Historic carbon burial spike in an Amazon floodplain lake linked to riparian deforestation near Santarem, Brazil

Luciana M. Sanders¹, Kathryn Taffs¹, Debra Stokes³, Christian J. Sanders², Alex Enrich-Prast⁴, Leonardo Nogueira Amora⁶,⁷, Humberto Marotta⁶,⁷

¹Southern Cross Geoscience, Southern Cross University, P.O. Box 157, Lismore, NSW 2480, Australia.
²National Marine Science Centre, School of Environment, Science and Engineering, Southern Cross University, Coffs Harbour, New South Wales, Australia.
³Marine Ecology Research Centre, Southern Cross University, P.O. Box 157, Lismore, NSW 2480, Australia.
⁴Laboratório de Biogeoquímica, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro (RJ), 21941 971, Brazil.
⁵Department of Environmental Change, Linköping University, 581 83, Linköping, Sweden.
⁶Ecosystems and Global Change Laboratory (LEMG-UFF) / International Laboratory of Global Change (LINCGlobal), Biomass and Water Management Research Center (NAB-UFF), Graduated Program in Geosciences (Environmental Geochemistry), Universidade Federal Fluminense (UFF), Av. Edmundo March, s/n° – Zip Code: 24210-310, Niterói/RJ- Brazil.
⁷Sedimentary and Environmental Processes Laboratory (LAPSA-UFF). Department of Geography, Graduated Program in Geography, Universidade Federal Fluminense (UFF), Av. Gal. Milton Tavares de Souza, s/n° - Zip Code: 24210-346, Niterói/RJ- Brazil.

*Corresponding author. E-mail address: l.sanders.13@student.scu.edu.au
Abstract

The forests along the Amazon Basin produce significant quantities of organic material, a portion of which is deposited in floodplain lakes. However, potentially important effects of ongoing deforestation in the watershed on these carbon fluxes is still poorly understood. Here, a sediment core was extracted from an Amazon floodplain lake to examine the relationship between carbon burial and land cover/use. Historical records from 1942 and satellite data from 1975 were used to calculate deforestation rates between 1942 and 1975, and 1975 to 2008 in four zones with different distances from the margins of the lake and its tributaries (100, 500, 1000 and 6000-m buffers). Sediment accumulation rates were determined from the $^{240+239}$Pu signatures and the excess $^{210}$Pb method, reaching near 3.8 and 4.2 mm year$^{-1}$ in the last 60 and 120 years respectively. The average carbon burial rates ranged between 100 and 350 g C m$^{-2}$ year$^{-1}$, with pulses of high carbon burial derived from the forest vegetation, as indicated by $\delta^{13}$C and $\delta^{15}$N signatures, which corresponded to heavy deforestation in the 1940 and 50s. Finally, our results revealed a potentially important spatial dependence of the OC burial in Amazon lacustrine sediments in relation to deforestation rates in the catchment. These deforestation rates were more intense in the riparian vegetation (100-m buffer) during the period 1942-1975 and the larger open water areas (500, 1000 and 6000-m buffer) during 1975-2008. The continued removal of vegetation from the interior of the forest was not related to the peak of OC burial in the lake, but only the riparian deforestation around 1950. Our novel findings suggest the importance of abrupt and temporary events in which some of the biomass released by the deforestation, especially restricted to areas along open water edges, might reach the depositional environments in the floodplain of the Amazon Basin.
1. Introduction

Rivers act as vectors, transporting sediment from land to ocean (Abril et al. 2014). Along this trajectory a significant proportion of the sediment load, including organic material, may be deposited in floodplains, creating zones of carbon accumulation (Smith et al. 2002, Dong et al. 2012, Hoffmann et al. 2013). This process is accelerated during flood events, when rivers and tributaries deposit organic material along the inundated floodplains (Smith et al. 2002). In some climate zones floodplains are seasonally inundated, with riparian zone vegetation dependent upon this seasonal influx of organic material. The vegetation acts to slow water velocity and trap the fine-grained, carbon rich sediment, within the low-energy environment (Aalto et al. 2003). Therefore, the riparian vegetation along her floodplains may be important for the organic matter deposition and the Amazon carbon cycle.

The importance of tropical wetland ecosystems in the carbon cycle is well documented (Downing et al. 1993, Melack et al. 2004, Zocatelli et al. 2013, Abril et al. 2014, Marotta et al. 2014). It has been shown that wetlands in the warm tropics are some of the most productive biological communities in the world (Neue et al. 1997), representing an important sink for nutrients (Marotta et al. 2009) and carbon (Peixoto et al. 2016), as well as sources of organic substrates to carbon gas production in inland waters (Marotta et al. 2010). However, these wetland ecosystems are also highly threatened by land use activities, especially from deforestation, development of agricultural land and soil degradation (Junk 2013, Lucas et al. 2014). For example, the Amazon Basin wetlands are being degraded by farming activities such as commercial ranching, and an increase in road density (Goulding 1993).
Deforestation of the Amazon Basin accelerated toward the end of the 1970’s (Skole and Tucker 1993), when an estimated 15% of the pristine rainforest area was lost by the year 2003, increasing to approximately 18% by 2015 (INPE 2016). The ongoing loss of vegetation is responsible for a substantial increase in erosion rates and subsequent sediment inputs into Amazon rivers and lakes (Neill et al. 2013b). Yet these anthropogenic activities are potential sources of allochthonous organic matter that may increase carbon stores in the associated floodplain areas (Diaz and Rosenberg 2008, Stanley et al. 2012).

The city of Santarém, in central Amazon, was established in the mid-eighteenth century, approximately 650 km upstream from the Amazon River mouth and at its confluence with the River Tapajós (02°25’0.28”S and 54°42’41.57”W, Figure 1). In 1940, Santarém was only a small village with less than 0.5 km², surrounded by dense pristine rainforest (estimation from the historical mapping of the Santarém City Hall). This city quickly expanded, occupying 5.2 km² by the end of the 1970s and 49.3 km² currently (estimation from satellite images LANDSAT/SRTM). Jupindá Lake is 70 km East of from Santarém City, and receives surface water inflow from small streams draining from the forest and the main tributary Curuá-Una River, a large affluent of the Amazon River (Figure 1). The Lake has been affected by the deforestation associated with the expansion of Santarém City. Between the 1940’s and 1950’s, there was intense deforestation on the margins of rivers and streams in this area, used to supply the market of wood and forestry products (Amorim 2000, Cruz et al. 2011). In the 1970s, the Curuá-Una River was dammed (Curuá-Una Dam) 45 km upstream of Jupindá Lake to build the first hydroelectric plant of the Amazon Forest (LigockI 2003).
Jupindá Lake provides an ideal opportunity to investigate historical changes in organic carbon burial in a floodplain lake as a result of anthropogenic activities. This will aid identification of still-little known impacts of land cover changes on recent carbon burial rates in depositional environments of the Amazon floodplain. The objectives of this research are to investigate the affect deforestation and urban development has on carbon burial rates in a tropical floodplain wetland.

2. Methods

A 60 cm depth sediment core (diameter 7.5 cm) was collected in 2010 using a gravity corer in the center of the Jupindá Lake (02°27’43.60” S, 54° 5’1.30” W. The sediment core was sub sampled at 2 cm intervals. Dry bulk density (DBD, g cm$^{-3}$) was determined as the dry sediment weight (g) divided by the initial volume (cm$^3$). A homogenized portion was acidified to remove carbonate material, then dried and ground to powder for organic carbon (OC), nitrogen (N), $\delta^{13}$C, and $\delta^{15}$N analyses using a Flash Elemental Analyzer coupled to a Thermo Fisher Delta V IRMS (isotope ratio mass spectrometer). Analytical precision: C = 0.1 %, N = 0.1%, $\delta^{13}$C = 0.1‰ and $\delta^{15}$N = 0.15 ‰.

Samples were prepared for Pu dating following the method of Ketterer et al. (2004) with modifications to enable larger sample mass to be processed as a result of the likely lower Pu concentrations in the Southern Hemisphere (Sanders et al. 2014). To obtain a larger mass, sediment intervals were joined and homogenized so the sediment intervals for the $^{240}$Pu dating was 4 cm intervals. Sample aliquots ranging from 14 to
29 grams were dry-ashed at 600 °C for 16 hours, and leached with 50 mL of 16 M HNO₃. The leaching was conducted overnight at 80 °C with added ²⁴²Pu yield tracer (NIST 4334g, 19 picograms). Acid leaching (as opposed to complete dissolution with HF) is known to solubilize stratospheric fallout Pu, and there is little possibility that “refractory” HNO₃-insoluble Pu exists in the South America (Sanders et al. 2014). The leachates were diluted to 100 mL, filtered to remove solids, and the aqueous solutions were processed with TEVA resin (EICHrom, Lisle, IL, USA) in order to chemically isolate 3.0 mL Pu fractions in aqueous ammonium oxalate solution suitable for measurements by sector ICPMS. Pu determinations were performed using a VG Axiom MC operating in the single collector (electron multiplier) mode. The system was used with an APEX HF desolvating micronebulizer system (ESI Scientific, Omaha, NE, USA) with an uptake rate of 0.4 mL/minute. Qualitative mass spectral scans (averages of 50 sweeps over the mass range 237.4 – 242.6) were collected for selected samples prior to the electrostatic sector quantitative scanning of ²³⁸U⁺, ²³⁹Pu⁺, ²⁴⁰Pu⁺, and ²⁴²Pu⁺. Detection limits were evaluated based upon the analysis of two blanks and considerations regarding the obtained mass spectra. A detection limit of 0.01 Bq/kg of ²³⁹⁺²⁴⁰Pu is applicable for samples of nominal 25 g mass.

For ²¹⁰Pb dating, an intrinsic germanium detector coupled to a multi-channel analyzer was used. Freeze dried and ground sediments were packed and sealed in gamma tubes. Lead-210 and ²²⁶Ra activities were calculated by multiplying the counts per minute by a factor that includes the gamma-ray intensity and detector efficiency determined from standard calibrations. Identical geometry was used for all samples. Lead-210 activities were determined by the direct measurement of the 46.5 KeV gamma peak. Radium-226
activity was determined via the $^{214}$Pb daughter at 351.9 KeV. For $^{226}$Ra measurements, the packed samples were set aside for at least 21 days to allow for $^{222}$Rn to ingrow and establish secular equilibrium between $^{226}$Ra and its granddaughter $^{214}$Pb. Excess $^{210}$Pb activity was calculated by subtracting the supported $^{210}$Pb (i.e., $^{226}$Ra activity) from the total $^{210}$Pb activity. The sediment accretion rate for the previous 120 years was estimated by two methods derived from $^{210}$Pb dating, the Constant Initial Concentration (CIC) model assuming that this rate has not varied during the encompassed time span (Appleby and Oldfield 1992), and the Constant Rate of Supply (CRS) model based on a constant influx of unsupported, atmospheric $^{210}$Pb that allows a variable sediment rate (Ivanovich and Harmon 1992). Organic carbon accumulation rates were estimated from sediment accretion rates (mm yr$^{-1}$), dry bulk density (g cm$^{-3}$) and OC content.

The land/use cover analysis was based on documented historical information before 1975 and satellite images (Landsat/SRTM, Table 1) from 1975, 1985, 1995 and 2008 available from the United States Geological Survey (USGS). No significant deforestation occurred in the catchment area of the Jupindá Lake until early 1940’s (Amorim 2000, Cruz et al. 2011). Subsequent land/use changes were determined using satellite images (Gordon 1980, Munyati 2000). All satellite images were from low-water seasons to remove the influence of the flood pulse on the exposed area over years. The resolution of the images was 30 m, except that from the 1970’s which was resampled from 90 to 30 m (Table 1). This approach allowed an assessment of changes in land cover which could then be compared to results from carbon accumulation. Results of the spatial assessment were separated into two time periods; 1942-1975, or the timeframe between the onset of land clearing and the first satellite image, and 1975-2008 which provides a more detailed assessment of temporal changes to the study area. The time period 1942-1975 was
characterized by a rapid removal (peak until the 1960’s) of vegetation established at the margins of inland waters; especially *Aniba rosaeodora* (Pau-rosa) for extraction of oils, and *Mezilaurus itauba* and *Cedrela fissilis* (Louro-itaúba and Cedro, respectively) as hardwoods, and the opening of clearings for crops of textile fibers and subsistence products. Further, intensification of deforestation towards the interior of the forest and following the urban growth of Santarém is reported from the 1970’s, along with depleting vegetal resources near to the margins of lakes and running waters in this region was noted (Amorim 2000, Cruz et al. 2011).

In order to address the spatial dependence of recent OC burial in Jupindá Lake for deforestation, we analyzed the land/cover use in four buffer areas around this lake and contributing rivers or streams. The first buffer of 100 m represented the riparian forest protected area by the Brazilian laws for fluvial channels with a width of 50 to 200 m. Other buffers were progressively higher, with a width of 500, 1000 and 6000 m from the riverbank and lake margins (Figure 2). In addition, we considered only stretches of rivers and streams 65-km long from Jupindá Lake to analyze its catchment area of more direct influence. This criteria also allowed to avoid the interference of the artificial flooding on the margins of the Curuá-Una hydroelectric dam, which was built in 1977 (Fearnside 2005).

3. Results

Analyses of $^{239+240}$Pu were not detectable from the bottom of the sediment core until the 22-26 cm interval (Figure 43). This radioisotope was detected in the 18-22 cm
interval (0.029 ± 0.002 Bq/kg $^{239+240}$Pu) with the highest concentrations (0.047 ± 0.004 Bq/kg $^{239+240}$Pu) at the 16 cm depth. The $^{239+240}$Pu activities appears to spike at the 14 to 18 cm interval, which indicates the 1963 stratospheric fallout peak. It may be said with certainty that the material below 22 cm was deposited pre-bomb (that is, prior to the early 1950’s). This affixes an upper limit on the average sedimentation rate of near to 3.8 mm year$^{-1}$. The Pu atom ratio data indicate that the Pu is originating from stratospheric fallout (plutonium isotopic ratios ($^{240/239}$Pu) of ~0.18). These results are consistent with the $^{240}$Pu/$^{239}$Pu of 0.180 ± 0.014 discussed by Kelley et al. (1999).

The $^{210}$Pb and $^{226}$Ra profiles reveal a complex depositional environment with sedimentation variations in the upper intervals with disturbances, such as bio-turbation and resuspension in the upper ~ 20 cm of the sediment column (Figure 4). A decrease in $^{210}$Pb$_{ex}$ activity was found below the 20 cm depth interval. The $^{210}$Pb$_{ex}$ data distribution are as follows: $y = -0.0749x + 7.5$ (R$^2 = 0.73$; n=19; p < 0.01) from the 20 to the 60 cm interval, below the apparent mixed zone. Both estimates of sediment accretion rate during the 120 years from CIC and CRS models were similar, reaching 4.1 and 4.3 mm yr$^{-1}$ respectively, which were slightly higher than the ~ 60 year $^{239+240}$Pu dates (3.8 mm yr$^{-1}$).

The dry bulk density (DBD), total organic carbon (OC%), total nitrogen (TN%) content and the carbon and nitrogen (C/N) molar ratios along with the $\delta^{13}$C and $\delta^{15}$N values showed important increases towards the center of the sediment core Table 2. The relationship between $\delta^{13}$C and $\delta^{15}$N indicated different origins of OC in the sediment core (Figure 5) contributing to the significant relationship between recent OC burial and the $\delta^{13}$C (Figure 6).

The OC burial rates show an increasing trend from ~ 1930 to 1960 with a peak during
the 1940’s and 50’s (grey area in Figure 7). The carbon burial rates increased, from 150 g m$^{-2}$ year$^{-1}$ in the time period 1890 - 1940 to ~ 300 g m$^{-2}$ year$^{-1}$ between 1940 and 1950. Carbon accumulation then decreased to approximately 200 g m$^{-2}$ year$^{-1}$ from 1960 to 1980, after which a gradual decline in carbon burial was still measured. In relation to land use/cover in the surroundings of fluvial channels and the Jupindá lake over time, only the smallest buffer (100 m) showed more intense relative changes during the previous period 1942-1975, when the increase in deforested area was around 75 % higher than in the subsequent time period 1975-2008 (Figure 8).

4. Discussion

Overall, similar estimates of sediment accretion using different methodologies (i.e. 60 and 120 year trends from the $^{239+240}$Pu and $^{210}$Pb$_{ex}$ models, respectively) revealed an insight into changes in the sediment accumulation assessed here. This indicates that even though the origin of the organic material was modified, the sediment accumulation has varied little as indicated by the 60- or 120-year sediment accumulation rates. To present the historical profiles of the carbon burial rates, an average is taken between these two methods (4 mm year$^{-1}$), multiplied by the DBD and carbon content for each interval of the entire sediment core.

The high peak in carbon accumulation observed around 1950 appears to be associated with a shift in the source of organic material, inferred by changes in carbon and nitrogen contents and the isotopic fractioning toward the middle (from 40 to 20 cm depth interval) of the sediment column. This peak for different organic and inorganic variables in intermediate depths revealed changes not only in the amount but also in the
type of material being deposited over time. Previous studies have reported two common
origins for OC in the Amazon forest. Higher $\delta^{15}$N and more negative $\delta^{13}$C values could
indicate the presence of Santarém soil organic matter (such as that adjacent to the Jupindá
Lake), while lower $\delta^{15}$N and more variable $\delta^{13}$C values indicate particulate organic
carbon (POC) from the terrestrial vegetation in the catchment (Ometto et al. 2006,
Zocatelli et al. 2013). Here, a corresponding increase in OC%, TN% and OC burial rates
measured, with a peak near ~1950, suggesting higher inputs of organic matter into lake.
The higher $\delta^{13}$C signature, coupled with a lower $\delta^{15}$N indicates a greater influence from
the terrestrial Amazonian POC during the same period around 1950 (Ometto et al., 2006).

When looking for a cause for this change in the source of organic material, we
look to the analysis of land use change. Land clearing associated with early occupation
from the 1940s in the catchment area of the Jupindá Lake reveals a potential cause of the
increased carbon burial observed in this lake. Changes in land use and cover may
significantly affect recent OC burial in mid-high-latitude lakes (Anderson et al. 2013,
Dietz et al. 2015). Our results suggest that land clearing during the 1940’s and 50’s might
be related to increased organic matter deposition in the region’s floodplain lakes. During
this period, intense wood extraction and expansion of agricultural settlements occurred
(Amorim 2000, Cruz et al. 2011). One important consequence of deforestation in the
watershed is the silting up of lakes (Enea et al. 2012 ), including those at humid low-
latitude areas (Cohen et al. 2005, Bakoariniaina et al. 2006). The riparian forest systems
are generally effective in reducing the sediment transport by surface runoff, with the
removal of this vegetation increasing the erosion processes especially in the Amazon
basin due to intense rainfall (Neill et al. 2013a).
We also found a spatial dependence of the carbon accumulation in the Lake Jupindá, as the much lower OC burial was coupled to higher deforestation rates in those larger buffers around its margins and main fluvial channels (500, 1000 and 6000 m) in the period after 1975 (1975-2008) than that before (1942-1975). This confirms previous evidences that the recent deforestation process in the region was started in areas around running and lake waters (Amorim 2000, Cruz et al. 2011), and not in the interior of the forest. The enhanced OC burial in lacustrine sediments before 1975 was related to higher deforestation rates only in the riparian vegetation zone (100-m buffers), suggesting a higher influence of deforestation with decreasing distance to water courses. Therefore, the soil carbon enrichment to the aquatic sediments during the peaks of riparian deforestation may cause intense but temporary carbon burial events in the Amazon floodplain, representing a significant part of the total loss of terrestrial organic matter. In contrast, the continued removal of vegetation from the interior of the forest might be not directly related to increases of OC burial, even temporarily, in depositional aquatic ecosystems.

5. Conclusion

The $^{239+240}$Pu and $^{210}$Pb dating methods were combined with a spatial analysis of vegetation clearing to firstly calculate carbon accumulation rates, and then to interpret changes in sediment characteristics during the previous century. The Pu dating method closely approximates measurements from the $^{210}$Pb chronologies and hence offers mechanism to determine sedimentation rates and carbon accumulation in Amazon sediments. An increase in OC burial, 150 to $\sim$ 300 OC g m$^{-2}$ year$^{-1}$, coincides with
changes in the $\delta^{13}$C and $\delta^{15}$N signatures, likely influenced by the heavy deforestation in riparian systems of this region during the 1940s and 50’s. It is therefore suggested that the net increase in carbon burial towards the center of the sediment core, which represents the highest carbon burial rates during the 1950s, is a result of a change in source of organic matter deposition. The differing carbon burial rates along the sediment core reveals the potential complexity of carbon burial rates in the Amazon floodplain lakes, directly related to the development within the Basin. This work demonstrates a new understanding on spatial dependence of carbon burial capacity of the Amazon floodplain lakes with respect to advances in deforestation in the basin.

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CAPTIONS TO FIGURES

Figure 1. Floodplain Lake where the sediment core was collect, near the Amazon River and the city of Santarém, Brazil. This floodplain lake has a diameter of approximately 3 km.
Figure 2. Different buffer sizes (100m, 500m, 1km and 6km) along the stretch of the Curuá-Una river from Jupindá Lake (red) to the hydroelectric dam upstream (yellow).

Figure 3. $^{239+240}$Pu profile, indicating ~ 1950 when these radionuclides were first introduced into the atmosphere.

Figure 4. Excess $^{210}$Pb and $^{226}$Ra profile against depth.

Figure 5. $\delta^{13}$C vs $\delta^{15}$N. The Amazon River POM and Santarem soil organic matter values, adjacent to the study area, are taken from Zocatelli et al (2013).

Figure 6. Carbon burial as a function of $\delta^{13}$C.

Figure 7. $\delta^{13}$C, $\delta^{15}$N and carbon burial rate values in relation to age (year).

Figure 8. Percentage of modified areas in relation to the different buffers.

CAPTION TO TABLES

Table 1. Satellite acquisition data from United States Geological Survey (USGS) and the Curuá-Una River quota from Brazilian Water Agency (ANA).

Table 2. Depth profiles of dry bulk density (DBD), total organic carbon (OC%), total nitrogen (TN%) carbon and nitrogen (C/N) molar ratios, $\delta^{13}$C and $\delta^{15}$N.

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<td>-29.8</td>
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<td><strong>Average</strong></td>
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<td><strong>8.34</strong></td>
<td><strong>-28.9</strong></td>
<td><strong>4.0</strong></td>
<td><strong>0.2</strong></td>
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<tr>
<td><strong>Stand Dev</strong></td>
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<td><strong>2.1</strong></td>
<td><strong>0.8</strong></td>
<td><strong>1.9</strong></td>
<td><strong>0.1</strong></td>
<td><strong>4.2</strong></td>
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Figure 1.
Figure 2.
Figure 3.

$^{229+240}\text{Pu (Bq kg}^{-1}\text{)}$

0.00 0.02 0.04 0.06

Depth (cm)

~ 1950
Figure 4.

$^{210}\text{Pb}, \quad ^{226}\text{Ra} \text{ (Bq kg}^{-1}\text{)}$

Depth (cm)

0 10 20 30 40 50 60

100 200 300 400 500
Figure 5.
Figure 6.
Figure 7.
Figure 8.