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São Paulo, February 18 -19, 2016

"The role of rivers in the regional carbon cycle"

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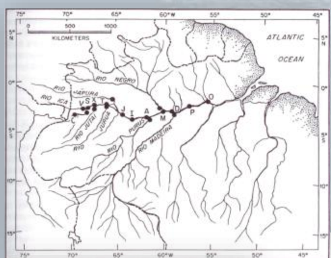

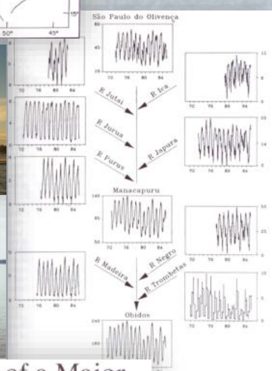

The Biogeochemistry of a Major River System: The Amazon Case Study

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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

Estimating cell-to-cell land surface drainage paths from digital channel networks, with an application to the Amazon basin

Emilio Mayorga, Miles G. Logsdon, Maria Victoria R. Ballester, Jeffrey E. Richey

Spatial and temporal variability of pCO_2 and CO_2 efflux in seven Amazonian Rivers

Maria de Fátima F. L. Rasera, Alex V. Krusche, Jeffrey E. Richey, Maria V. R. Ballester & Reynaldo L. Victória

Application of Isotope Techniques for Assessing Nutrient Dynamics in River Basins

IAEA

Estimating the Surface Area of Small Rivers in the Southwestern Amazon and Their Role in CO_2 Outgassing

Influences of land use and stream size on particulate and dissolved materials in a small Amazonian stream network

Intra and interannual variability in the Madeira River water chemistry and sediment load

Nei K. Leite · Alex V. Krusche · Maria V. R. Ballester · Reynaldo L. Victoria · Jeffrey E. Richey · Beatriz M. Gomes

A remote sensing/GIS-based physical template to understand the biogeochemistry of the Ji-Paraná river basin (Western Amazônia)

Water Balance for the Ji-Paraná River Basin, Western Amazon, Using a Simple Method through Geographical Information Systems and Remote Sensing

Land cover map production for Brazilian Amazon using NDVI SPOT VEGETATION time series

A. Rodrigues, A.R.S. Marcal, D. Furlan, M.V. Ballester, and M. Cunha

Seasonal variation in dissolved carbon concentrations and fluxes in the upper Purus River, southwestern Amazon

Cleber Salimon · Eliete dos Santos Sousa · Simone R. Alin · Alex Vladimir Krusche · Maria Victoria Ballester

Deforestation alters the hydraulic and biogeochemical characteristics of small lowland Amazonian streams

Christopher Neill, Linda A. Deegan, Suzanne M. Thomas, Christie L. Haupert, Alex V. Krusche, Victoria M. Ballester and Reynaldo L. Victoria

Loss of Nutrients From Terrestrial Ecosystems to Streams and the Atmosphere Following Land Use Change in Amazonia

Eric A. Davidson, Christopher Neill, Alex V. Krusche, Victoria V. R. Ballester, Daniel Markewitz, and Ricardo de O. Figueiredo

A remote sensing/GIS-based physical template to understand the biogeochemistry of the Ji-Paraná river basin (Western Amazônia)

Intra and interannual variability in the Madeira River water chemistry and sediment load

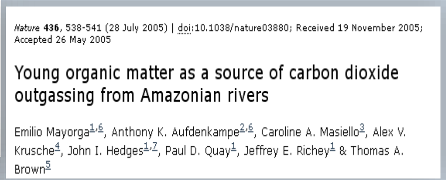
Recent Reserach :

- Rivers and freshwater ecosystems release high levels of CO_2 to the atmosphere
- Globally these waters process, transport and sequester 2.7 Pg C yr^{-1} [(a)]
- Similar value to the estimated for terrestrial ecosystems carbon sequestration from human activities (2.8 Pg C yr^{-1} [(b)])


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

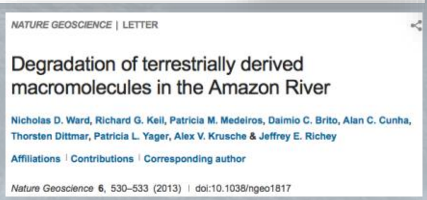
Jeffrey E. Richey*, John M. Melack†, Anthony K. Aufdenkampe*, Victoria M. Ballester‡ & Laura L. Hess†

NATURE | VOL 416 | 11 APRIL 2002 |


Nature 436, 538-541 (28 July 2005) | doi:10.1038/nature03880; Received 19 November 2005; Accepted 26 May 2005

Young organic matter as a source of carbon dioxide outgassing from Amazonian rivers

Emilio Mayorga[1,6], Anthony K. Aufdenkampe[2,6], Caroline A. Masiello[3], Alex V. Krusche[4], John I. Hedges[1,7], Paul D. Quay[1], Jeffrey E. Richey[1] & Thomas A. Brown[5]


NATURE GEOSCIENCE | LETTER

Degradation of terrestrially derived macromolecules in the Amazon River

Nicholas D. Ward, Richard G. Keil, Patricia M. Medeiros, Daimio C. Brito, Alan C. Cunha, Thorsten Dittmar, Patricia L. Yager, Alex V. Krusche & Jeffrey E. Richey

Affiliations | Contributions | Corresponding author

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Biogeochemistry
An International Journal
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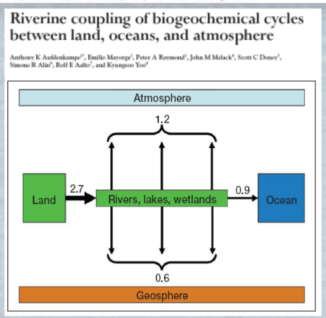
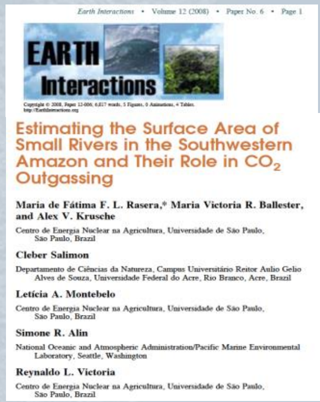
Biogeochemistry


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


Earth Interactions • Volume 12 (2008) • Paper No. 6 • Page 1

EARTH Interactions

Estimating the Surface Area of Small Rivers in the Southwestern Amazon and Their Role in CO_2 Outgassing

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Global Change Biology

Global Change Biology (2014), doi: 10.1111/gcb.12646

Methane emissions from Amazonian Rivers and their contribution to the global methane budget

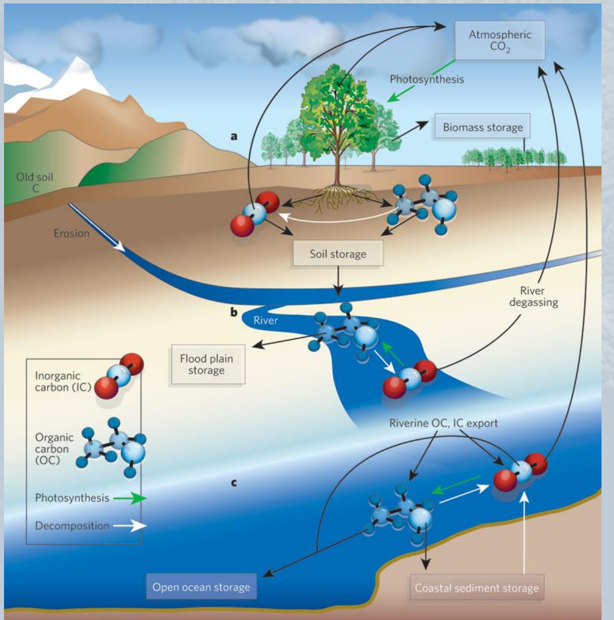
HENRIQUE O. SAWAKUCHI[1], DAVID BASTVIKEN[2], ANDRÉ O. SAWAKUCHI[3], ALEX V. KRUSCHE[1], MARIA V. R. BALLESTER[1] and JEFFREY E. RICHEY[4]


Global Change Biology

Global Change Biology (2012), doi: 10.1111/gcb.12083

Evasion of CO_2 from streams – The dominant component of the carbon export through the aquatic conduit in a boreal landscape

MARCUS B. WALLIN*†, THOMAS GRABS*, ISHI BUFFAM‡, HJALMAR LAUDON§, ANNELI ÅGREN§, MATS G. ÖQUIST§ and KEVIN BISHOP*†



Raymond, 2005)

Fluvial processing plays a key role on carbon (and associate nutrients) transport and re-cycling not only in the watersheds but also in the oceans that receive their waters.

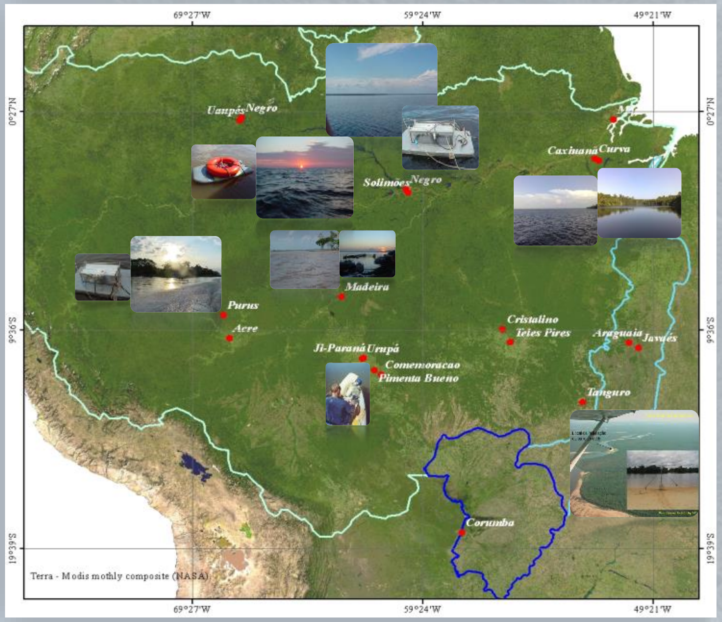
[(a)] Battin et al., 2009; Tranvik et al., 2009, [(b)] Canadell et al., 2007;

Challenge:

develop tools to comprehensively describe Amazonian fluvial biogeochemistry and the role of rivers in the regional C cycle to predict their responses to climate change

Overall objective

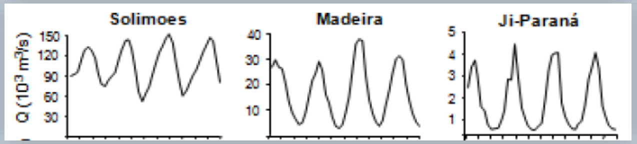
Produce scientific data on Amazonian fluvial systems to feed a carbon base basin wide model to predict their responses to global climate change and regional land use change



Long term data collection : 20 extensive sampling (Rede Beija-Rio), distributed in the Amazon basin

+

Intensive campaigns employing several measurement methods and laboratory experiments at least once at each stage of the hydrograph, at several spatial scales



We have demonstrated that the rivers of the Amazon play an important role in the regional carbon cycle

- Evading to the atmosphere ~0,5 Gt C yr^{-1}
- 13 x more C than discharged to the ocean:
  - TOC: 0,036 and DIC: 0,035 Gt.yr^{-1}
  - Higher than the amount released by regional deforestation at it's peak (0,38 GtC yr^{-1}, ~25.000 km^2. yr^{-1})

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

NATURE | VOL 416 | 11 APRIL 2002 |

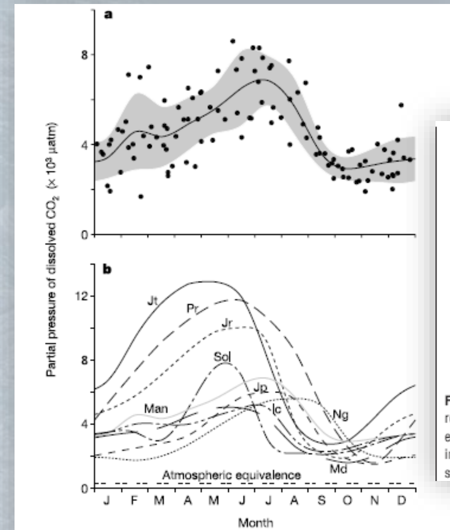


Figure 3 Seasonal distributions of carbon dioxide dissolved in rivers of the central Amazon basin. **a**, A ten-year time-series station on the mainstem Amazon near Manaus (Man, by the confluence of the Negro and Solimões) offers a high-resolution image of seasonality. **b**, Annual profiles for major tributaries derived from thirteen expeditions to observation

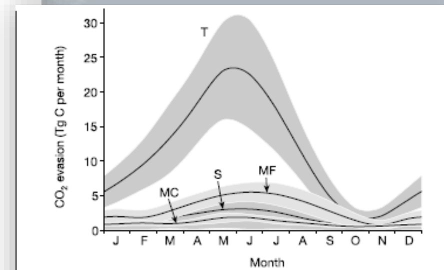
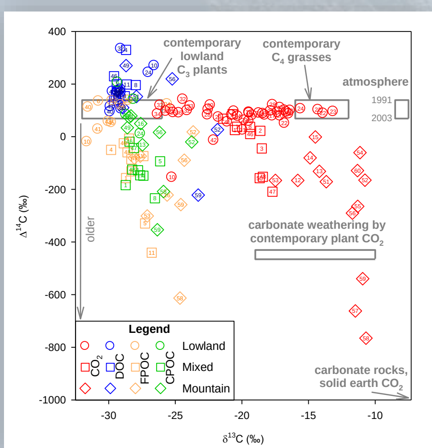


Figure 4 Spatially integrated sequences of monthly carbon dioxide evasion for the respective hydrographic environments (identified in Fig. 2). Lines represent the best estimate of long-term means, whereas shaded regions represent the 67% confidence interval for the range of values likely in a particular year. The upper confidence limit for streams, hidden from view, extends nearly to the upper limit for floodplains.

What is these CO_2 main source?



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- In channel respiration of young labile organic matter (~5 year)

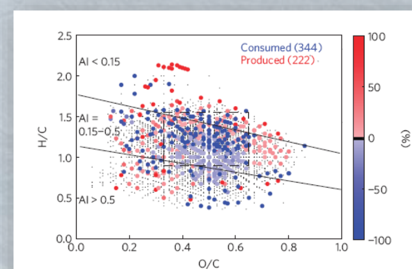

Figure 1 | Van Krevelen diagrams of incubated Amazon River DOM. The relative degradation/production of DOM compounds (based on hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios) after a 10-day incubation period. Of the 2,804 compounds detected (black), 344 were consumed (blue) and 222 were produced (red). Most consumed DOM compounds have element ratios consistent with lignin and other polyphenols (centred rectangle). Compounds with an aromaticity index

NATURE GEOSCIENCE | LETTER

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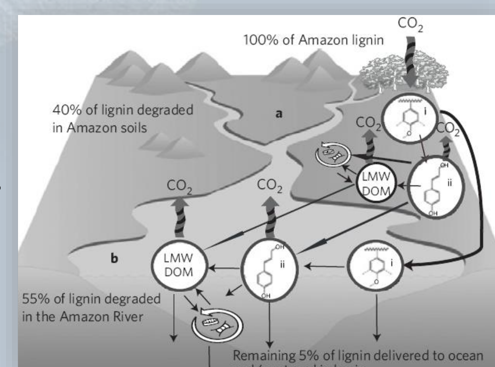
Nature Geoscience 6, 530–533 (2013) | doi:10.1038/ngeo1817

- 55 % of terrestrial lignin is degraded by in channel bacteria



Smaller rivers (channel wide < 100 m)

Earth Interactions • Volume 12 (2008) • Paper No. 6 • Page 1

EARTH Interactions

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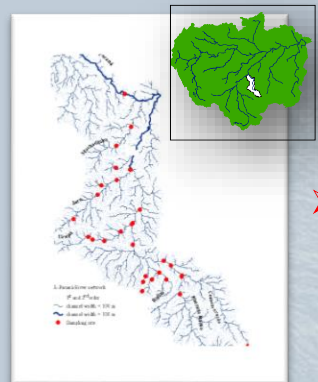
Rasera et al., 2008



Ji-Paraná River Basin

CO_2 evasion main C export pathway:

289 Gg C yr^{-1}

➢ ~2,4 x the amount of C exported as dissolved inorganic carbon (121 Gg C y^{-1}) and 1,6 x as dissolved organic carbon (185 Gg C y^{-1})

Earth Interactions • Volume 12 (2008) • Paper No. 6 • Page 12

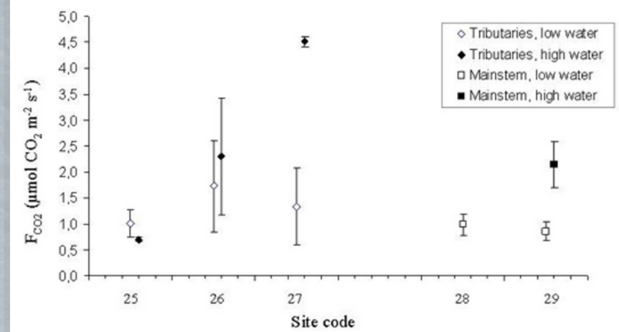
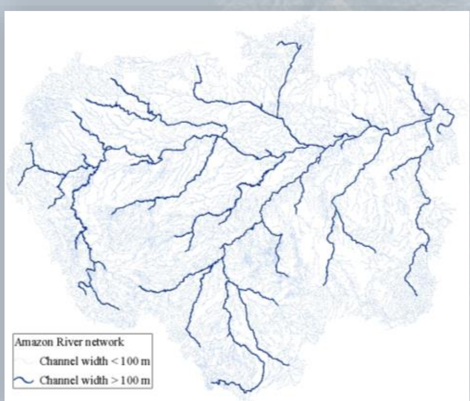


Figure 4. Average CO_2 flux in tributaries and the Ji-Paraná River main stem at low and high water periods. The numbers correspond to rivers: 25 = Comemoração, 26 = Pimenta Bueno, 27 = Urupá, 28 = first site at Ji-Paraná, and 29 = second site at Ji-Paraná.



~92% of the Amazon river network are small rivers,

usually supersaturated with CO_2

- surface small rivers area: 0,3 ± 0,05 millions of km^2,
- Potential evasion to the atmosphere:170 ± 42 Tg C y^{-1} as CO_2
- Relevant role in the regional carbon cycle

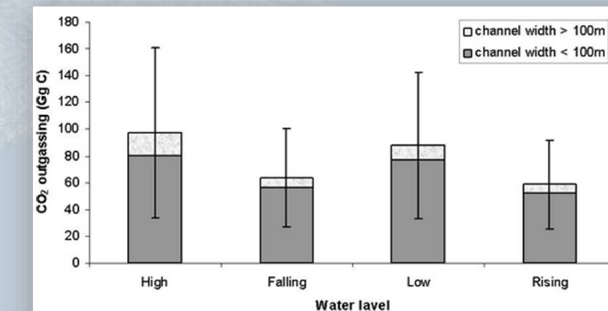


Figure 5. Carbon dioxide outgassing from rivers of the Ji-Paraná River basin during low, rising, high, and falling water periods. The uncertainty bar corresponds to the combined standard uncertainty resulting from contributions of calculated surface area and CO_2 fluxes measured with chambers.

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Journal of Hydrology 315 (2005) 167–182

Journal of Hydrology

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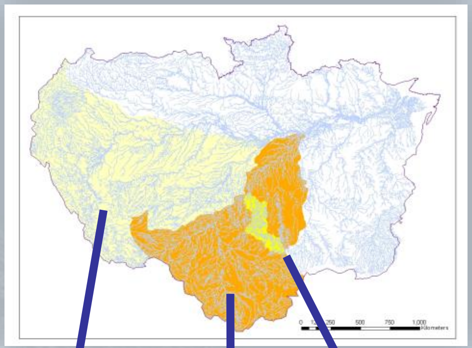
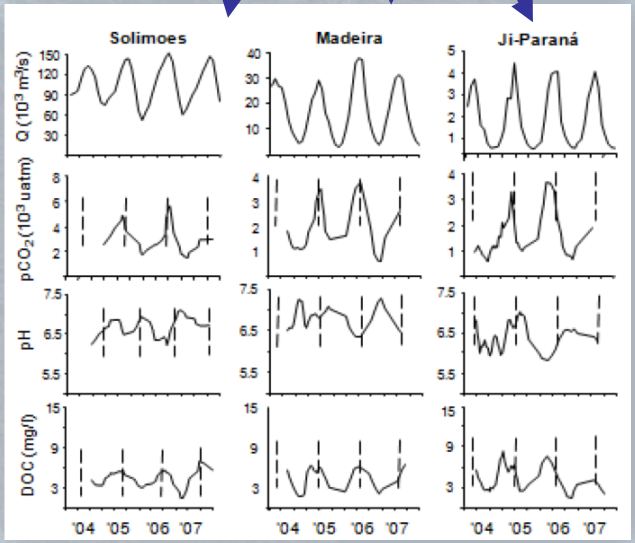
Estimating cell-to-cell land surface drainage paths from digital channel networks, with an application to the Amazon basin

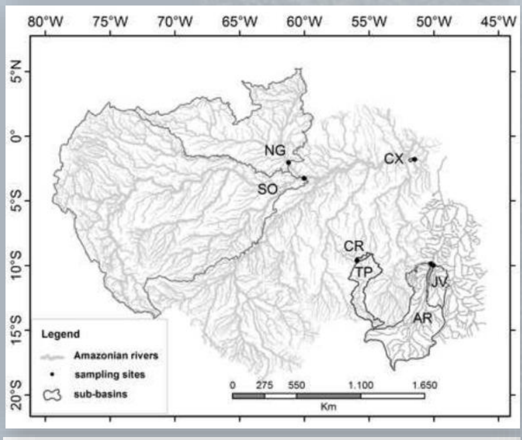
Emilio Mayorga[a,*], Miles G. Logsdon[a,1], Maria Victoria R. Ballester[b,2], Jeffrey E. Richey[a,1]

What is the main C dynamic controller in these ecosystems?



The most striking finding of our current integrated network approach is that, regardless of any scale or basin characteristic, the distribution of biogenic species show the same seasonal patterns, tightly connected to the hydrograph





Biogeochemistry
DOI 10.1007/s10533-013-9854-0

Spatial and temporal variability of pCO_2 and CO_2 efflux in seven Amazonian Rivers

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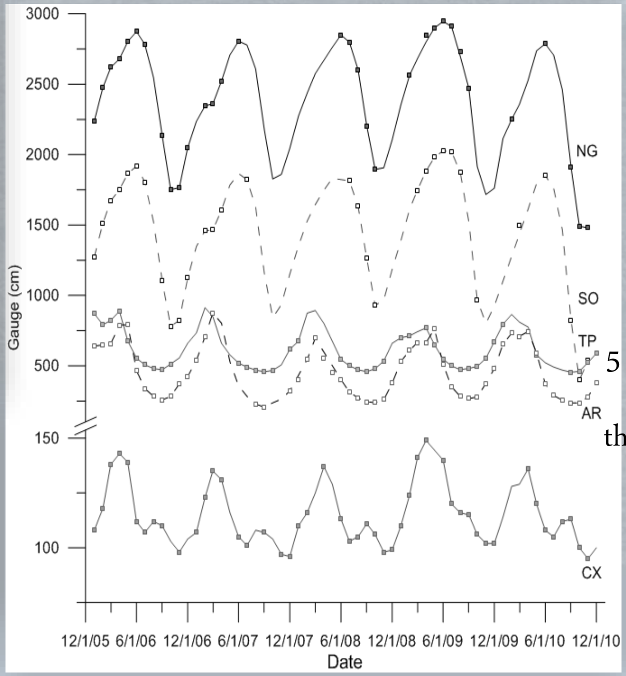
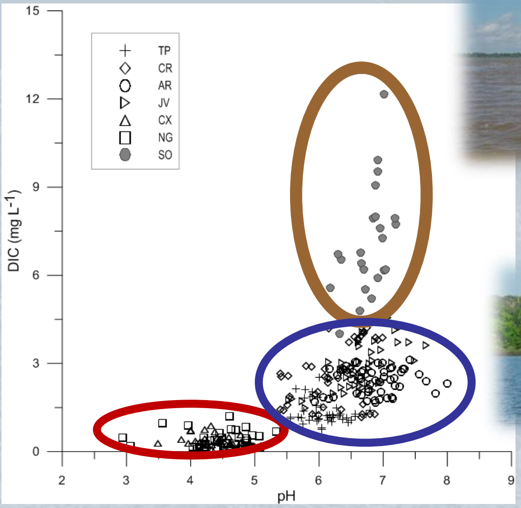


5 year time series of CO_2 fluxes in Amazon rivers, spanning the whole hydrograph and encompassing representative rivers of the region

While these river can be separated into 3 groups according to their water characteristics:

Group I- drain low lands, highly weathered, high levels of DOM, low DIC and pH

Negro, Cristalino and Caxiuanã



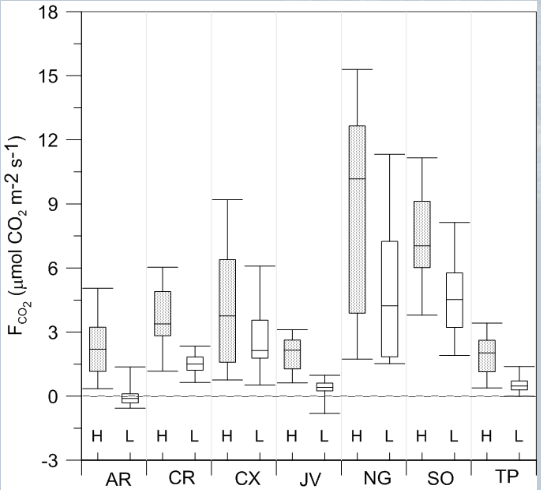
Solimões

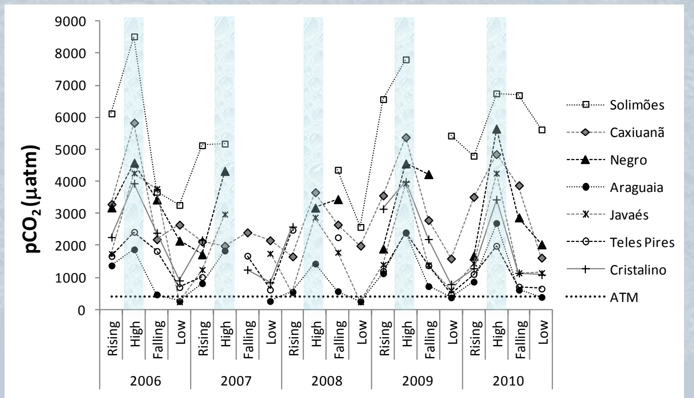
Group II- High sediment transport from the Andes, high DIC concentrations and pH ~ neutral

Teles Pires, Javaés

Group III- drain the Brazilian shield, low sediments and OM, inter medium DIC levels, pH ~ neutral

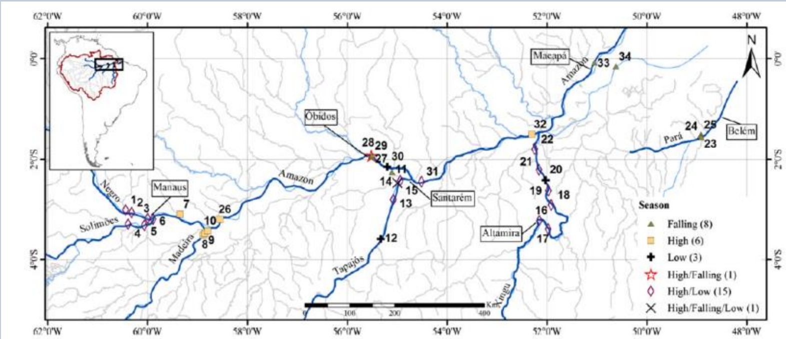
CO_2 Fluxes seasonal cycles





High viariability for both low and high water: -0,8 a 15,3 mmol CO_2 m^{-2} s^{-1}

- CO_2 Fluxes always higher at high water
- Key to develop adequate models to describe C cycle: a seasonal pattern link to the hydrograph can simplify scaling



Global Change Biology

Global Change Biology (2014), doi: 10.1111/gcb.12646

Methane emissions from Amazonian Rivers and their contribution to the global methane budget

HENRIQUE O. SAWAKUCHI[1], DAVID BASTVIKEN[2], ANDRÉ O. SAWAKUCHI[3], ALEX V. KRUSCHE[1], MARIA V. R. BALLESTER[1] and JEFFREY E. RICHEY[4]

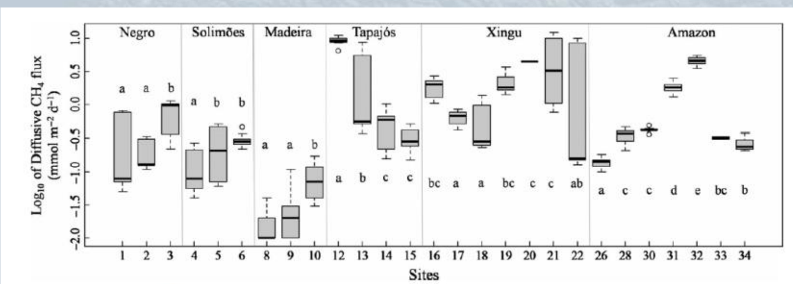


Fig. 3 Diffusive fluxes (log transformed) between sites measured in each river. Numbers in the x-axis are the sites showed in Fig. 1 and Table 1. Letters above or below the boxes indicate the grouping of sites within each river based on a one-way ANOVA with Tukey's test ($P < 0.05$) to determine which sites had similar emissions (e.g. Sites with an *a* in their letter combination were significantly different from those without an *a* in their combination).

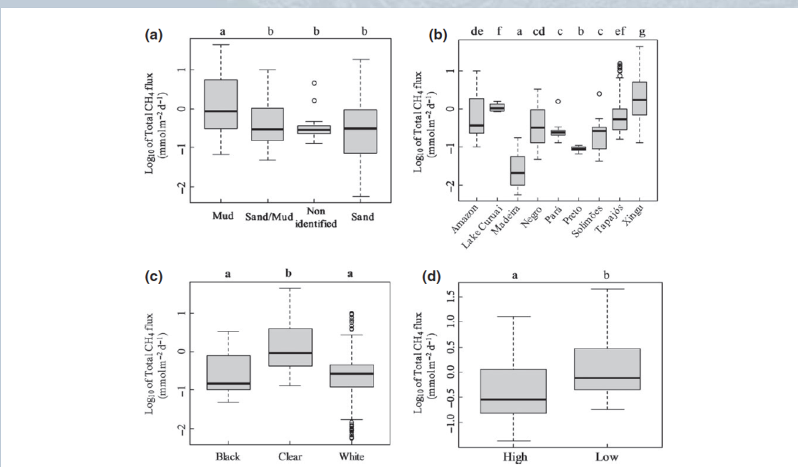


Fig. 5 $\mathrm{Log_{10}}$ of total CH_4 flux (mmol m^{-2} d^{-1}) comparisons of sites in regard to (a) different types of sediments, (b) source river, (c) river water type, and (d) river water level (seasonal comparison performed with only sites measured during both seasons). Letters above graphics show grouping according to Tukey *post hoc* test ($P < 0.05$).

- Wide spatial and temporal variability
- Hydrograph differential effect
- We estimate an emission of 0.49(±0.09) Tg CH_4 yr^{-1} from large rivers Or 44 – 65% of the global tropical river CH_4 emissions and 22 – 28% of the global river emission
- These values are to 31–84% higher than the previous estimate (Bastviken et al., 2011)

Two mechanism of emission, diffusion and ebullition + Methane oxidation MOX

Global Change Biology
Global Change Biology (2016) 22, 1075–1085, doi: 10.1111/gcb.13169

Oxidative mitigation of aquatic methane emissions in large Amazonian rivers

HENRIQUE O. SAWAKUCHI[1], DAVID BASTVIKEN[2], ANDRÉO. SAWAKUCHI[3], NICHOLAS D. WARD[4], CLOVIS D. BORGES[1], SIU M. TSAI[1], JEFFREY E. RICHEY[5], MARIA VICTORIA R. BALLESTER[1] and ALEX V. KRUSCHE[1]
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varied according to hydrologic regime and general tributaries geochemical characteristics.

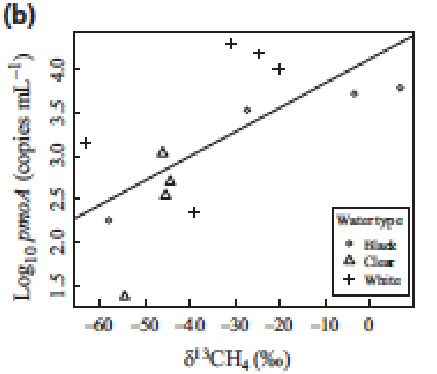
E.G.: Higher levels of MOX at high water in black and white water rivers and minimal in clear water at low water

Table 3 Concentration ([CH_4]; μM) and $\delta^{13}CH_4$ (average, SD ‰ and *n* replicates) of CH_4 in the water and in sediment bubbles (%), estimated range of total MOX (%), and total input (mmol m^{-2} day^{-1}), as well as the number of *pmoA* gene copies in the water (copies mL^{-1})

Location no*	River	Water season	Water type	$\delta^{13}CH_4$ air	[CH_4] water	$\delta^{13}CH_4$ water	[CH_4] bubble	$\delta^{13}CH_4$ bubble	MOX† Eqn 1	MOX† Eqn 2	Input Eqn 1	Input Eqn 2	*pmoA*
1	Negro	High	Black	−42.7	0.02	5.6 ± 0.1 (2)	–	‡	100§	91–96	¶	5.18–10.84	5192
2	Negro	High	Black	−42.4	0.05	−27.3 ± 1.4 (3)	–	‡	100§	74–83	¶	1.85–2.81	3419
3	Negro	Low	Black	−46.3	0.13	−58.1 ± 2.7 (3)	26	−79.4 ± 2.8	65–85	49–58	1.35–3.23	0.93–1.15	179
4	Solimões	High	White	−43.3	0.02	−24.6 ± 9.4 (2)	4	−43.1 ± 1.9	100§	76–85	¶	1.05–1.64	20395
5	Preto	High	Black	−41.9	0.06	6.9 ± 0.6 (3)	–	‡	100§	91–96	¶	1.01–2.14	6166
6	Madeira	High	White	−42.1	0.04	−20.3 ± 1.1 (3)	9	−45.4 ± 4.3	100§	79–87	¶	0.19–0.31	9901
7	Amazon	High	White	−42.6	0.10	−24.6 ± 0.8 (3)	–	‡	100§	76–85	¶	4.44–6.92	15146
8	Amazon	Low	White	−42.3	0.04	−39.4 ± 2.9 (3)	59	−85.4 ± 0.1	100§	77–85	¶	4.52–7.09	221
9	Tapajós	Low	Clear	−43.2	0.50	−49.0 ± 0.3 (3)	7	−71.3 ± 3.7	68–89	50–60	7.02–21.29	4.57–5.67	
10	Tapajós	High	Clear	−43.7	0.06	−44.4 ± 0.2 (3)	–	‡	79–100§	56–66	10.69	5.12–6.59	504
11	Xingu	High	Clear	−41.9	0.25	−45.4 ± 0.2 (3)	8	−61.7 ± 0.2	50–65	40–49	5.85–8.55	4.92–5.77	347
12	Xingu	Low	Clear	–	0.15	−54.5 ± 0.7 (3)	45	−60.6 ± 0.2	18–24	17–22	3.61–3.89	3.56–3.78	23
13	Xingu	High	Clear	−41.9	0.32	−46.1 ± 0.2 (3)	7	−63.7 ± 1.1	53–71	42–51	6.34–10.01	5.12–6.08	1076
14	Amazon	High	White	−42.9	0.31	−63.1 ± 0.9 (3)	–	‡	22–29	20–26	1.36–1.50	1.33–1.43	1386

*Locations showed in the map in Fig. 1.
†Range calculated using *a* = 1.033 and *a* = 1.025 from Zhang *et al*. (2013).
‡No data available. For calculation, an average from the other sites −70.4‰ was used as the CH_4 signature.
§Overestimation by the equation indicating approximately 100% oxidation.
¶Noncalculated. When MOX from Eqn 1 is 100% the input from the same equation cannot be estimated.

(b)



Abundance of genetic markers for MOX bacteria (pmoA) were positively correlated with enhanced signals of oxidation: independent support for the detected MOX patterns.

1082 H. O. SAWAKUCHI *et al.*

Table 4 Estimated ranges of diffusive emissions, input to the water column, and oxidation of CH_4 (Tg CH_4 yr^{-1}). Diffusive fluxes were calculated based on averages per river available in Sawakuchi *et al.* (2014). Values in bold represents the estimative for all large rivers in the Amazon basin

Rivers	River Area (km^2)	Input to the water column	Diffusive flux to atmosphere	MOX	MOX (%)
Negro	12 309	0.07–0.78	0.031–0.038	0.04–0.74	54–95
Solimões	31 576	0.19–0.30	0.042–0.050	0.15–0.25	74–83
Amazon	9577	0.07–0.40	0.051–0.068	0.02–0.33	32–83
Preto da Eva	80	0.0005–0.0010	0.000041–0.000043	0.0004–0.0010	91–96
Madeira	11 477	0.013–0.021	0.002–0.003	0.010–0.018	82–85
Tapajós	6441	0.17–0.25	0.068–0.103	0.10–0.15	59–60
Xingu	6760	0.14–0.40	0.101–0.132	0.04–0.26	28–67
Others	12 992	0.14–0.38	0.046–0.062	0.09–0.32	66–84
Amazon	**91 212**	**0.80–2.52**	**0.34–0.46**	**0.45–2.07**	**57–82**

(MOX): diffusive CH_4 flux can be reduced by ~ 28 – 96 %

- MOX in large Amazonian rivers can consume from 0.45 to 2.07 Tg CH_4 yr^{-1} or up to 7% of the estimated global soil sink.
- Climate change and changes in hydrology (e.g. construction of dams) can alter this balance, influencing CH_4 emissions to atmosphere.

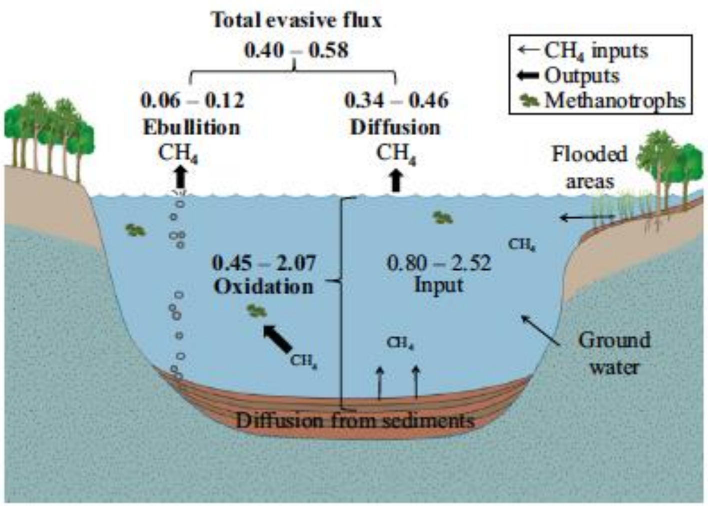
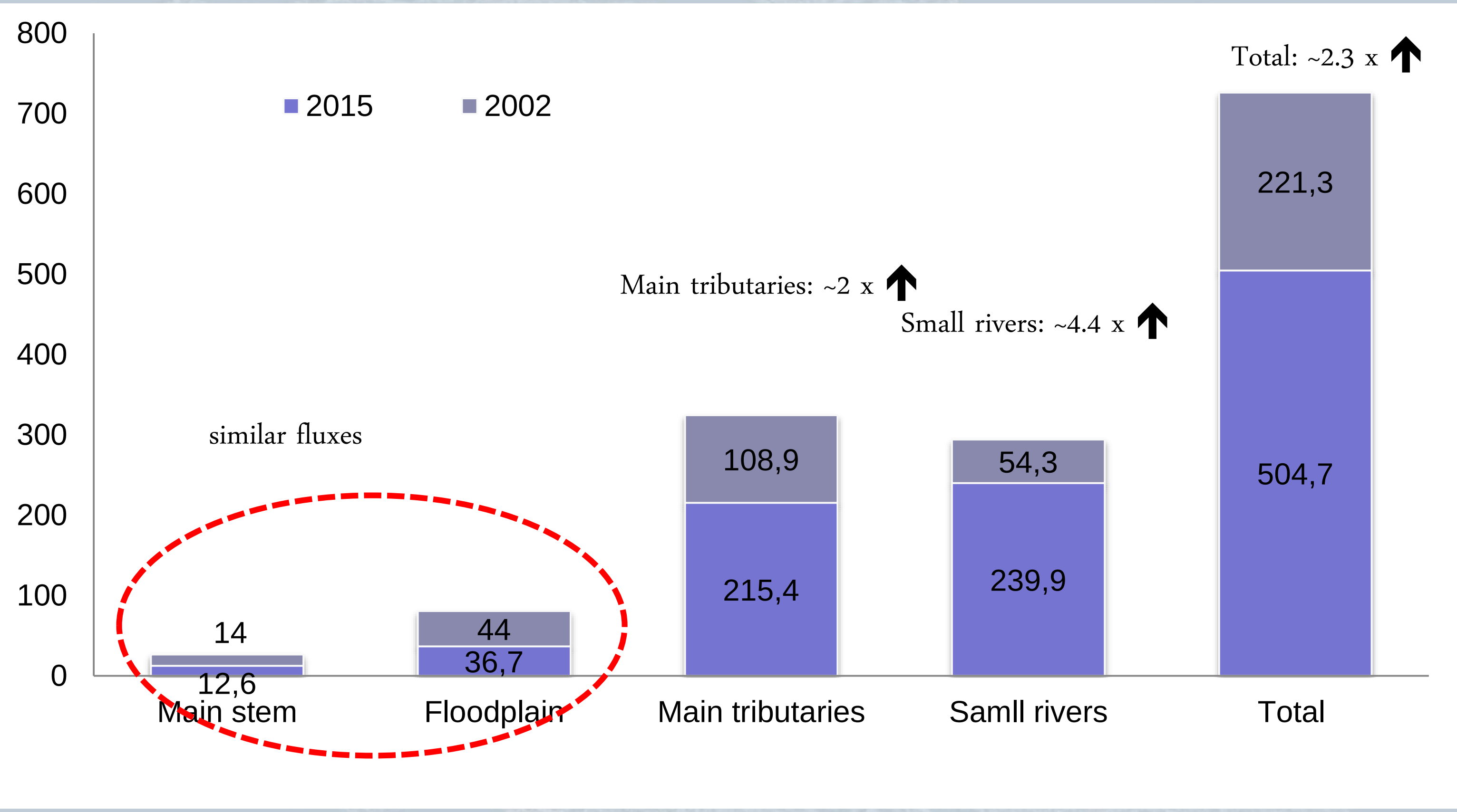


Fig. 4 Net inputs and outputs (Tg CH_4 yr^{-1}) of water column CH_4 in the Amazon River. CH_4 is exported from groundwater, seasonally flooded areas, and anoxic sediments along the riverbed and margins into the oxic layer in the sediment and water column (plain arrows and numbers indicate input). A fraction of this CH_4 is released directly to the atmosphere as bubbles (i.e., ebullition) and the rest is dissolved in the water, where it is subjected to oxidation by methanotrophs and diffusive evasion to the atmosphere (bold arrows and numbers). Figure adapted from: ian.umces.edu.

The role of rivers in the regional carbon cycle

C exported as CO_2 (Tg yr^{-1})



- Current CO_2 flux: 0.8 Pg C yr^{-1} for upstream rivers from Óbidos (~70 % of the amazon basin)
- This value is 60 % higher than our previous measurements
- Fluxes are highly correlate to the hydrograph, moreover climate changes can lead to a significant change in ecosystem metabolism