LETTER

Carbon accumulation in Amazonian floodplain lakes: A significant component of Amazon budgets?

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Abstract

The Amazon floodplains cover approximately 10% of the Amazon Basin and are composed of predominantly anoxic sediments that may store large amounts of carbon. Our study combines 210Pb derived sedimentation rates from four recently analyzed sediment cores (n = 4) with previously published organic carbon (OC) burial estimates (n = 18) to provide a broad, first order estimate of carbon accumulation in Amazon floodplain lakes. The OC burial rates were 266 ± 57 g C m⁻² yr⁻¹. This rate is several folds greater than those reported for lakes in arctic, boreal, temperate, and tropical regions. The large amount and spatial variation of OC burial rates in these floodplain lakes highlights the need for increased sampling efforts to better measure these potentially important components of the Amazon Basin carbon budget.

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Author Contribution Statement: LMS, KT, DS, CJS and HM designed and planned study; AEP and HM performed the sampling in the field; LMS, CJS, PAM, and JMS did the laboratory analysis; PAM made Fig. 1. LMS wrote the paper. All authors reviewed and edited the manuscript.

Data Availability Statement: Data are available in the Figshare repository at https://figshare.com/s/627a46f1183ed8a65724.

Additional Supporting Information may be found in the online version of this article.

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The forest of the Amazon Basin assimilates 14% of the world’s CO₂ via annual gross photosynthesis (Song-Miao et al. 1990; Zhao and Running 2010). Much of this organic matter remains within the Amazon Basin as plant biomass and soil carbon (Moreira-Turcq et al. 2004; Junk 2013; Zocatelli et al. 2013; Espírito-Santo et al. 2014). Indeed, almost half of the carbon across the Amazon Basin may be stored underground as roots and soils (Zhao and Running 2010; Espírito-Santo et al. 2014; Whitaker et al. 2014). During periods of intense rain and flooding, organic material is exported from catchments via leaching and runoff (Mayorga et al. 2005; Ward et al. 2013). Rivers within the Amazon Basin carry megatons of organic material, a large portion of which is deposited on the floodplains and in floodplain lakes when the seasonal flooding subsides (Hedges et al. 1986; Aalto et al. 2003; Moreira-Turcq et al. 2004; Mortillaro et al. 2012; Moreira-Turcq et al. 2013; Sobrinho et al. 2016). As a result, the floodplains and their lakes may be significant carbon sinks in the Amazon Basin because of slow organic material decomposition in mostly anaerobic sediments (Mertes 1994; Hamilton et al. 2002; Dong et al. 2012; Ferland et al. 2014).

Floodplain lakes are inundated year-round and behave as organic matter producers as well as potential carbon storage systems along the Amazon Basin (Moreira-Turcq et al. 2004; Dong et al. 2012; Getirana and Paiva 2013). Although the importance of floodplains for carbon cycling has been addressed (Zocatelli et al. 2013; Abril et al. 2014; Marotta et al. 2014), the contribution of the Amazon floodplain lakes to the Amazon, and therefore the global carbon cycle, has not been taken into full consideration (Abril et al. 2014). Our objective of this study was to quantify and compile measures of organic carbon (OC) burial rates in a wide range of Amazonian floodplain lakes along gradients of size and location and compare them to published values from other lakes across the globe. The dataset includes floodplain lakes of various sizes, positioned in close proximity to the major rivers of the Amazon Basin (Madeira, Negro, Amazon, Tapajós and Solimões Rivers; Fig. 1) and in regions within the major water types (white, black, and clearwater; Table 1). All OC burial rate estimates included in this dataset are based on sediment accumulation rates derived from 210Pb dating methods, representing the past century.

Methods

Sediment cores from our 2012 field survey were collected in four floodplain lakes within the Amazon Basin (Table 1). The dataset included in this work include these cores from our own survey (n = 4) and carbon accretion rates reported in the literature (n = 18), encompassing a broad range of floodplain lakes in the Amazon Basin. The total dataset of 22 cores include sampling locations in proximity to the major rivers of the Basin (e.g., Madeira, Solimões, Amazon, Negro, and Tapajós), which also represent three different river water types (white, black, and clearwater; Table 1).
The four sediment cores in our own survey (Table 1) were collected with a 7 cm diameter and 50 cm (length) acrylic tube by means of percussion and rotation to minimize compression. Sediment cores were then sectioned in 2 cm intervals in the field until the bottom of each core (~ 40 cm depth). The sediment cores were subsequently analyzed for radionuclide concentrations in an HPGe gamma detector and sediment dates were calculated using the $^{210}$Pb dating method (Appleby and Oldfield 1992).

Freeze dried and ground sediments were packed and sealed in gamma tubes. The $^{210}$Pb and $^{226}$Ra activities were calculated by using a factor that includes the gamma detector efficiency, as previously determined from certified reference material IAEA-300 (Baltic Sea Sediment) and the gamma-ray intensity. The $^{210}$Pb and $^{226}$Ra activities were measured using the 46.5 KeV and 351.9 KeV gamma peaks, respectively. Prior to radionuclide measurements, samples were set aside for at least 3 weeks, to allow for $^{222}$Rn to ingrow and establish secular equilibrium between $^{226}$Ra and its granddaughter $^{214}$Pb. The excess $^{210}$Pb activities were determined by subtracting the $^{226}$Ra concentrations (i.e., supported $^{210}$Pb) from the total $^{210}$Pb concentrations. The sediment accumulation rates (cm yr$^{-1}$), taken from the $^{210}$Pb constant initial concentration (CIC) dating method, and the dry bulk density (g cm$^{-3}$) in each interval (cm) were used to determine mass accumulation rates (Appleby and Oldfield 1992). OC was determined either through the dry combustion method at 550°C for 2 h, using a conversion factor of 1.724 (Schumacher 2002) and/or Flash Elemental Analyzer, along with a ratio mass spectrometer (IRMS) (Thermo Fisher Delta) (see Table 1). OC accumulation rates were determined from the sediment accretion rates (cm yr$^{-1}$), dry bulk densities (g cm$^{-3}$) and OC content, following procedures detailed elsewhere (Sanders et al. 2016).

Our dataset compilation includes work that contained the minimal parameters to determine carbon burial rates in the Amazon floodplain lakes. Carbon burial data was taken from peer reviewed literature that used the $^{210}$Pb dating method and that contained organic material or OC content data along with dry bulk densities (Table 1). We found a total of 18 sediment cores from four peer reviewed papers that contained these parameters (Table 1). An analysis of variance at a confidence level of 0.05 was performed to test whether types of lakes were different. Once differences were encountered, a two tailed Tukey-Kramer was performed to separate individual pairs of lake types at 95% level of confidence.

There are currently no accurate estimates on floodplain lake areal extents. However, of the approximately 840,000 km$^2$ of the Amazon floodplain wetlands, between 56,000 and 73,000 km$^2$ may be classified as permanently

### Table 1. Description of samples used to calculate average organic carbon burial in floodplain lakes of the Amazon Basin. Refer to the Supporting Information Metadata and Figure 1 for location of sites.

| Site            | Core id | Main river | Water type | Soil OC (%) | OC burial (g m$^{-2}$ yr$^{-1}$) | OC method | Source                        |
|-----------------|---------|------------|------------|-------------|---------------------------------|-----------|-------------------------------|
| Santa Ninha     | TA11    | Amazon     | White water| 0.8         | 91                              | IRMS      | Cordeiro et al. (2008)        |
| Calado Site 1a  |         | Solimoes   | Black water| 12.6        | 70                              | CHN analyzer | Smith et al. (2002)    |
| Calado Site 3a  |         | Solimoes   | Black water| 6.8         | 49                              | CHN analyzer | Smith et al. (2002)    |
| Calado Site 4a  |         | Solimoes   | Black water| 2.2         | 25                              | CHN analyzer | Smith et al. (2002)    |
| Calado Site 1b  |         | Solimoes   | Black water| 12.5        | 55                              | CHN analyzer | Smith et al. (2002)    |
| Calado Site 3b  |         | Solimoes   | Black water| 6.7         | 56                              | CHN analyzer | Smith et al. (2002)    |
| Calado Site 4b  |         | Solimoes   | Black water| 2.3         | 11                              | CHN analyzer | Smith et al. (2002)    |
| Pacoval Site 1a | PA02    | Amazon     | White water| 1.5         | 100                             | IRMS      | This work                    |
| Lago Verde Site | PA09    | Tapajos     | Clear water| 3.7         | 475                             | IRMS      | This work                    |
| Acarabixi Site 1| PA04    | Negro       | Black water| 25.0        | 265                             | IRMS      | Cordeiro et al. (2008)        |
| Demaracao Site 1|         | Machado     | Black water| 6.9         | 500                             | LOI       | This work                    |
| Cristalino Site |         | Negro       | Black water| 2.5         | 28                              | CHN analyzer | Devol et al. (1988)      |
| Jacaretinga Site|         | Madeira     | White water| 2.5         | 43                              | CHN analyzer | Devol et al. (1988)      |
| Paca Site 1     |         | Jamari      | Clear water| 7.8         | 193                             | LOI       | This work                    |
| Paca Site 2     | 2B      | Jamari      | Clear water| 9.4         | 385                             | LOI       | Bonotto and Vergotti (2015)  |
| Araca Site 1    | 3B      | Jamari      | Clear water| 5.7         | 1123                            | LOI       | Bonotto and Vergotti (2015)  |
| Brasileira Site | 4B      | Jamari      | Clear water| 5.0         | 260                             | LOI       | Bonotto and Vergotti (2015)  |
| Tucunare Site   | 5B      | Jamari      | Clear water| 3.6         | 551                             | LOI       | Bonotto and Vergotti (2015)  |
| Nazare Site 1   | 6B      | Madeira     | Black water| 3.5         | 158                             | LOI       | Bonotto and Vergotti (2015)  |
| Conceicao Site 1| 7B      | Madeira     | Black water| 7.7         | 662                             | LOI       | Bonotto and Vergotti (2015)  |
| S. Catarina Site| 8B      | Madeira     | Black water| 6.1         | 390                             | LOI       | Bonotto and Vergotti (2015)  |
| Demaracao Site 2| 9B      | Machado     | Black water| 7.6         | 365                             | LOI       | Bonotto and Vergotti (2015)  |
flooded open water systems during low and high waters, respectively (Hess et al. 2015). In order to provide conservative upscaling to the entire Amazon, we assumed a minimum permanently flooded open water area (56,000 km²) to represent a broad, first order estimate of the Amazon floodplain lake areal extent.

Results and discussion

A downcore decrease in $^{210}$Pb activity was found in the four sediment cores from the surface to a depth of 29 cm (Fig. 2). Estimated OC burial rates from these cores ranged from 100 g m$^{-2}$ yr$^{-1}$ to 500 g m$^{-2}$ yr$^{-1}$ (Table 1). We combined our OC burial rates with those reported in other Amazon studies, giving an average rate of 266 (± 57) g C m$^{-2}$ yr$^{-1}$ over the past century, with median and geometric means at 175 g C m$^{-2}$ yr$^{-1}$ and 145 g C m$^{-2}$ yr$^{-1}$, respectively. The OC burial rates values ranged from 11 g C m$^{-2}$ yr$^{-1}$ to 1123 g C m$^{-2}$ yr$^{-1}$, with a true population mean from 154 to 378 (95% C.I.). These rates are several fold greater and significantly higher (Tukey-Kramer; $p < 0.05$) than those reported for lakes in other climatic regions, including arctic (Sobek et al. 2009), boreal (Ferland et al. 2014), temperate (Dietz et al. 2015) and tropical (Alcocer et al. 2014) lakes (6 g C m$^{-2}$ yr$^{-1}$, 2 g C m$^{-2}$ yr$^{-1}$, 33 g C m$^{-2}$ yr$^{-1}$, and 24 g C m$^{-2}$ yr$^{-1}$, respectively) (see Fig. 3 for details), and in subtropical floodplain lakes (15 g C m$^{-2}$ yr$^{-1}$) (Dong et al. 2012). Therefore, in spite of large spatial variability, OC burial rates in the Amazon lakes are clearly several fold greater than those reported for other lacustrine systems worldwide (Fig. 3).

The data used for this study includes carbon burial rates in the main regions of the Amazon Basin, including lakes associated with whitewater ($n = 3$), blackwater ($n = 13$ cores), and clearwater ($n = 6$) river floodplains (Table 1). Our results show that lakes of the floodplain of white, black and clearwater rivers accumulated carbon at a rate of $78 \pm 14$, $203 \pm 57$ and $498 \pm 124$ (SE) g C m$^{-2}$ yr$^{-1}$, respectively (Fig. 3B). Clearwater floodplain lakes had significantly higher carbon burial rates than black and white water lakes (Tukey-Kramer; $p < 0.05$). Black and white river floodplain lakes were not significantly different ($p > 0.05$). Delineating the regions of different lake types is essential for decreasing uncertainty in calculating carbon burial in Amazon floodplain lakes. For instance, whitewater lakes contain large amounts of dissolved minerals and suspended particulates that originates from the Andes mountain range (Junk et al. 2015). These
waters are rich in clay, high in nutrients and very fertile (Guyot et al. 2007). In contrast, blackwater rivers originate from tropical forest runoff, and are high in humic material, have a low pH, suspended matter and are poor in nutrients (Abril et al. 2014). Clearwater rivers are considered intermediate in terms of fertility due to the low concentrations of dissolved minerals (Junk 2013) as these highly transparent waters drain regions of relatively low soil erosion.

Upscaling these OC burial rates to the Amazon Basin area is very challenging because of large uncertainties in the area of the lakes, their ephemeral nature and the variable sequestration rates reported in the literature. In order to provide conservative upscaling, we assumed a minimum Amazon floodplain lake area of 56,000 km². This estimate is related to a conservative value for open water systems during low waters, and does not include small lakes due to image resolution issues (Hess et al. 2015). Using this conservative first order estimate, Amazon floodplain lakes accumulate approximately 15 Tg yr⁻¹ of OC. While the permanent lakes included here are likely to have greater OC burial rates than ephemeral floodplains surrounding the lakes, some carbon is also expected to accumulate on the ephemeral floodplains not included in our upscaling exercise.

In summary, this study has established that the floodplain lakes located within the Amazon Basin accumulate significant quantities of carbon compared to other freshwater lakes, and are an important component of the carbon cycle in the Amazon Basin. However, our dataset cannot establish local variability in burial rates and the large variability likely reflects this dynamic system (Constantine et al. 2014). Indeed, OC burial may be driven by lake morphology (Blais and Kalff 1995), but very little information is available on lake morphology of the Amazon floodplain lakes. Our first order estimate implies that Amazon floodplain lakes may accumulate 266 (± 57 (SE) g C m⁻² yr⁻¹ which is in the same range as the net carbon sink of the Amazon forests (270 g C m⁻² yr⁻¹) (Ometto et al. 2005), and carbon evasion, CO₂ and CH₄ degassing, from the Amazon rivers and wetlands (120 g C m⁻² yr⁻¹) (Richey et al. 2002; Abril et al. 2014). The high OC burial rates of these floodplain lakes indicate that even though these systems only represent about 1% of the total Amazon Basin area, they may contribute disproportionately to the overall Amazon, and therefore, global carbon cycle. Because of the small sample size currently available (n = 22 lakes; Table 1), additional datasets are required to refine our estimates and decrease uncertainty when upscaling carbon burial rates.

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