless of how ocean basins are divided up





To understand this result, consider an isolated water column…



ℓ physical length scale

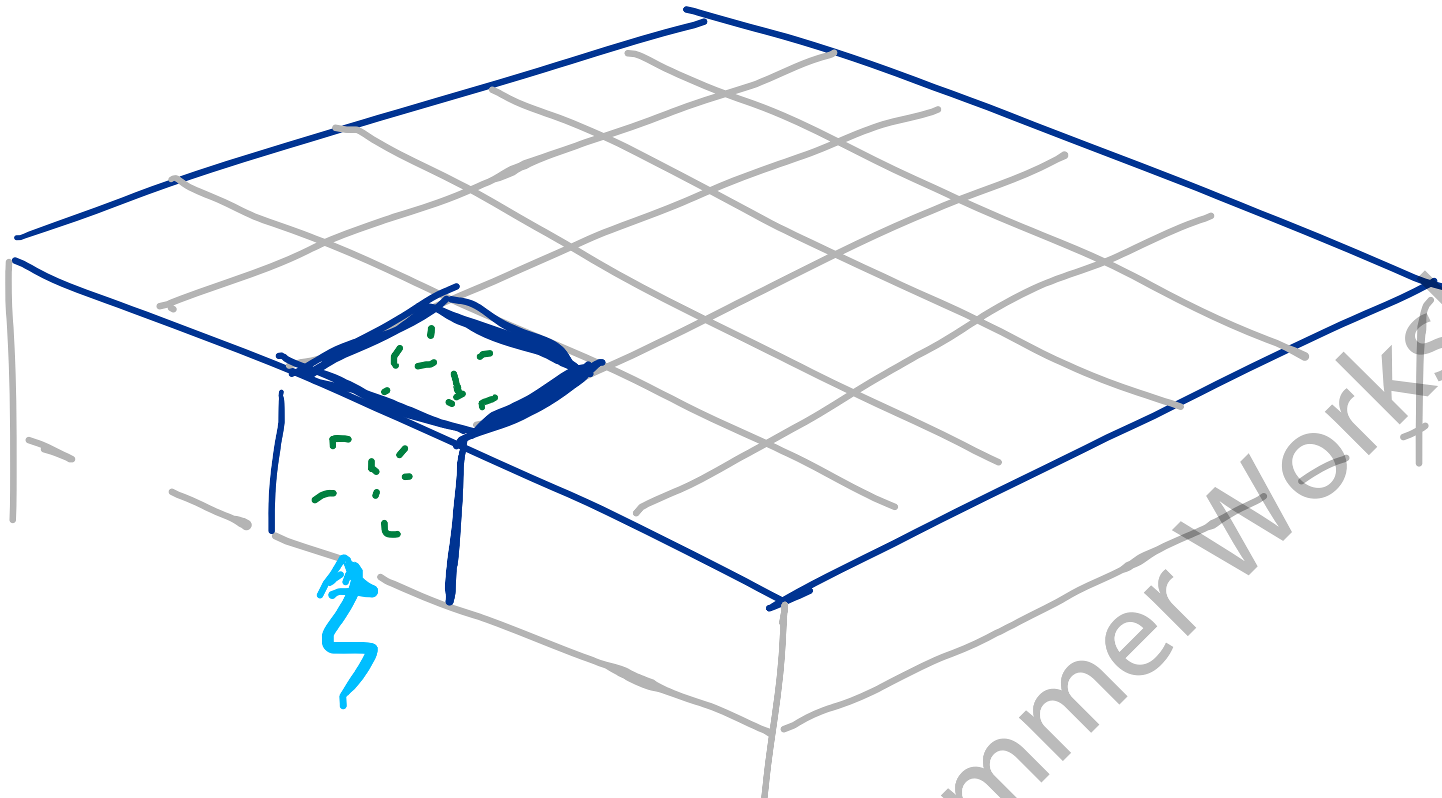
$V_i \sim \ell^3$ volume of water column

$P_i \sim V_i^{\alpha}$ productivity scaling

$\ell_c \sim \left(\varepsilon / \mu^3 \right)^{1/2}$ critical length scale matching growth rate to available energy (ε = dissipation)

$\mu = \tau^{-1}$ growth rate = 1/growth timescale

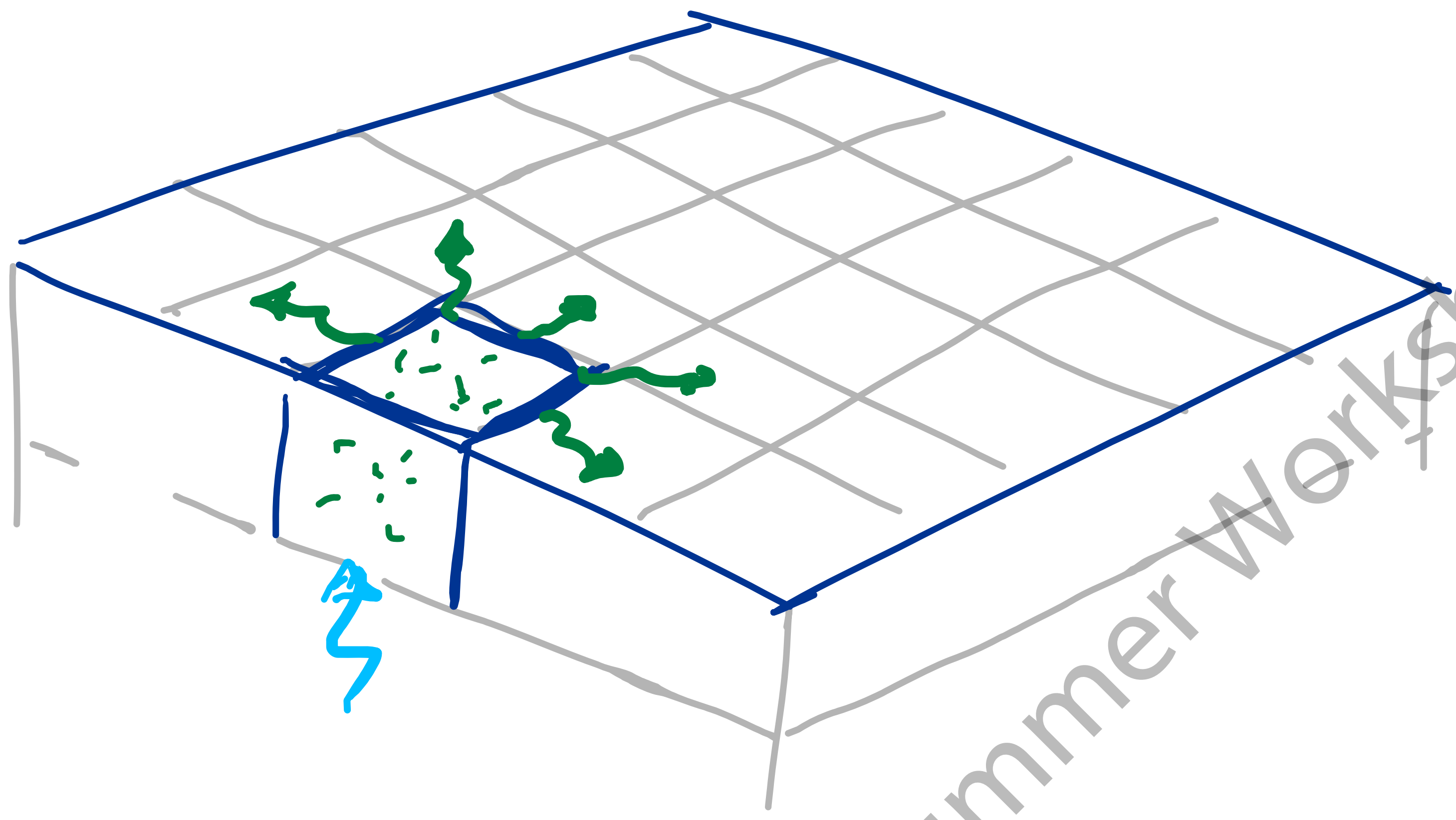
Next, imagine that this water column is the only source of upwelling in a region of the ocean that is otherwise unproductive



The productivity of the region is the sum of the individual water columns

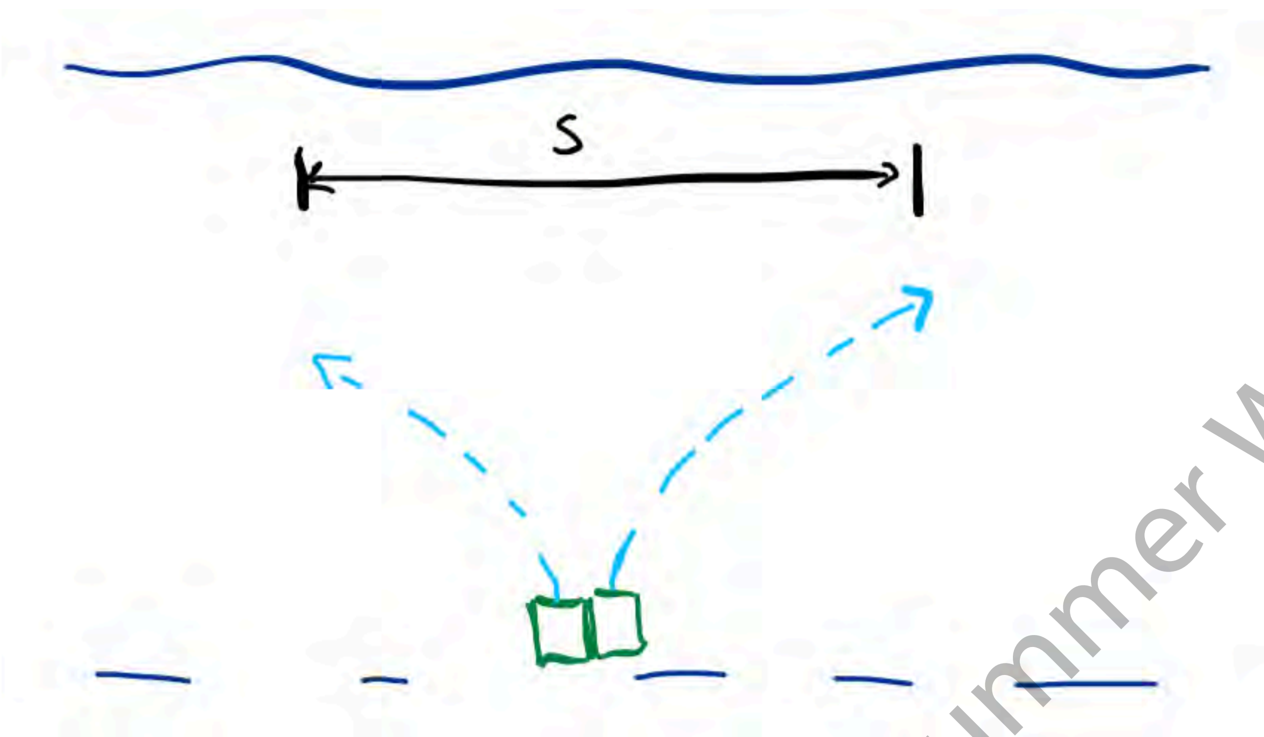
$$P_{TOT} = \sum_{n} P_i = n\bar{P}_i$$

This theoretical ocean can only have increased productivity with lateral spreading coupled to continued upwelling



Without lateral spreading, vertical motions simply mix down existing organic N with the upward movement of inorganic N

The relative horizontal diffusivity of upwelled nitrogen scales with dissipation and the horizontal distance, *s*



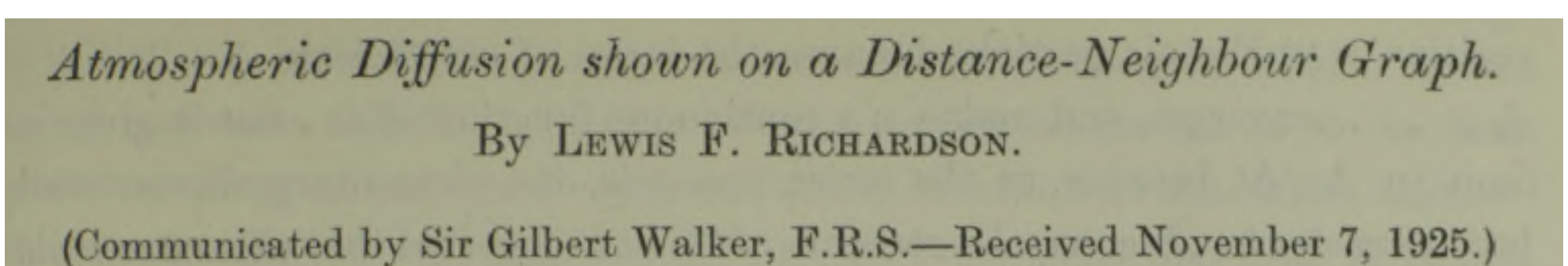
$$\tfrac{1}{2}\,\mathrm{d}s^2/\mathrm{d}t \propto \epsilon^{1/3} s^{4/3}$$

$$\varepsilon \approx \frac{L^2}{T^3}$$

Progress in Oceanography 70 (2006) 113–125

Turbulent dispersion in the ocean

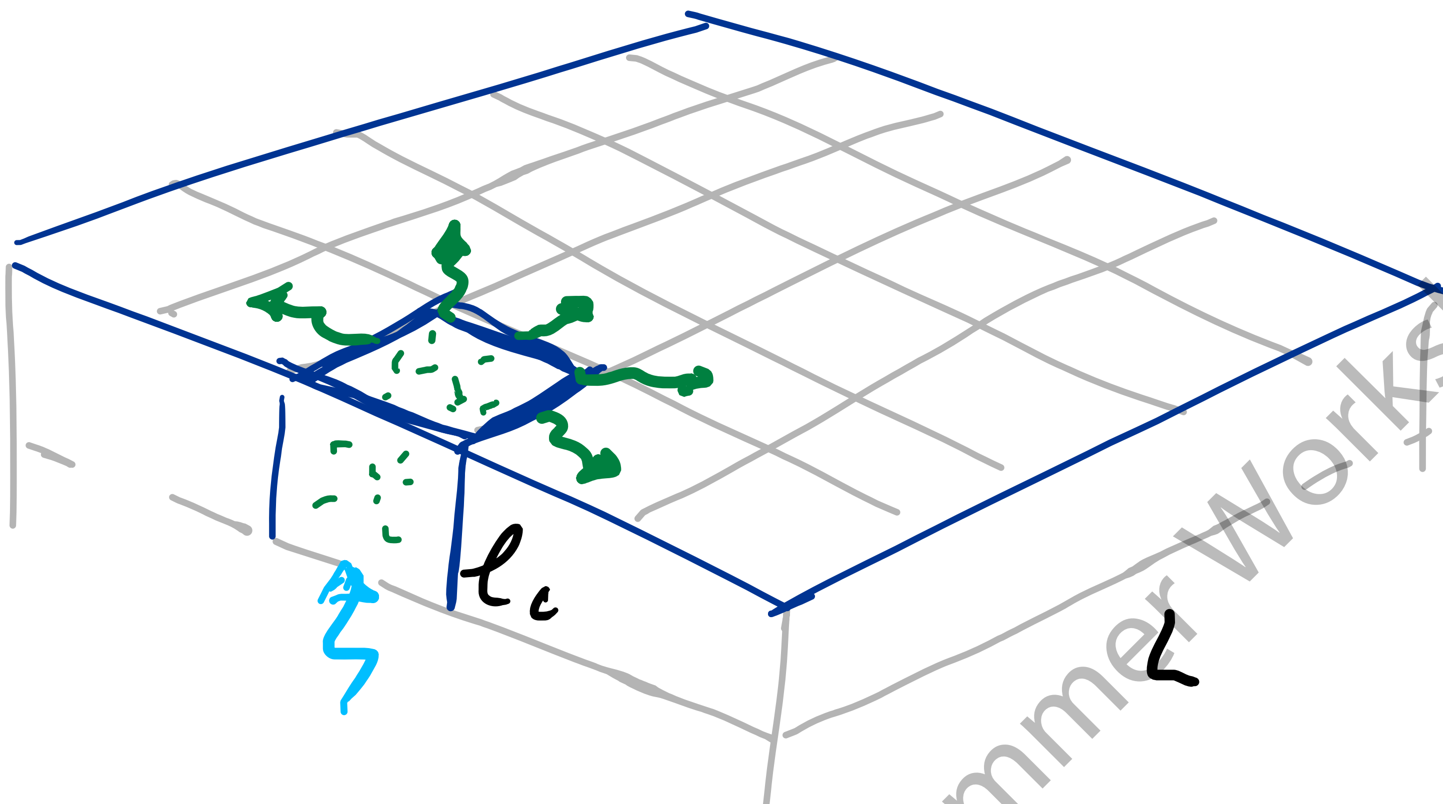
Chris Garrett *


Atmospheric Diffusion shown on a Distance-Neighbour Graph.

By Lewis F. Richardson.

(Communicated by Sir Gilbert Walker, F.R.S.—Received November 7, 1925.)

Thus, for the appropriate physical regimes, we can expect both vertical mixing and lateral transport to scale with dissipation



$$\varepsilon \approx \frac{\ell_c^{\,2}}{\tau^3} \approx \frac{L^2}{T^3}$$

JOURNAL OF PHYSICAL OCEANOGRAPHY

Interpreting Energy and Tracer Spectra of Upper-Ocean Turbulence in the Submesoscale Range (1–200 km)

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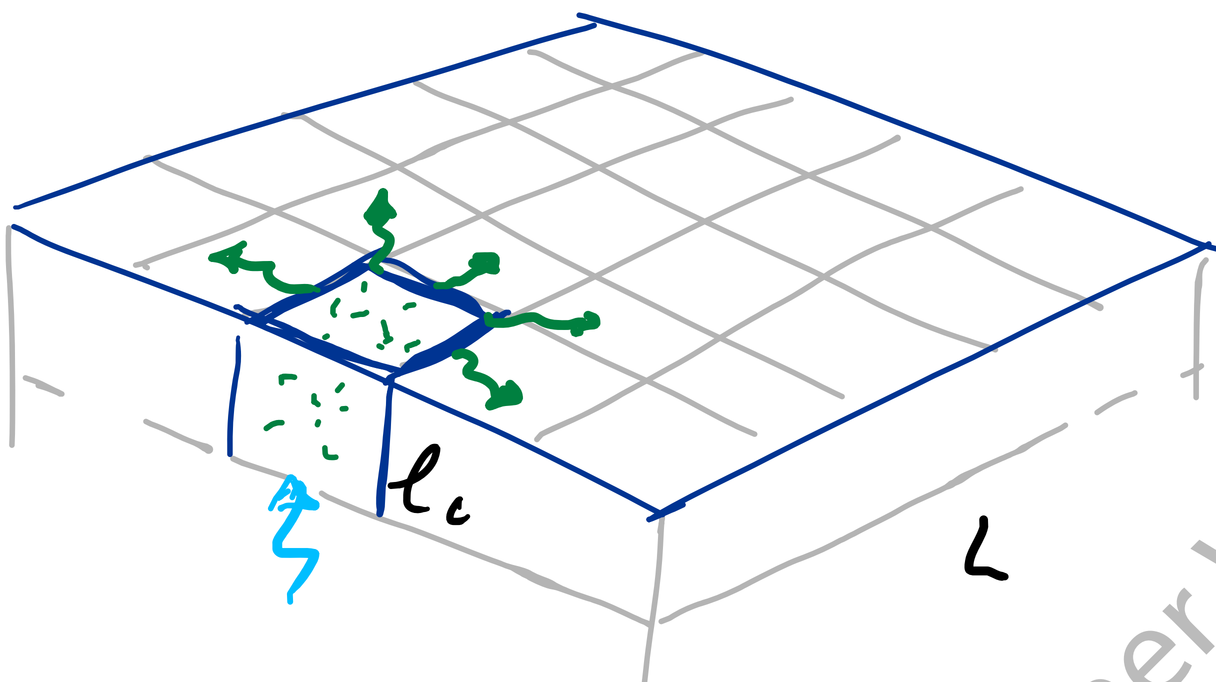
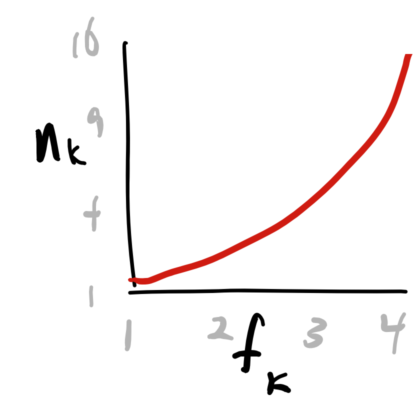
ICBST total community metabolism scales with the same ratio of timescales found in MTE theory



$$\ell_c^{-2} \simeq \frac{T^3}{\tau^3}\frac{1}{L^2}$$

$$n \simeq \frac{L^2}{\ell_c^2}$$

$$n_k \simeq f_k^2 = \frac{\ell^2}{\ell_c^2}$$

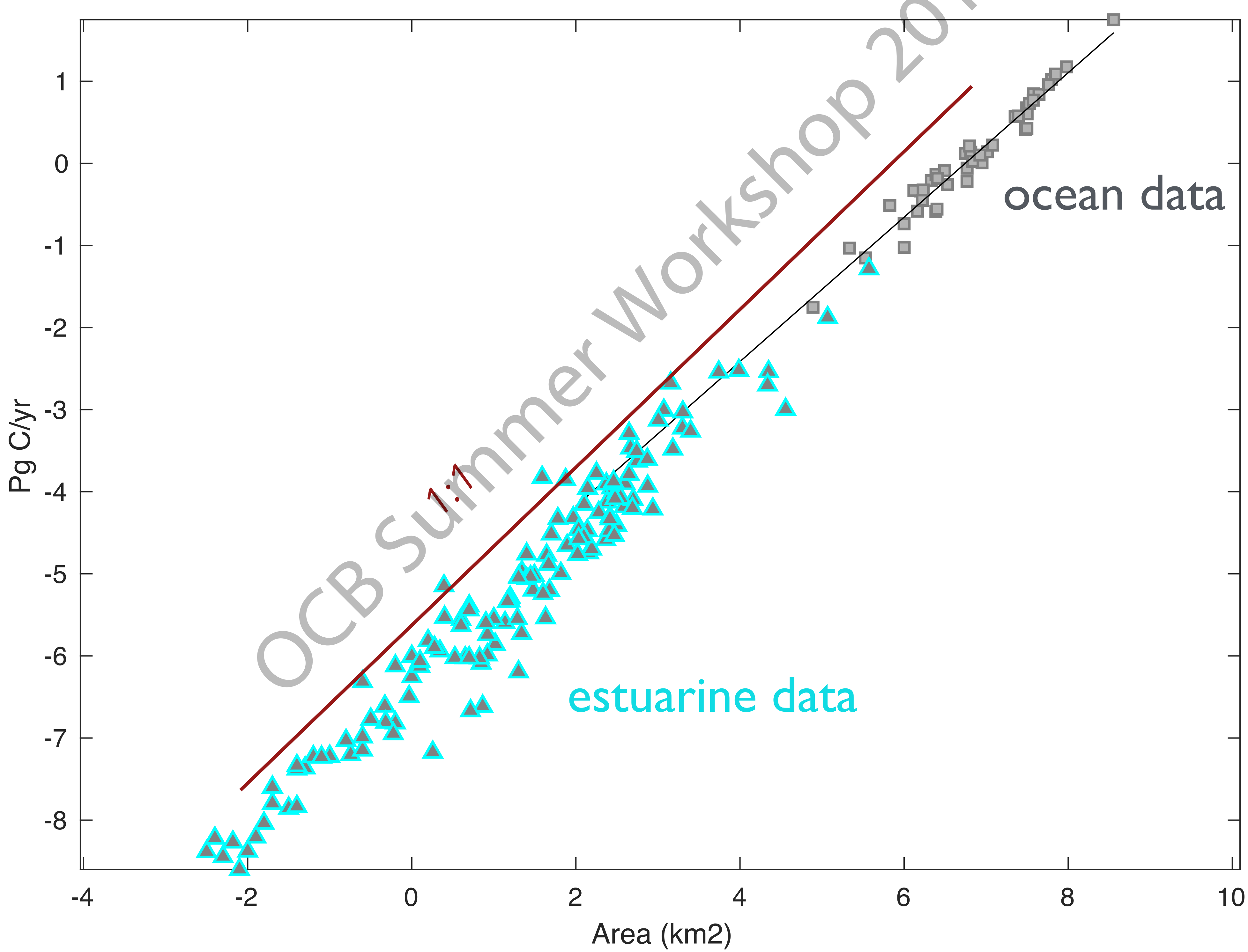


$$P_{TOT} = \sum_k \left(\sum_{n_k} P_{i,k}\right) = \sum_k n_k \bar{P}_{i,k}$$

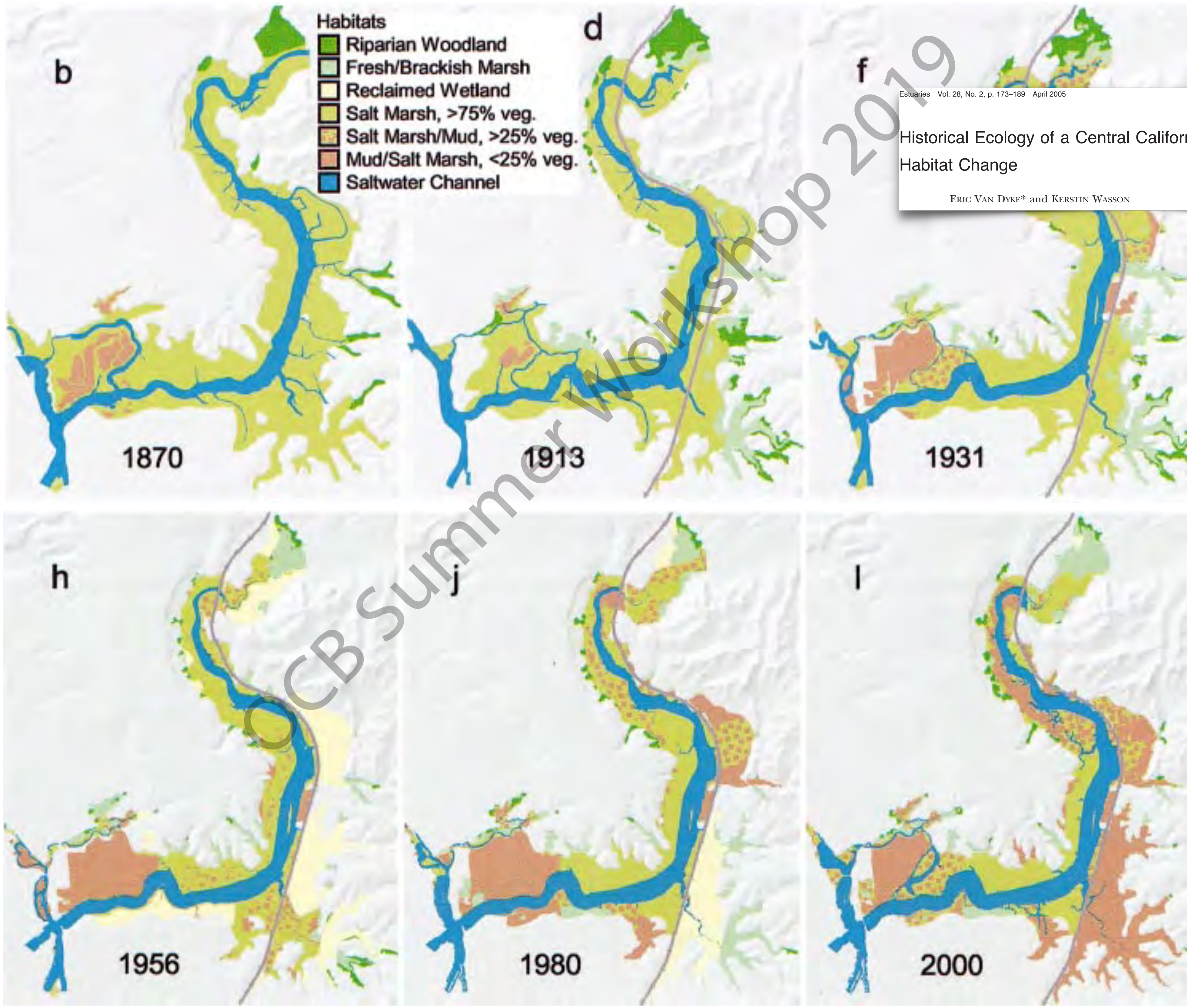
$$P_{TOT} \simeq \sum_k \frac{\ell^2}{\ell_{c,k}^2}\bar{P}_{i,k} \simeq \sum_k \frac{\ell^2}{L^2}\frac{T^3}{\tau^3}\bar{P}_{i,k}$$

$$P_{TOT} \sim \frac{T^3}{\tau^3}\sum_k \frac{1}{n}\frac{f_k^2}{f_k^{3\alpha}} V_i^{\alpha} \sim \frac{T^3}{\tau^3}\sum_k \frac{n_k}{n}\frac{V_i^{\alpha}}{f_k^{3\alpha}}$$

What can we do with the observation that estuaries and ocean basins scale similarly with regard to primary production?



What are some possible applications of these ideas?
(1) estimating role of lost habitats



Estuaries Vol. 28, No. 2, p. 173–189 April 2005

Historical Ecology of a Central California Estuary: 150 Years of Habitat Change

Eric Van Dyke* and Kerstin Wasson

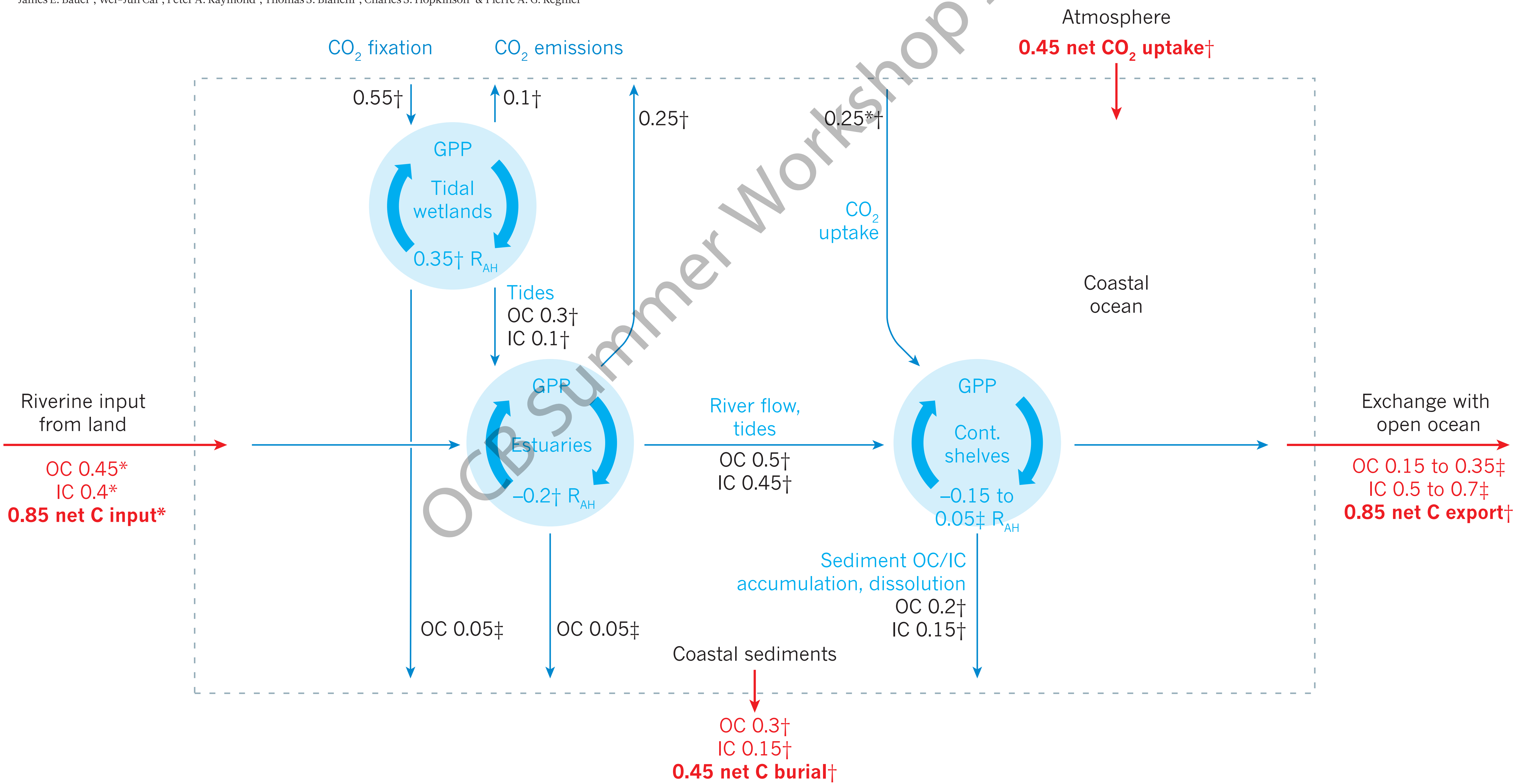
What are some possible applications of these ideas?
(2) constraining current budgets

REVIEW

doi:10.1038/nature12857

The changing carbon cycle of the coastal ocean

James E. Bauer[1], Wei-Jun Cai[2], Peter A. Raymond[3], Thomas S. Bianchi[4], Charles S. Hopkinson[5] & Pierre A. G. Regnier[6]

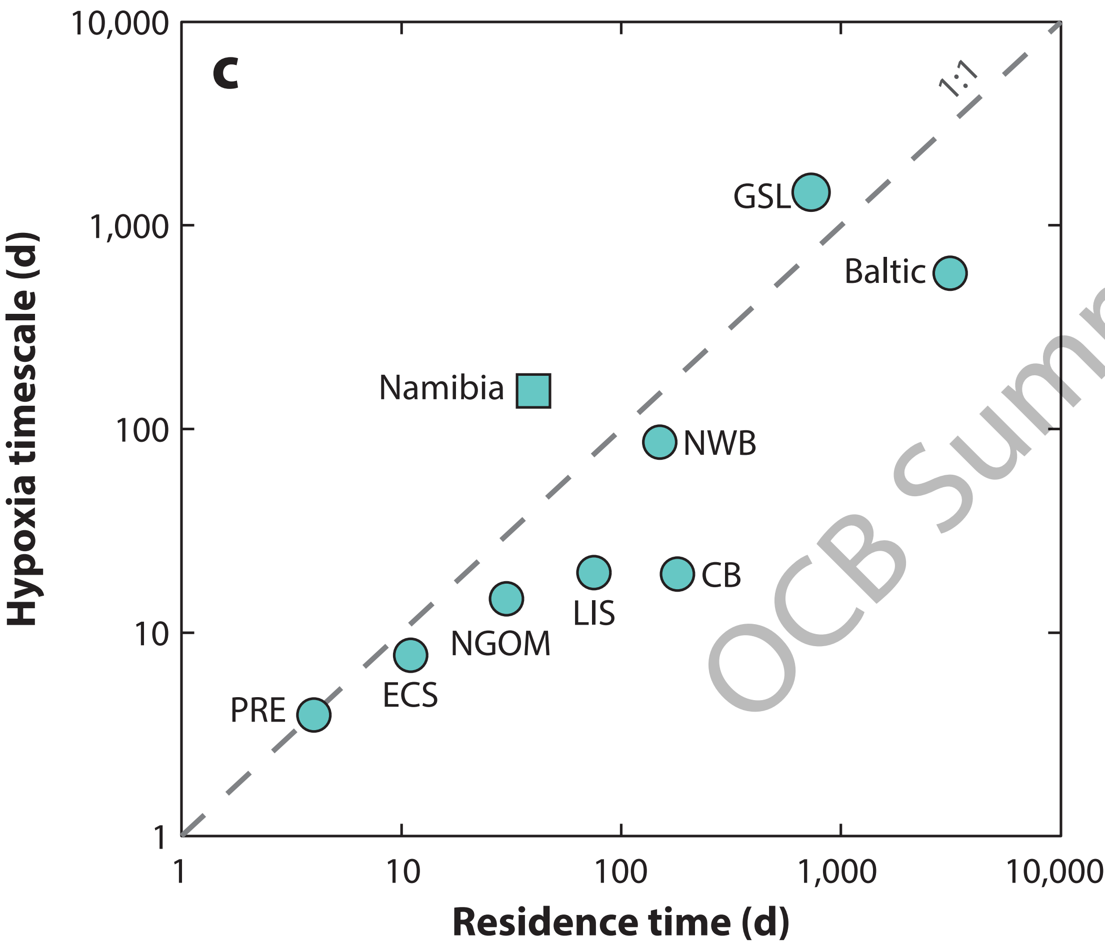


What are some possible applications of these ideas?
(3) interpreting other spatial patterns

Annual Review of Marine Science

Biogeochemical Controls on Coastal Hypoxia

Katja Fennel[1] and Jeremy M. Testa[2]

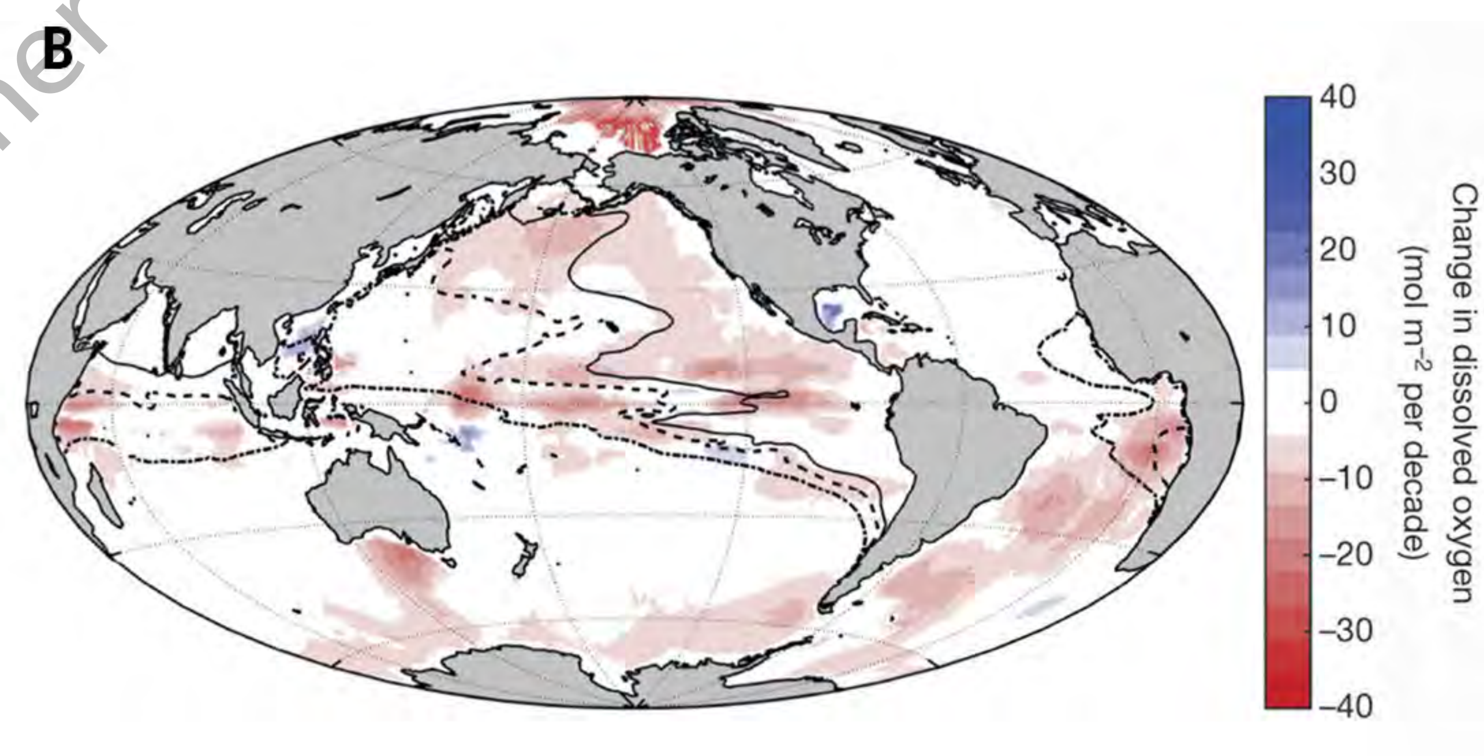


REVIEW

OCEANS

Declining oxygen in the global ocean and coastal waters

Denise Breitburg,[1*] Lisa A. Levin,[2] Andreas Oschlies,[3] Marilaure Grégoire,[4] Francisco P. Chavez,[5] Daniel J. Conley,[6] Véronique Garçon,[7] Denis Gilbert,[8] Dimitri Gutiérrez,[9,10] Kirsten Isensee,[11] Gil S. Jacinto,[12] Karin E. Limburg,[13] Ivonne Montes,[14] S. W. A. Naqvi,[15]† Grant C. Pitcher,[16,17] Nancy N. Rabalais,[18] Michael R. Roman,[19] Kenneth A. Rose,[19] Brad A. Seibel,[20] Maciej Telszewski,[21] Moriaki Yasuhara,[22] Jing Zhang[23]



What are some possible applications of these ideas? (4) predicting future states

Progress in Oceanography 136 (2015) 60–70

Continued increases in Arctic Ocean primary production

Kevin R. Arrigo *, Gert L. van Dijken

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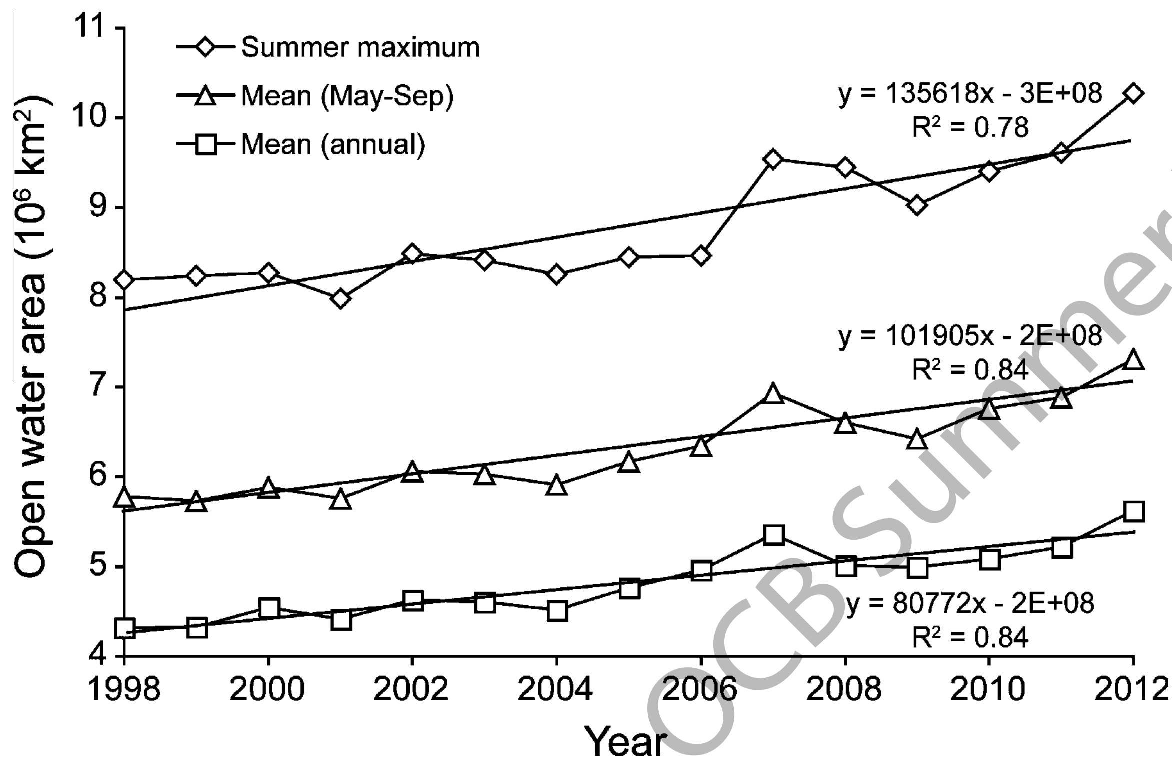
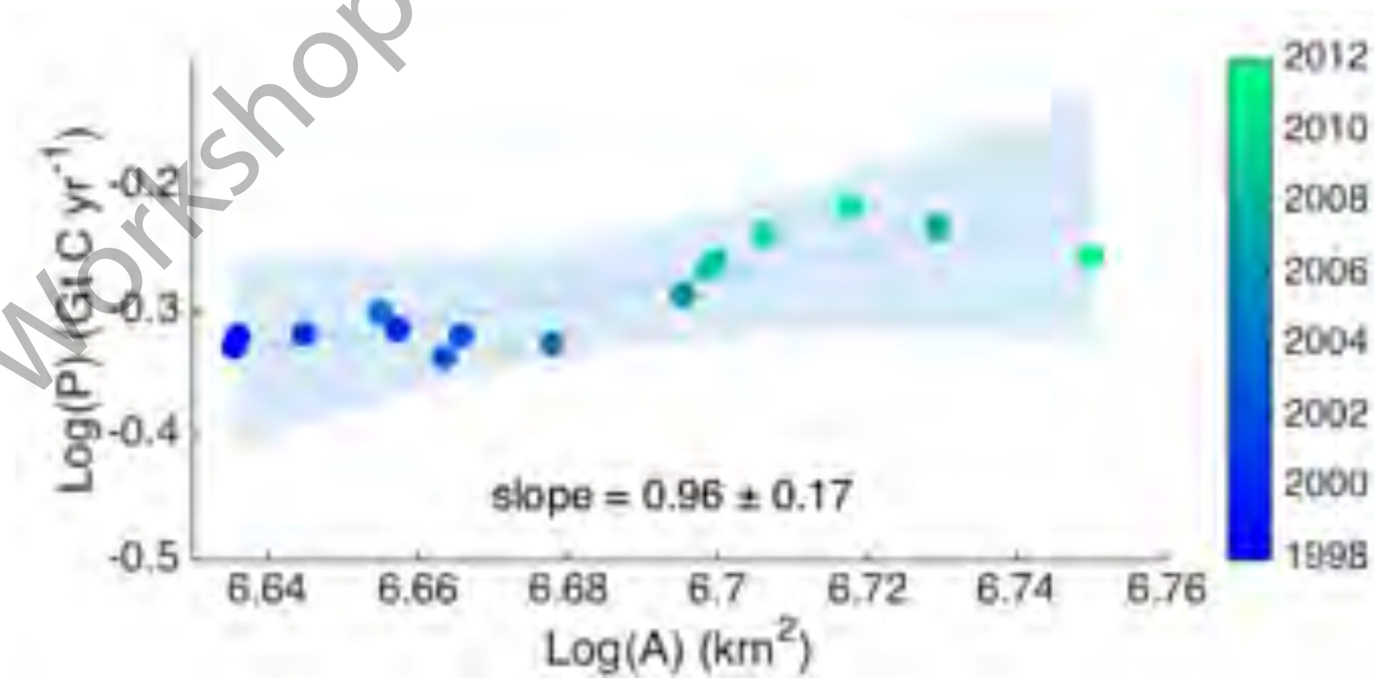
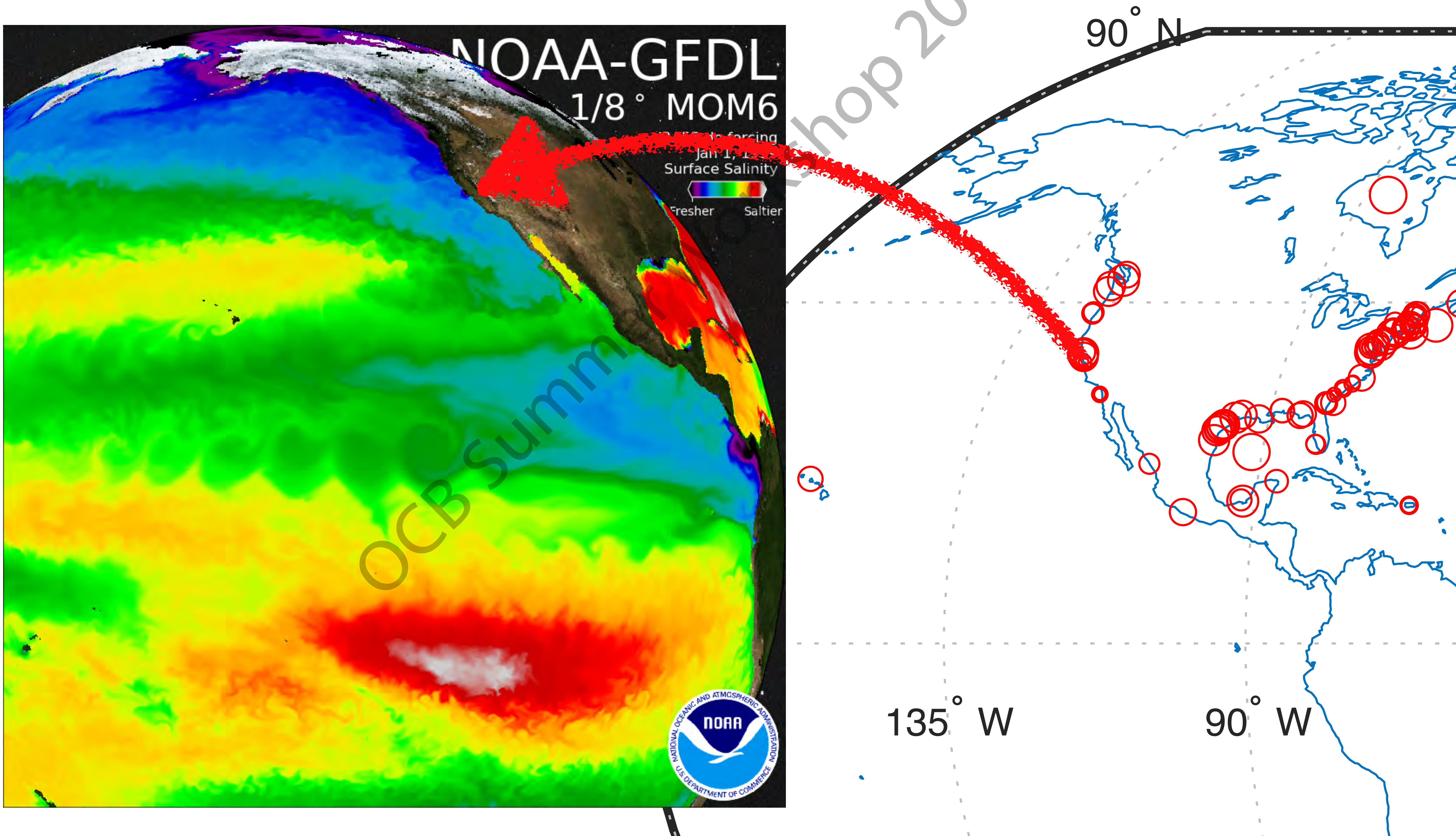


Fig. 2. Changes in the amount of open water area in the Arctic Ocean between 1998 and 2012 based on three different metrics (summer maximum open water area, mean open water area between 1 May and 31 September, and annual mean open water area).



What are some possible applications of these ideas?
(5) parameterizing sub-grid scale processes in GOMs



In summary

Estuaries

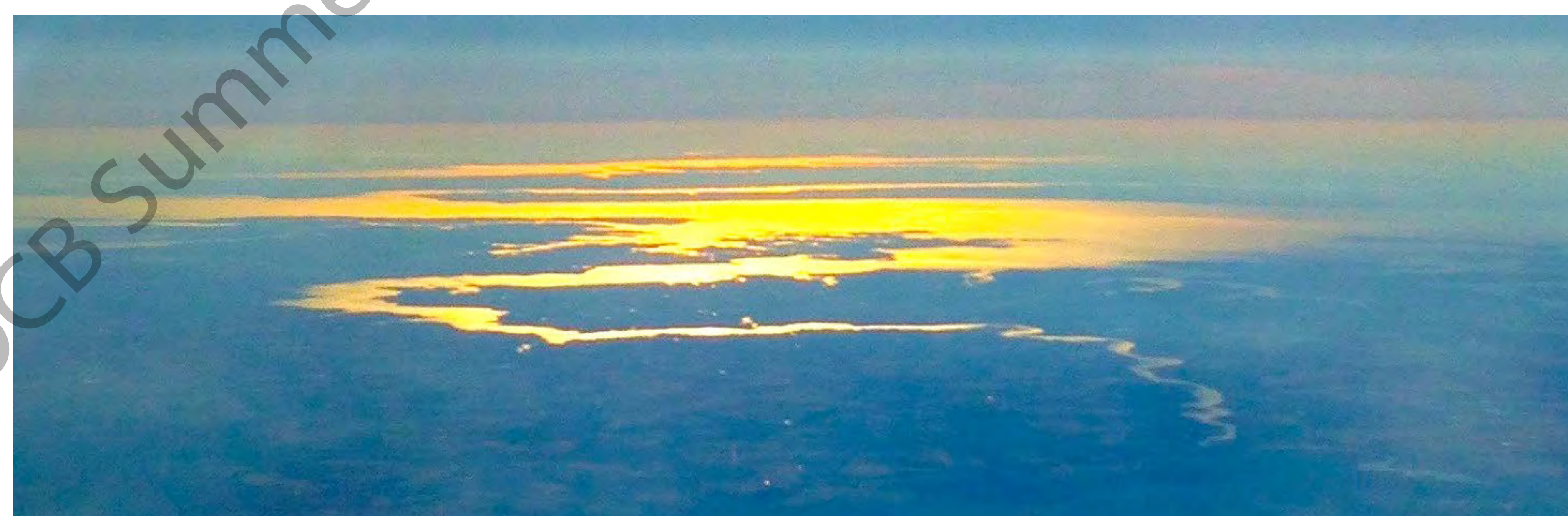
Ecosystem metabolism scales nonlinearly with size
(related to changes in transport time driven primarily by depth)

area-productivity relationships

metabolic scaling theory may provide insights into estuarine and ocean physics

Ocean

Community metabolism scales nonlinearly with size
(related to changes in transport time that scale with dissipation?)



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