An homage to Santiago (St. James)

Or: *why is there some much carbon (research) in freshwaters*

With sincere apologies to G. E. Hutchinson for stealing the title

Santiago= Santo Iago = St. James

Statue just outside

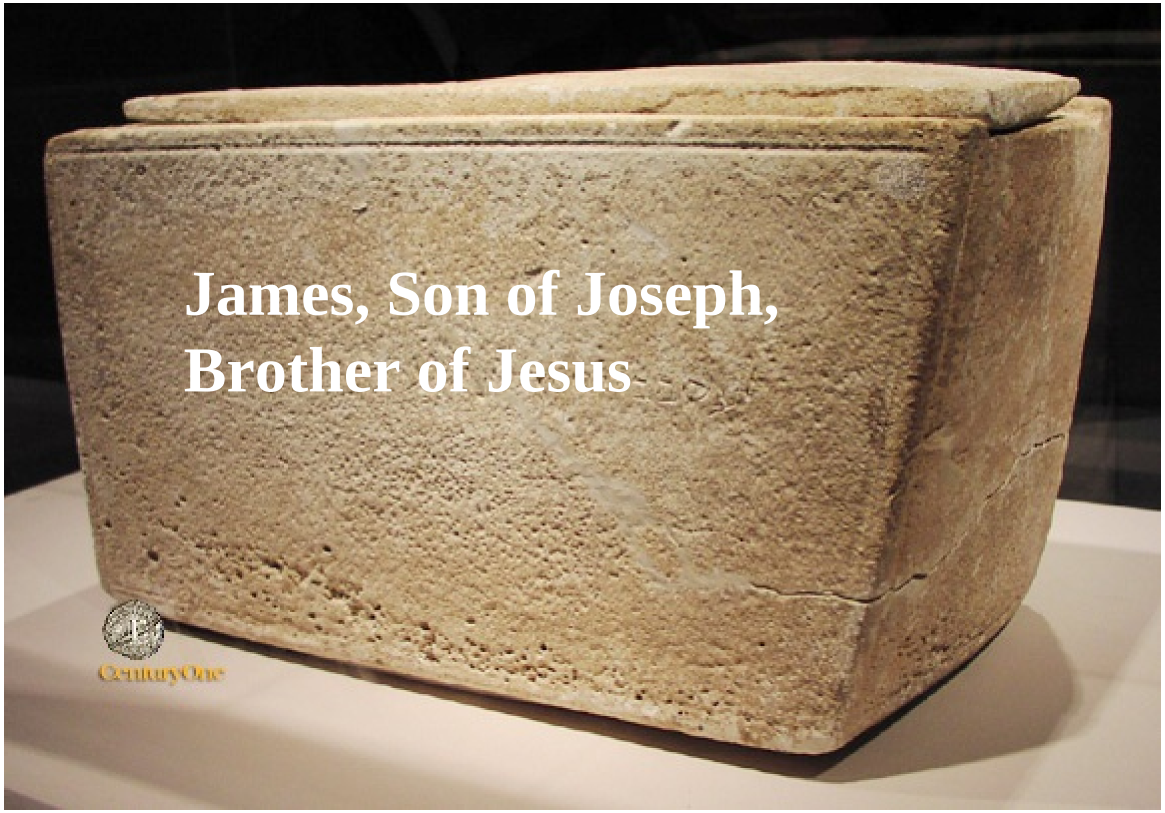
Portrait by Albrect Durer, 1500

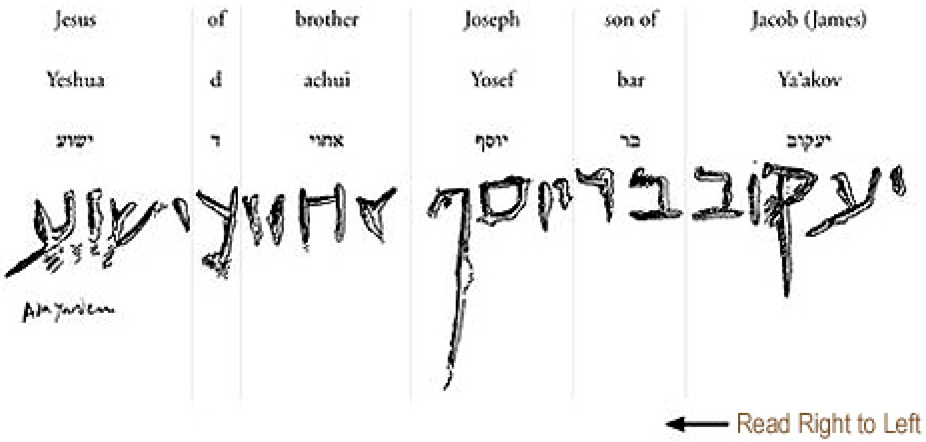
Who was St. James?

Close relative, maybe brother, of Jesus.

Tradition has James interred here at the *"starry field"* (campos des stellas)

So Santiago de Compostela.





The St. James ossuary found in Jerusalem on 2002.

The inscription has been discredited as a forgery.

So maybe St. James is really here in Santiago

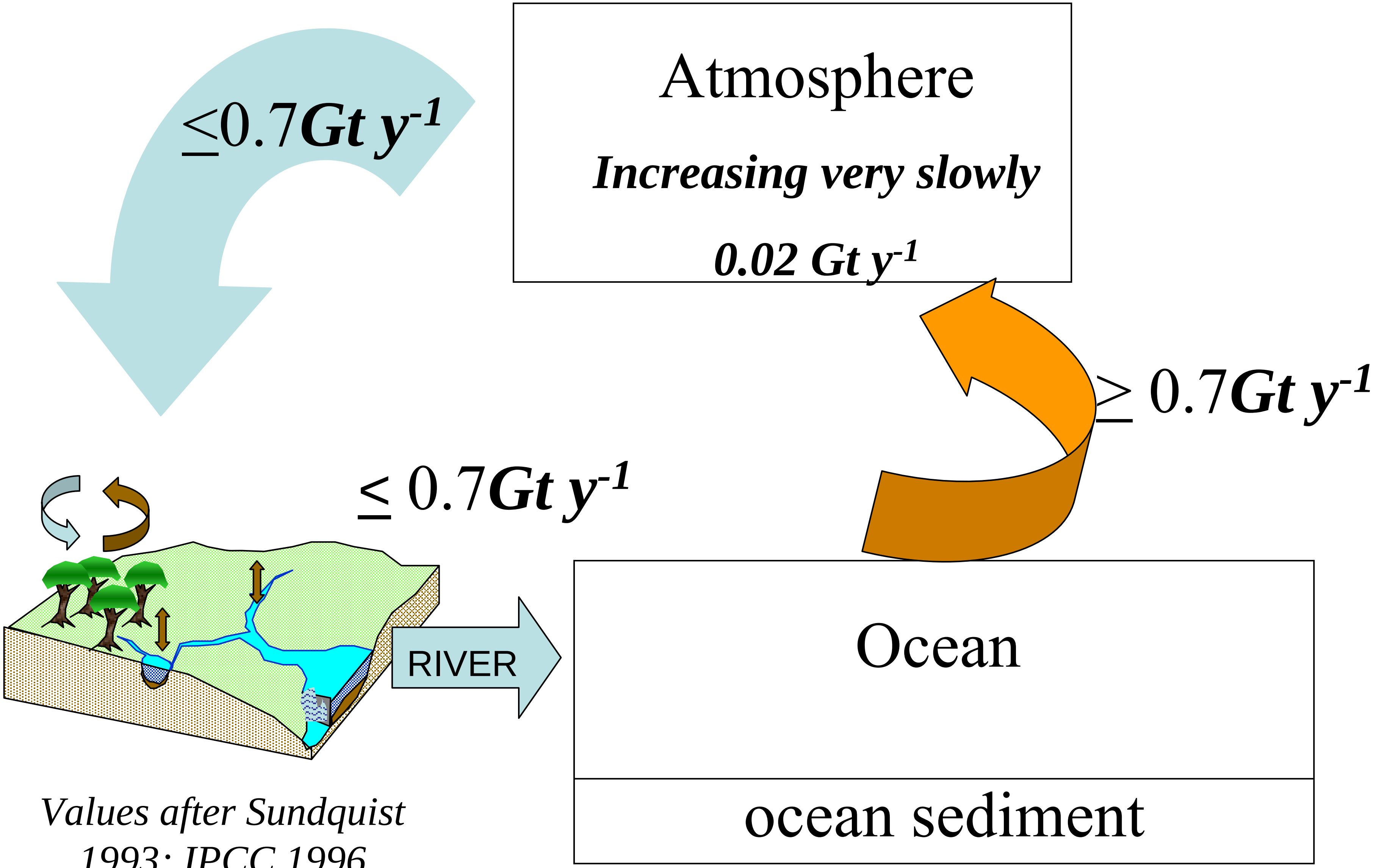
The connection between St. James and limnology and oceanography

- St. James was martyred ~42 AD.
- The C cycle 2,000 years ago was not as it is today.
- Ocean was a net SOURCE of CO_2 to the atmosphere.
- Atmospheric CO_2 was near steady state
- Good time frame to look at the role of freshwaters

This talk

- Are freshwaters just a footnote to regional and global C balance?
- How does freshwater C transport affect the ocean?
- What happens to terrestrial C in lakes and rivers?
- Identify some research opportunities in the freshwater C cycle.

Post glacial (10,000 y) – St. James C cycle



≤ 0.7***Gt y***$^{-1}$

Atmosphere

Increasing very slowly

0.02 Gt y^{-1}

$\geq$ 0.7***Gt y***$^{-1}$

$\leq$ 0.7***Gt y***$^{-1}$

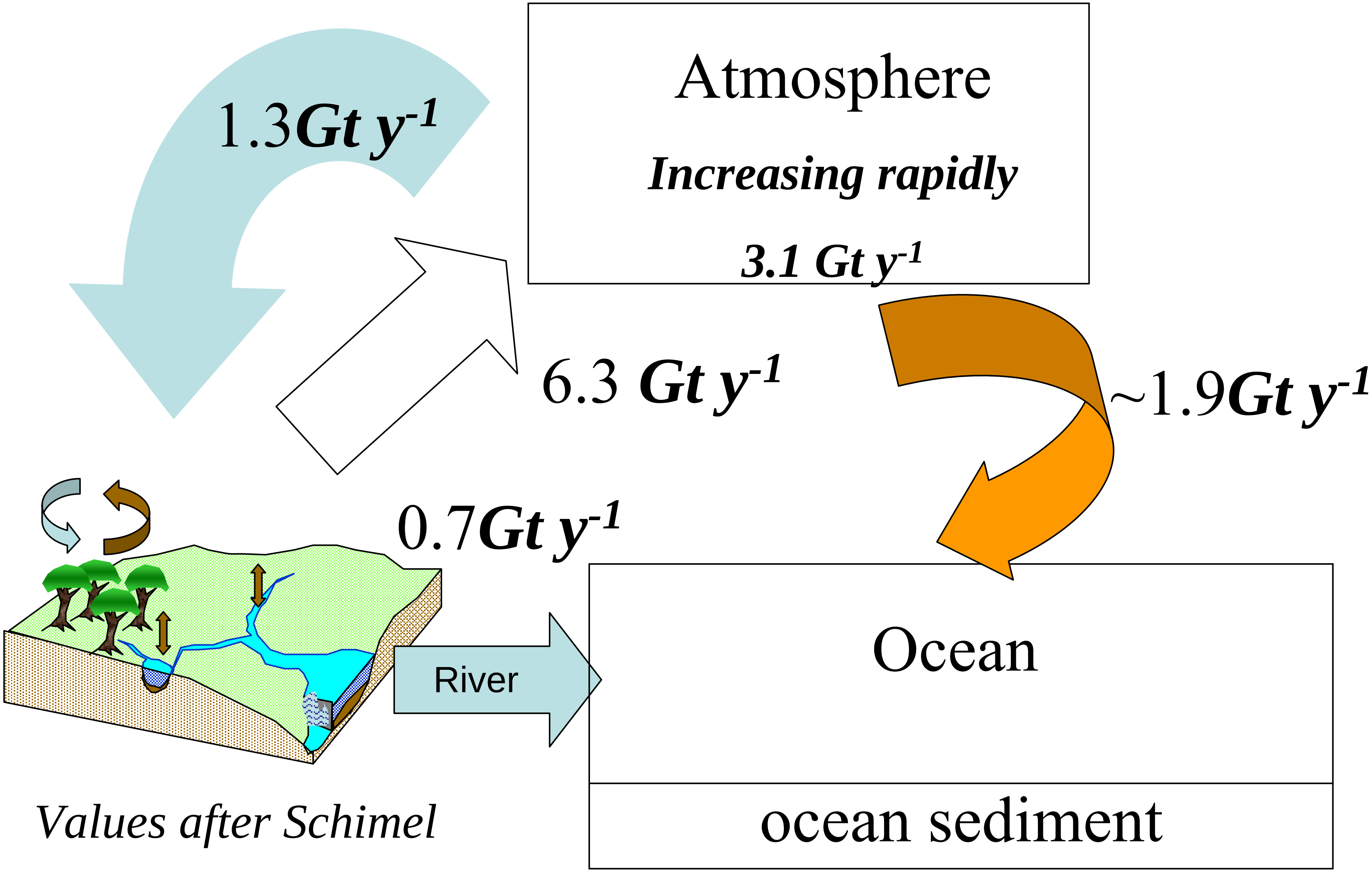
RIVER

Ocean

ocean sediment

Values after Sundquist 1993; IPCC 1996

Modern (50 y)



1.3***Gt y***$^{-1}$

Atmosphere

Increasing rapidly

3.1 Gt y^{-1}

6.3 ***Gt y***$^{-1}$

~1.9***Gt y***$^{-1}$

0.7***Gt y***$^{-1}$

River

Ocean

ocean sediment

Values after Schimel et al 2001

The St. James (Santiago) C cycle

- NEP on land is largely exported – storage is small.
- Riverine export of terrestrial NEP completes the cycle.
- Implies that riverine C is ‘rapdily’ returned to the atmosphere as CO_2
- The ocean (as a whole) is net heterotrophic (R>GPP) fueled by terrestrial C delivered by rivers.

The modern C cycle

- There is a missing C sink on ‘land’ of some 1.3 Gt C y^{-1}.
- The ocean is a large physical sink of CO_2 due to rising atmospheric levels.
- The ocean is still net heterotrophic
- Riverine transport can no longer escape the ocean to the atmosphere because the net flux is reversed – it has been capped by fossil fuel combustion.

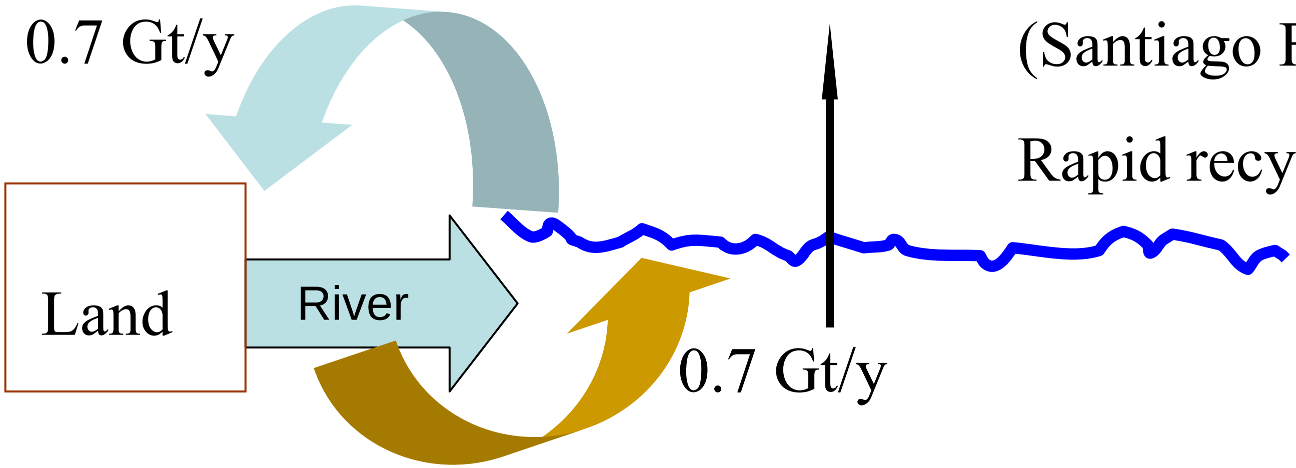
So, part of the ‘missing sink’ may actually be riverine transport

- Even if the magnitude of transport has not changed, this C no longer reaches the atmosphere.
- One way trip of about 0.7 Gt y^{-1}
- So the “terrestrial sink” is perhaps 1.3-0.7 or 0.6 Gt C y^{-1}.
- *Our terrestrial colleagues should set their sites on finding a **smaller** sink on land*.
- *Oceanographers should consider an oceanic sink which is **larger** than that implied by delta pCO_2 with the atmosphere.*

St. James Shuffle

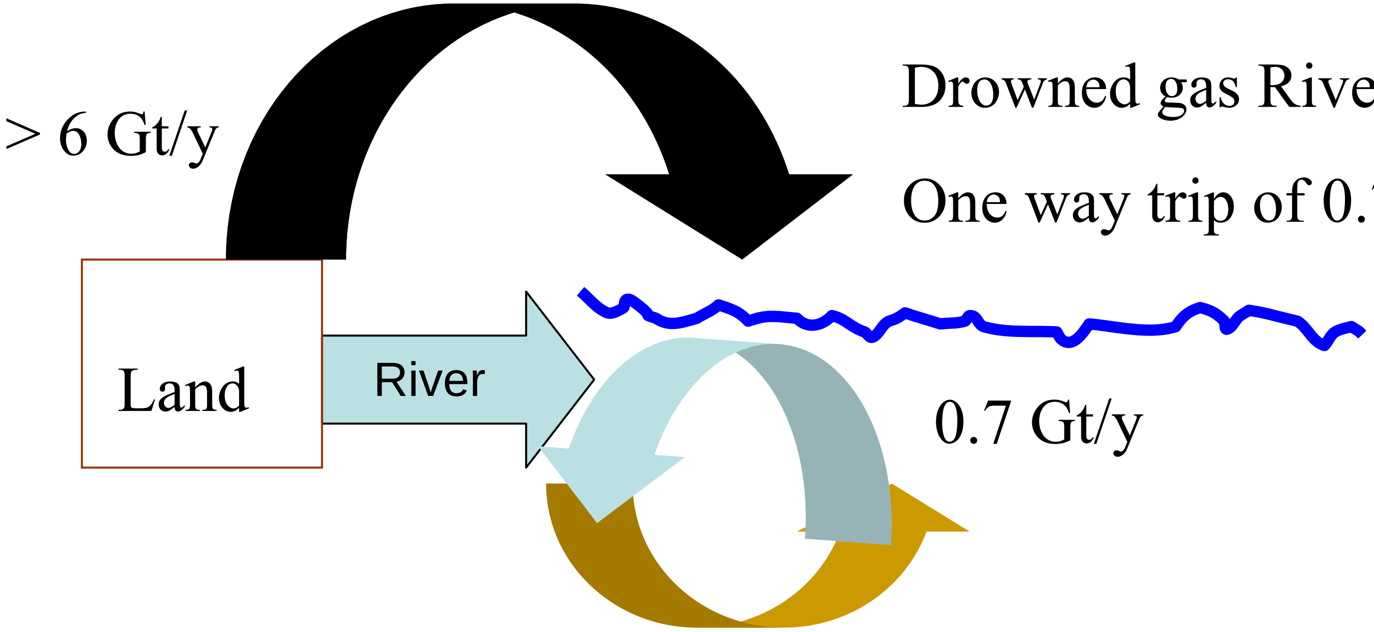
(Santiago Fandango)

Rapid recycle of 0.7 Gt/y



Drowned gas River-Dance

One way trip of 0.7 Gt/y



So you might want to study freshwaters to balance the global C budget. Controversial.

Blame these folks (NCEAS working group)

Hear the experts on these topics:

- **SS26 Respiration in Aquatic Ecosystems: Current Understanding and Future Directions**
  Organizers: Peter J. Le B. Williams and Paul A. del Giorgio. (Wed & Thurs afternoon)
- **SS47 Autotrophic and Heterotrophic Relationships in Streams and Rivers**
  Organizers: Bill Sobczak, Sergi Sabater. (Wed Posters)
- **SS89 Global Limnology**
  Organizers: Yves Prairie, Jonathan Cole. (Mon PM and Tues Posters)

Some net heterotrophy algebra

- **G**ross **P**rimary **P**roduction (GPP)
  - Total photosynthesis.
- **R**espiration (R)
  - Includes autotrophic and heterotrophic
- GPP – R = **N**et **E**cosysytem **P**roduction
  - NEP can be POSITIVE or NEGATIVE
- If R > GPP, NEP is negative. R is subsidized by external input or ‘mining’ of prior storage.

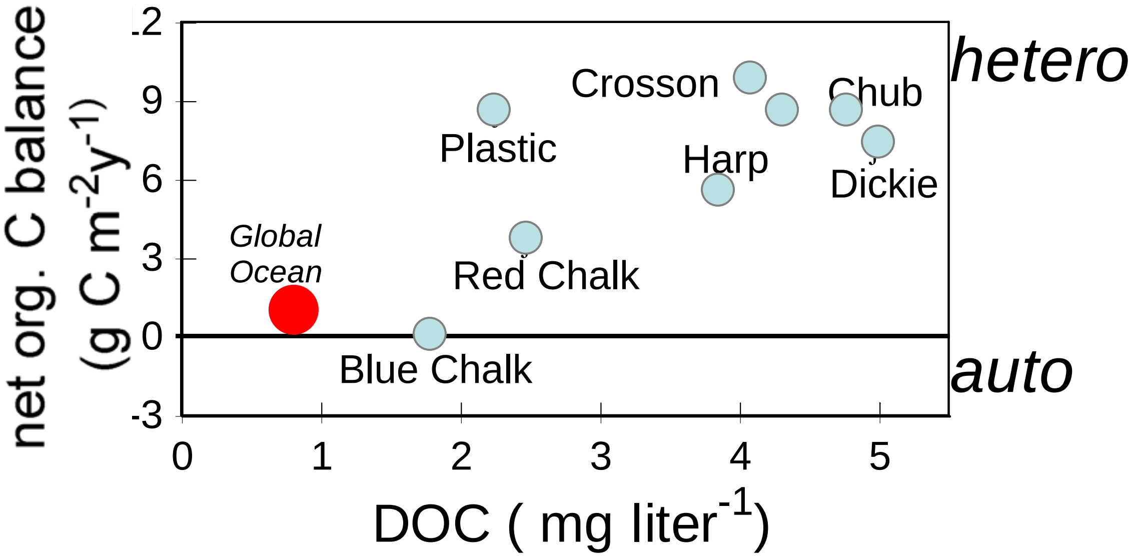
Net heterotrophy by mass balance

- NEP = GPP –R (*difficult to measure if low!*)
- Can also do it without R or GPP

- NEP = **B**urial + **E**xport – external **I**nput
- If I > (B+E), NEP is Negative.

Oceanic NEP is negative

- For the global ocean (*organic* C values)
  - **E**xport is negligible
  - **B** = ~0.12 Gt C y^{-1}
  - Riverine org C **I**nput =~ 0.4 Gt C y^{-1}
  - NEP = B+E-I = 0.12 +0 -0.4 = **-**0.28 Gt C y^{-1}
  - Therefore R > GPP by about 0.28 Gt C y^{-1}
- Ocean is a biological CO_2 source of 0.28 Gt C y^{-1}
- But the ***total*** source 0.7 Gt C y^{-1} (for the St. James Ocean)
- Remaining 0.42 (e.g. 0.7 - 0.28) from the inorganic C inputs in rivers and from carbonate precipitation.



Lake organic C mass balances (*from Dillon and Molot 1997*).

net balance = I - (B + E)

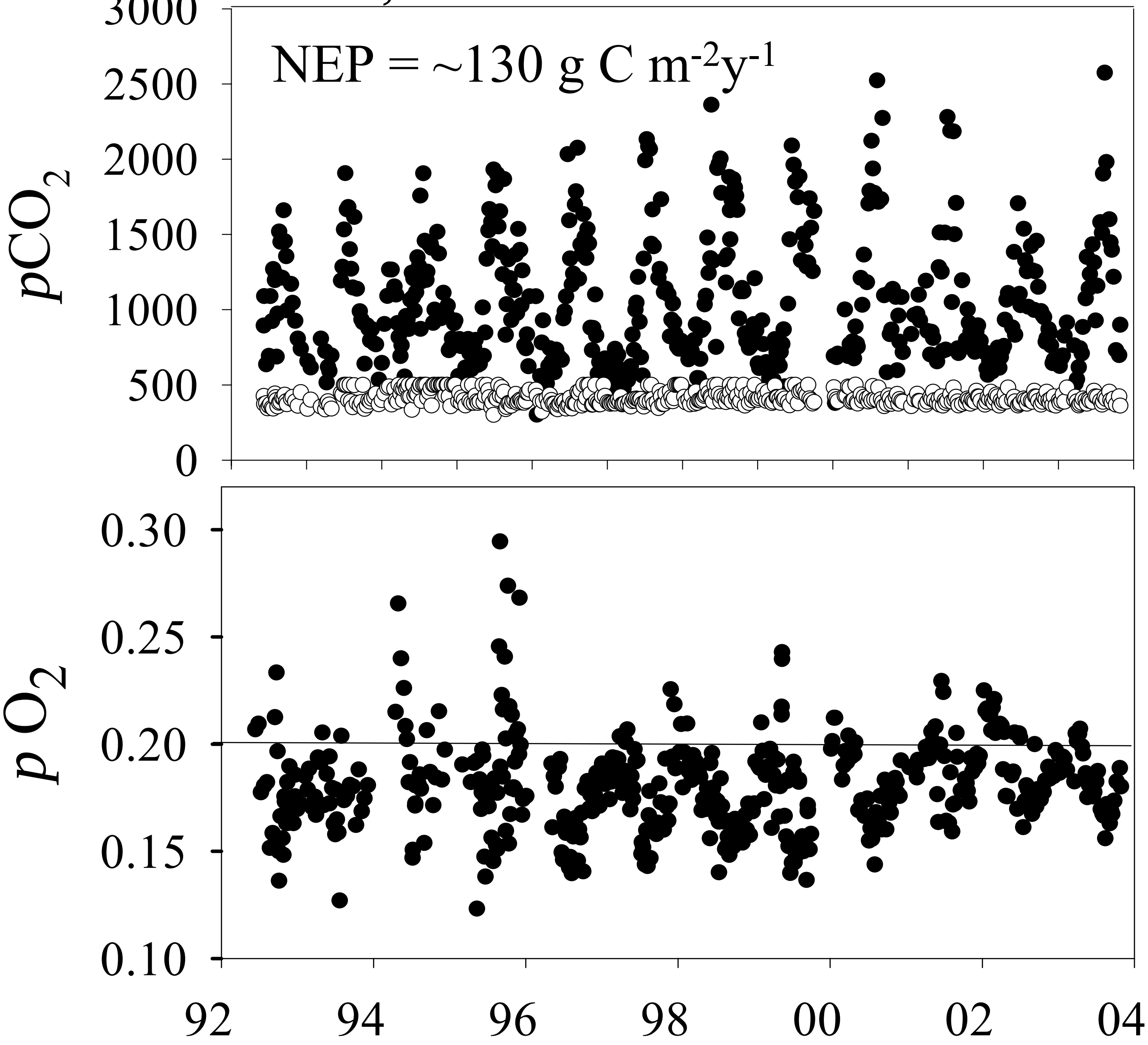
For lakes, rivers can easily measure NEP by direct gas flux

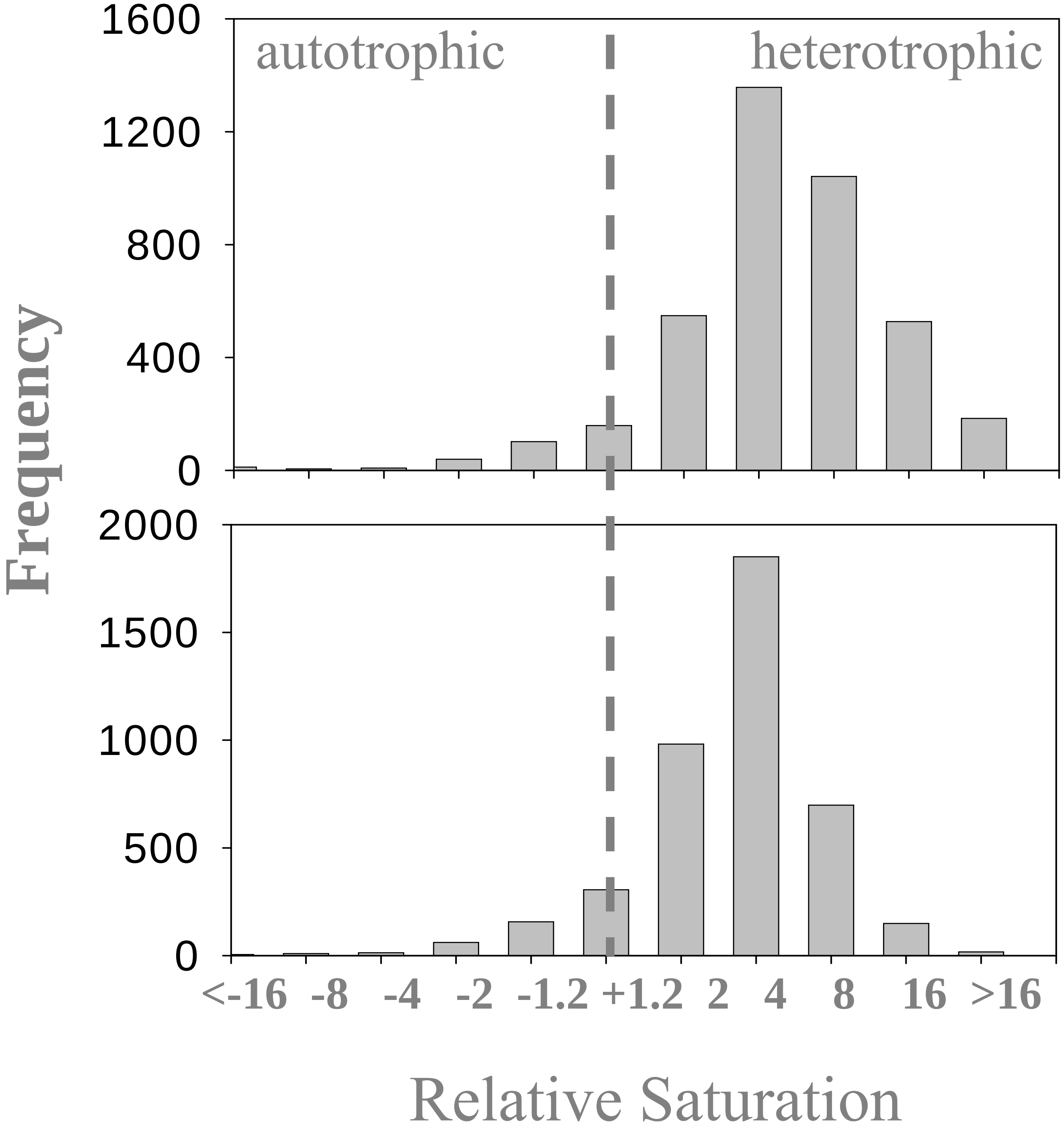
- So, NEP = B+E – I;
- NEP typically NEGATIVE
- NEP = GPP-R; So R should be > GPP

- Consequence, lake should be SINK for O_2 and SOURCE of CO_2 to atmosphere.

Hudson River

Hudson River – *Raymond et al. 1997; Cole and Caraco 2001*


NEP = ~130 g C $m^{-2}y^{-1}$



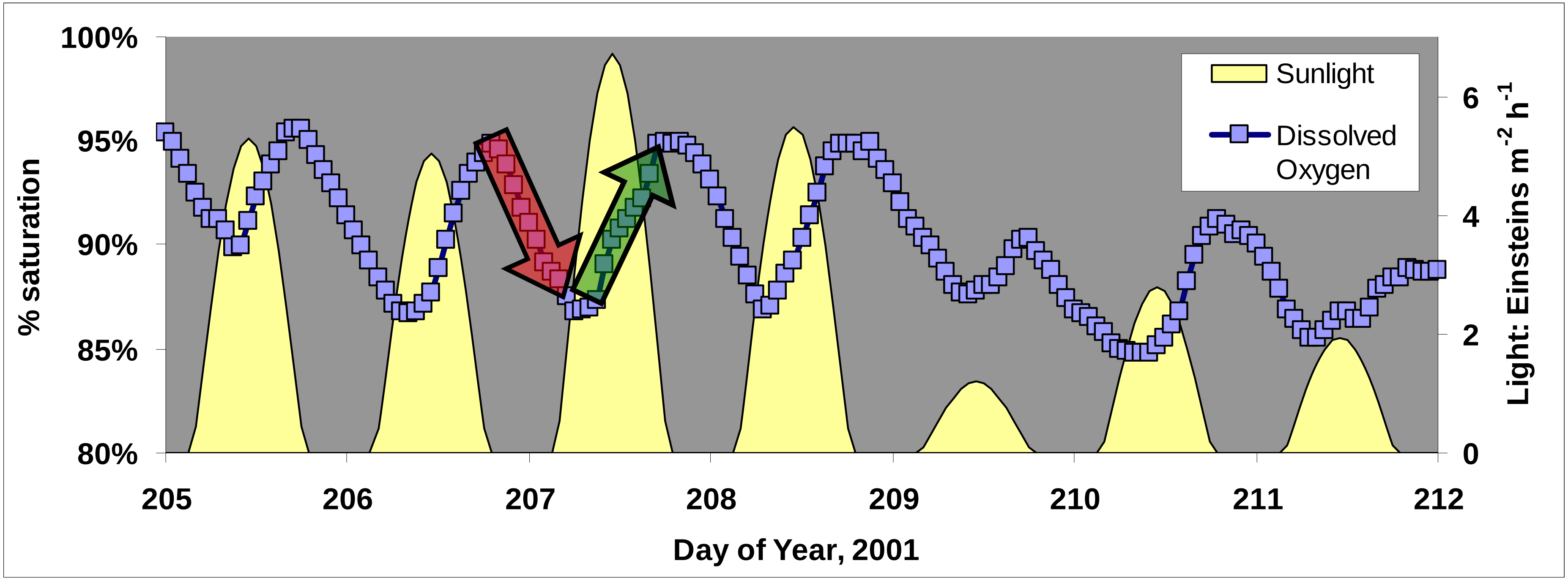
Rivers

Cole & Caraco 2001

Lakes

Cole et al. 1994

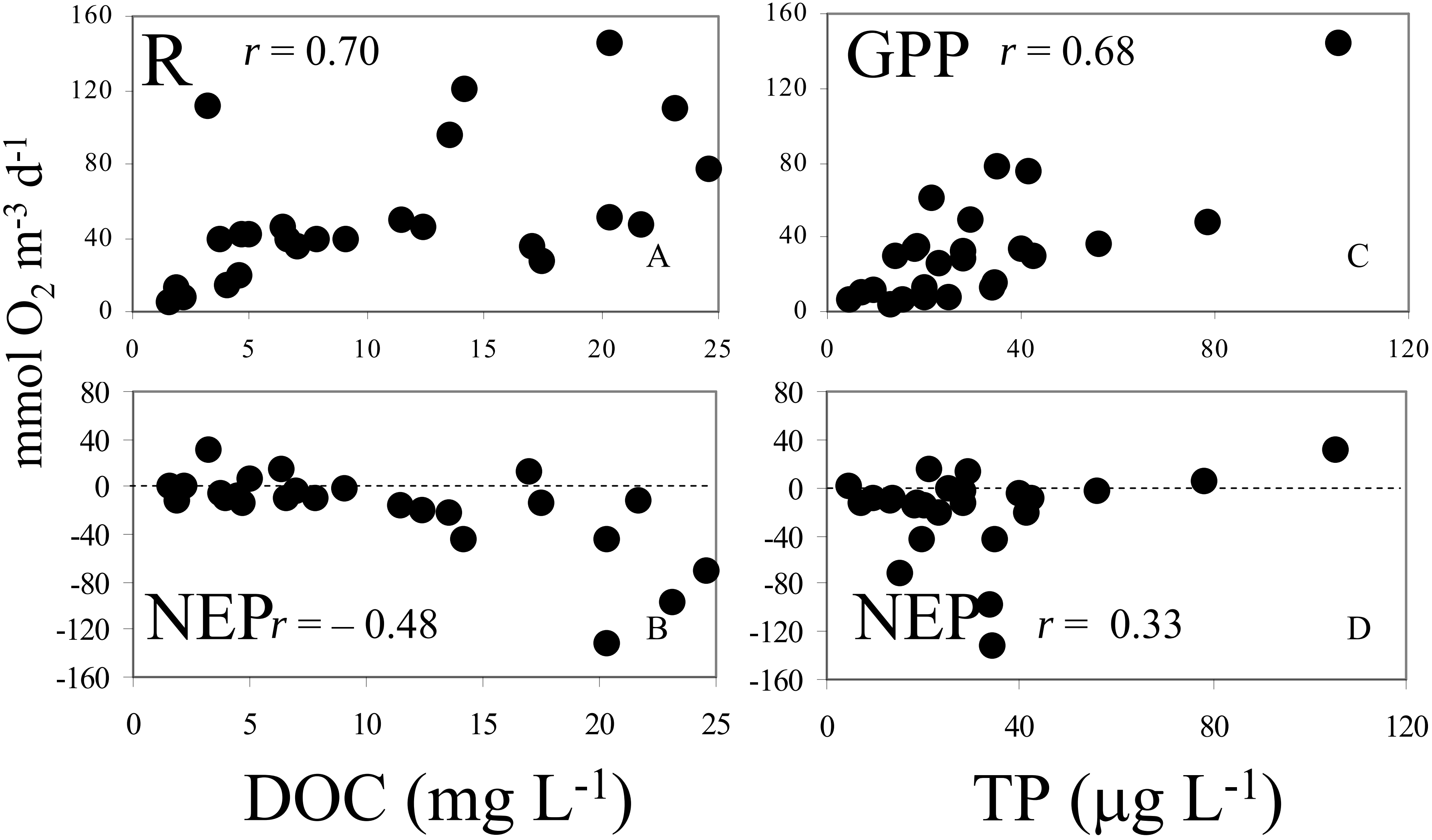
Continuous In-situ oxygen measurements (O_2 measurement every 5 minutes)



See Van de Bogert et al. SS83 - Spatial Processes in Marine and Freshwater Ecosystems **Poster Number: 159: Tuesday, 21 June 20**

25 Lakes. Continuous *in situ* sondes.

Hanson et al. 2003 (L&O)



In lakes R>GPP but lakes also store organic C in sediments

- This is not a paradox.
- This is the result of the terrestrial subsidy.
- True for the ocean as well.
- The terrestrial subsidy in lakes is very large. Co-equal with primary production.
- Globally lakes bury about 40% as much organic C as does the world’s ocean.

Organic C burial in lakes is large

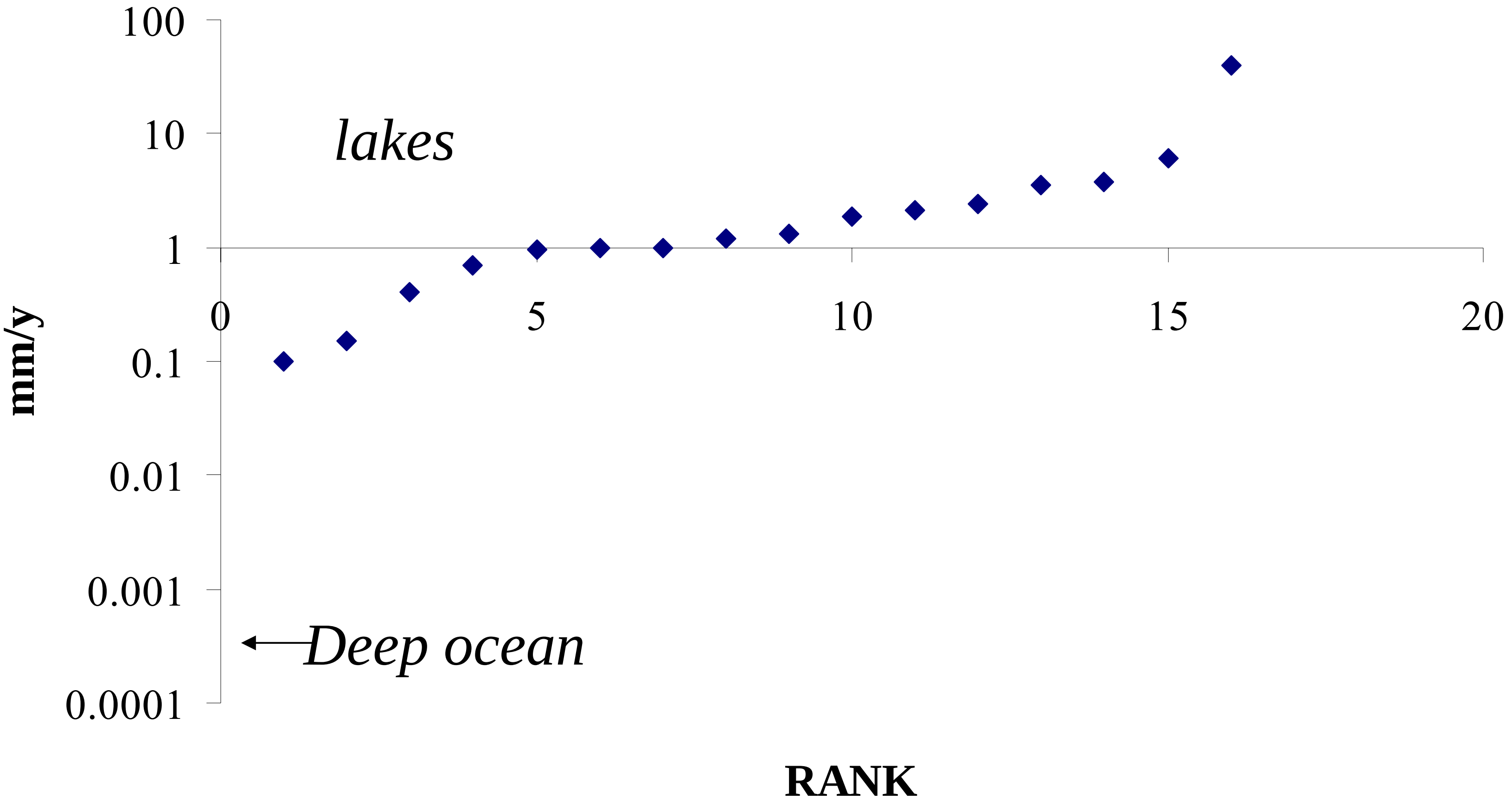
- Natural lake organic C burial
  - 0.065 Gt y-1 (Mullholland and Elwood 1982)
  - 0.034 Gt y-1 (Dean and Gorham 1998; Stallard 1998)
- Lakes sequester 28 to 54% as much organic C as does the global ocean!
- Oceanic organic C burial ~0.12 Gt y^{-1}

40% as much organic C burial as the ocean?

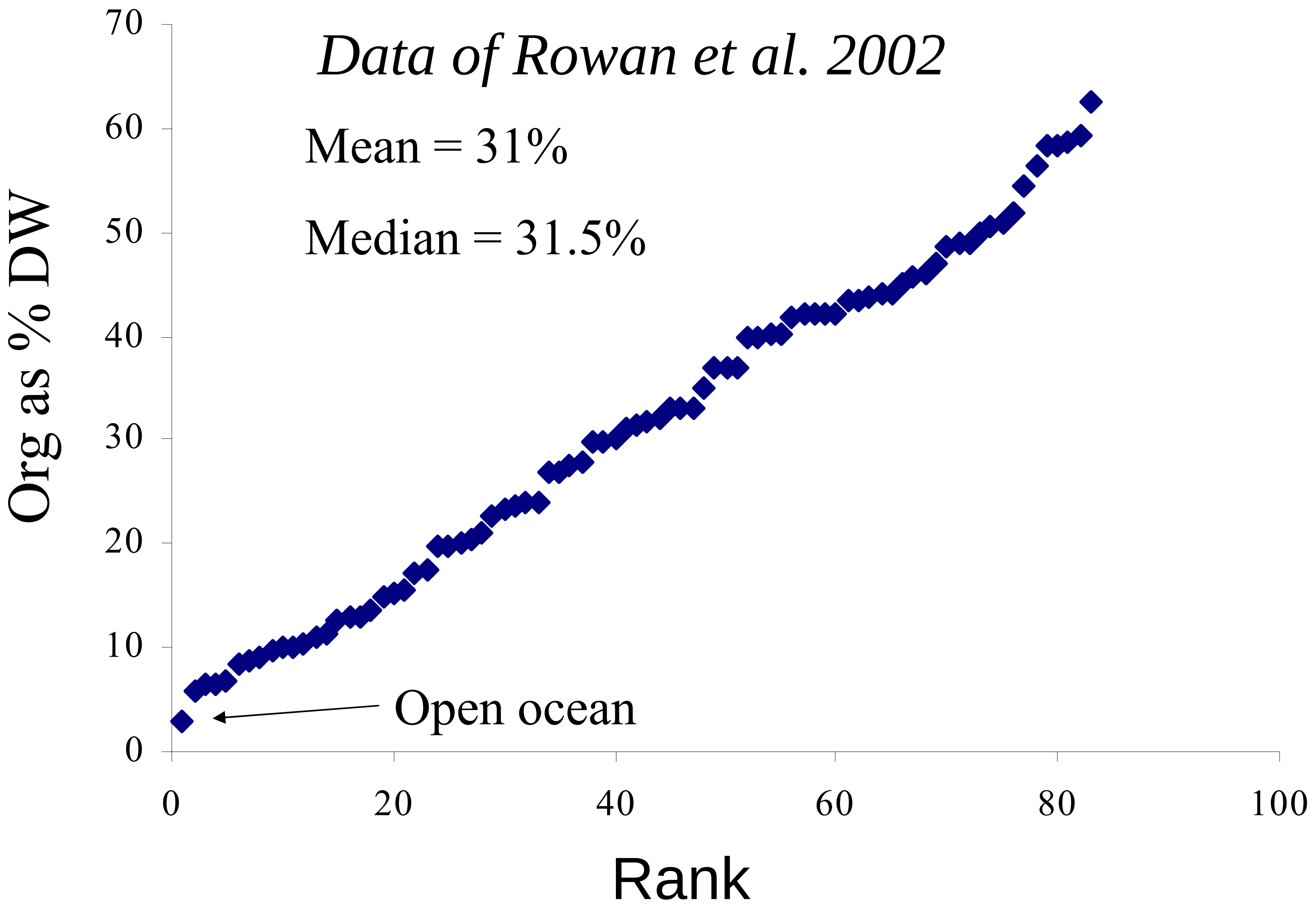
- Global area of lakes is small
- Sedimentation rate is much higher than in the ocean.
- Organic C content is much higher than in the ocean.

Accumulation rates in lakes

Kalff 2003, Likens 85, others



Lake sediment organic content



Data of Rowan et al. 2002

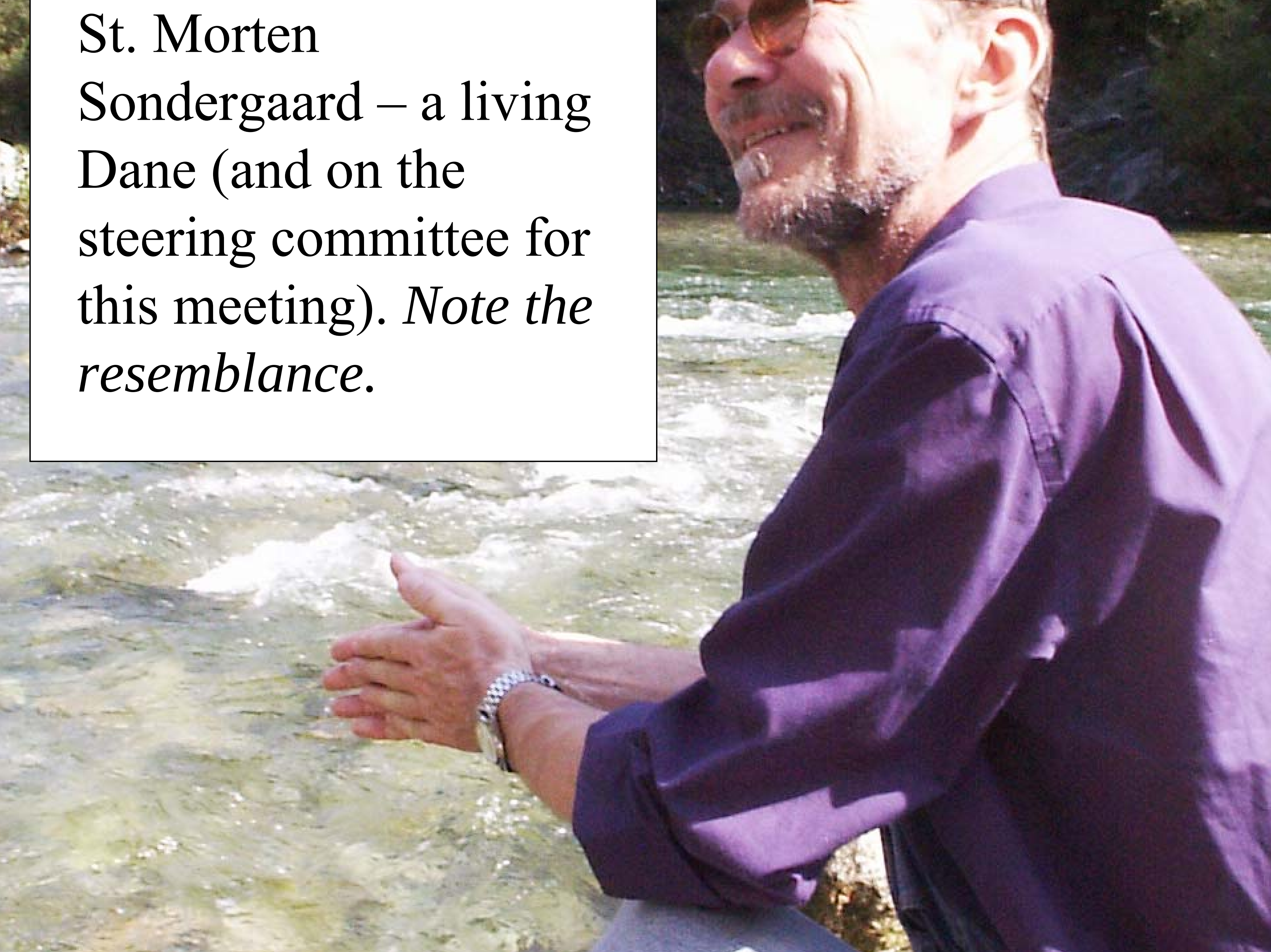
Mean = 31%

Median = 31.5%

Open ocean

High organic C content in freshwater sediments.

This Danish man from 500 BC (so somewhat older than our St. James) was preserved in bog sediment.



St. Morten Sondergaard – a living Dane (and on the steering committee for this meeting). *Note the resemblance*.

Why did Morten’s progenitor preserve – or why do freshwater sediment have so much organic C?

- (*From the Tollund man web site*)
- No oxygen, therefore no bacteria, and no rotting.
- *Sphagnum* inhibits bacteria
- Special acids inhibit bacteria
- Tannins ‘tan’ the hide.

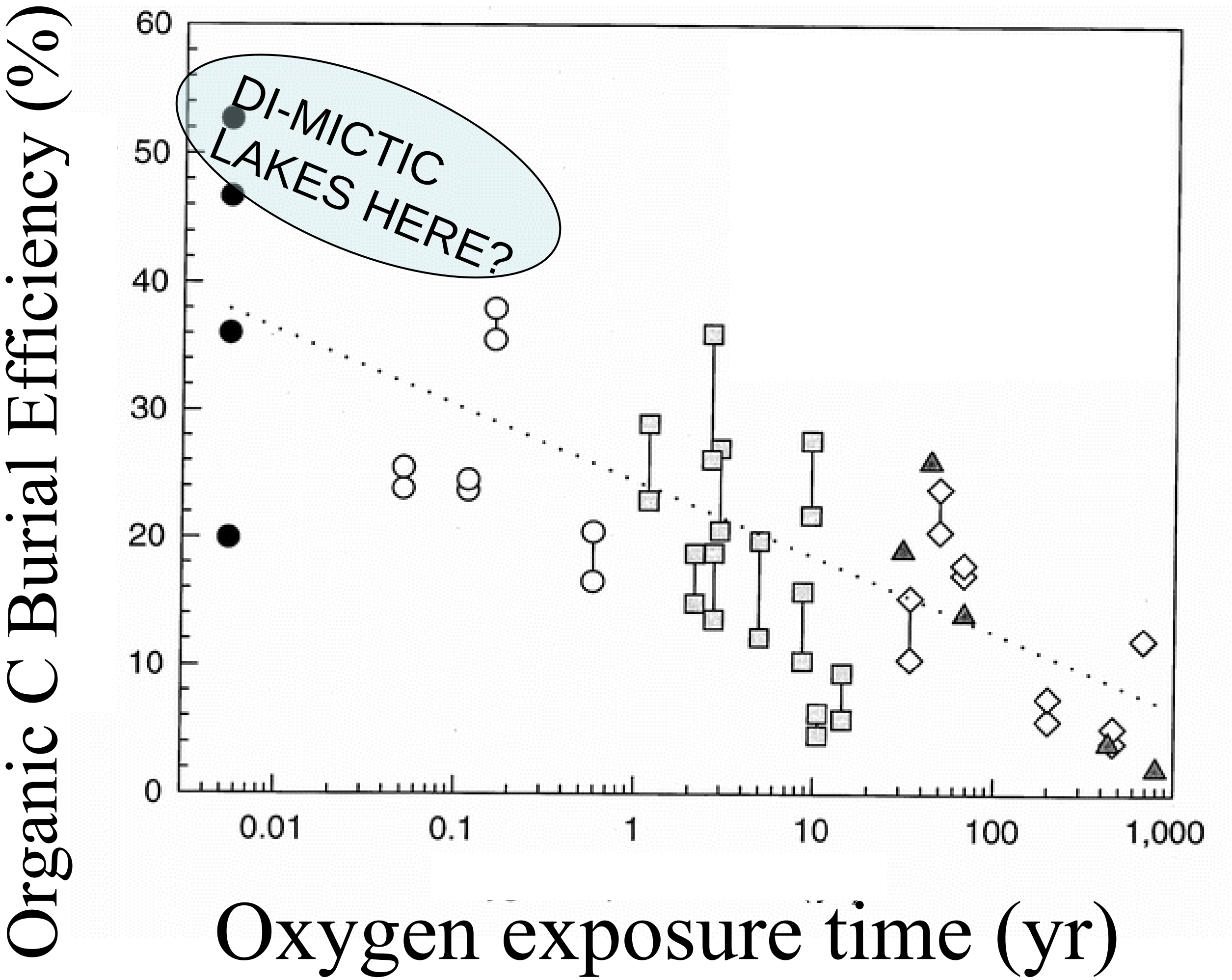
Why do lakes bury so much organic C?

- Rich theory of C preservation in the sea
  - Oxygen exposure time hypothesis
  - Sorptive preservation hypothesis
- Poorly developed theory in freshwaters.
  - Low oxygen (a real possibility)
  - Low sulfate (especially compared to ocean)
  - High lignin (plus low O_2) – *can be dismissed*
- Certainly not close to a universal law of C burial in freshwaters.

Burial Efficiency- Oxygen exposure time

Hartnett et al. 1998 Nature

Burial Efficiency = Burial / Input = Burial / (Burial + Respiration)



An empirical organic content model

Hakanson 2003

$$IG = SMTH((58.3 - (9.69 \cdot pH) - (1.64 \cdot (ADA/Area)\hat{}0.5) + (2.70 \cdot D_{rel}) + (17.6 \cdot \log(Col))), 52, 10)$$

IG = loss on ignition (%DW)

SMTH= 52 week smoothing function

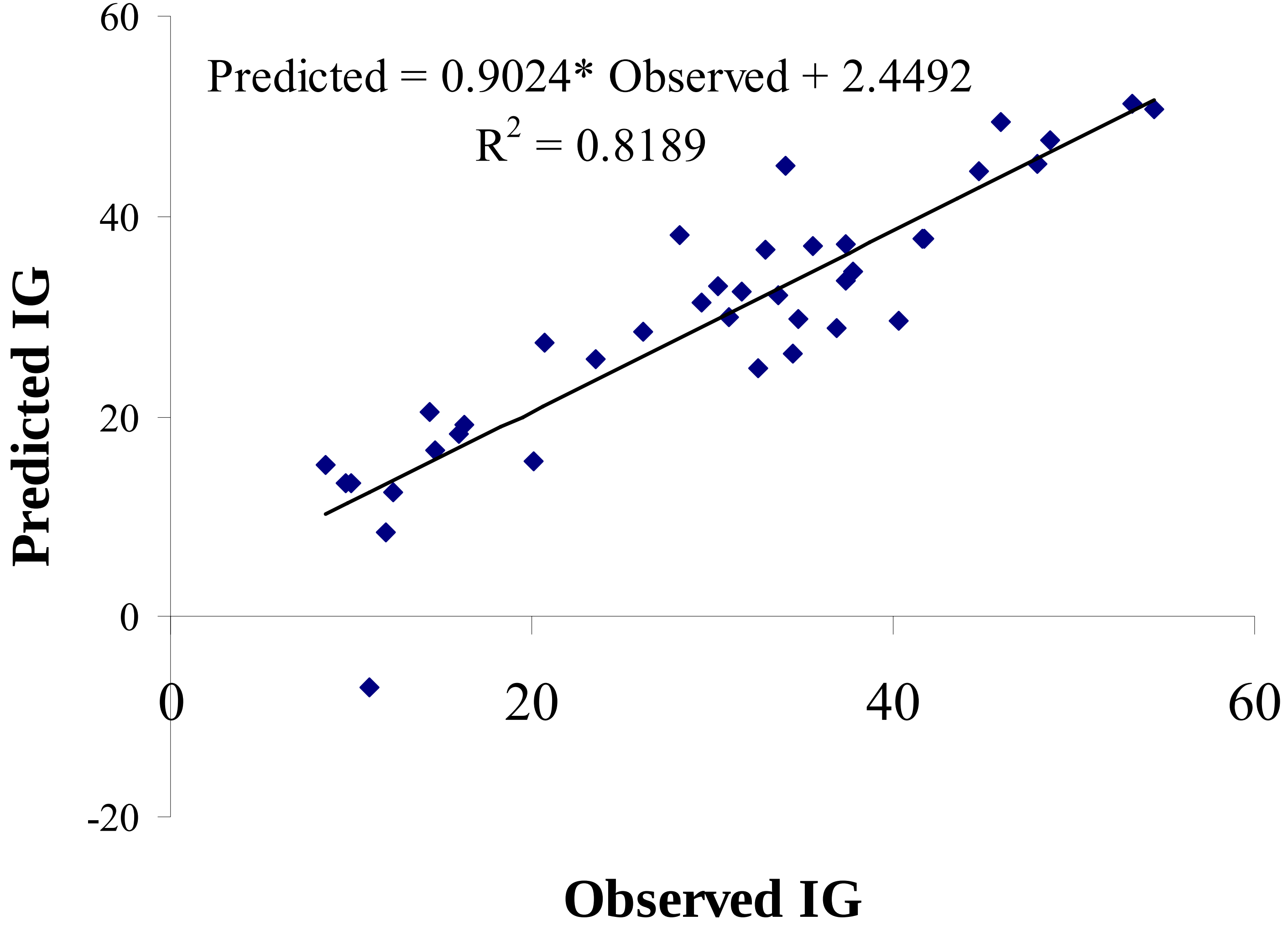
ADA = drainage area; A lake area

Drel = relative depth;

color = water color

Drel is the relative depth (= Dmax · √π/(20 · √Area),

NOTE – oxygen is NOT part of this model!!



Carbon in freshwaters – summary so far

- Globally, lakes bury about 40% as much organic C as does the ocean.
- We do not have good models for C preservation in lake sediments. ***Research opportunity***.
- River delivery of organic and inorganic C to the ocean is an important term in the global C balance.
- Lakes and rivers tend to be net heterotrophic – must respire some terrestrial C.
- Does this terrestrial C move up the food web?

Allochthony

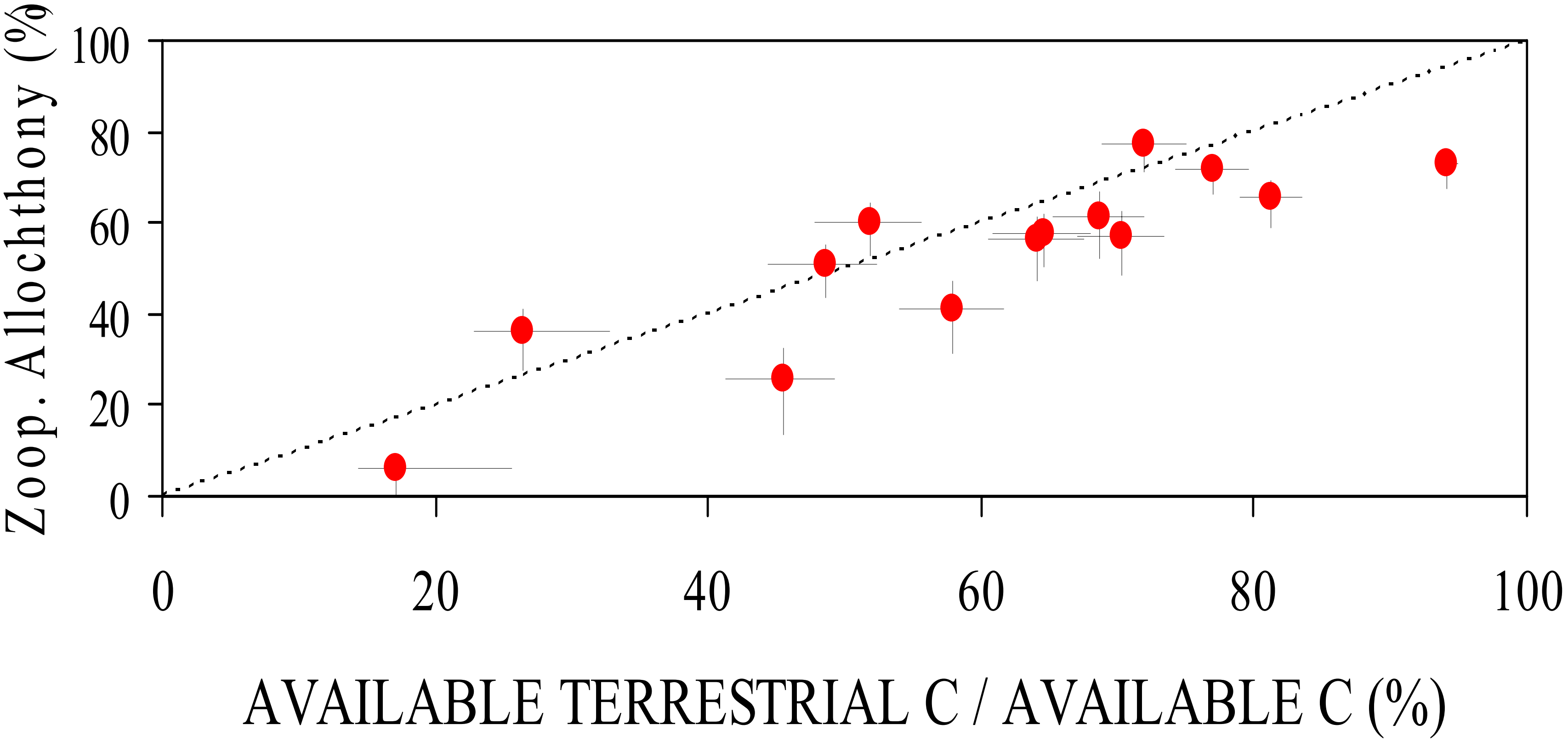
- *Allochthony* is amount of terrestrial organic C supporting the biomass or respiration of an aquatic compartment.
- What fraction of zooplankton biomass is made of maple leaves versus phytoplankton, for example.
- Several studies and approaches.

Allochthony approaches

- Ambient stable isotopes (^{13}C).
  - Need a contrast between end-members
    - Terrestrial signal versus aquatic primary producer
    - Works great in the ocean
    - Fails in many lakes because of lack of contrast
- Ambient radiocarbon (^{14}C).
  - Has worked in some environments
    - In some cases terrestrial input is very old
- Experimental alteration of C isotopes for whole lake
  - Hard to do but has worked in some environments
- Model who eats whom and what.

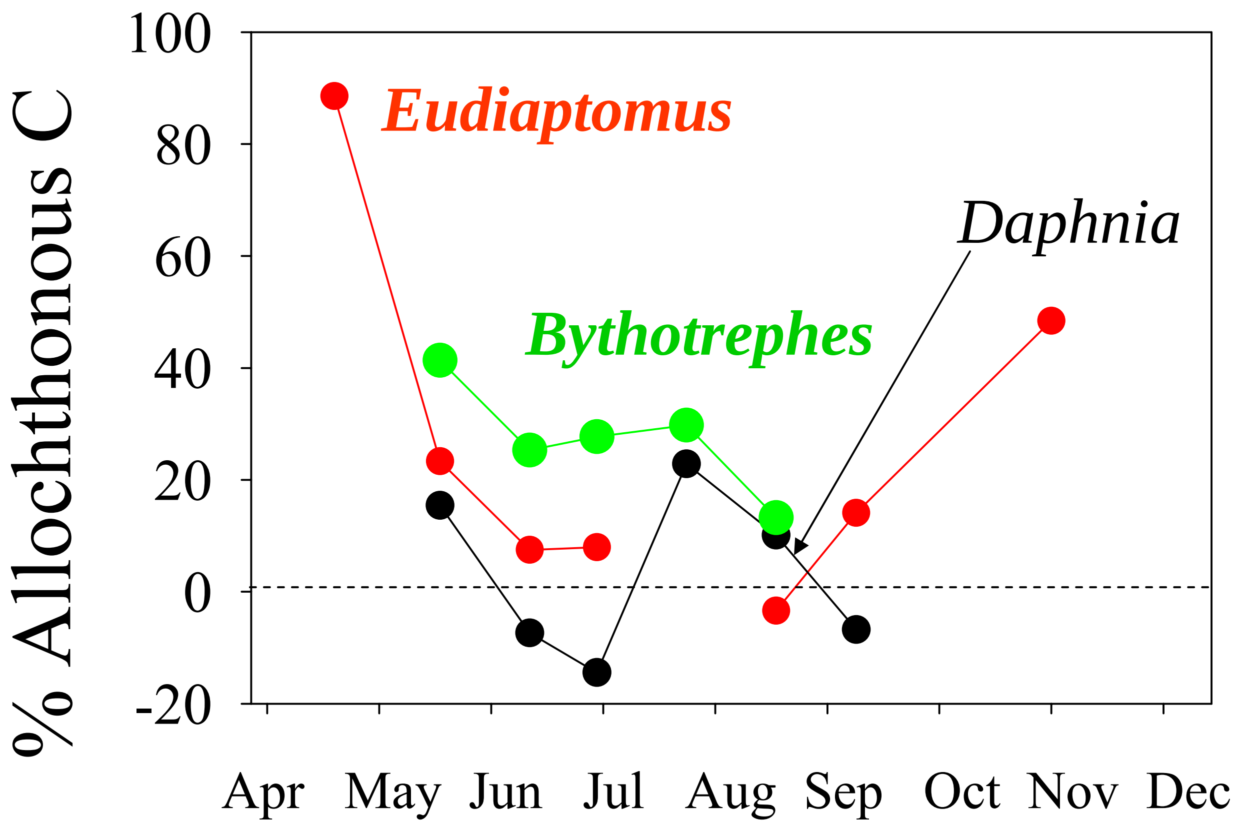
15 lakes in Sweden. Ambient ^{13}C with model (many assumptions).

From Karlsson et al. 2003 L&O



function of BP and PP

Loch Ness. Ambient ^{13}C – complex calculation
modified from Grey et al. 2001 L&O



Zooplankton can be substantially terrestrial. Varies with species and time.

Whole lake ^{13}C addition

See Pace et al. SS06 - Fate and Effects of Terrestrial DOM in Aquatic Ecosystems: Thursday, 23 June 2005 18:15

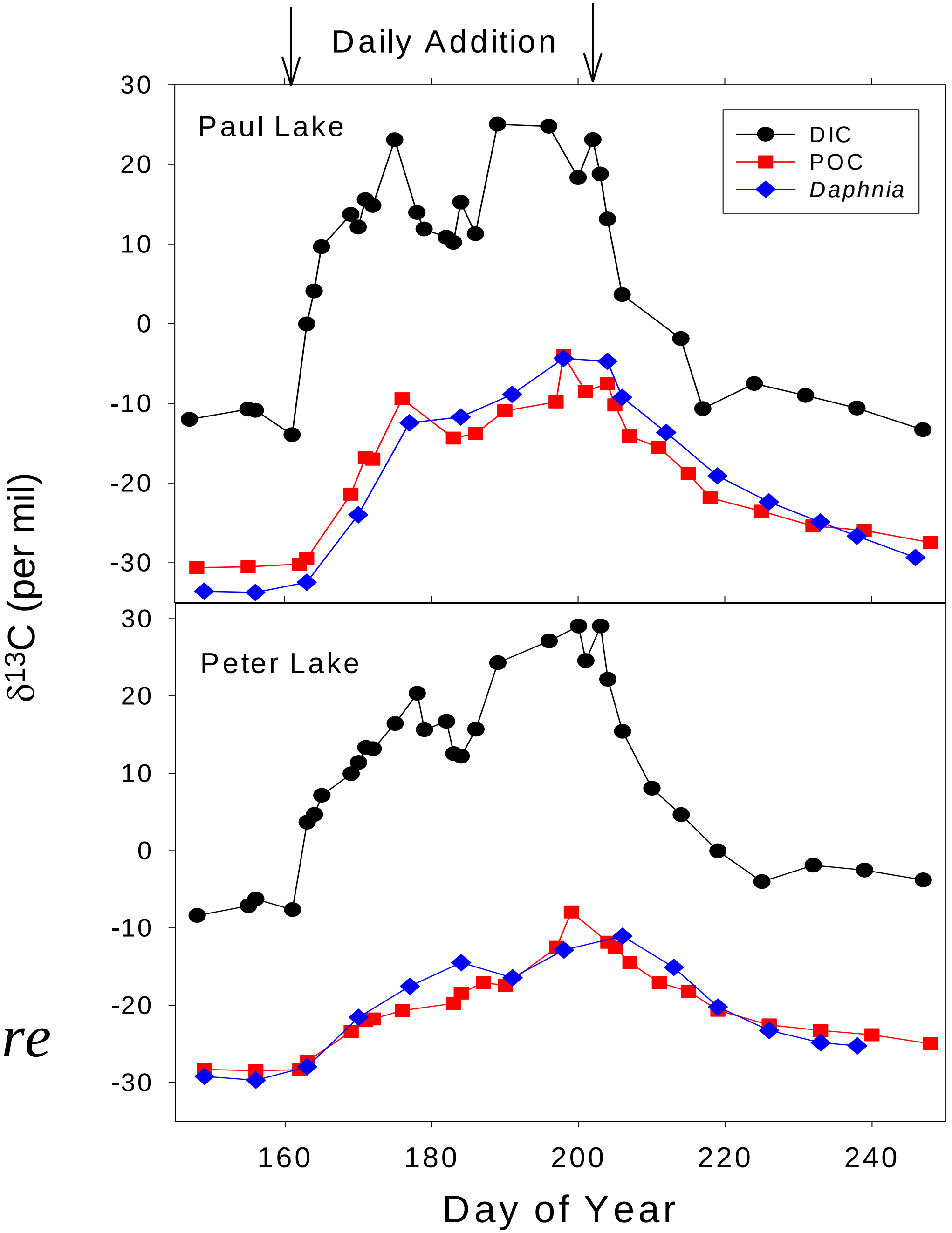
Mike Pace (dark blurry object) manipulating a lake (in blue)

Approach

- Daily additions $NaH^{13}CO_3$ to lakes over 6 weeks
- Measure movement of C-13 through DIC, POC, DOC, and food web constituents
- Evaluate alternative models for C-13 dynamics of POC and Zooplankton to determine significance of terrestrial C

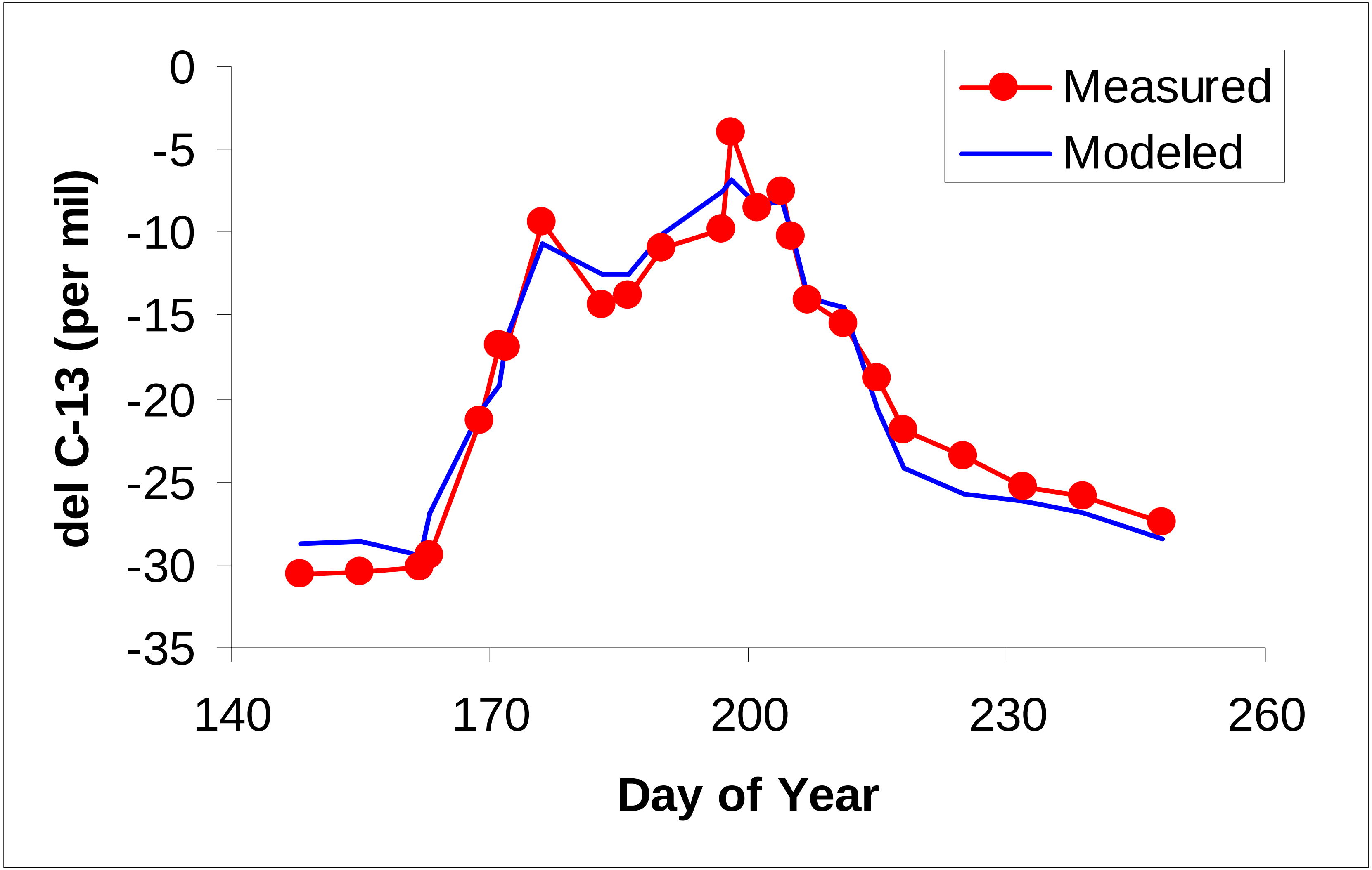
We have combined whole lake ^{13}C additions with several very different modeling approaches.

Steve Carpenter (*left*) modeling an elephant (*right*).



Pace et al. Nature 2004

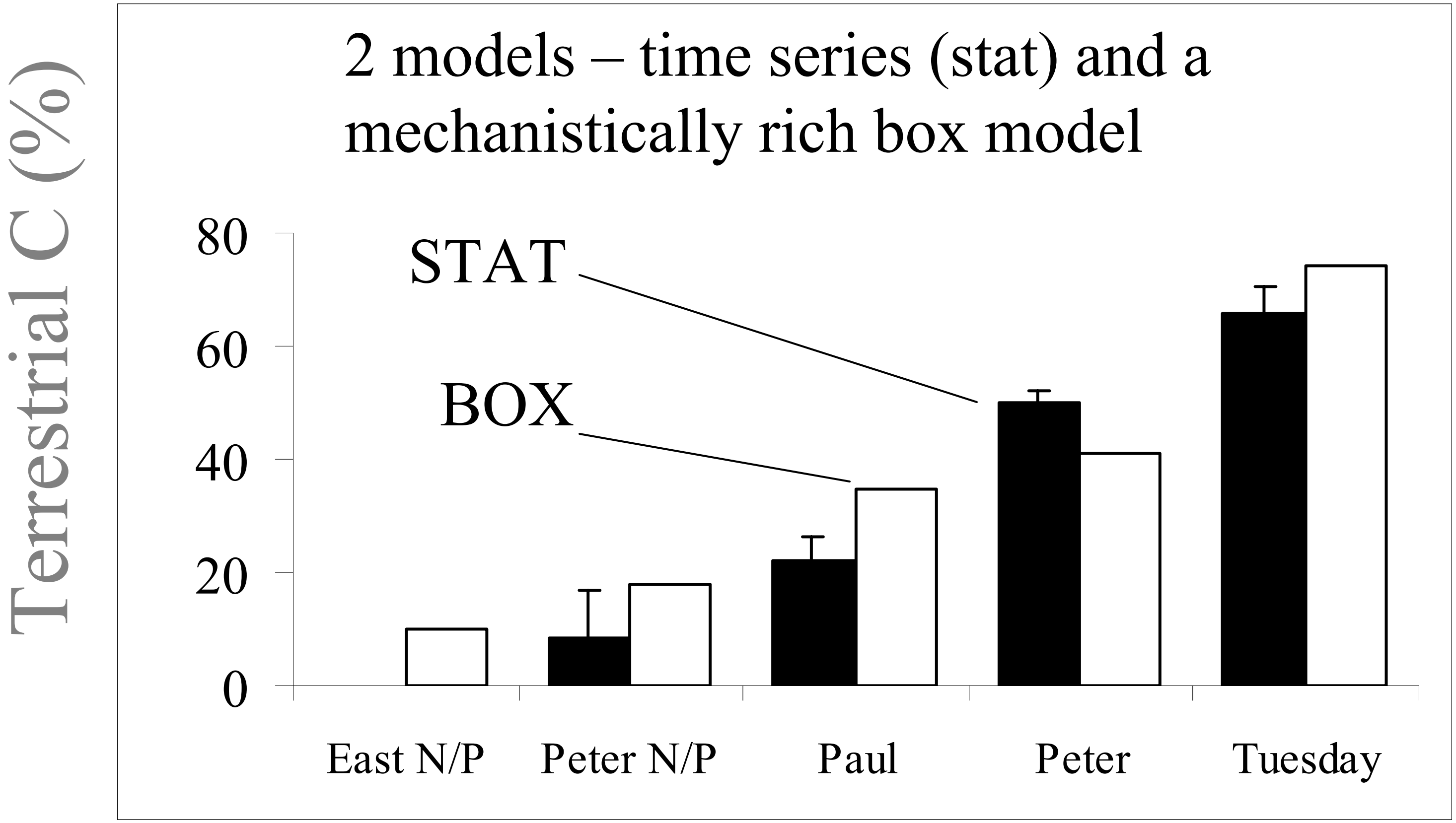
Paul Lake POC-13: Model 3



Pace et al. Nature 2004

C supporting zooplankton

Cole et al. 2002; Pace et al. 2004; Carpenter et al. In press

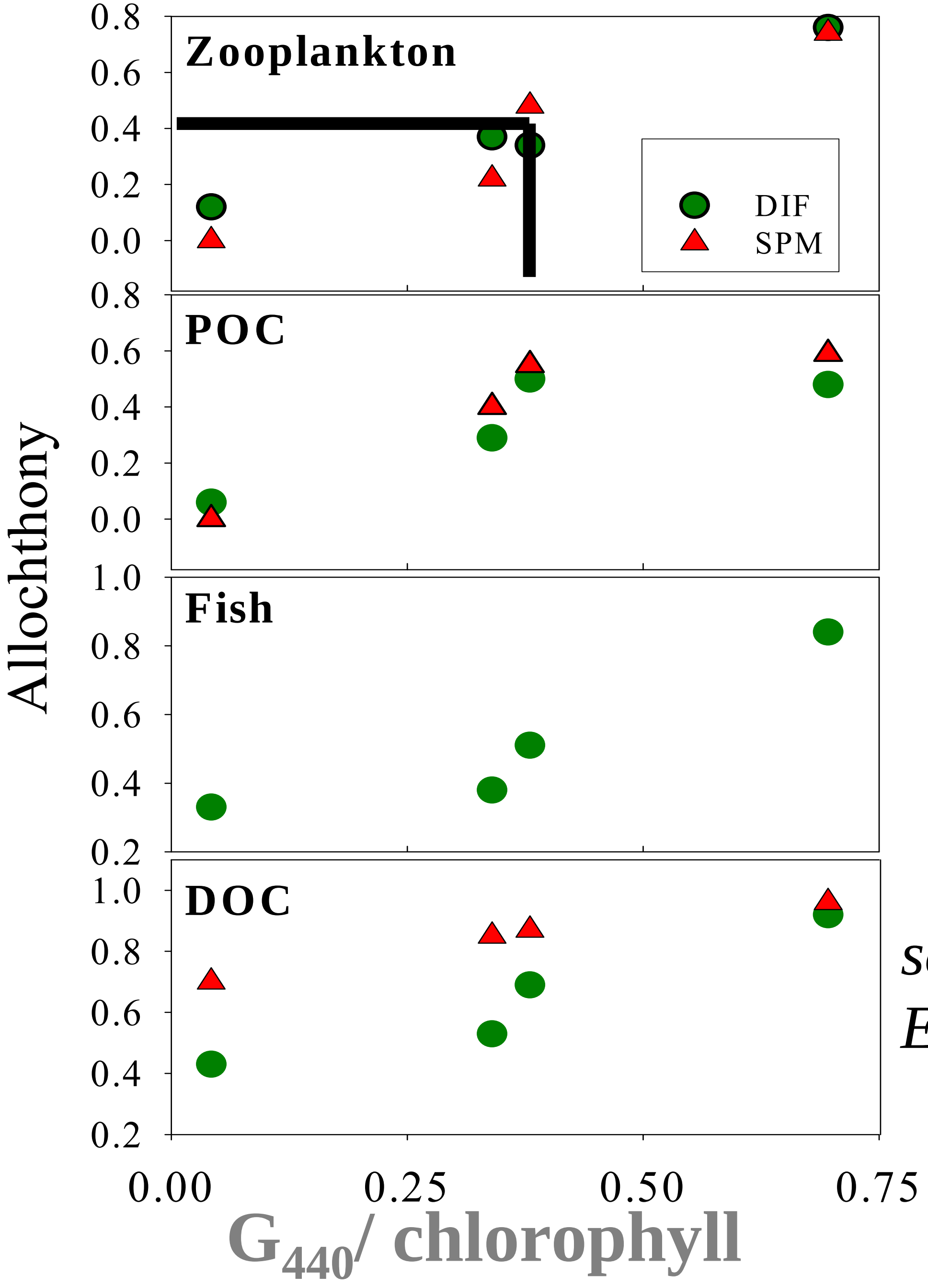

2 models – time series (stat) and a mechanistically rich box model

FERTILIZED **AMBIENT**

Allochthony varies – the jury is out

SYSTEM	COMPONENT	% ALLOCH	METHOD	*REF*
15 Swedish Lakes	zooplankton	20-80%	Ambient ^{13}C	*Karlsson et al. 2003*
Loch Ness	Zooplankton w seasonal variation	0-80%	Ambient ^{13}C	*Jones et al 1998; Grey et al. 2001*
5 N. Wisconsin Lakes	Zooplankton, yoy fish, *Chaoborus*	5-80%	Whole-lake ^{13}C addition	*Cole et al 2002; Pace et al. 2004; Carpenter et al. in press*
4 N. Wisconsin Lakes	Pelagic bacteria	30-70%	Whole-lake ^{13}C addition	*Kritzberg et al. 2004*
L. Ortrasket	Bacterial Respiration	>80%	C mass balance and isotopes	*Jonsson et al. 2001*

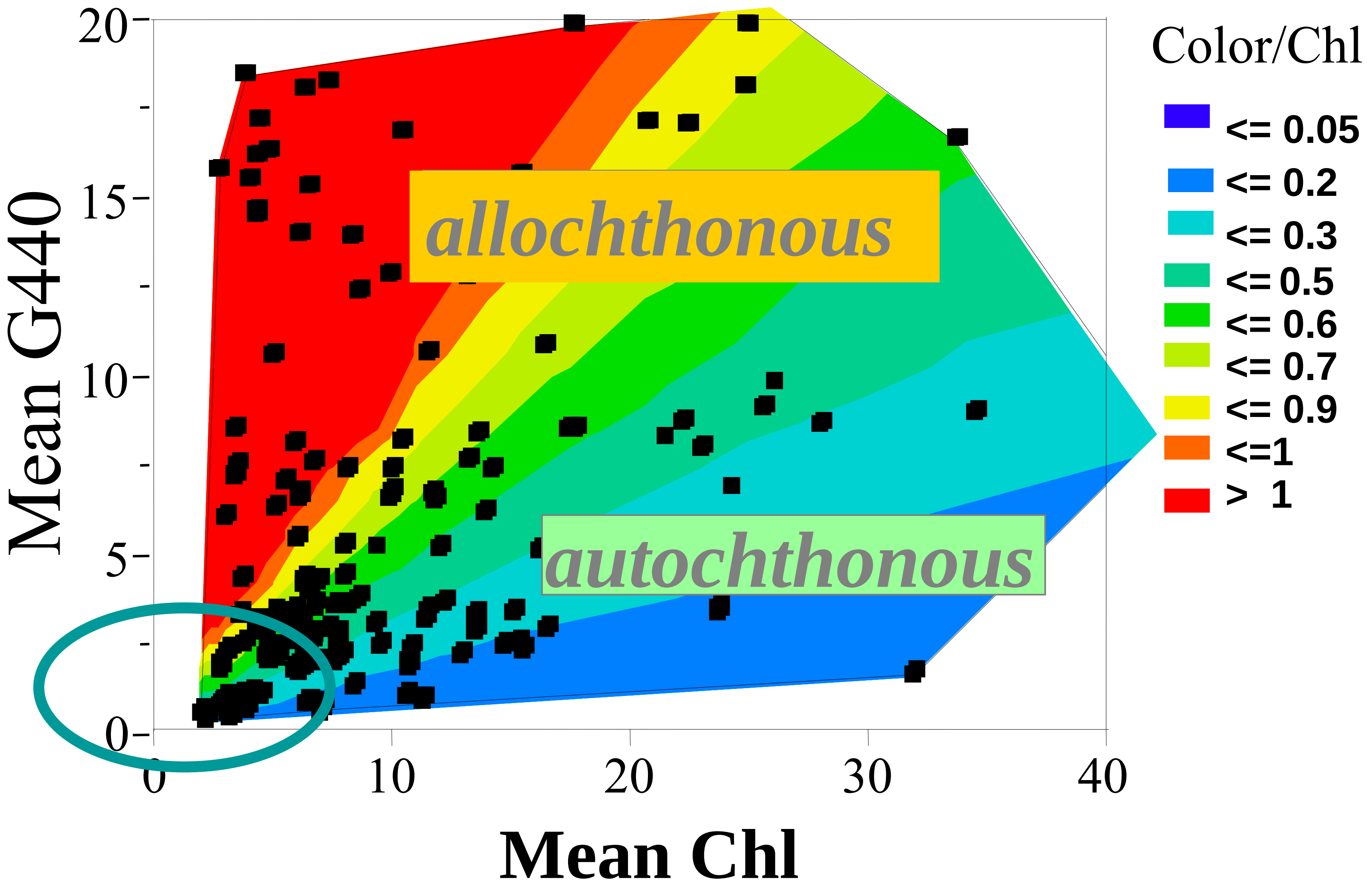
SYSTEM	Component	% Alloch	Method	*Ref*
Humic Lake, Sweden	Cladocerans	> 40%	Ambient ^{13}C	*Meili et al. 1992*
Orinoco flood plain	Fish and invertebrates	~0%	Ambient ^{13}C	*Hamilton et al. 2001*
Rocky Mt. Stream	invertebrates	20-60%	Ambient ^{13}C	*McCutchan and Lewis 2002*
San Francisco estuary (FW)	Pelagic web	~0%	Ambient ^{13}C, other	*Sobczak et al. 2005*
	System R	>90%		
Hudson River	Fish and most inverts	~0%	Ambient ^{14}C, ^{13}C other	*Caraco et al. 2005*
	Bosmina, Chironomids	>50%		
Hudson River	Pelagic bacteria (multi sites)	0-50%	Ambient ^{14}C, ^{13}C other	*McCalister et al. 2004*



Color – abs at 440 nm – (G_{440})

chromaphoric dissolved organic matter

see Carpenter et al Ecology (in press)


Mean G440
20
15
10
5
0
0
10
20
30
40
Mean Chl
allochthonous
autochthonous
Color/Chl
<= 0.05
<= 0.2
<= 0.3
<= 0.5
<= 0.6
<= 0.7
<= 0.9
<=1
> 1

Conclusions

- The modern C cycle is different than the Santiago (St. James) C cycle.
- Riverine transport at present is a sink (0.7 Gt) where for St. James it was a rapid transfer back to the atmosphere.
- Lakes are surprisingly important in the C cycle at the milennium time step. Lakes bury ~40% as much Org C as the ocean
- Allochthony in lakes and rivers is a hot topic but the jury is out.