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

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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 8 field campaigns between 2009 and 2011. At our sampling reach in Porto Velho, Brazil, the Madeira River transports ~177–247 Gg yr$^{-1}$ of P, mostly linked to particles (~85%). Concentrations and loads of all P forms have a maximum at rising waters and a minimum at low waters. Total P concentrations were substantially higher at a given discharge at rising water than at a similar discharge at falling water. 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. Because most of the P is particulate, however, we hypothesize that the planned proliferation of hydropower dams in the Madeira basin has the potential to reduce P loads substantially, possibly counteracting any 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, Madeira River, phosphorus, precipitation

Introduction

The Amazon landscape comprises whitewater, clearwater, and blackwater rivers as a result of the geomorphological properties of their catchments (Stallard and Edmond 1983). Whitewater 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 whitewater rivers, giving them their typical high turbidity (McClain and Naiman 2008). In comparison, blackwater and clearwater rivers, have upper catchments in lowland, highly weathered Precambrian shields, thus transporting low quantities of nutrients (Stallard and Edmond 1983). When compared to clearwater and blackwater rivers, whitewater rivers deliver almost 20 times more phosphorus (P) to the Amazon River (Richey and Victoria 1993). The whitewater Madeira River alone is responsible for more than one-third of the total Amazon River P load at Óbidos (~700 km upstream the mouth at the Atlantic Ocean), estimated at 1000 Gg yr$^{-1}$ (1 Gg = 10$^9$ g; 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). As with 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 whitewater rivers (locally known as várzeas) can be up to 50% more productive than the floodplains of low-nutrient clearwater and blackwater 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 concern about a loss in connectiv- ity between upstream and downstream areas due to the imminent hydropower boom in Andean rivers (Finer and Jenkins 2012, Tundisi et al. 2014, Zarfl et al. 2014). Currently, 7 hydropower plants operate in the Andean part of the Madeira River basin (Bolivia and Peru), 5 of which have an energy capacity <100 MW. Another 19 dams are planned for the next 2 decades, 14 of which will have an energy capacity >100 MW (Finer and Jenkins 2012). In addition, 2 mega dams are 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 because these 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 (Espinoza Villar et al. 2013). 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, few studies have investigated the biogeochemistry of this large tropical river (e.g., Mortatti et al. 1989, Leite et al. 2011). One study 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 Bolivia, Peru, and Brazil. With an area of $1.4 \times 10^6$ km$^2$, it covers 23% of the Amazon basin and drains 35% of the Andean Amazon (Guyot et al. 1996). The main stem of the Madeira River is formed after the confluence of the Beni and Mamoré rivers, near the Brazil–Bolivia border. The Beni and Mamoré are turbid rivers originating in the Bolivian Andes and drain about 75% of Ordovician dark shales and sandstones with some carbonates (Lyons and Bird 1995). Sediment yield data show that this upper part of the basin exhibits the highest erosion rates in the Amazon basin (Guyot et al. 1996). The Madre de Dios River, another important Andean-born river that originates in the Peruvian Andes, drains terrains where carbonates and some evaporites predominate (Leite et al. 2011 and references therein). The southeastern portion of the Madeira River basin drains metamorphic rocks (Stallard and Edmond 1983). The largest cities within the Madeira River basin are La Paz and Santa Cruz de la Sierra in Bolivia and Porto Velho in the lowland part of the basin in Brazil. Together, these 3 cities comprise a population of ~3.5 million people; otherwise, the Madeira River basin is sparsely inhabited.

The strong seasonal variability in precipitation in the Madeira River basin (Espinoza Villar et al. 2013) creates clearly defined flood pulses (Leite et al. 2011). Discharges in the Madeira River vary considerably between low and high waters (Fig. 1), averaging 31 200 m$^3$ 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 (Espinoza Villar et al. 2009) when the Madeira River is in the rising water period (Fig. 1). The travel time of water from the headwaters to Porto Velho is about 10 days at the mean flow speed at our sampling reach (1.4 m s$^{-1}$). The Madeira River flows into the Amazon River in the central Amazon, downstream from the municipality of Manaus, Brazil.

The drainage area of the Madeira River until Porto Velho (elevation = 42 m a.s.l.) is estimated at 976 000 km$^2$. At this point, the Madeira River annually transports $3.19 \times 10^6$ tons of suspended sediments (Leite et al. 2011), which are deposited and resuspended at high rates along
its course (Espinoza Villar et al. 2013). At Porto Velho, the average discharge is 19 100 m$^3$ s$^{-1}$ (this study), the channel width ranges between 0.6 and 5.9 km, the depth varies between 7 and 24 m, and flow velocities range between 0.28 and 1.23 m s$^{-1}$ (Bonthius et al. 2012).

**Sampling and laboratory analyses**

We sampled 5 different sites across a 100 km stretch of the Madeira River within the municipality of Porto Velho, Brazil, between 2009 and 2011 (Fig. 2). At each site, samples were taken with a Van Dorn water sampler from the upper 0.5 m and about 1 m above the bottom at the middle of the main channel. The mean depth at the sampling stations ranged from 12 m in low water season to 24 m in high water season. Measurements of chemical variables along a transect perpendicular to the river axis indicate that mixing of water masses is practically complete at this portion of the Madeira River (Leite et al. 2011).

We performed 8 field campaigns between 2009 and 2011, comprising 2 annual cycles and encompassing all hydrological phases: high, falling, low, and rising waters. Total P (TP) was measured on unfiltered samples. Total dissolved P (TDP) and soluble reactive P (SRP) samples were filtered through GF/C filters, and the retained material 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). TP and TDP were measured after persulfate digestion, whereas samples for SRP were not digested. Particulate P was calculated as the difference between TP and TDP. All statistical analyses were performed on Sigma Plot 11.0, and $p < 0.05$ 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 from the Jaci-Paraná River and upstream from the Jamari River, the 2 largest tributaries on this portion of the Madeira River; thus, there is no contribution of water from major tributaries.

**Fig. 1.** Mean monthly precipitation in the Bolivian Andes (black bars) and in the Bolivian plain (grey bars) based on data obtained in Espinoza 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.

**Fig. 2.** (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) Detail of the study area, with grey circles representing the 5 sampling stations. The whole study stretch is within Porto Velho municipality, and the urban area is highlighted in the light gray square.
Our dataset comprises concomitant measurements of discharge and P concentration during the 4 periods of the flood pulse (low, rising, high, and receding waters) in combination with daily discharge records, which required us to 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 method produces less biased results if the dataset covers a broad range of discharges and concentrations and discharge is measured with high frequency (Quilbé et al. 2006). These 2 conditions are fulfilled by our dataset, and we therefore estimated loads as follows:

\[
L = \frac{\sum(Q_i \cdot C_i)}{\sum(Q_i)} \cdot \frac{\sum(Q_j)}{n},
\]

where \(L\) = load \((g \, s^{-1})\); \(Q_i\) = discharge at time \(i\) \((m^3 \, s^{-1})\); \(C_i\) = concentration at time \(i\) \((g \, m^{-3})\); \(Q_j\) = discharge at time \(j\), according to the daily measurements; and \(n\) = 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 (Fig. 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 5360 m\(^3\) s\(^{-1}\) in September to 35 350 m\(^3\) s\(^{-1}\) in March (Fig. 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**

Surface and bottom concentrations of the different P forms were not significantly different (Mann-Whitney test, \(p > 0.05\)). Similarly, the concentrations measured at the 5 stations were not statistically different (ANOVA, \(p > 0.05\)). Although cross-sectional variation is observed in large Amazonian rivers (e.g., Curtis et al. 1979, Lewis and Saunders 1984), for this study we considered that the average of bottom and surface denotes the water column concentration and that the average of the water column concentrations of the 5 stations is representative of the entire 100 km stretch.

Total particulate P (TPP) comprised on average 85% of TP in the Madeira River within our sampling stretch, with greater shares at rising (84%) and high water levels (89%) than in low (48%) and falling waters (73%). These values are in agreement with the strong positive correlation between TP and suspended sediments (Spearman’s correlation, \(R = 0.80, \ p < 0.05\); data not shown); the concentrations of suspended sediments ranged from 49 mg L\(^{-1}\) at low water in 2010 to 444 mg L\(^{-1}\) at rising water in 2010 (data not shown). The concentrations of TP and TPP showed clear seasonal variations, with maximum at rising water and minimum at low water (Fig. 3). The peak of TPP and TP concentrations (rising and high waters) matched the peak of upstream precipitation (Fig. 1). TDP and SRP concentrations showed a less defined seasonal pattern (Fig. 3) with no significant difference between phases (ANOVA; \(p = 0.42\)), yet rising and high waters of the 2009–2010 annual cycle exhibited higher SRP concentrations.

The loads of TP and TPP peaked at rising and high waters and reached minimum values at low waters (Fig. 4). Integrating over the year, the annual transport of TP in the Madeira River 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 SRP transport varied between 9 Gg in the 2010–2011 annual cycle and 23 Gg in the 2009–2010 annual cycle.

![Fig. 3. (A) Total phosphorus (TP); (B) total 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). Traces indicate standard deviation.](image-url)
Water discharge versus P concentrations

Although TP concentrations were generally higher at elevated water levels, discharge was not a reliable predictor of TP (Fig. 5). Generally, a given discharge at falling water exhibited substantially lower TP concentrations than a similar discharge at rising water. This trend is best exemplified in the 2009–2010 annual cycle, when discharges were similar during the falling and rising water field campaigns (about 25 000 m³ s⁻¹), but the concentration was 3-fold higher at rising water (Fig. 5).

Discussion

P concentrations and loads

Our results suggest that the Madeira River plays a central role in the Amazon P cycle, transporting on average 212 Gg yr⁻¹ of TP at Porto Velho (~1000 km upstream from 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 discharged into the Amazon River because deposition, resuspension, and input of P from tributaries occurs along the course until the confluence (Espinoza Villar et al. 2013). The amount of P being transported at Porto Velho is comparable to ~20% of the Amazon River load at Óbidos, however, about 1000 km upstream from the Amazon estuary (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 TP load 40% higher and a mean discharge 35% higher than the 2010–2011 annual cycle, indicating the major role of climate, namely precipitation, in driving P transport in the Madeira River.

The average TP concentration of the Madeira River at Porto Velho (278 µg L⁻¹) is slightly higher than the average concentration of the Amazon River at Óbidos (232–239 µg L⁻¹; Devol et al. 1991, Lewis et al. 1995), 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. The composition of the TP pool in the Madeira River was similar to that reported for the Amazon River (Devol et al. 1991, Richey and Victoria 1993), however, with 80% of P being linked to particles and 10% occurring as SRP. The particulate P is mostly Andean-derived because Andean headwaters are the main sources of suspended sediments to Amazonian whitewater rivers (Devol et al. 1995). This source is evident when concentrations of TP in the Madeira River are compared to TP concentrations in the Jamari River, the largest clearwater tributary near our sampling stretch. The concentration of TP in the Jamari River averages 32 µg L⁻¹ (Ecology and Environment do Brasil, unpubl. data), almost one order of magnitude below the Madeira average.

Although our results indicate substantial amounts of P in the Madeira River, our findings are likely conservative because particulate P concentrations may be underestimated by the persulfate digestion method according to a study in Amazonian turbid waters (Engle and Sarnelle 1990). Nevertheless, because our results are close to those reported for Amazonian whitewater rivers (e.g., Devol et al. 1991, Lewis et al. 1995), it is unlikely that applying the persulfate digestion method resulted in substantial underestimation.
Andean headwaters are considered the main source of suspended sediments to whitewater rivers (e.g., Devol et al. 1995, McClain and Naiman 2008), and 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 (Espinoza Villar et al. 2009). The peak of P concentrations before water discharge suggests 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, TP concentrations are substantially lower than at a similar discharge during rising water (Fig. 4) because sediment and associated P input has been exhausted. The existence of much higher concentrations on the rising limb of the hydrograph when compared to similar flows on the falling limb suggests that a clockwise hysteresis may exist (Steegen et al. 2000), although 4 data points per year may be too few to infer a hysteresis effect from a discharge–concentration plot. These findings have 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. The Madeira River did not meet this qualification, however, justifying our use of a discharge-weighted method for load calculation.

The prevalence of particulate P, which is likely strongly adsorbed to iron and aluminum oxide surfaces (Berner and Rao 1994), 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). The amount of potentially bioavailable P in the water may be underestimated, however, considering that SRP can reversibly sorb onto the surfaces of mineral particles, especially in rivers with high concentrations of suspended sediments such as the Madeira (Mueller et al. 2006). Accordingly, a previous study showed that 16–38% of the algal-available P in the whitewater 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, although the particulate P fraction is dominant, significant biological uptake of P from the particulate fraction is likely.

Potential responses to precipitation change and damming

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 2000 m a.s.l. in the eastern slopes of the Andes are projected to experience a significant increase in precipitation by 2100 (Urrutia and Vuille 2009). Annual increases may reach up to 400 mm yr⁻¹ at altitudes between 1000 and 2000 m. Maximum precipitation is registered at these altitudes (Espinoza Villar et al. 2009), and hence P erosion and entrainment into rivers is probably maximum as well. Because our results and previous studies (e.g., Devol et al. 1995) suggest that precipitation in the upper basin is positively correlated to TP 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 low energy generation capacities. The projected 270% increase in the number of dams in the Madeira River and some of its Andean tributaries within the next 2 decades (Finer and Jenkins 2012), however, may result in a great increase in sedimentation. Globally, >50% of the flux of suspended sediments in regulated basins is lost due to trapping in reservoirs (Vörösmarty et al. 2003). In places with a high density of hydropower dams, such as Asia, the transport of suspended sediments from the larger rivers has declined by >75% (Gupta et al. 2012). Considering the particulate P accounting for 80% of TP 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% compared to pre-dam conditions (Yang et al. 2005), which led to a 77% reduction in TP 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), evidence from other regulated rivers suggests that P trapping behind dams built in Amazonian whitewater rivers will likely be substantial and should be a major ecological concern.
To our knowledge, this is the first seasonal assessment of loads and concentrations of P in the Madeira River, information that is crucial to understanding 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 previous findings 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 hypothesis is consistent with observations for worldwide rivers; although sediment yield due to soil erosion displays an increasing trend, sediment fluxes from world rivers display a declining trend due to retention in reservoirs (Syvitski et al. 2005). The upper mineral layer of várzea soils is about 6 times more enriched in P than that of igapós, resulting in a net primary production up to 50% higher in várzea flooded forests (Worbes 1997). In addition, evidence indicates 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 whitewater rivers rise and provide nutrients to the várzeas (Piedade et al. 2001). In contrast, because of high P to nitrogen ratios, nitrogen, not P, may be the controlling nutrient to primary producers, as observed on the Orinoco floodplain (Lewis et al. 2000), but this is not known for the Madeira floodplain.

Although estimates of how much P transport could be reduced by damming are poorly constrained and the extent to which floodplains are P-limited is uncertain, the proliferation of dams in the upper basin will likely have detrimental effects on the P transport to lowland ecosystems. This supposition may also be valid for other Amazonian rivers originating in the Andes, including the Amazon main stem, considering that more than 150 dams are planned in the Andean Amazon within the next 2 decades (Finer and Jenkins 2012). Based on the radical decreases in the growth rates of downstream wetlands observed in response to nutrient retention behind dams in other parts of the world (Yang et al. 2005), we suggest that, in the long term, the combined effect of building several Andean dams will potentially affect downstream primary production in lowland Amazon floodplains.

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