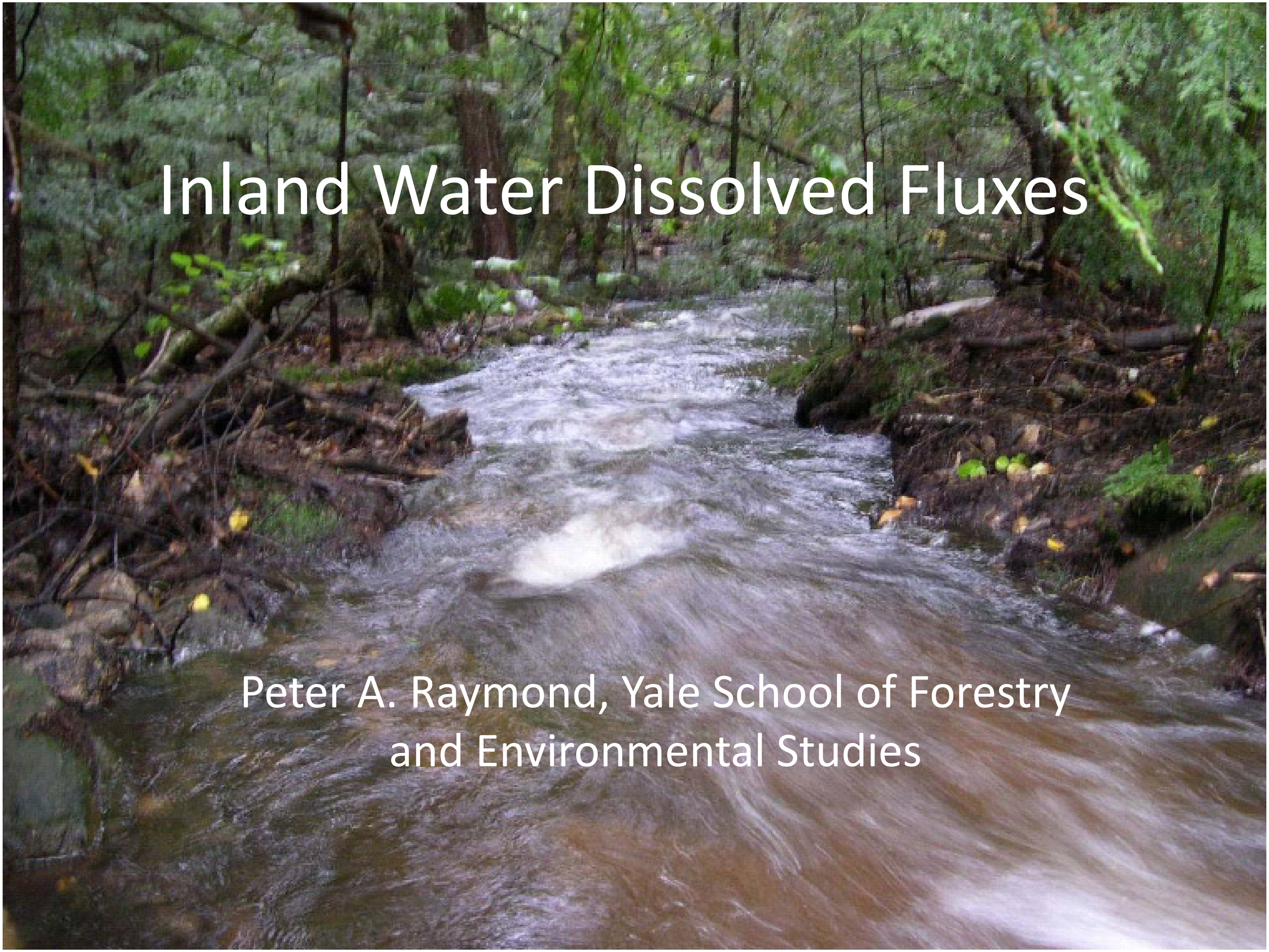
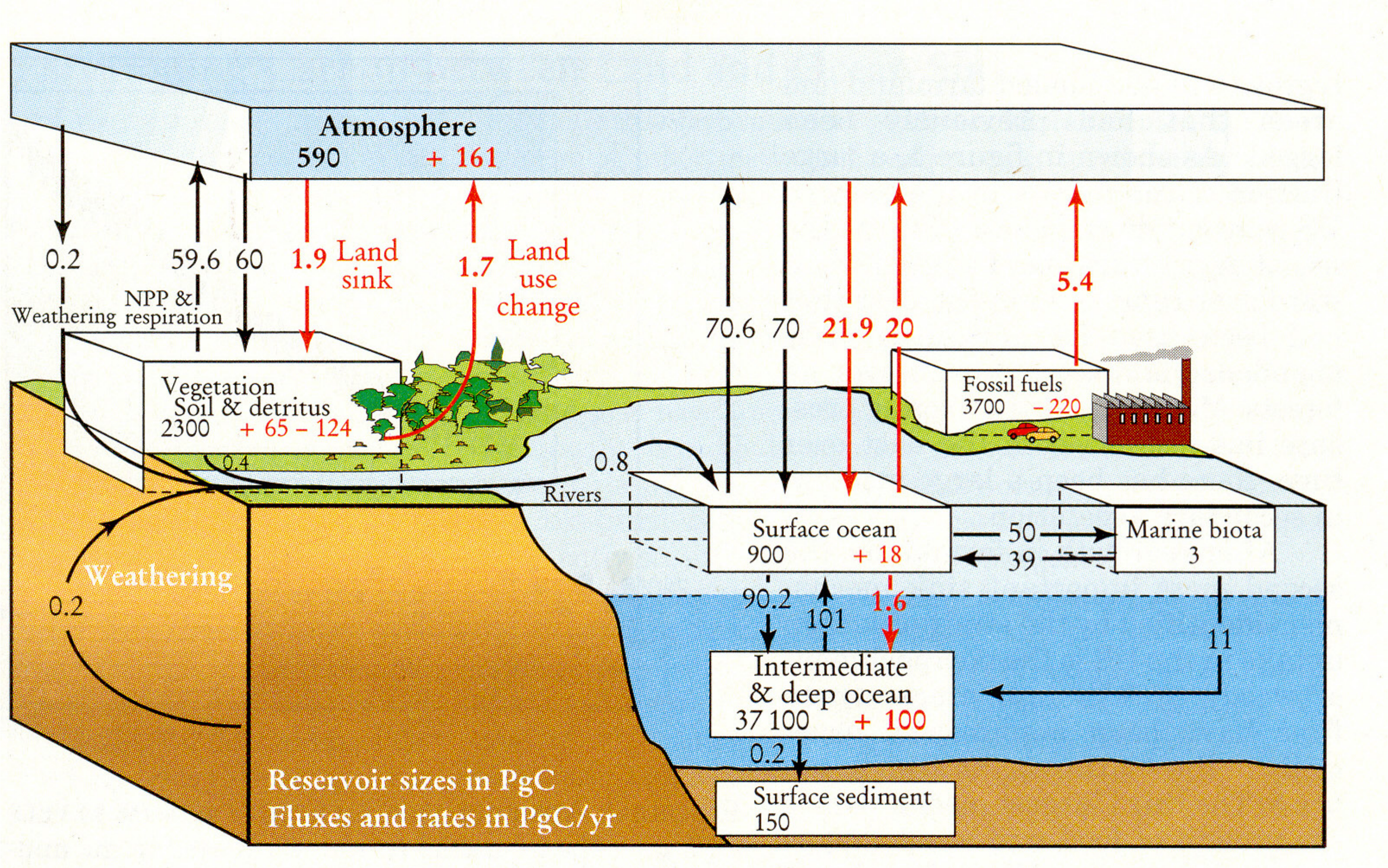


Inland Water Dissolved Fluxes

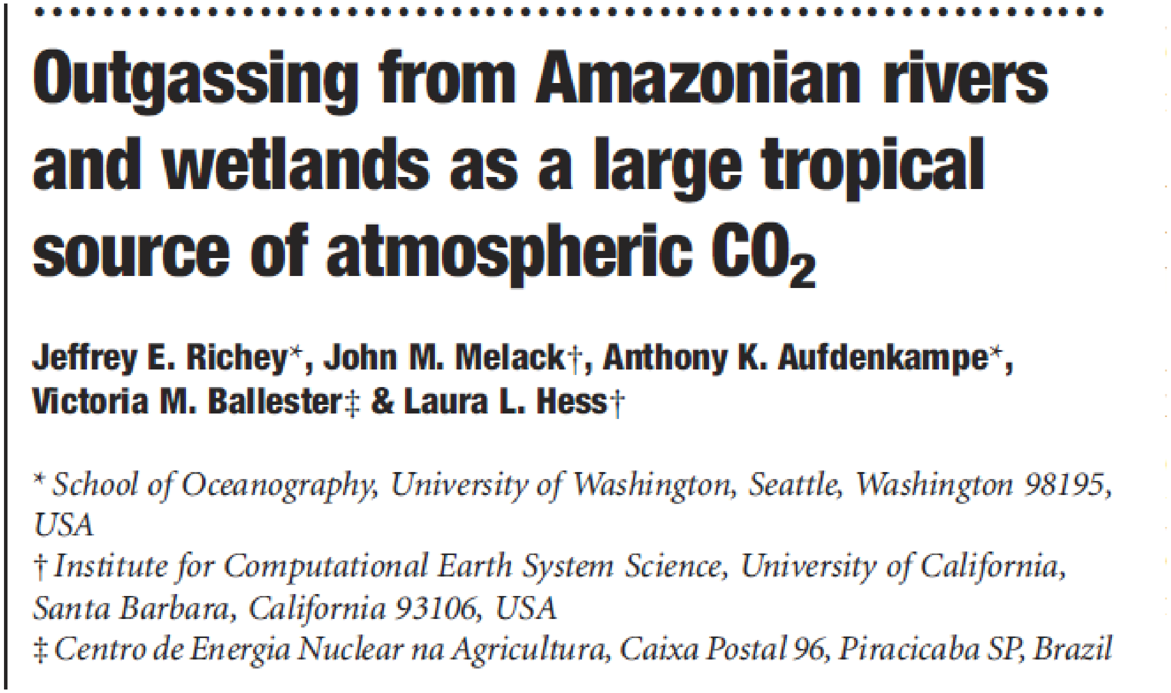
Peter A. Raymond, Yale School of Forestry
and Environmental Studies

Evolution of Inland Water C



Sarmiento and Gruber (2002)

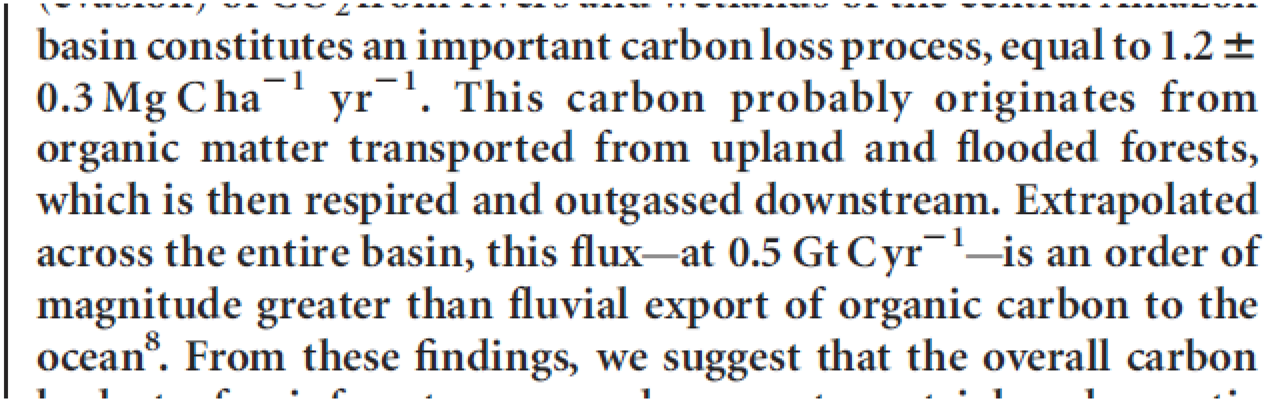
Richey et al.



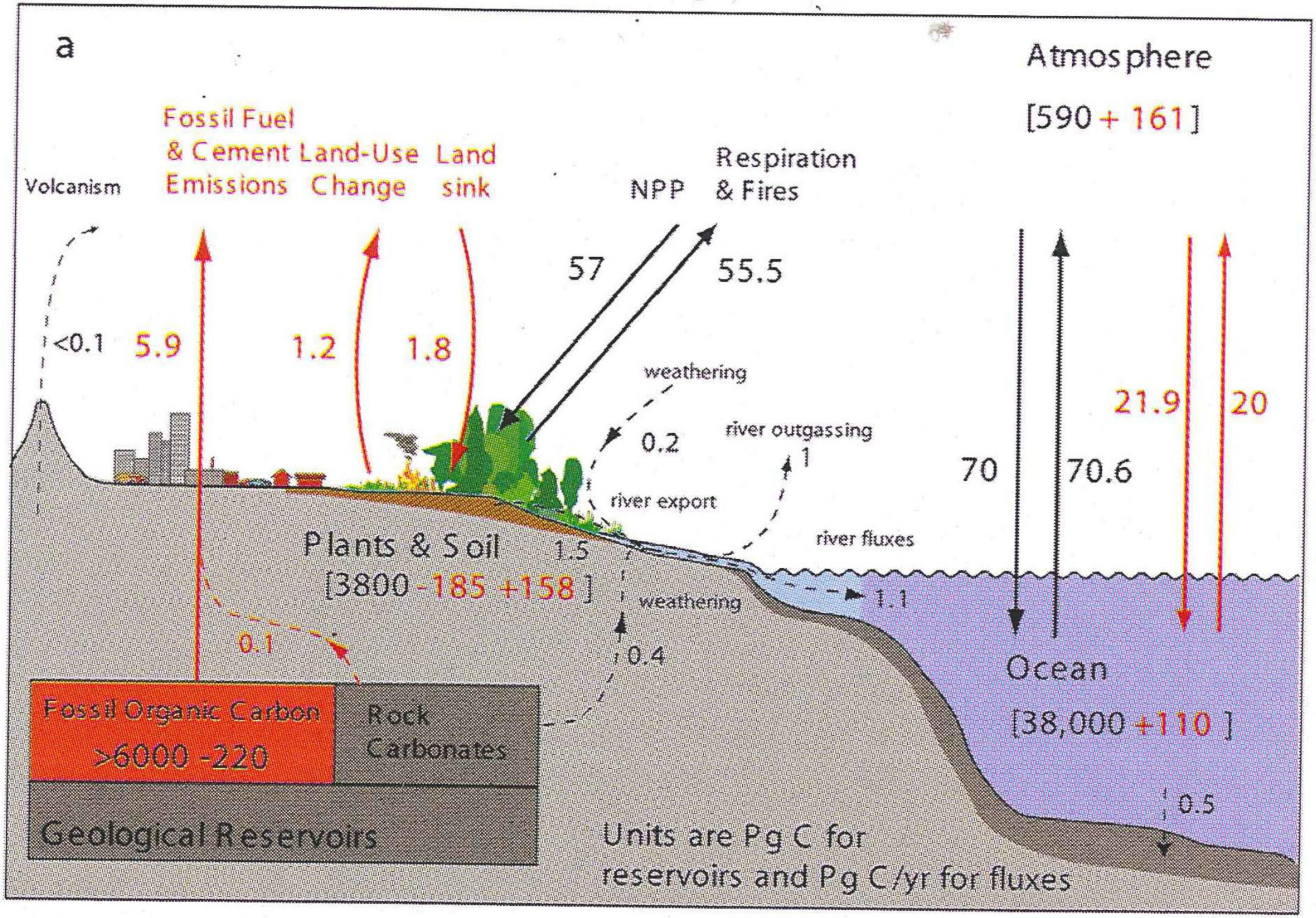
Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2

Jeffrey E. Richey*, John M. Melack†, Anthony K. Aufdenkampe*, Victoria M. Ballester‡ & Laura L. Hess†

** School of Oceanography, University of Washington, Seattle, Washington 98195, USA*
† Institute for Computational Earth System Science, University of California, Santa Barbara, California 93106, USA
‡ Centro de Energia Nuclear na Agricultura, Caixa Postal 96, Piracicaba SP, Brazil



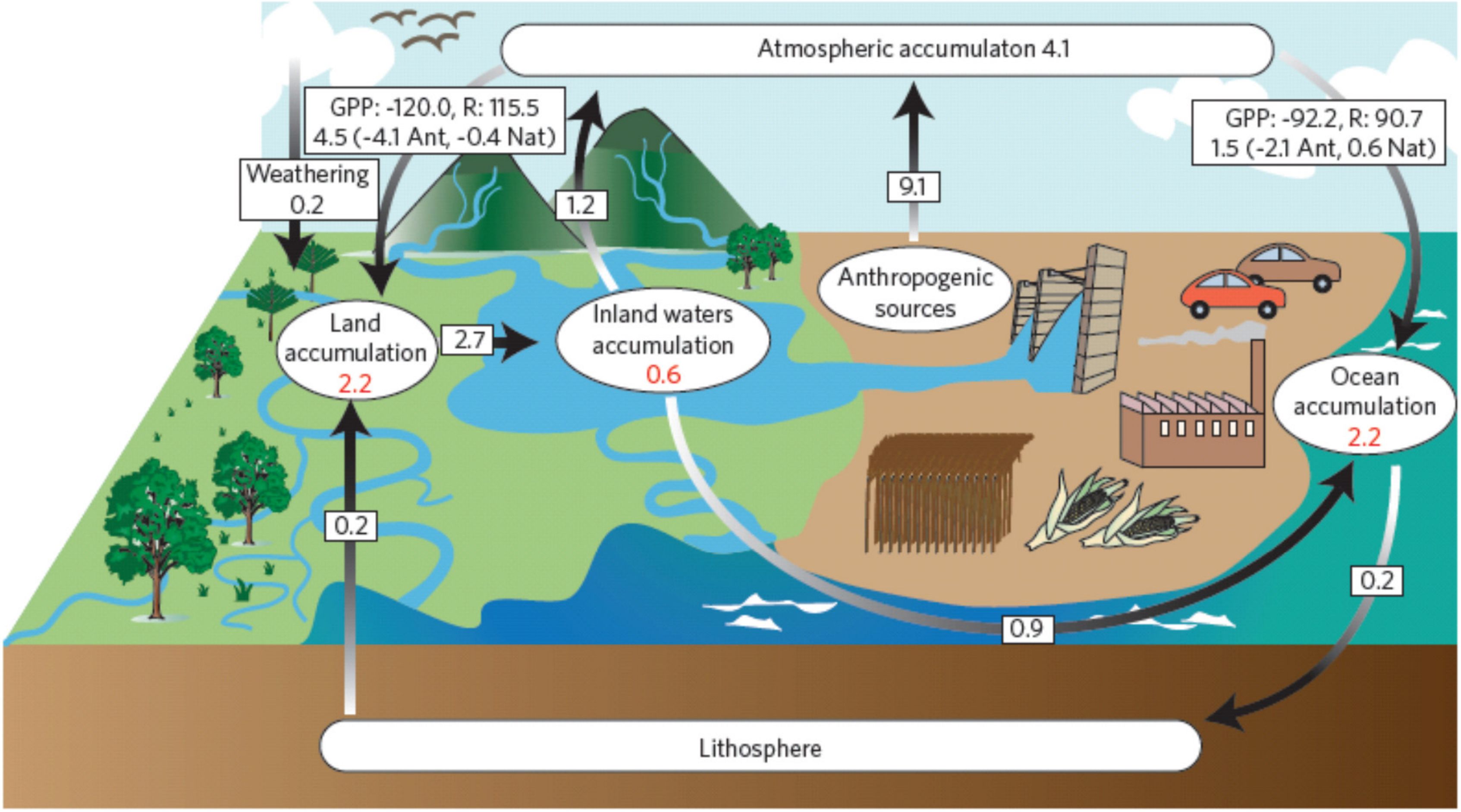
basin constitutes an important carbon loss process, equal to 1.2 ± 0.3 Mg C ha^{-1} yr^{-1}. This carbon probably originates from organic matter transported from upland and flooded forests, which is then respired and outgassed downstream. Extrapolated across the entire basin, this flux—at 0.5 Gt C yr^{-1}—is an order of magnitude greater than fluvial export of organic carbon to the ocean[8]. From these findings, we suggest that the overall carbon

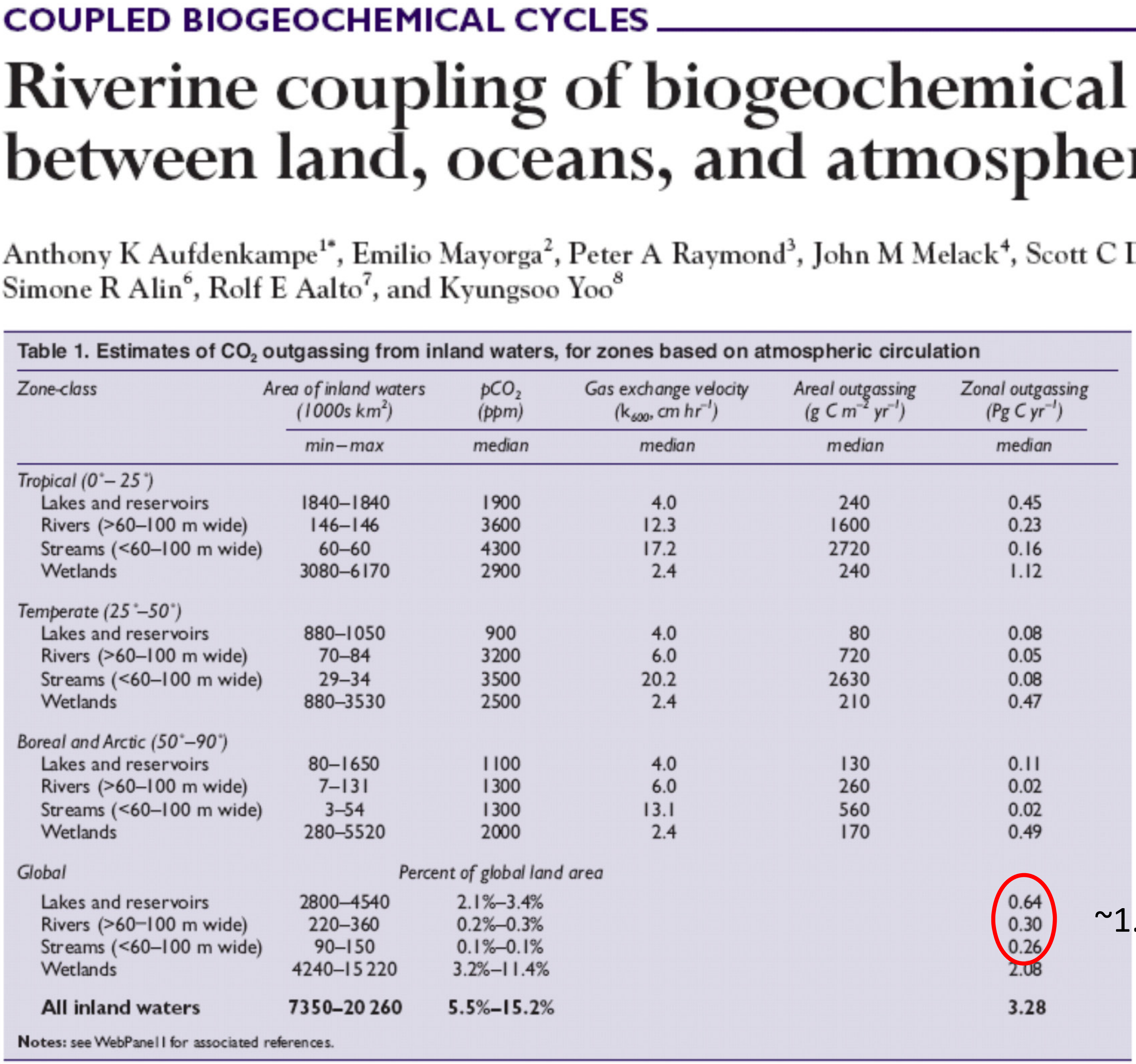


Sabine et al 2004

The boundless carbon cycle

Tom J. Battin, Sebastiaan Luyssaert, Louis A. Kaplan, Anthony K. Aufdenkampe, Andreas Richter and Lars J. Tranvik





COUPLED BIOGEOCHEMICAL CYCLES

Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere

Anthony K Aufdenkampe[1*], Emilio Mayorga[2], Peter A Raymond[3], John M Melack[4], Scott C Doney[5], Simone R Alin[6], Rolf E Aalto[7], and Kyungsoo Yoo[8]

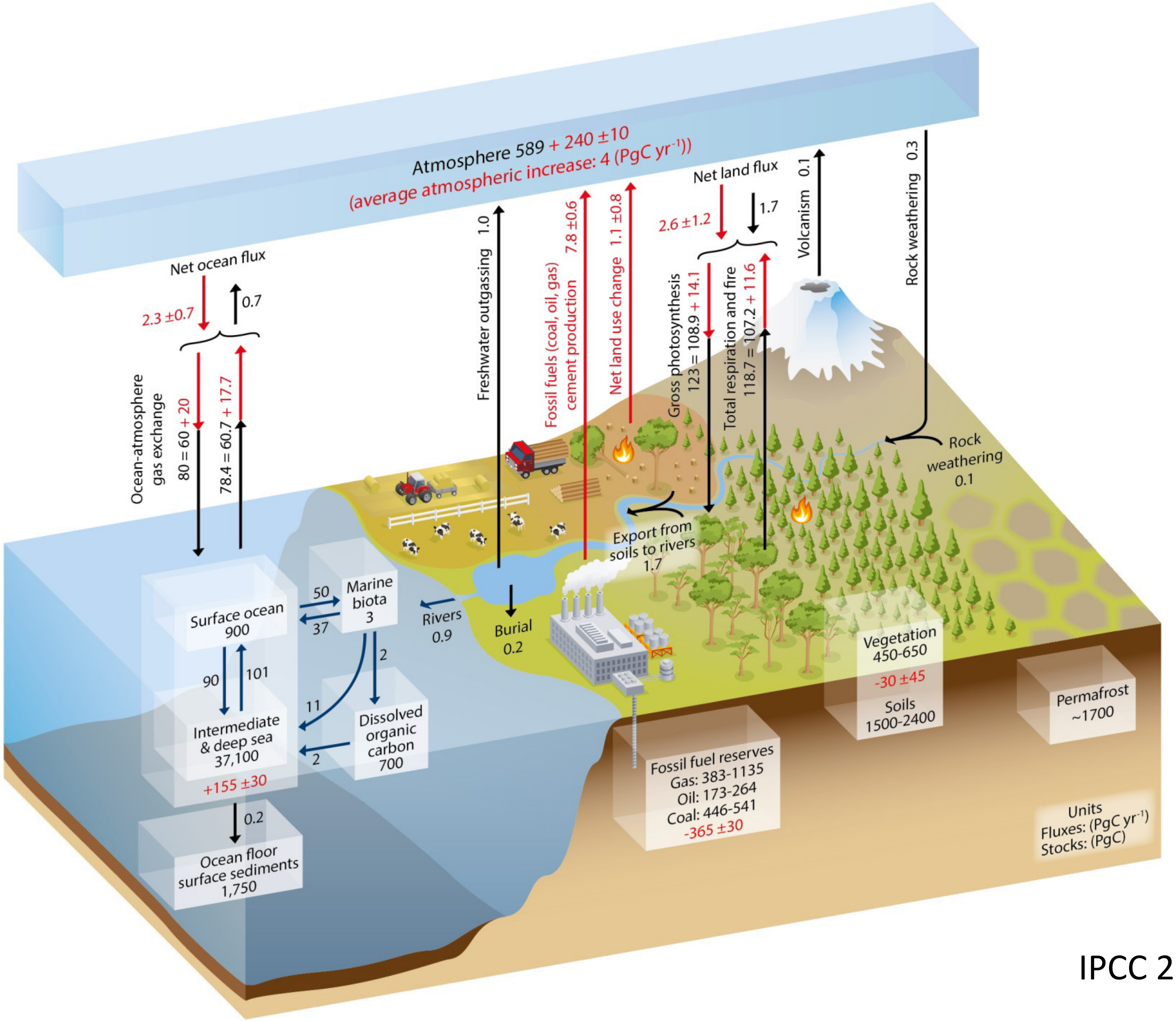
Table 1. Estimates of CO_2 outgassing from inland waters, for zones based on atmospheric circulation

Zone-class	*Area of inland waters (1000s km²)*	*pCO_2 (ppm)*	*Gas exchange velocity (k_{600}, cm hr^{-1})*	*Areal outgassing (g C m^{-2} yr^{-1})*	*Zonal outgassing (Pg C yr^{-1})*
	min – max	*median*	*median*	*median*	*median*
Tropical (0°– 25°)					
Lakes and reservoirs	1840–1840	1900	4.0	240	0.45
Rivers (>60–100 m wide)	146–146	3600	12.3	1600	0.23
Streams (<60–100 m wide)	60–60	4300	17.2	2720	0.16
Wetlands	3080–6170	2900	2.4	240	1.12
Temperate (25°–50°)					
Lakes and reservoirs	880–1050	900	4.0	80	0.08
Rivers (>60–100 m wide)	70–84	3200	6.0	720	0.05
Streams (<60–100 m wide)	29–34	3500	20.2	2630	0.08
Wetlands	880–3530	2500	2.4	210	0.47
Boreal and Arctic (50°–90°)					
Lakes and reservoirs	80–1650	1100	4.0	130	0.11
Rivers (>60–100 m wide)	7–131	1300	6.0	260	0.02
Streams (<60–100 m wide)	3–54	1300	13.1	560	0.02
Wetlands	280–5520	2000	2.4	170	0.49
Global		*Percent of global land area*			
Lakes and reservoirs	2800–4540	2.1%–3.4%			0.64
Rivers (>60–100 m wide)	220–360	0.2%–0.3%			0.30
Streams (<60–100 m wide)	90–150	0.1%–0.1%			0.26
Wetlands	4240–15 220	3.2%–11.4%			2.08
All inland waters	**7350–20 260**	**5.5%–15.2%**			**3.28**

Notes: see WebPanel I for associated references.

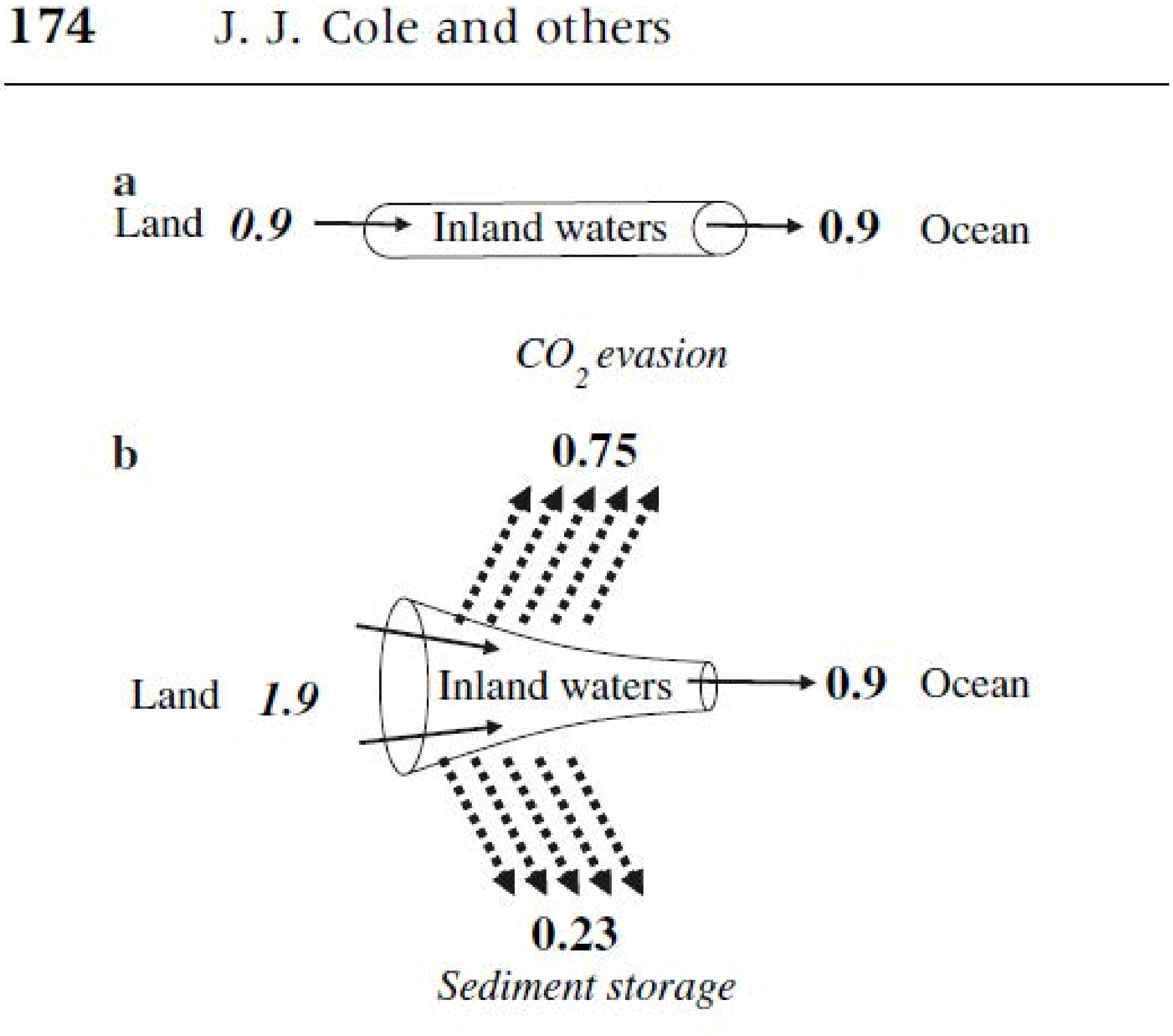
~1.2

2011


Atmosphere 589 + 240 ±10
(average atmospheric increase: 4 (PgC yr^{-1}))
Net ocean flux
2.3 ±0.7
0.7
Ocean-atmosphere gas exchange
80 = 60 + 20
78.4 = 60.7 + 17.7
Freshwater outgassing 1.0
Fossil fuels (coal, oil, gas) cement production 7.8 ±0.6
Net land use change 1.1 ±0.8
Net land flux
2.6 ±1.2
1.7
Gross photosynthesis 123 = 108.9 + 14.1
Total respiration and fire 118.7 = 107.2 + 11.6
Volcanism 0.1
Rock weathering 0.3
Rock weathering 0.1
Export from soils to rivers 1.7
Surface ocean 900
50
37
Marine biota 3
Rivers 0.9
Burial 0.2
90
101
11
2
Intermediate & deep sea 37,100
+155 ±30
Dissolved organic carbon 700
2
0.2
Ocean floor surface sediments 1,750
Vegetation 450-650
-30 ±45
Soils 1500-2400
Permafrost ~1700
Fossil fuel reserves
Gas: 383-1135
Oil: 173-264
Coal: 446-541
-365 ±30
Units
Fluxes: (PgC yr^{-1})
Stocks: (PgC)

IPCC 2013

Active Pipe Model



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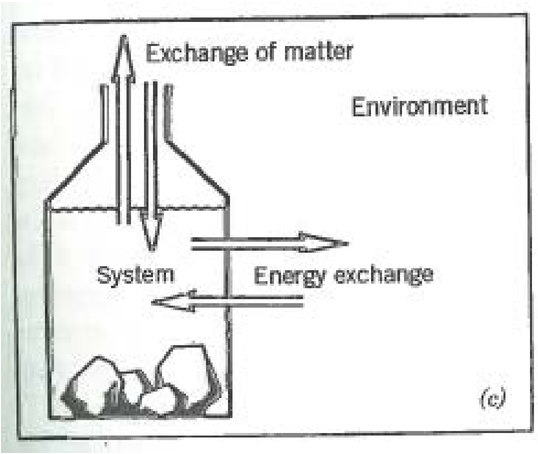
- Inland Waters historically seen as “passive pipe”
- Currently trying to work out fluxes of “active pipe” model

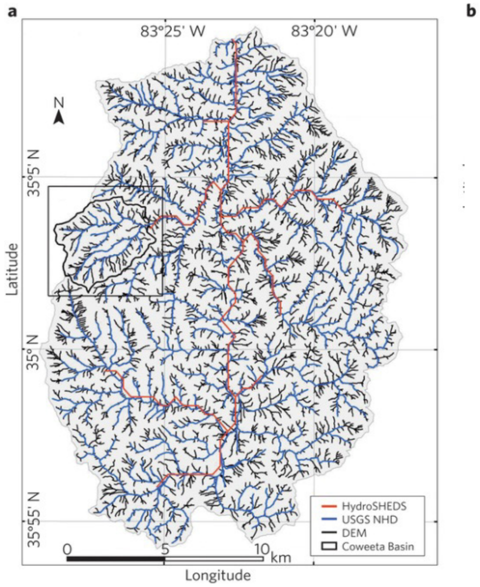
Global Inland Water CO_2 Evasion

CO_2 Concentration Gradient x Surface Area x Gas Transfer Velocity



Stumm and Morgan

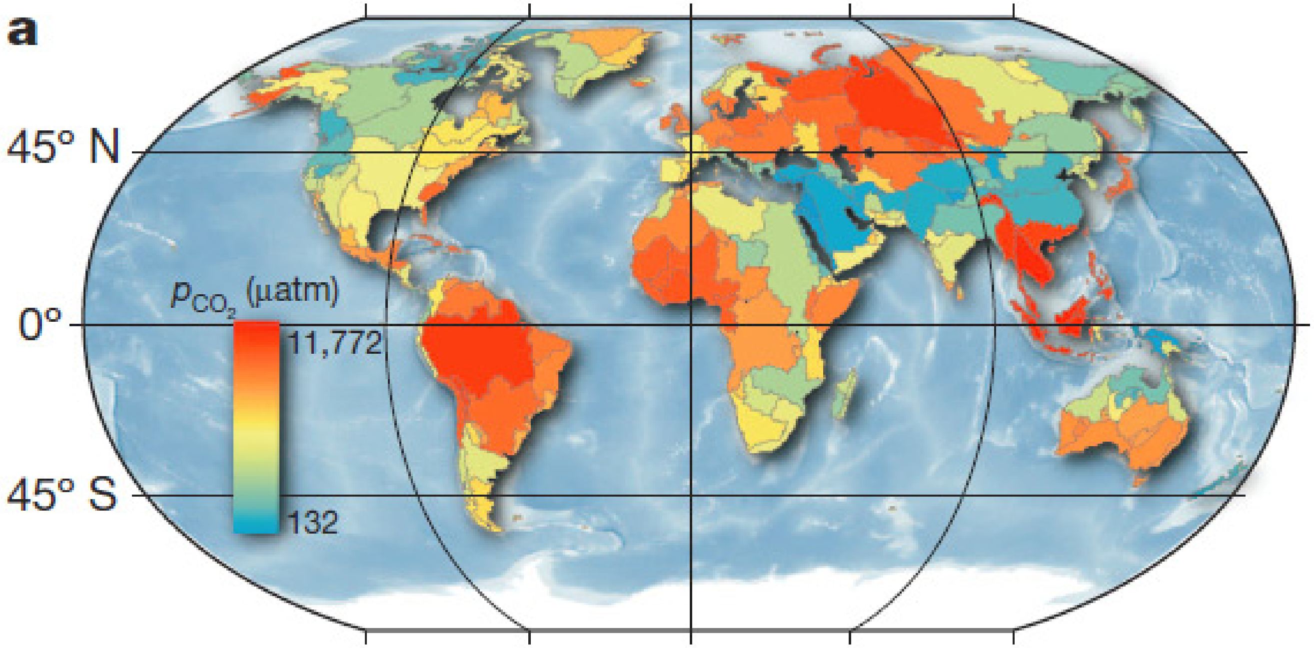
x



Benstead and Leigh, 2012

x

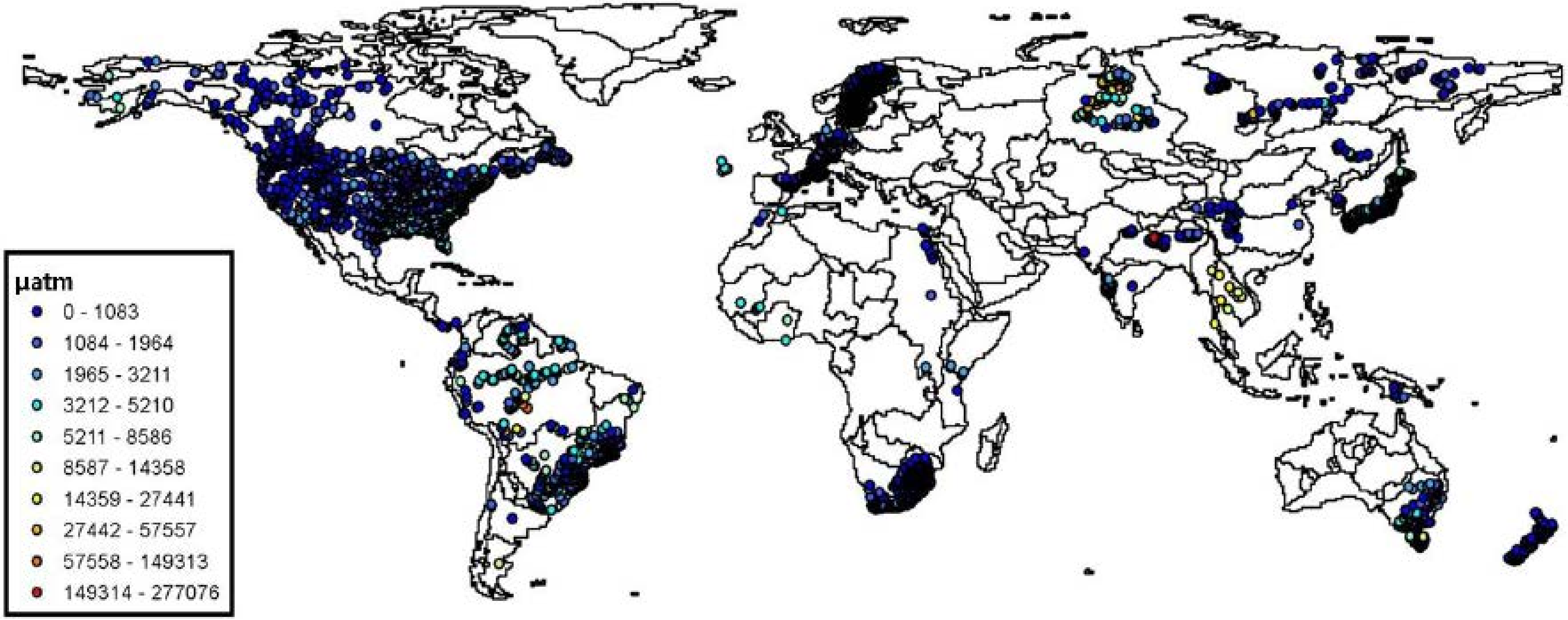
River CO2



Raymond et al. 2013

- 6,709 sites with CO_2 calculated from alkalinity and pH
- Not correlated strongly with anything
- Regional CO_2 was interpolated from individual sites
- Global average= ~3500 µatm (used medians)

Stream/River CO_2 Sites

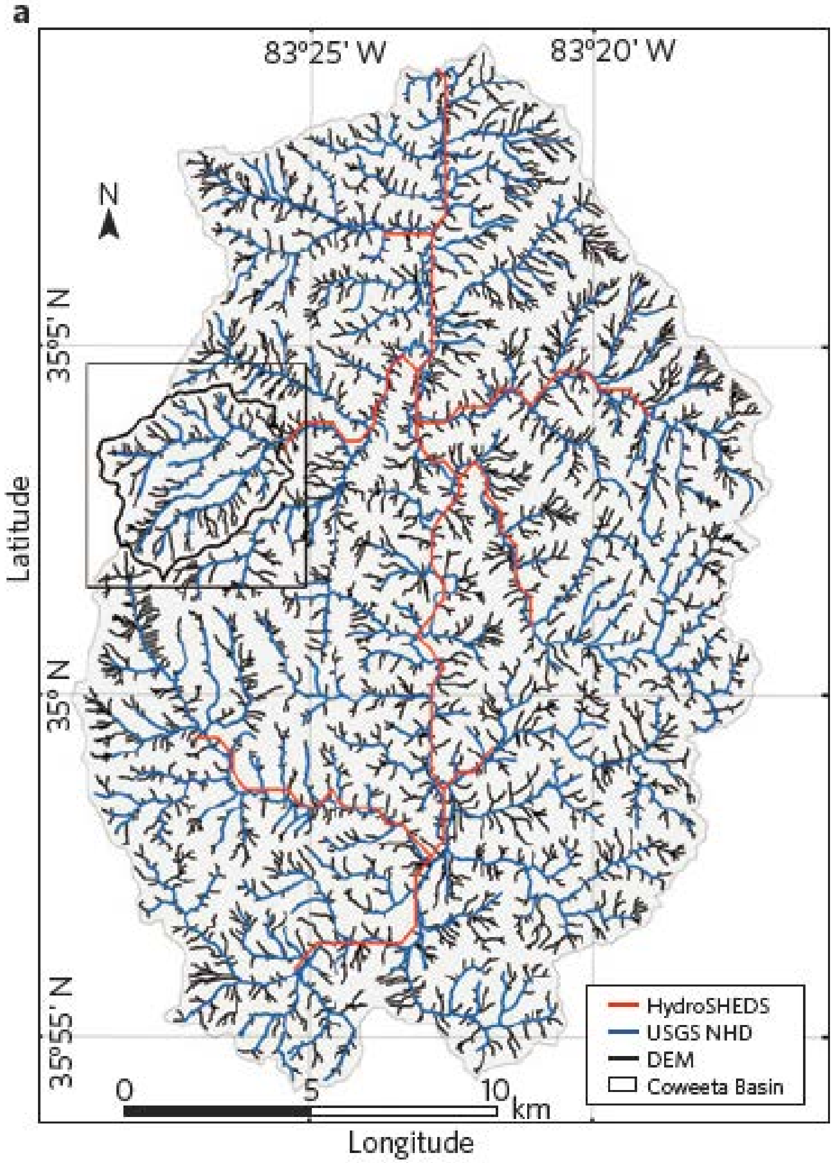


- 6,709 sites with CO_2 calculated from alkalinity and pH
- Not correlated strongly with anything
- Regional CO_2 was interpolated from individual sites
- Global average= ~3500 µatm (used station medians)

Stream Surface Area

- Very few estimates of global stream and river surface area. *No spatially resolved estimate*.
- Estimated from length and width by stream order
- Length gathered from HydroSHEDS
- Width from discharge and hydraulic equations
- Corrected for stream drying and freezing

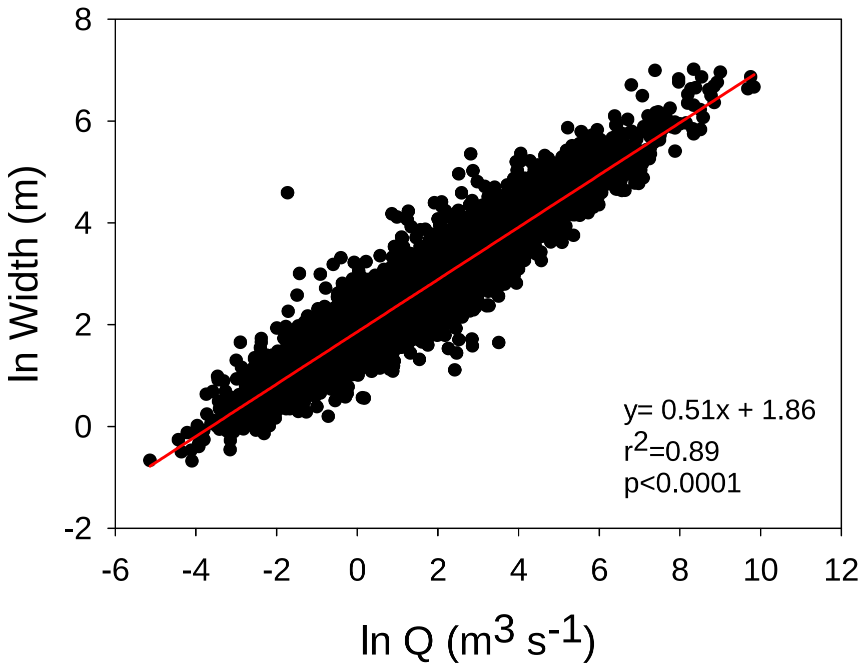
Stream Surface Area - Length



Benstead and Leigh 2012

- Use digital elevation maps
- Global: HydroSHEDS for length (Lehner et al. 2008).
- United States: National Hydraulic Data set (NHD)
- NHD has a better resolution than HydroSHEDS

Stream Surface Area- Width Comparing Two Data Sets



Raymond et al. submitted from USGS data

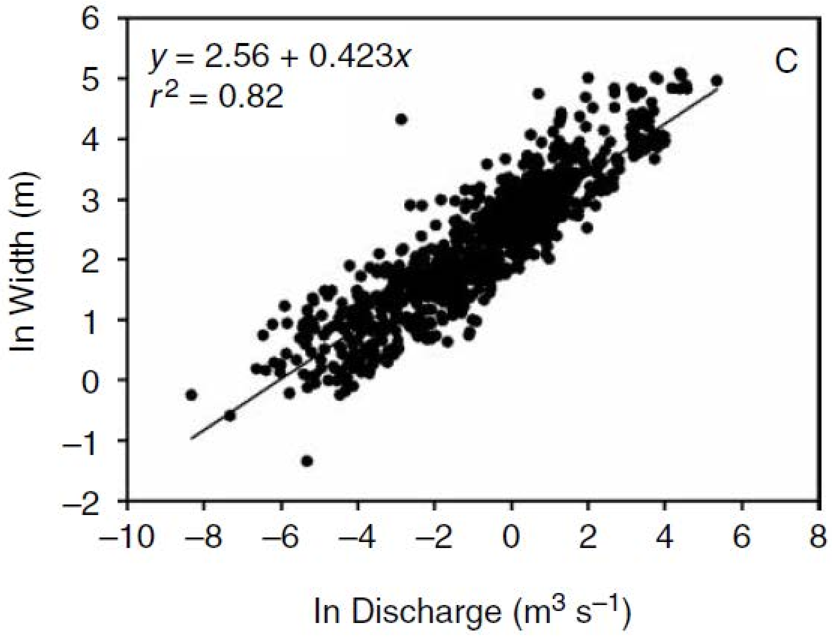


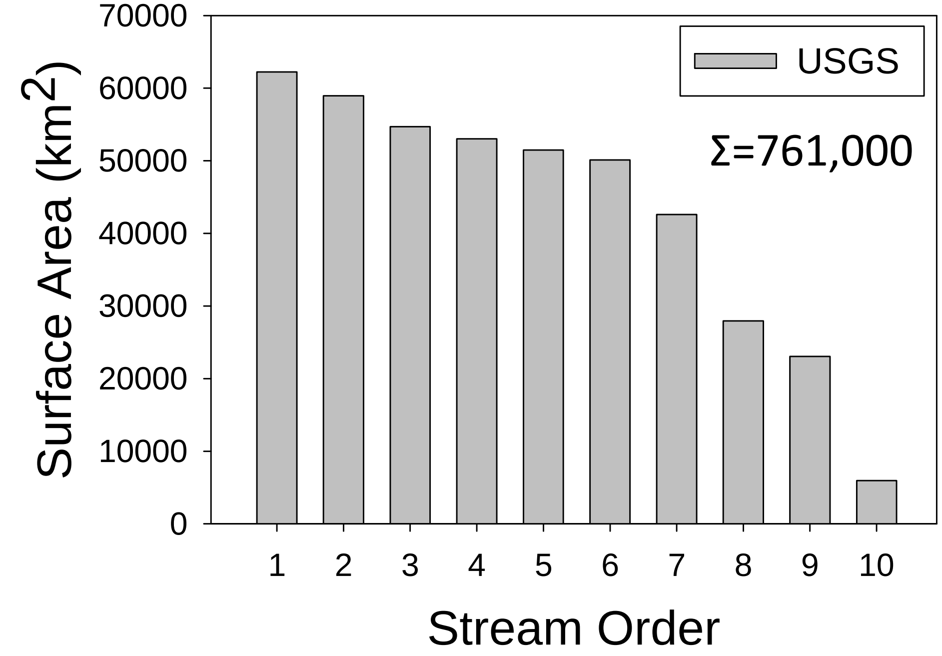
Fig. 1 Hydraulic geometry relationships for streams and rivers of this study. Presented are the relationships between discharge and velocity (A), depth (B), and width (C).

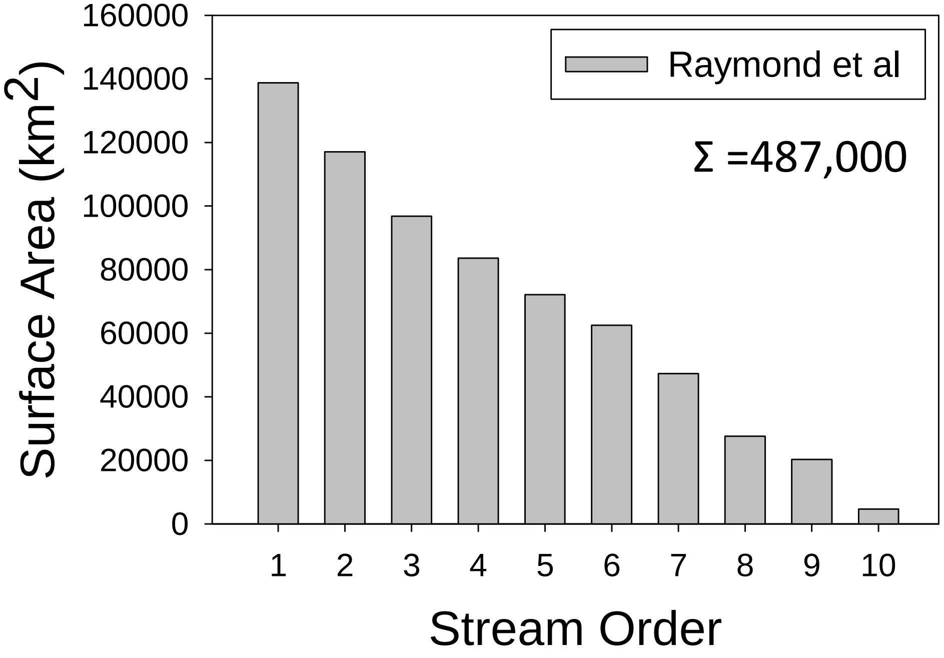
Raymond et al. 2012

$$W = aQ^b$$

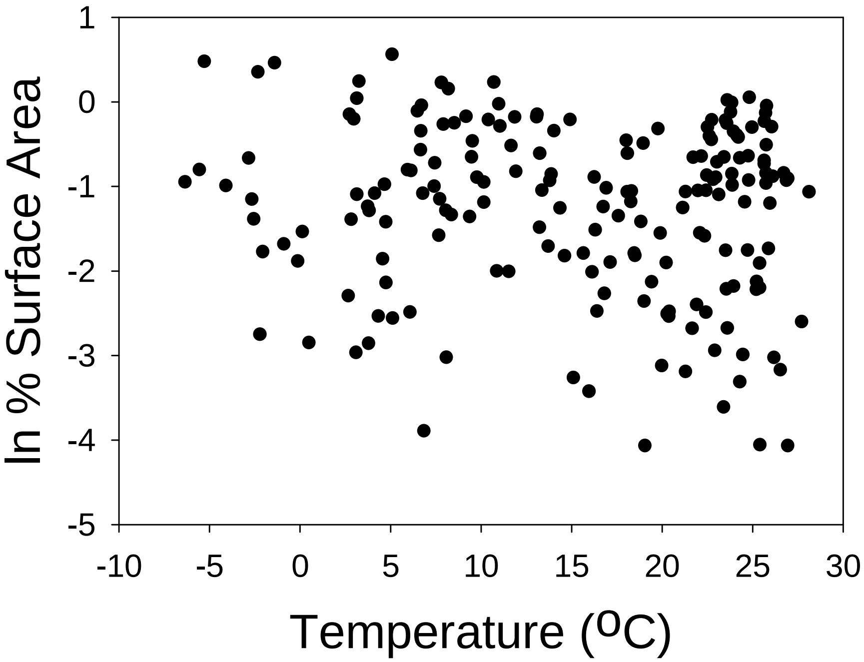
Global surface area by stream order

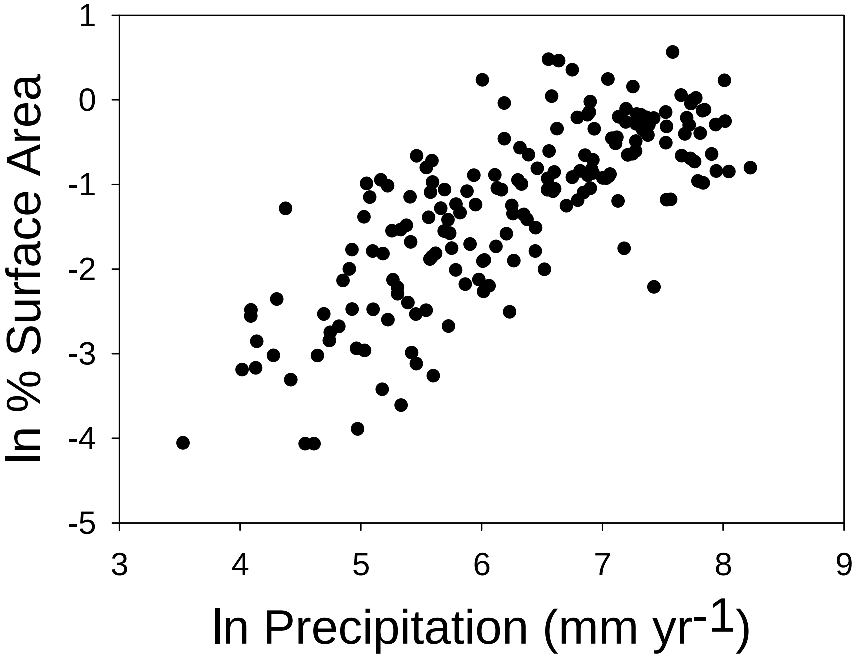
- Large differences due to equations
- Importance of small streams





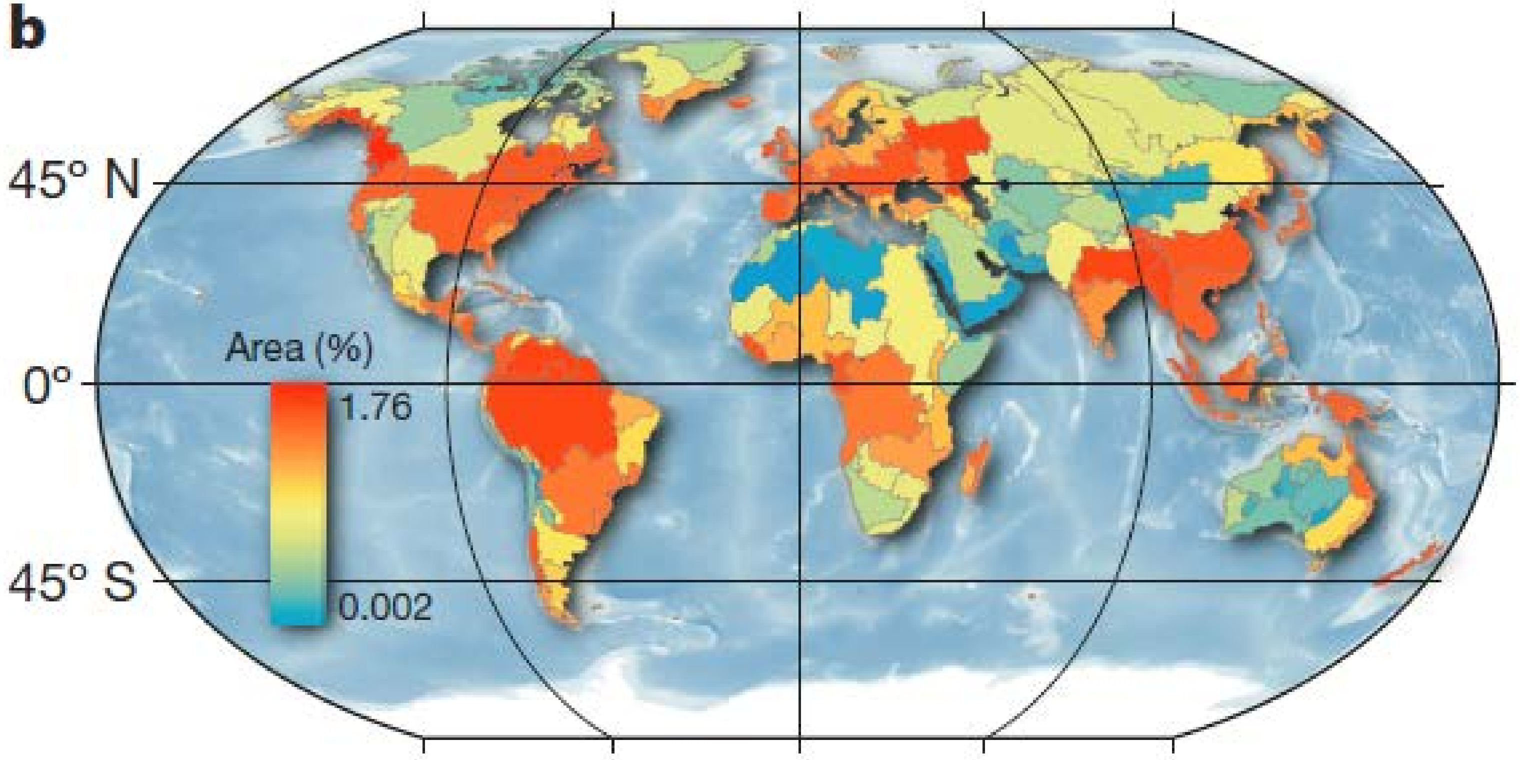
Climatic Regulation of Surface Area





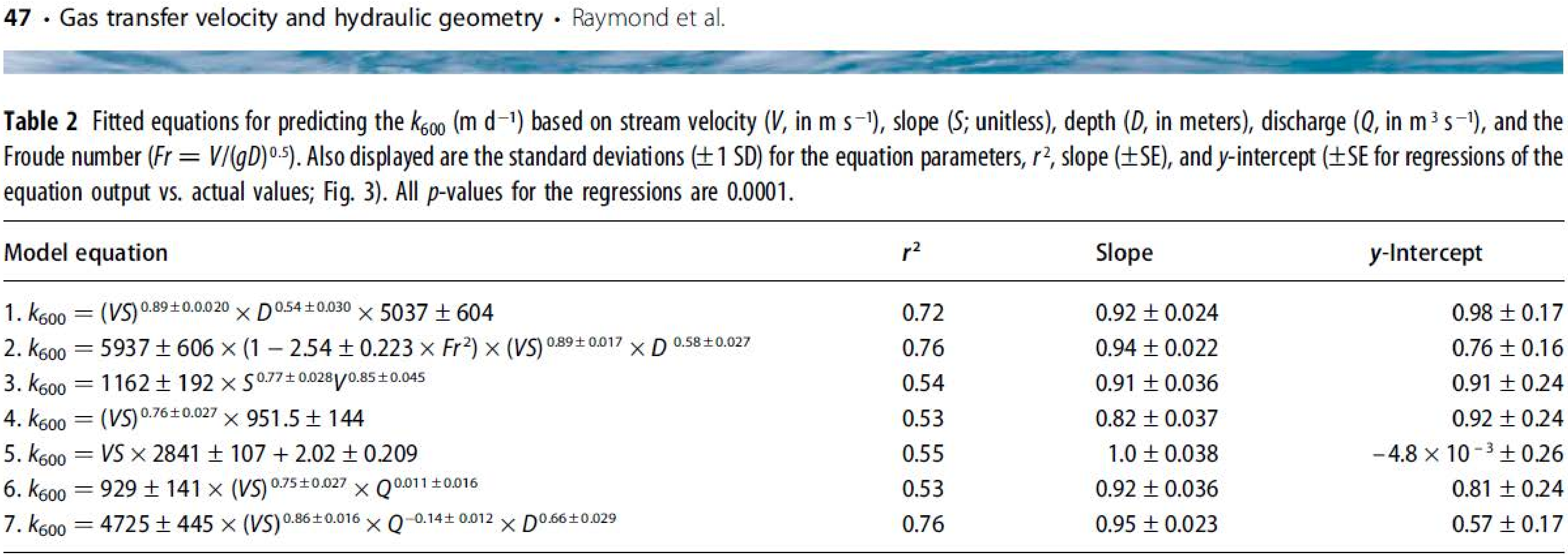
- Greater surface area in wetter regions.
- Width relationship with Precip, stronger than length Density

River Surface Area



- Total Surface area of 624,000km^2 (0.5% earth surface)
- Aufdenkampe 2011: 320,000-510,000km^2
- Downing et al. 2012: 485,000-662,000km^2
- Approximately 88,000km^2 is blocked by ice
- Approximately 84,000km2 not active due to drying

Stream Gas Transfer Velocity (k_{600})



47 · Gas transfer velocity and hydraulic geometry · Raymond et al.

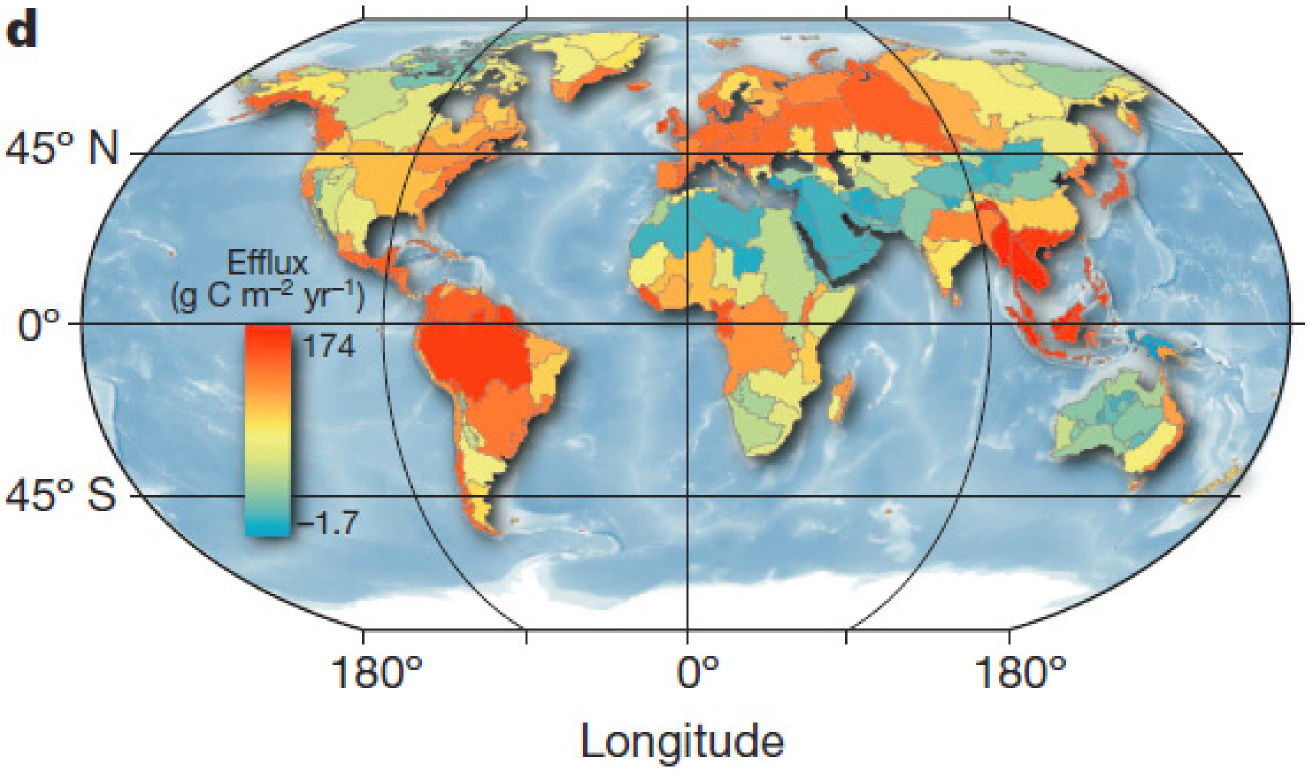
Table 2 Fitted equations for predicting the k_{600} (m d^{-1}) based on stream velocity (V, in m s^{-1}), slope (S; unitless), depth (D, in meters), discharge (Q, in m^3 s^{-1}), and the Froude number ($Fr = V/(gD)^{0.5}$). Also displayed are the standard deviations (±1 SD) for the equation parameters, r^2, slope (±SE), and y-intercept (±SE for regressions of the equation output vs. actual values; Fig. 3). All p-values for the regressions are 0.0001.

Model equation	r^2	Slope	y-Intercept
1. $k_{600} = (VS)^{0.89 \pm 0.0.020} \times D^{0.54 \pm 0.030} \times 5037 \pm 604$	0.72	0.92 ± 0.024	0.98 ± 0.17
2. $k_{600} = 5937 \pm 606 \times (1 - 2.54 \pm 0.223 \times Fr^2) \times (VS)^{0.89 \pm 0.017} \times D^{0.58 \pm 0.027}$	0.76	0.94 ± 0.022	0.76 ± 0.16
3. $k_{600} = 1162 \pm 192 \times S^{0.77 \pm 0.028} V^{0.85 \pm 0.045}$	0.54	0.91 ± 0.036	0.91 ± 0.24
4. $k_{600} = (VS)^{0.76 \pm 0.027} \times 951.5 \pm 144$	0.53	0.82 ± 0.037	0.92 ± 0.24
5. $k_{600} = VS \times 2841 \pm 107 + 2.02 \pm 0.209$	0.55	1.0 ± 0.038	$-4.8 \times 10^{-3} \pm 0.26$
6. $k_{600} = 929 \pm 141 \times (VS)^{0.75 \pm 0.027} \times Q^{0.011 \pm 0.016}$	0.53	0.92 ± 0.036	0.81 ± 0.24
7. $k_{600} = 4725 \pm 445 \times (VS)^{0.86 \pm 0.016} \times Q^{-0.14 \pm 0.012} \times D^{0.66 \pm 0.029}$	0.76	0.95 ± 0.023	0.57 ± 0.17

- K_{600} is a function of turbulence at the surface of streams
- Calculated from slope and velocity (Raymond et al. 2012) from 563 independent measuremens
- Velocity estimated from discharge and hydraulic equations
- Slope gathered from Hydrosheds

$$V = cQ^d$$

Global Stream/River Evasion



- 1.8Pg yr^{-1} (2.2 with lakes and reservoirs)
- 70% of CO2 from 20% of Earth surface
- High Fluxes from Southeast Asia, Amazonia, Central America, Europe, regions of South America west of the Andes, Southeast Alaska, western Africa, and the eastern edge of East Asia

(hypothetical) Sources of 2.2 Pg yr^{-1}

- Soil CO_2
  - Assume all soil water entering inland waters (40,000km^3 yr^{-1}) has CO_2 concentration of 50,000µatm that evades = 1.0Pg yr^{-1}.

(hypothetical) Sources of 2.2 Pg yr^{-1}

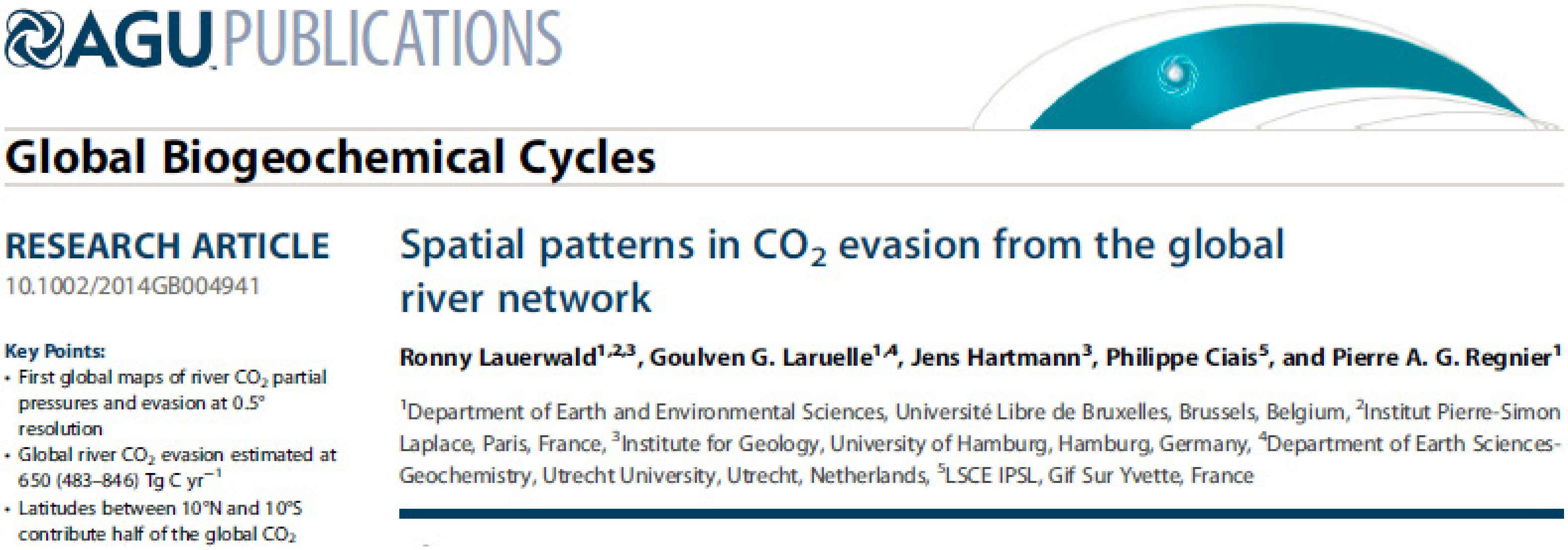
- Soil CO_2. 1 Pg yr^{-1}
- Terrestrial OM Decomposition
  - Assume lateral transport of soil OM is twice as large as what is exported to the ocean and that this OM is oxidized and evaded as CO_2. ~0.4Pg yr^{-1}

(hypothetical) Sources of 2.2 Pg yr^{-1}

- Soil CO_2. 1 Pg yr^{-1}
- Terrestrial OM Decomposition. 0.4Pg yr^{-1}
- Wetland and riparian root respiration.
  - Assume 20% of wetland NPP (6Pg yr^{-1}) is transferred laterally as C and evaded as CO_2

(hypothetical) Sources of 2.2 Pg yr^{-1}

- Soil CO_2. 1 Pg yr^{-1}
- Terrestrial OM Decomposition. 0.4Pg yr^{-1}
- Wetland and riparian root respiration. 1.2Pg yr^{-1}



AGU PUBLICATIONS

Global Biogeochemical Cycles

RESEARCH ARTICLE

10.1002/2014GB004941

Key Points:
- First global maps of river CO_2 partial pressures and evasion at 0.5° resolution
- Global river CO_2 evasion estimated at 650 (483–846) Tg C yr^{-1}
- Latitudes between 10°N and 10°S contribute half of the global CO_2

Spatial patterns in CO_2 evasion from the global river network

Ronny Lauerwald[1,2,3], Goulven G. Laruelle[1,4], Jens Hartmann[3], Philippe Ciais[5], and Pierre A. G. Regnier[1]

[1]Department of Earth and Environmental Sciences, Université Libre de Bruxelles, Brussels, Belgium, [2]Institut Pierre-Simon Laplace, Paris, France, [3]Institute for Geology, University of Hamburg, Hamburg, Germany, [4]Department of Earth Sciences-Geochemistry, Utrecht University, Utrecht, Netherlands, [5]LSCE IPSL, Gif Sur Yvette, France

- Significantly lower estimate
  - – 0.65 vs 1.3 Pg yr^{-1}

nature geoscience

ARTICLES

PUBLISHED ONLINE: 20 JULY 2015 | DOI: 10.1038/NGEO2486

Globally significant greenhouse-gas emissions from African inland waters

Alberto V. Borges[1*], François Darchambeau[1], Cristian R. Teodoru[2], Trent R. Marwick[2], Fredrick Tamooh[2,3], Naomi Geeraert[2], Fredrick O. Omengo[2], Frédéric Guérin[4], Thibault Lambert[1], Cédric Morana[2], Eric Okuku[2,5] and Steven Bouillon[2]

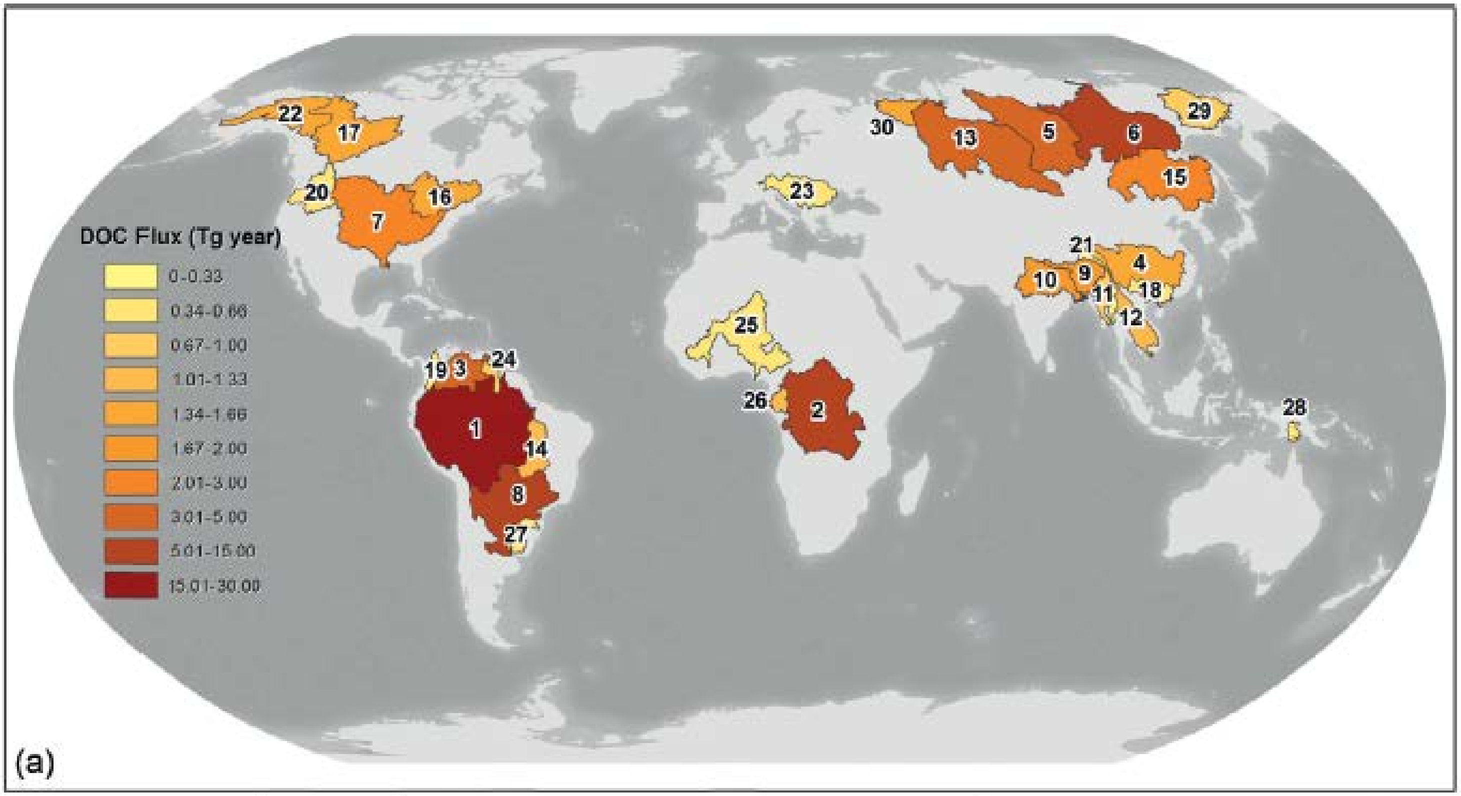
- Significantly higher estimate
  - – 0.4 vs 0.1 Pg yr^{-1}

How much riverine DOC makes it to the ocean?

Study	Estimate ($Pg\ yr^{-1}$)
Schlesinger and Melack (1981)	0.37-0.41
Ludwig et al. (1996)	0.21
Meybeck (1993)	0.20
Aitkenhead and McDowell (2000)	0.36
Meybeck (1982)	0.22
Harrison et al. (2005) **Seitzenger et al. (2005)**	0.17
Mayorga et al. (2010)	0.16
Dai et al. (2012)	0.21-0.22
Raymond and Spencer (2014)	0.25

- There are now numerous estimates
- They are a bit incestuous in the data they utilize (still room for improvement)
- Annual variation of ~25%

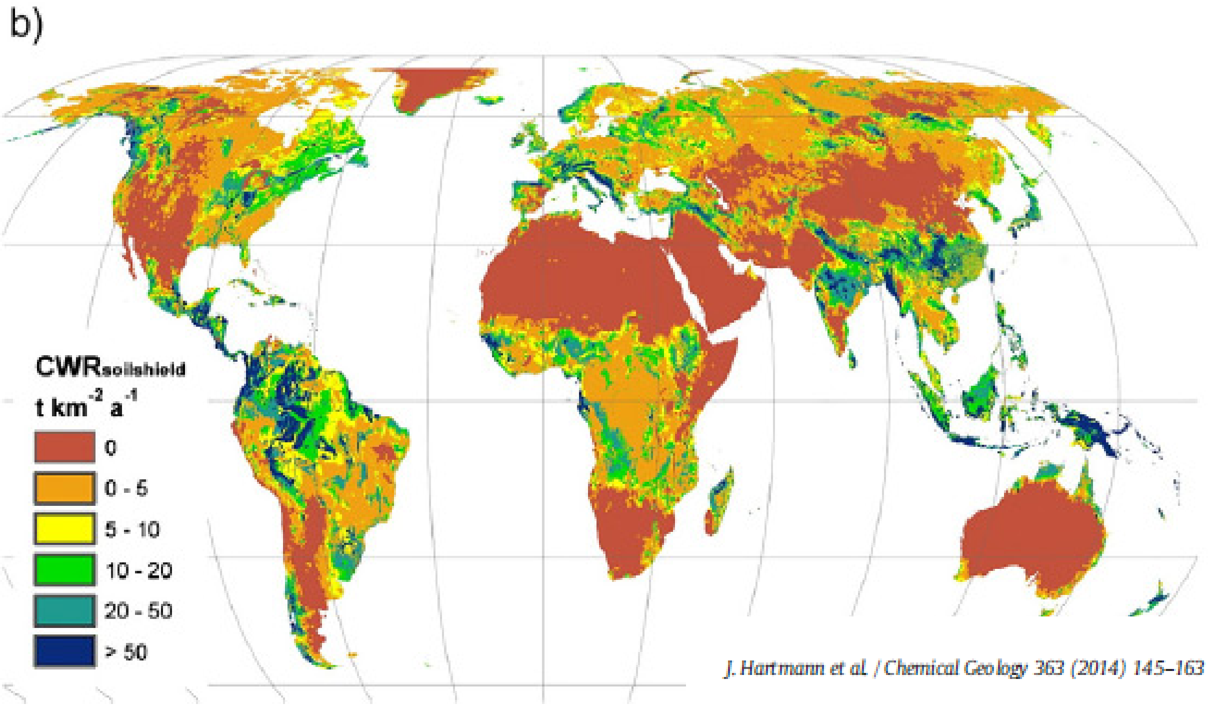
DOC flux for top 30 rivers ranked by discharge



Raymond and
Spencer (2014)

- 36% of land draining into ocean
- 50% of global ocean discharge

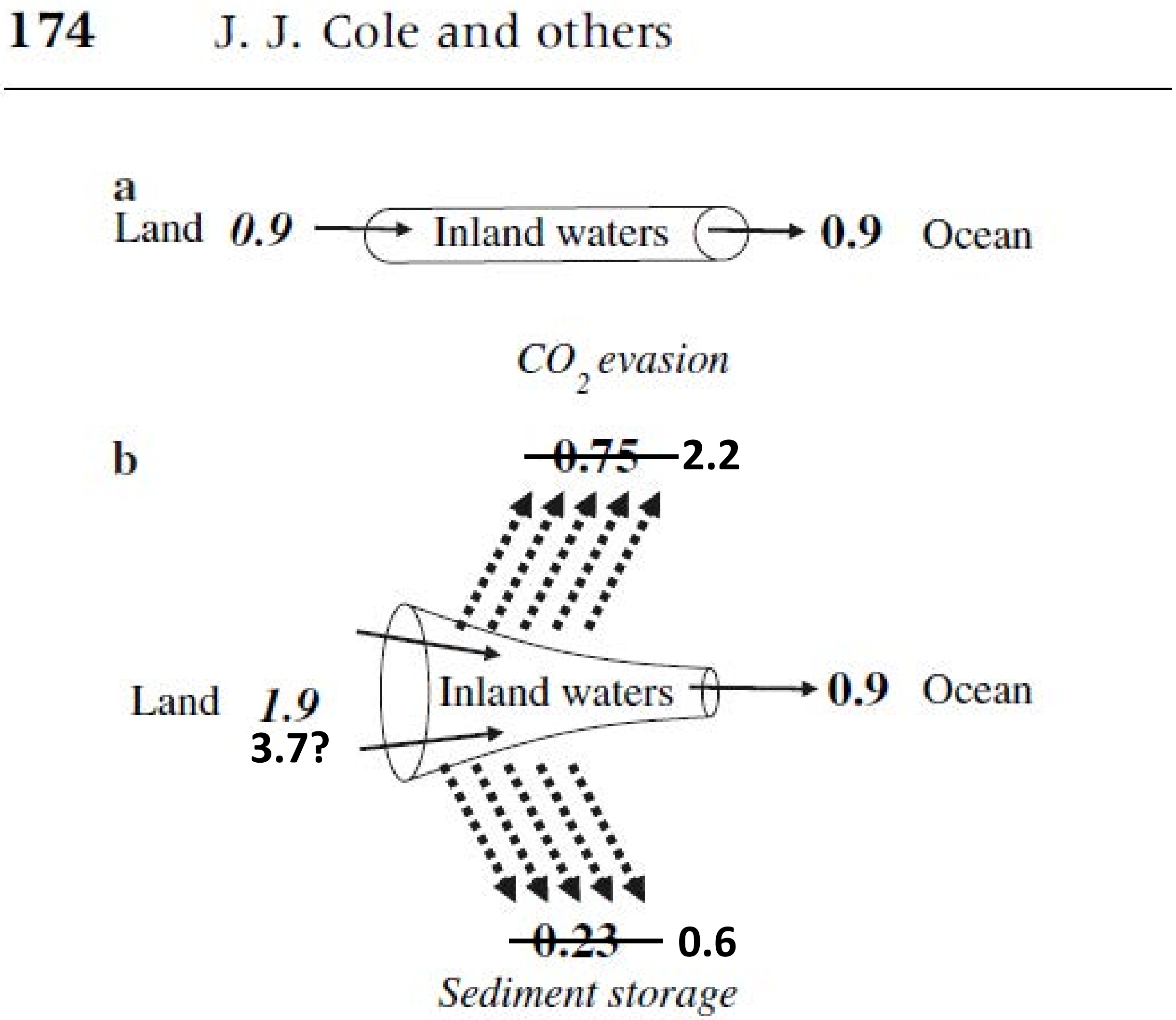
DIC/Alkalinity Fluxes



J. Hartmann et al. / Chemical Geology 363 (2014) 145–163

- Facilitated by strong relationship between fluxes and climate/lithology
- 70% of flux, 10% area
- ~0.35 Pg C yr^{-1} (as bicarbonate)

Active Pipe Model-Global



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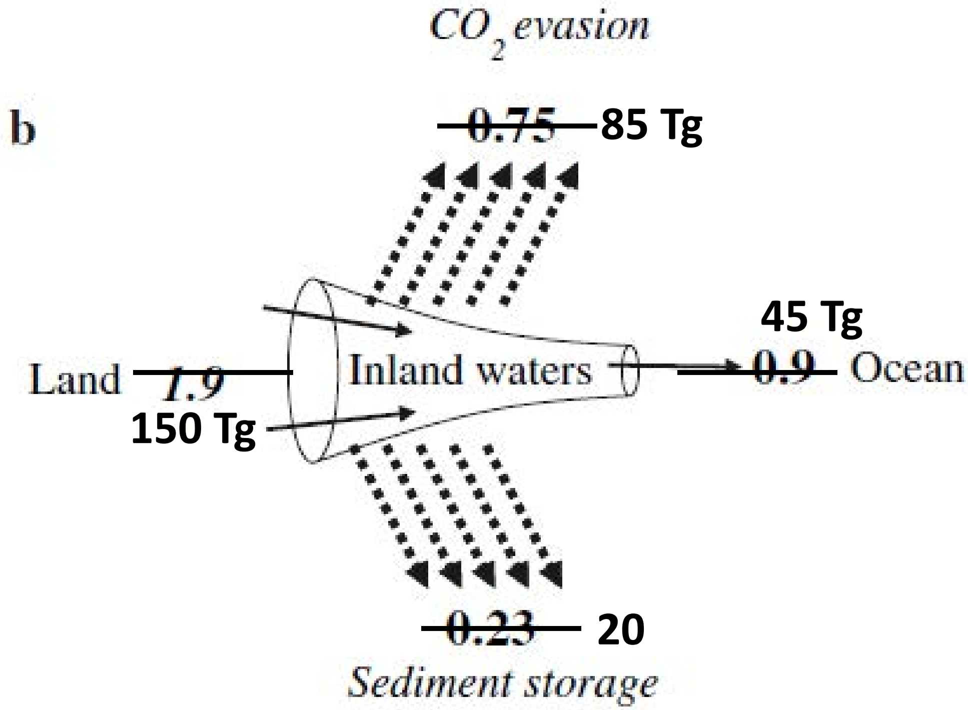
Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting

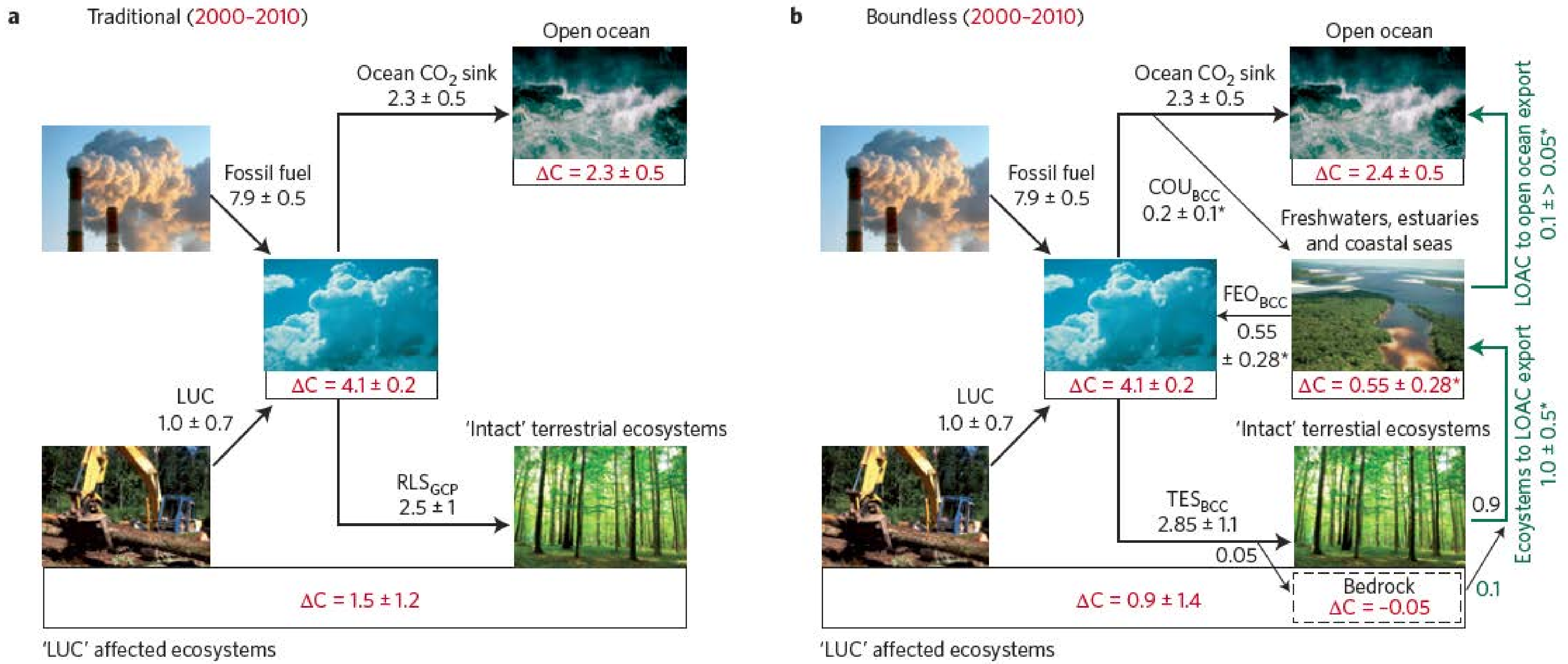
David Butman[a,b,1], Sarah Stackpoole[c], Edward Stets[a], Cory P. McDonald[d], David W. Clow[c], and Robert G. Striegl[a]

[a]US Geological Survey, Boulder, CO 80303; [b]School of Environmental and Forest Sciences and the Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195; [c]US Geological Survey, Denver, CO 80225; and [d]Wisconsin Department of Natural Resources, Madison, WI 53707

Edited by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved November 12, 2015 (received for review June 29, 2015)



NATURE GEOSCIENCE DOI: 10.1038/NGEO1830 REVIEW ARTICLE



Regnier et al. 2013

Thank you

- Funding: NASA grant (NNX11AH68G)
- Jens Hartmann, Ronny Lauerwald, Sebastian Sobek, Cory McDonald, Mark Hoover, David Butman, Rob Striegl, Emilio Mayorga, Christoph Humborg, Pirkko Kortelainen, Hans Durr, Michel Meybeck, Philippe Ciais, Peter Guth
- Rob Spencer