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Phosphorus transport by the largest Amazon tributary (Madeira River, Brazil) and its sensitivity to precipitation and damming

Rafael M. Almeida¹, Lars Tranvik², Vera L. M. Huszar³, Sebastian Sobek², Raquel Mendonça², Nathan Barros¹, Gina Boemer⁴, João Durval Arantes Jr.⁴, Fábio Roland^{1*}

¹Laboratory of Aquatic Ecology, Department of Biology, Federal University of Juiz de Fora, Juiz de Fora, Brazil

²Limnology, Department of Ecology and Genetics, Uppsala University, Uppsala, Sweden

³Laboratório de Ficologia, Museu Nacional, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

⁴Ecology and Environment do Brasil Ltda., Rio de Janeiro, Brazil.

*corresponding author: fabio.roland@ufjf.edu.br

Abstract

Originating in the Bolivian and Peruvian Andes, the Madeira River is the largest tributary of the Amazon River in terms of discharge. Andean rivers transport large quantities of nutrient-rich suspended sediments and are the main source of phosphorus (P) to the Amazon basin. Here, we show the seasonal variability in concentrations and loads of different P forms (total, particulate, dissolved and soluble reactive P) in the Madeira River through eight field campaigns between 2009-2011. At our sampling reach (Porto Velho, Brazil), the Madeira River transports about 177-247 Gg P yr⁻¹, mostly linked to particles (~85%). Concentrations and loads of all P have a maximum at rising waters and a minimum at low waters. Total P concentrations were substantially lower at a given discharge at falling water than at a similar discharge at rising water, indicating a clockwise hysteresis. The peak of P concentrations matched the peak of rainfall in the upper basin, suggesting an influence of precipitation-driven erosion. Projected precipitation increase in the eastern slopes of the Andes could enhance sediment yield and hence the P transport in the Madeira River. However, as most of the P is particulate, we hypothesize that the planned proliferation of hydropower dams in the Madeira basin has the potential to reduce P loads substantially, possibly counteracting precipitation-related increases. In the long term, this could be detrimental to highly productive downstream floodplain forests that are seasonally fertilized with P-rich deposits.

Key words: Amazon, Andes, floodplain, hydropower dams, hysteresis effect, Madeira River, phosphorus, precipitation

Introduction

The Amazon landscape comprises white-, clear- and black-water rivers, as a result of the geomorphological properties of their catchments (Stallard and Edmond 1983).

White-water rivers, such as the large Madeira and Solimões/Amazon rivers, originate in the Andes cordillera. Because of the young and easily erodible rock these mountains are an important source of phosphorus-rich sediments to white-water rivers, giving them their typical high turbidity (McClain and Naiman 2008). The black- and clear-water rivers, on the other hand, have their upper catchments in lowland, highly weathered Precambrian shields, thus transporting low quantities of nutrients (Stallard and Edmond 1983). When compared to clear- and black-water rivers, white-water rivers deliver almost 20 times more phosphorus (P) to the Amazon River (Richey and Victoria 1993). The white-water Madeira River alone is responsible for over one-third of the total Amazon River P load at Óbidos (~ 700 km upstream the mouth at the Atlantic Ocean), estimated in 1,000 Gg ($1 \text{ Gg} = 10^{12} \text{ g}$) per year (Richey and Victoria 1993).

In terms of discharge, the Madeira River is the fourth largest tropical river in the world and the greatest tributary of the Amazon River (Latrubesse et al. 2005; McClain and Naiman 2008). Like in the majority of large Amazonian rivers, discharge varies substantially over the year in the Madeira River (Leite et al. 2011). As a result, the river water seasonally overflows the banks, depositing nutrient-rich sediments onto the floodplains, ultimately boosting primary production and supporting high biological diversity (McClain and Naiman 2008). Owing to the high availability of P and other nutrients, the floodplains of Amazonian white-water rivers (locally known as *várzeas*) can be up to 50% more productive than the floodplains of low-nutrient clear- and black-water rivers (locally known as *igapós*) (Worbes 1997).

Because the high productivity of Amazonian *várzeas* is sustained by deposition of nutrient-rich sediments derived from the Andes, there is a concern about a loss in the connectivity between up- and downstream areas due to the imminent hydropower boom in Andean rivers (Finer and Jenkins 2012; Tundisi et al. 2014; Zarfl et al. 2014). There are currently seven hydropower plants in operation in the Andean part of the Madeira River basin (Bolivia and Peru), five of which have energy capacity lower than 100 MW. Another 19 dams are planned for the next two decades, 14 of which will have energy capacity higher than 100 MW (Finer and Jenkins 2012). In addition, there are two mega dams under construction in the Madeira River within the municipality of Porto Velho, Brazil (Jirau and Santo Antônio dams). This basin-wide increase in the number of dams may dramatically reduce the supply of sediments from the headwaters to downstream floodplains, as regulated basins trap substantial amounts of sediments in reservoirs (Vörösmarty et al. 2003).

In addition to the looming hydropower boom, changes in temperature and precipitation will probably affect the Madeira River basin over the next decades. Climate projections show an overall tendency of temperature increase in the Andes (Christensen et al. 2007), whereas precipitation is projected to either increase or decrease depending on the location (Urrutia and Vuille 2009), due to the high spatial climate variability in mountain regions (Villar et al. 2009). This changing climate may affect weathering and erosion rates, and thereby the downstream delivery of P.

Despite the enormous dimensions of the Madeira River and the risk that upcoming basin-wide changes represent to its ecosystems, there is only a handful of studies on the biogeochemistry of this large tropical river (e.g. Leite et al. 2011; Mortatti et al. 1989). One study has estimated the Madeira River delivery of P to the Amazon River (Richey and Victoria 1993), but to our knowledge none have investigated the seasonal patterns

in detail. This lack of background studies becomes particularly problematic considering that the Madeira River basin will soon be regulated by dams. Here, we investigated the seasonal patterns of P concentrations and transport in the Madeira River, to further discuss how P transport could be altered in the near future in the light of the Andean hydropower boom and precipitation changes.

Methods

Site description

The Madeira River basin spans over Bolivia, Peru and Brazil. With an area of 1.4×10^6 km², it covers 23% of the Amazon basin and drains 35% of the Andean Amazon (Guyot et al. 1996). The headwaters are located in the Peruvian and Bolivian Andes, where the strong annual variability in precipitation (Villar et al. 2009) creates clearly defined flood pulses (Leite et al. 2011). Discharges in the Madeira River vary considerably between low and high waters (**FIGURE 1**), averaging $31,200 \text{ m}^3 \text{ s}^{-1}$ at the mouth (Moreira-Turcq et al. 2003). Similarly, precipitation in the headwaters shows a large variability over the year, peaking in January (Villar et al. 2009), when the Madeira River is at the rising water period (**FIGURE 1**). The Madeira River flows into the Amazon River in the central Amazon, downstream the municipality of Manaus, Brazil.

The drainage area of the Madeira River until Porto Velho (elevation = 42 m asl) is estimated in 976,000 km². At this point, the Madeira River annually transports 319×10^6 tons of suspended sediments (Leite et al. 2011). At Porto Velho, the average discharge is $19,100 \text{ m}^3 \text{ s}^{-1}$ (this study), the channel width ranges between 0.6-5.9 km, the depth varies between 7-24 m, and flow velocities range between $0.28\text{-}1.23 \text{ m s}^{-1}$ (Bonthius et al. 2012).

Sampling and laboratory analyses

We sampled five different sites across a 100-km stretch of the Madeira River within the municipality of Porto Velho (Brazil) (**FIGURE 2**). Samples were taken from the upper 0.5 m and about 1 m above the bottom, at the middle of the main channel.

Measurements of chemical variables along a transect perpendicular to the river axis indicate that the mixing of the water masses is practically complete at this portion of the Madeira River (Leite et al. 2011). Surface and bottom concentrations of the different P forms were not significantly different (Mann-Whitney test, $p > 0.05$). Similarly, there was no statistical difference in the concentrations measured at the five stations (ANOVA, $p > 0.05$). Therefore, we consider that the water column is vertically mixed (i.e. the average of bottom and surface denotes the water column concentration) and that the average of the water column concentrations of the five stations is representative of the entire 100-km stretch investigated here.

We performed eight field campaigns between 2009 and 2011, comprising two annual cycles and encompassing all hydrological phases: high, falling, low, and rising waters. Total phosphorus (total P) was measured on unfiltered samples. Total dissolved phosphorus (total dissolved P) and soluble reactive phosphorus (soluble reactive P) were measured on samples filtered through GF/C filters. The material retained on GF/C filters was analyzed gravimetrically to assess the content of suspended sediments (Wetzel and Likens 2000). All P forms were measured by the colorimetric molybdate blue method (Wetzel and Likens 2000). Total P and total dissolved P were measured after persulfate digestion, whereas samples for soluble reactive P were not digested. Particulate P was calculated as the difference between total P and total dissolved P. In Amazonian rivers with high concentrations of suspended sediments, the standard

persulfate digestion method sometimes underestimates total P concentrations, due to insufficient recovery of aluminum- and iron-bound particulate P (Engle and Sarnelle 1990). We discuss the consequences of this and hypothesize on how applying alternative methodologies would have influenced the final result. All statistical analyses were performed on Sigma Plot 11.0, and a $p < 0.05$ was adopted as the acceptance threshold level of the tests.

Calculation of P loads

Data on river discharge were obtained from the Porto Velho gauging station (code 15400000), available at the website of the Brazilian National Water Agency (<http://hidroweb.ana.gov.br>). The sampling stretch and the discharge gauging station are downstream the Jaci-Paraná River and upstream the Jamari River, the two largest tributaries at this portion of the Madeira River; thus, there is no contribution of water from major tributaries.

Our data set comprises concomitant measurements of discharge and P concentration during the four periods of the flood pulse (low, rising, high and receding waters) in combination with daily discharge records, which made us choose a discharge-weighted method for load estimation. This method calculates the average load from discharge-weighted concentration and the average discharge over the whole time interval. Among the methods that integrate loads using mean discharge and concentration values, the discharge-weighted is the one that produces less biased results if the data set covers a broad range of discharges and concentrations, and discharge is measured with high frequency (Quilbé et al. 2006). These two conditions are fulfilled by our data set, and we estimated loads as follows:

$$L = \frac{\sum(Q_i * C_i)}{\sum(Q_i) * \sum(Q_j)/n}$$

(1)

where L = load (g s⁻¹); Q_i = discharge at time *i* (m³ s⁻¹); C_i = concentration at time *i* (g m⁻³); Q_j = discharge at time *j*, according to the daily measurements; n = number of all daily measurements of discharge.

Results

Upstream precipitation and river water discharge

The Bolivian Andes receive less rain than the Bolivian plain, but both regions display a similar seasonal pattern in precipitation, with a maximum in January and a minimum in July (**FIGURE 1**). These regions are the main source of water to the Madeira River.

The strong seasonal variation in precipitation creates clearly defined flood pulses in the Madeira River, with the average discharge at Porto Velho ranging from 5,360 m³ s⁻¹ in September to 35,350 m³ s⁻¹ in March (**FIGURE 1**). Based on the hydrograph of the Madeira River at Porto Velho, we considered low water to prevail from August to October; rising water from November to February; high water from March to April; and falling water from May to July.

P concentrations and loads

Total particulate P composed on average 85% of total P in the Madeira River within our sampling stretch, with greater shares at rising and high water levels (low water = 48%; rising water = 84%; high water = 89%; falling water = 73%). This is in agreement with

the strong positive correlation between total P and suspended sediments (Spearman's correlation, $r = 0.80$, $p < 0.05$; data not shown). The concentrations of total P and particulate P showed clear seasonal variations, with maximum at rising water and minimum at low water (**FIGURE 3**). The peak of particulate and total P concentrations (rising and high waters) matched the peak of upstream precipitation (**FIGURE 1**). Total dissolved P and soluble reactive P concentrations did not exhibit any clear seasonal pattern (**FIGURE 3**).

The loads of total and particulate P peaked at rising and high waters and reached minimum values at low waters (**FIGURE 4**). Integrating over the year, the Madeira River's annual transport of total P at Porto Velho ranged between 177 Gg in the 2010-2011 annual cycle and 247 Gg in the 2009-2010 annual cycle. Of these, about 84-87% were in the particulate form. The soluble reactive P transport varied between 9 Gg in the 2010-2011 annual cycle and 23 Gg in the 2009-2010 annual cycle.

Hysteresis effect between water discharge and P concentrations

Although total P concentrations were generally higher at elevated water levels, discharge was not a good predictor of total P (**FIGURE 5**). There was a clockwise hysteresis between discharge and total P – that is, a given discharge at falling water exhibited substantially lower total P concentrations than a similar discharge at rising water. This is best exemplified in the 2009-2010 annual cycle, when discharges were similar during the falling and rising water field campaigns (about $25,000 \text{ m}^3 \text{ s}^{-1}$), but the concentration was 3-fold higher at rising water (**FIGURE 5**).

Discussion

Our results suggest that the Madeira River plays a central role in the Amazon P cycle, transporting on average 212 Gg yr^{-1} of total P at Porto Velho ($\sim 1,000 \text{ km}$ upstream its confluence with the Amazon River). The deposition of part of this load supplies lowland wetlands with nutrients, boosting primary production (McClain and Naiman 2008). Given the distance to the mouth, our results do not specifically reflect the amount of P that enters into the Amazon River, as there is deposition and input of P from tributaries along the course until the confluence. However, the amount of P being transported at Porto Velho is comparable to about 20% of the Amazon River load at Óbidos (Devol et al. 1991; Richey and Victoria 1993). The high interannual variation in the loads is mainly the result of interannual variation in discharges. The 2009/2010 annual cycle exhibited a total P load 40% higher and a mean discharge 35% higher than the 2010/2011 annual cycle. This indicates the major role of climate (i.e. precipitation) in driving P transport in the Madeira River.

The average total P concentration of the Madeira River at Porto Velho ($278 \mu\text{g L}^{-1}$) is slightly higher than the average concentration of the Amazon River at Óbidos ($232 \mu\text{g L}^{-1}$, Devol et al., 1991), probably because P in the Amazon River is more diluted by nutrient-poor waters of the Negro and Trombetas rivers, as well as other smaller tributaries. However, the composition of the total P pool in the Madeira River was similar to that reported for the Amazon River (Devol et al. 1991; Richey and Victoria 1993), with 80% of P being linked to particles and 10% occurring as soluble reactive P. The particulate P is mostly Andean-derived, as Andean headwaters are the main sources of suspended sediments to Amazonian white-water rivers (Devol et al. 1995). This is evident when concentrations of total P in the Madeira River are compared to total P

concentrations in the Jamari River, the largest clear-water tributary nearby our sampling stretch. The concentration of total P in the Jamari River averages $32 \mu\text{g L}^{-1}$ (Ecology and Environment do Brasil, data not published), which is almost one order of magnitude below the Madeira's average.

Our results indicate substantial amounts of P in the Madeira River. Still, they are likely to be conservative, since particulate P concentrations may be underestimated by the persulfate digestion method according to a study in Amazonian turbid waters (Engle and Sarnelle 1990). Nevertheless, since our results are very close to those reported for Amazonian white-water rivers (e.g. Devol et al. 1991), it is unlikely that applying the persulfate digestion method has resulted in substantial underestimation.

The peak of particulate P in the Madeira River at Porto Velho (January, rising water phase) matches the peak of precipitation in its Andean headwaters (Villar et al. 2009). This may be the cause of the positive (clockwise) hysteresis between total P concentrations and discharge, as the significant increase in sediment flushing during rainfall events causes clockwise hysteresis (Steege et al. 2000). A clockwise hysteresis indicates that P concentrations peak before water discharge, suggesting that the erodible P is promptly flushed to the river via runoff after precipitation, but the ground water that percolates to the rivers more slowly does not transport as much P. As a result, at a given discharge during falling water, total P concentrations are substantially lower than at a similar discharge during rising water (**FIGURE 4**), since sediment and associated P input has been exhausted. This hysteresis has an implication for load calculation in the Madeira River. Regression methods (i.e. the so-called rating curve) between discharge and concentrations are commonly used to determine nutrient loads in large rivers (Quilbé et al. 2006), but the use of such methods requires a strong linear relationship

between discharge and concentrations, which was not the case in the Madeira River. This justifies why we used a discharge-weighted method for load calculation.

The prevalence of particulate P indicates that the majority of P in the Madeira River is not readily bioavailable in the water column, but rather settles on the floodplains, eventually contributing to their productivity (McClain and Naiman 2008). However, the amount of potentially bioavailable P in the water may be underestimated, considering that soluble reactive P can reversibly sorb onto the surfaces of mineral particles, especially in rivers with high concentrations of suspended sediments such as the Madeira (Muller et al. 2006). Accordingly, a previous study showed that between 16 and 38% of the algal-available P in the white-water Amazon River is bound to particles (Engle and Sarnelle 1990). Additionally, phosphate can be released from suspended sediments (Chase and Sayles 1980; Fox et al. 1986), and the deposited P may become mobilized and bioavailable after undergoing transformation under certain chemical conditions (e.g. low pH and low oxygen concentration) (Silva and Sampaio 1998). Hence, even though the particulate P fraction is dominating, significant biological uptake of P from the particulate fraction is likely.

Expected changes in the Andean climate (Christensen et al. 2007; Urrutia and Vuille 2009) and the planned construction of reservoirs over the basin (Finer and Jenkins 2012) can alter P loads of the Madeira River in the near future. Areas up to 2,000 meters above sea level in the eastern slopes of the Andes are projected to experience significant increase in precipitation by 2100 (Urrutia and Vuille 2009). Annual increases may reach up to 400 mm per year in altitudes between 1,000 and 2,000 meters. Maximum precipitation is registered in these altitudes (Villar et al. 2009), and hence P erosion and entrainment into rivers is probably maximum as well. As our results and previous studies (e.g. (Devol et al. 1995)) suggest that precipitation in the upper basin is

positively correlated to total P concentrations in discharge water, the Madeira River P load may increase in the future on the basis of existing scenarios.

Damming has the opposite effect, resulting in diminished P concentrations because of sedimentation in reservoirs (Zhou et al. 2013). All existing dams in the Andean part of the Madeira River basin are located in small headwaters and have little energy generation capacities. However, the projected 270% increase in the number of dams in the Madeira River and some of its Andean tributaries within the next two decades (Finer and Jenkins 2012) may result in a great increase in sedimentation. Globally, more than 50% of the flux of suspended sediments in regulated basins is lost due to trapping in reservoirs (Vörösmarty et al. 2003). In places with large hydropower density like Asia, the transport of suspended sediments from the larger rivers has declined by more than 75% (Gupta et al. 2012). Considering the particulate P accounting for 80% of total P in the Madeira River and assuming the average sediment trapping efficiency by dams in regulated basins worldwide (50%), the Madeira River P load could decline by about 40%. In some cases, damming results in an even higher trapping of P. For instance, the sediment loads of the highly dammed Yangtze River in Asia have decreased by 91% as compared to pre-dam conditions (Yang et al. 2005), which led to a 77% reduction in total P load to the lower basin (Zhou et al. 2013). In the Zambezi River basin in Africa, one single dam reduced 60% of the Kafue River P fluxes, decreasing the P delivery to a downstream Ramsar site wetland (Kunz et al. 2011). Although the estimate we present here may be speculative given that the degree of sedimentation depends on factors still unknown such as dam configuration (e.g. volume, flooded area, residence time), evidences from other regulated rivers suggest that P trapping behind dams built in Amazonian white-water rivers will likely be substantial and should be of major ecological concern.

To our knowledge, this is the first seasonal assessment of loads and concentrations of P in the Madeira River, which is crucial to understand the likely effects of future environmental changes on P dynamics. The apparent relationship between precipitation-driven erosion rates in the upper basin and P concentrations corroborates that increased Andean precipitation may enhance the supply of sediment and associated nutrients to Amazonian floodplains (Aalto et al. 2003). However, any potential future precipitation-driven increase in P load will likely be counteracted by the basin-wide proliferation of dams. This is consistent with observations for worldwide rivers: although sediment yield due to soil erosion displays an increasing trend, sediment fluxes from world rivers displays a declining trend due to retention in reservoirs (Syvitski et al. 2005). The upper mineral layer of *várzea* soils is about six times more enriched in P than that of *igapós*, which results in a net primary production up to 50% higher in *várzea* flooded forests (Worbes 1997). In addition, there is evidence showing that fertilization with P increases the primary production of phytoplankton in Amazon floodplain lakes (Setaro and Melack 1984), and the growth rate of aquatic macrophytes peaks when white-water rivers rise and provide nutrients to the *várzeas* (Piedade et al. 2001). Although estimates of by how much P transport could be expected to be reduced by damming are poorly constrained, it is very likely that the proliferation of dams in the upper basin will have detrimental effects on the P transport to lowland ecosystems. This may also be valid for other Amazonian rivers originating in the Andes, including the Amazon main stem, considering that over 150 dams are planned to be built in the Andean Amazon within the next two decades (Finer and Jenkins 2012). Radical decreases in the growth rates of downstream wetlands have been observed in response to nutrient retention behind dams in other parts of the world (Yang et al. 2005). Therefore, we suggest that, in the long

term, the combined effect of building several Andean dams may significantly affect downstream primary production in lowland Amazon floodplains.

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Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 1 - Mean monthly precipitation in the Bolivian Andes (black bars) and in the Bolivian plain (grey bars), based on data obtained in Villar et al. 2009. These authors used an Ascendant Hierarchical Classification to create the mean monthly precipitation on hundreds of meteorological stations widely distributed over each of these geographic areas. The mean monthly discharge of the Madeira River at Porto Velho (Brazil) is shown in the black circles. R = rising water, H = high water, F = falling water, L = low water.

Figure 2 – Map of the study area. (A) Representation of the Amazon basin (light gray), highlighting the Madeira River basin (dark gray) with the mainstream (black line) and its major Andean tributaries; the dark grey square shows the study area. (B) Zoomed in map of the study area, with grey circles representing the five sampling stations. The

whole study stretch is within Porto Velho municipality, and the urban area is highlighted in the light gray square.

Figure 3 – (A) Total phosphorus (TP), (B) particulate phosphorus (TPP), (C) total dissolved phosphorus (TDP) and (D) soluble reactive phosphorus (SRP) concentrations in the Madeira River at Porto Velho during the annual cycles of May 2009-April 2010 (black bars) and May 2010-April 2011 (grey bars). The traces indicate the standard deviation.

Figure 4 – (A) Total phosphorus (TP), (B) total particulate phosphorus (TPP), (C) total dissolved phosphorus (TDP) and (D) soluble reactive phosphorus (SRP) loads in the Madeira River at Porto Velho during the annual cycles of May 2009-April 2010 (black bars) and May 2010-April 2011 (grey bars).

Figure 5 – Clockwise hysteresis as observed after plotting total phosphorus concentrations against water discharge at Porto Velho. R = rising water, H = high water, F = falling water, L = low water.