frontiers in Marine Science

CORRECTION
published: 08 September 2020
doi: 10.3389/fmars.2020.00688

Corrigendum: Carbon Dioxide Emissions along the Lower Amazon River

Henrique O. Sawakuchi[1,2]*, **Vania Neu**[3], **Nicholas D. Ward**[4,5], **Maria de Lourdes C. Barros**[1], **Aline M. Valerio**[6], **William Gagne-Maynard**[2], **Alan C. Cunha**[7], **Diani F. S. Less**[7], **Joel E. M. Diniz**[7], **Daimio C. Brito**[7], **Alex V. Krusche**[1] **and Jeffrey E. Richey**[2]

[1] Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, Brazil, [2] School of Oceanography, University of Washington, Seattle, WA, United States, [3] Instituto Sócio Ambiental e dos Recursos Hídricos, Universidade Federal Rural da Amazônia, Belém, Brazil, [4] Whitney Laboratory for Marine Bioscience, University of Florida, St. Augustine, FL, United States, [5] Marine Sciences Laboratory, Pacific Northwest National Laboratory, Sequim, WA, United States, [6] Departamento de Sensoriamento Remoto, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil, [7] Departamento de Meio Ambiente e Desenvolvimento, Universidade Federal do Amapá, Macapá, Brazil

Keywords: GHG emission, CO_2 emission, Lower Amazon, CO_2 outgassing, river, global CO_2 emission

OPEN ACCESS

Edited and reviewed by:
Marta Álvarez,
Instituto Español de Oceanografía,
Spain

Correspondence:
Henrique O. Sawakuchi,
riqueoliveira@yahoo.com.br

Specialty section:
This article was submitted to Marine Biogeochemistry, a section of the journal Frontiers in Marine Science

Received: *18 July 2020*
Accepted: *29 July 2020*
Published: *08 September 2020*

Citation:
Sawakuchi HO, Neu V, Ward ND, Barros MdLC, Valerio AM, Gagne-Maynard W, Cunha AC, Less DFS, Diniz JEM, Brito DC, Krusche AV and Richey JE (2020) Corrigendum: Carbon Dioxide Emissions along the Lower Amazon River. Front. Mar. Sci. 7:688. doi: 10.3389/fmars.2020.00688

A Corrigendum on

Carbon Dioxide Emissions along the Lower Amazon River
by Sawakuchi, H. O., Neu, V., Ward, N. D., Barros, M. d. L. C., Valerio, A. M., Gagne-Maynard, W., et al. (2017). Front. Mar. Sci. 4:76. doi: 10.3389/fmars.2017.00076

In the original article, there was an error in the upscaling of site-specific flux rates to local emissions for the different areas considered in the paper for the lower Amazon River. Hence, the error propagated throughout our local and global estimates presented in different sections of the paper and **Tables 3**, **4**. Minor mistakes were also in the discharge values for lower and rising sampling season for IDs 5 (South Macapá) and 6 (North Macapá), which are switched in **Table 1** and the values of Areas 1 and 2 presented in the Methods.

Several corrections have been made to the text of the article and the updated sections are as follows:

Abstract: "We estimate that the lower Amazon River mainstem emits 20 Tg C year^{-1} within our study boundaries, or as much as 48 Tg C year^{-1} if the entire spatial extent to the geographical mouth is considered. Emissions from the Xingu and Tapajós lower tributaries contribute an additional 2.3 Tg C year^{-1}. Including these values with updated basin scale estimates and estimates of CO2 outgassing from small streams we estimate that the Amazon running waters outgasses as much as 0.95 Pg C year^{-1}, increasing the global emissions from inland waters by 15% for a total of 2.45 Pg C year^{-1}. These results highlight the lower reaches of large rivers as a missing gap in basin-scale and global carbon budgets. In the case of the Amazon River, the previously unstudied tidally-influenced reaches contribute to 5% of CO2 emissions from the entire basin."

Methods section, subsection Annual CO_2 Emissions from the Lower Amazon River, the first paragraph:

"We divided the main channel into two zones: (Area 1) our study boundaries from Óbidos to Macapá, which has a surface area of 7,118 km^2, and (Area 2) the region extending from Macapá to the geographical river mouth, which has an additional surface area of 11,261 km^2 (Figure 1)."

Results section, subsection Upscaling CO_2 Emissions from the Lower Amazon River:

"The total flux of CO_2 from the main channel of the lower Amazon River was calculated for two zones (Figure 1) for each 3-month hydrologic period and annually (**Table 3**). The most conservative

TABLE 1 | CO_2 fluxes to atmosphere (FCO_2), partial pressure of CO_2 in the water (pCO_2), gas transfer velocity (k_{600}) measurements according to site and season (mean ± SD) and measurements of mean depth (z), water velocity (w), discharge (Q) and wind speed (U_{10}).

ID	Site (River)	Sampling season	FCO_2 (μmol m^{-2} s^{-1})	pCO_2 (μatm)	k_{600} (cm h^{-1})	z (m)[a]	w (cm s^{-1})	Q (m^3 s^{-1})	U_{10} (m s^{-1})
1	Óbidos (Amazon)	Falling	16.06 ± 1.68	6148 ± 326	36.09 ± 13.78	54.2	183	257,277	6.6
		High	9.39 ± 2.04	6106 ± 441	17.74 ± 3.16	51.5	192	253,959	–
		Low	11.79 ± 4.04	2458 ± 6	54.32 ± 1.79	49.4	106	122,274	–
		Rising	5.89 ± 3.45	2572 ± 57	27.62 ± 16.59	32.8	106	122,172	4.5
2	Alter do Chão (Tapajós)	Falling	1.07	450	–	23.5	20	10,018	1.5
		High	1.75	1650	16.03			24,428	–
		Low	0.76	449	–	24	9	3,658	–
		Rising	2.4	896	–	10.7	27	10,480	5.4
3	Almeirim (Amazon)	Falling	13.59 ± 4.25	3857 ± 583	40.69 ± 14.71	28.1	182	282,688	3.5
		High	15.09	5406 ± 24	30.97	29.1	187	298,913	–
		Low	5.84 ± 1.97	1657 ± 168	52.11 ± 20.15	26.2	87	124,831	–
		Rising	2.49 ± 1.1	1714 ± 165	30.38 ± 15.5	16.8	102	137,117	3.2
4	Porto de Moz (Xingu)	Falling	2.39	508	174.22*			3,093	7.5
		High	7.85*	5001*	17.06			16,804	–
		Low	0.87	506	133.66*			1,674	–
		Rising	2.07	1117	42.92			14,288	4.1
5	Macapá South (Amazon)	Falling	3.9 ± 1.39	2471 ± 275	18.97 ± 7.1	24.6	50	146,473	4.8
		High	17.27 ± 0.26	4761 ± 3	42.27 ± 0.38	24	72	204,056	–
		Low	1.74	1490	16.03	17.5	31	132,998	–
		Rising	2.45 ± 0.99	1645 ± 197	28.65 ± 5.67	10.6	28	103,593	3.7
6	Macapá North (Amazon)	Falling	5.47 ± 3.05	3400 ± 565	20.51 ± 15.36	19.4	55	113,371	3.4
		High	16.79 ± 1.99	4489 ± 618	45.47 ± 13.08	18.5	64	140,692	–
		Low	3.71 ± 0.62	1272 ± 158	46.98 ± 0.04	22.7	48	61,539	–
		Rising	2.19 ± 0.87	1281 ± 22	15.8 ± 0.66	9.4	37	53,265	3.4

**Outliers removed for statistical analysis.*

estimates (Area 1) only included the boundaries of this study, from Óbidos to Macapá, which had an average wetted surface area of 7,118 km^2. The flux of CO_2 from Area 1 was 20 Tg C year^{-1}. Area 2 extends from Macapá to the region of the mouth where the connection to land terminates, which had an additional surface area of 11,261 km^2. Area 2 had a total CO_2 flux of 28 Tg C year^{-1}, based on an extrapolation of average values measured across the north and south Macapá channels (**Table 3**). The sum of fluxes for these two zones, or the total emissions from Óbidos to the actual river mouth was 48 Tg C year^{-1}. The emissions from the lower Tapajós and Xingu rivers were 1.40 and 0.86 Tg C year^{-1}, respectively. Including these two tributaries to the budget would add more 2.26 Tg C year^{-1}."

Discussion section, the eighth paragraph:

"Here we considered two different areas for upscaling annual CO_2 emissions from the lower Amazon River. Our most conservative estimate, including the area from Óbidos to Macapá (Area 1), was 20 Tg C year^{-1}. Area 2, which extends to the geographic terminus of the river, is a relatively short distance compared to Area 1, but covers 58% more surface area than the Óbidos to Macapá reach (**Table 3**). Applying the average FCO_2 observed near Macapá, we estimate Area 2 to emit 28 Tg C year^{-1}, which combined with the upstream section totalize 48 Tg C year^{-1}. Emissions from the Xingu and Tapajós tributaries contribute an additional 2.3 Tg C year^{-1}, resulting in a total flux of 51 Tg C year^{-1} from the lower Amazon River basin. This estimate for the lower Amazon River, alone, is roughly 53% in magnitude compared to CO_2 emissions from all rivers in the conterminous United States (97 Tg C year^{-1}; Butman and Raymond, 2011) and ∼12% of past estimates of basin-scale emissions from the Amazon (0.47 Pg C year^{-1}; Richey et al., 2002)."

Discussion section, the ninth paragraph:

"Adding our estimations of the fluxes estimated for Area 1 and the sum of Area 1 and 2 to estimations by Richey et al. (2002) increases basin-scale CO_2 outgassing to 0.49 and 0.52 Pg C year^{-1}, respectively. A recent re-evaluation of basin-wide outgassing estimates upstream of Óbidos was done using a combination of direct flux measurements and more detailed k-values calculations along with observations by Alin et al. (2011) for tributaries and streams. It was estimated that basin scale CO_2 outgassing upstream from Óbidos was roughly 0.8 Pg C year^{-1} (Rasera et al., 2013). First order streams add an additional 0.1 Pg C year^{-1} to basin scale CO_2 fluxes in the Amazon basin (Johnson et al., 2008). Adding our estimates for the lower river to these values results in basin-wide budgets of 0.92 Pg C year^{-1} and 0.95 Pg C year^{-1} for Area 1 and the sum of Area 1 and 2, respectively (**Table 4**). Replacing these new estimates for the Amazon in the

TABLE 3 | Seasonal CO_2 emissions in the Amazon River channel considering different areas.

Season	CO_2 emission (Tg C year^{-1})			
	Area 1	Area 2	Tributaries	Total
Area (km^2)	7,118	11,261	3,769	22,149
Falling	5.4	5.0	0.5	10.9
High	8.9	18.1	0.6	27.6
Low	3.9	2.9	0.3	7.1
Rising	1.9	2.5	0.8	5.1
Total	20.0	28.5	2.3	50.8

Estimates for tributaries only include the lower reaches measured in this study.

TABLE 4 | CO_2 emission estimates for rivers and streams in the Amazon.

	CO_2 emission (Pg C year^{-1})	References
Lower Amazon Area 1	0.020	This study
Lower Amazon Area 1 + Area 2 + tributaries	0.051	This study
Large rivers in Amazon upstream Óbidos	0.47	Richey et al., 2002
Large rivers in Amazon upstream Óbidos	0.80	Rasera et al., 2013
Amazon streams	0.10	Johnson et al., 2008

global CO_2 budget by Raymond et al. (2013) increases the global budget by as much as 18% for a total of 2.48 Pg C year^{-1}."

Discussion section, the tenth paragraph:

"In the case of this updated global budget, the Amazon River represents 38% of global CO_2 emissions. However, the contribution of other tropical rivers to the global budget are likely also underestimated considering that most tropical rivers are even less well-characterized than the Amazon, particularly in the lower reaches, where we've demonstrated that emissions can be high relative to the rest of the basin. Furthermore, we have not included the entirety of the Amazon in our newest budgets. For example, the Tapajós and Xingu rivers were not included due to their large spatial expanse and minimal data coverage. The lower portion of these tributaries, alone (Figure 1), emit roughly 2.3 Tg C year^{-1}, and these estimates do not encompass their entire surface area nor potentially elevated CO_2 concentrations closer to their headwaters."

Discussion section, the eleventh paragraph:

"Another factor that can lead to an underestimation of basin-wide budgets is not including Amazon River water that travels further offshore from Area 2 and along the coastline. For example, the Amazon River can remain unmixed with the ocean as far as 60 km offshore from Area 2 (Molinas et al., 2014). Abril et al. (2014) estimated that only 18% of the CO_2 from a point source would be degassed in a stretch of approximately 150 km downstream in the Amazon River taking into account a k-value of 15 cm h^{-1} and water current of 150 cm s^{-1}. Thus, it is reasonable to assume that the mouth of the Amazon is the last point source of CO_2 to the Amazon plume, sustaining significant emissions for a significant distance offshore. This region, along with near-shore coastal waters, is not included in any studies of CO_2 cycling in the Amazon River plume in the Atlantic Ocean due to a lack of sampling and terrestrial contamination of remote sensing products by adjacency effect near-shore (Cooley et al., 2007; Subramaniam et al., 2008). We estimate that Area 3 may emit up to an additional 31 Tg C year^{-1}, but note that this is a simple calculation based on measurements at Macapá. Further exploration of this offshore area is essential for constraining the total basin-wide CO_2 flux. Although it is too early to confidently incorporate this offshore freshwater region (Area 3) into basin-wide budgets, this rough estimation highlights that expansive regions of offshore freshwater plumes may be an important missing gap in aquatic carbon budgets."

Concluding Remarks section, the first paragraph, the third sentence:

"Here we show that the lower reaches of the Amazon River are an active area in terms of freshwater CO_2 emissions from the Amazon, and perhaps the world, although, lower river reaches have yet to be adequately studied in other comparable tropical systems."

Concluding Remarks section, the second paragraph, the first and second sentences:

"The enormous surface area of the lower Amazon River (18,379 km^2) is slightly less than half of the area of rivers and stream in the conterminous United States (Butman and Raymond, 2011), and similarly emits roughly half as much CO_2 to the atmosphere. This area alone releases an amount of CO_2 in the same order of magnitude than the uptake by the Amazon River plume in the Atlantic Ocean (Kortzinger, 2003; Cooley et al., 2007; Subramaniam et al., 2008)."

The authors apologize for these errors and state that they do not change the scientific conclusions of the article in any way. The original article has been updated.

REFERENCES

Abril, G., Martinez, J. M., Artigas, L. F., Moreira-Turcq, P., Benedetti, M. F., Vidal, L., et al. (2014). Amazon River carbon dioxide outgassing fuelled by wetlands. *Nature* 505, 395–398. doi: 10.1038/nature12797

Alin, S. R., Rasera, M. F. F. L., Salimon, C. I., Richey, J. E., Holtgrieve, G. W., Krusche, A. V., et al. (2011). Physical controls on carbon dioxide transfer velocity and flux in low-gradient river systems and implications for regional carbon budgets. *J. Geophys. Res. Biogeosci.* 116:G01009. doi: 10.1029/2010jg001398

Butman, D., and Raymond, P. A. (2011). Significant efflux of carbon dioxide from streams and rivers in the United States. *Nat. Geosci.* 4, 839–842. doi: 10.1038/ngeo1294

Cooley, S. R., Coles, V. J., Subramaniam, A., and Yager, P. L. (2007). Seasonal variations in the Amazon plume-related atmospheric carbon sink. *Glob. Biogeochem. Cycles* 21:GB3014. doi: 10.1029/2006gb002831

Johnson, M. S., Lehmann, J., Riha, S. J., Krusche, A. V., Richey, J. E., Ometto, J., et al. (2008). CO_2 efflux from Amazonian headwater streams represents a significant fate for deep soil respiration. *Geophys. Res. Lett.* 35:L17401. doi: 10.1029/2008gl034619

Kortzinger, A. (2003). A significant CO_2 sink in the tropical Atlantic Ocean associated with the Amazon River plume. *Geophys. Res. Lett.* 30:2287. doi: 10.1029/2003gl018841

Molinas, E., Vinzon, S. B., Vilela, C. D. X., and Gallo, M. N. (2014). Structure and position of the bottom salinity front in the Amazon Estuary. *Ocean Dynamics* 64, 1583–1599. doi: 10.1007/s10236-014-0763-0

Rasera, M. F. F. L., Krusche, A. V., Richey, J. E., Ballester, M. V. R., and Victória, R. L. (2013). Spatial and temporal variability of pCO_2 and CO_2 efflux in seven Amazonian Rivers. *Biogeochemistry* 116, 241–259. doi: 10.1007/s10533-013-9854-0

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., et al. (2013). Global carbon dioxide emissions from inland waters. *Nature* 503, 355–359. doi: 10.1038/nature12760

Richey, J. E., Melack, J. M., Aufdenkampe, A. K., Ballester, V. M., and Hess, L. L. (2002). Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2. *Nature* 416, 617–620. doi: 10.1038/416617a

Subramaniam, A., Yager, P. L., Carpenter, E. J., Mahaffey, C., Bjorkman, K., Cooley, S., et al. (2008). Amazon River enhances diazotrophy and carbon sequestration in the tropical North Atlantic Ocean. *Proc. Natl. Acad. Sci. U.S.A.* 105, 10460–10465. doi: 10.1073/pnas.0710279105