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Articles

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Suspended sediments and organic matter in mountain headwaters of the Amazon River: Results from a 1-year time series study in the central Peruvian Andes

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Abstract

Few studies have examined the dynamics of sediments and suspended organic matter and their export from headwater basins in the Andes Mountains to the Amazon River, despite the fact that the Andes are the primary source of sediments to the lower Amazon basin. We measured river discharge as well as the concentration, $\delta^{15}N$, $\delta^{13}C$, %N, and %OC of coarse and fine suspended sediments (CSS and FSS) in the Chorobamba River, located in the central Andean Amazon of Peru. Samples were taken at least weekly over an entire year (July 2004–July 2005), with additional sampling during storms. Concentrations of particulate organic matter (POM) were generally low in the study river, with concentrations increasing by up to several orders of magnitude during episodic rain events. Because both overall flow volumes and POM concentrations increased under stormflow conditions, the export of POM was enhanced multiplicatively during these events. We estimated that a minimum of 80% of annual suspended sediment transfer occurred during only about 10 days of the year, also accounting for 74% of particulate organic carbon and 64% of particulate organic nitrogen transport. Significant differences occurred between seasons (wet and dry) for $\delta^{13}C$ of coarse and fine POM in the Chorobamba River, reflecting seasonal changes in organic matter sources. The time series data indicate that this Andean river exports approximately equal amounts of fine and coarse POM to the lower Amazon. The observation that the vast majority of sediments and associated OM exported from Andean rivers is mobilized during short, infrequent storm events and landslides has important implications for our understanding of Amazon geochemistry, especially in the face of incipient global change.
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1. INTRODUCTION

Mountain streams form the headwaters of all of the Earth's major river basins and act as a critical first stage in biogeochemical cycles controlling downstream processes. Rivers flowing from young tropical mountain ranges are especially important due to the convergence of high rainfall, dense forests, and accelerated weathering regimes. On a global scale, rivers draining tropical mountains deliver the greatest loads of sediments and associated organic matter and nutrients to the ocean (Milliman and Meade, 1983). At the same time, tropical mountain rivers remain some of the least studied, yet most highly vulnerable aquatic ecosystems on Earth. Climate change, deforestation, impoundments, and mining have brought tremendous and

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accelerating change to these systems (Beniston, 2003; Harden, 2006; Wohl, 2006; Vanacker et al., 2007). The hydrological importance of tropical montane rivers is undisputed (Viviroli and Weingartner, 2004 and references therein).

Investigators have postulated that the eastern Andes are a source of particulate organic carbon (OC) to the Amazon (Richey et al., 1990; Quay et al., 1992; Hedges et al., 1994, 2000), but studies conducted in the Andean headwaters have had insufficient spatial and temporal coverage to definitively prove or disprove this (McClain et al., 1995; Townsend-Small et al., 2005, 2007). Although a connection between sediment loading, OC content of sediments, and storm events has been postulated for rivers in the Andean Amazon (Townsend-Small et al., 2005), no explicit relationship has been shown because previous studies have been conducted at short time scales. Physical processes such as erosion occurring in montane watersheds exert significant control over POC composition and concentration (Blair et al., 2004). The percent of OC in suspended sediments decreases during high sediment loading events (Meybeck, 1982; Devol and Hedges, 2001; Mayorga and Aufdenkampe, 2002; Coynel et al., 2005), because events such as storms or landslides change the relative amounts of soil minerals, organic matter (OM), and leaf litter delivered to rivers (Blair et al., 2004). In general, particulate OM is less dense than other suspended sediment fractions such as minerals; consequently, OM may contribute a larger component of total suspended sediments (TSS) during base flow (Mayorga and Aufdenkampe, 2002).

Despite the decrease in %OC with increasing sediment concentration, in most mountainous rivers the bulk of C and N inputs from the landscape occur during floods associated with high sediment loading, induced either by storms or snowmelt. In the mountainous Santa Clara River basin (California, USA), a major storm resulted in increased suspended POC concentration derived from deep soil horizons and ancient bedrock, whereas, younger, fresher soils were preferentially transported during low flow (Masiello and Druffel, 2001). In Puerto Rico, increases in stream discharge were associated with increases in suspended sediment, POC, PON, and dissolved OC concentrations (McDowell and Asbury, 1994). However, the specific effects of storm or landslide events on POM concentration or composition in rivers in the Andean Amazon have not been defined.

In order to determine flow-dependent discharges of POM from the Andes and the provenance of transported POM, we conducted a 1-year time series study in the Pachitea Basin of Peru. We gauged river discharge and measured the concentration (fine and coarse suspended sediment [FSS and CSS]) and organic composition ($\delta^{13}C$, $\delta^{15}N$, %OC, %N) of suspended sediments on a weekly and event-based time frame.

2. METHODS

2.1. Study area

The study was conducted in the vicinity of Oxapampa, Peru (10.57°S, 75.40°W; approximately 1800 m above sea level [masl]), located in central Peru on the eastern flanks of the Andes in the Amazon headwaters (Fig. 1). The study site is located in the Pachitea River Basin, which discharges into the Ucayali River just upstream of the city of Pucallpa, Peru. The Chorobamba watershed is about 337 km^2 in area and ranges from approximately 4000 masl at the headwaters to about 1800 masl where the river was sampled. Over most of this elevation range, the river flows through incised river valleys in steep canyons covered by montane tropical forest. Landslides are very common in the area and a major contributor of sediments to the channel. At approximately 2000 masl the valleys open up and the river begins to meander across broad valley bottoms, but at the sampling point, the gradient is still steep, the river is fast and follows a single, straight channel most of the time. The riverbed in the Oxapampa area is characterized by sand and rocks, with no major areas of fine sediment deposition, which are characteristic of the lower Amazon basin (Mertes et al., 1996; Dunne et al., 1998). In short, the Chorobamba basin is similar to many described in the Bolivian Amazon: purely erosive with no visible significant sinks of sediment, and above the foreland basins that trap sediment before rivers discharge from the Andes to the Amazon (Safran et al., 2005; Aalto et al., 2006).

The climate in the Peruvian Andes is generally wet in the austral summer months (October through March) and dry in the winter (April through September) (Fig. 2). Because of this seasonal fluctuation, river discharge is greatest in the summer and lowest in winter. The total rainfall at the sampling point over the study period was 1570 mm (Fig. 2). However, it should be noted that this measurement does not represent total rainfall in the watershed, as we have observed that storms are very localized and can range from short and intense to long periods of steady rain. Unfortunately there are no other rain gauges in the watershed, thus we have no information about localized storm event duration or intensity in subwatersheds, which could be major contributors to high discharge/high sediment loading events.

2.2. Sample collection

The river was sampled for suspended particles every Wednesday for one year, from July 20, 2004 through July 21, 2005. Additional samples were collected during high flow events. River water was collected in rinsed 1 L HDPE wide mouth Nalgene bottles and transported back to the field station in Oxapampa (~1 km from sampling site) for immediate processing. A known volume of water was first passed through pre-weighed 60 μm nylon mesh filters (Millipore) to collect coarse suspended sediments (CSS). The filtrate was passed through pre-combusted, pre-weighed glass fiber filters (Whatman GF/F), with a pore size of about 0.7 μm: this fraction was defined as fine suspended sediment (FSS). Filters were dried for 48 h at 60 °C, weighed to determine sediment mass, and stored in tight-fitting plastic Petri dishes until they could be analyzed for chemical composition.

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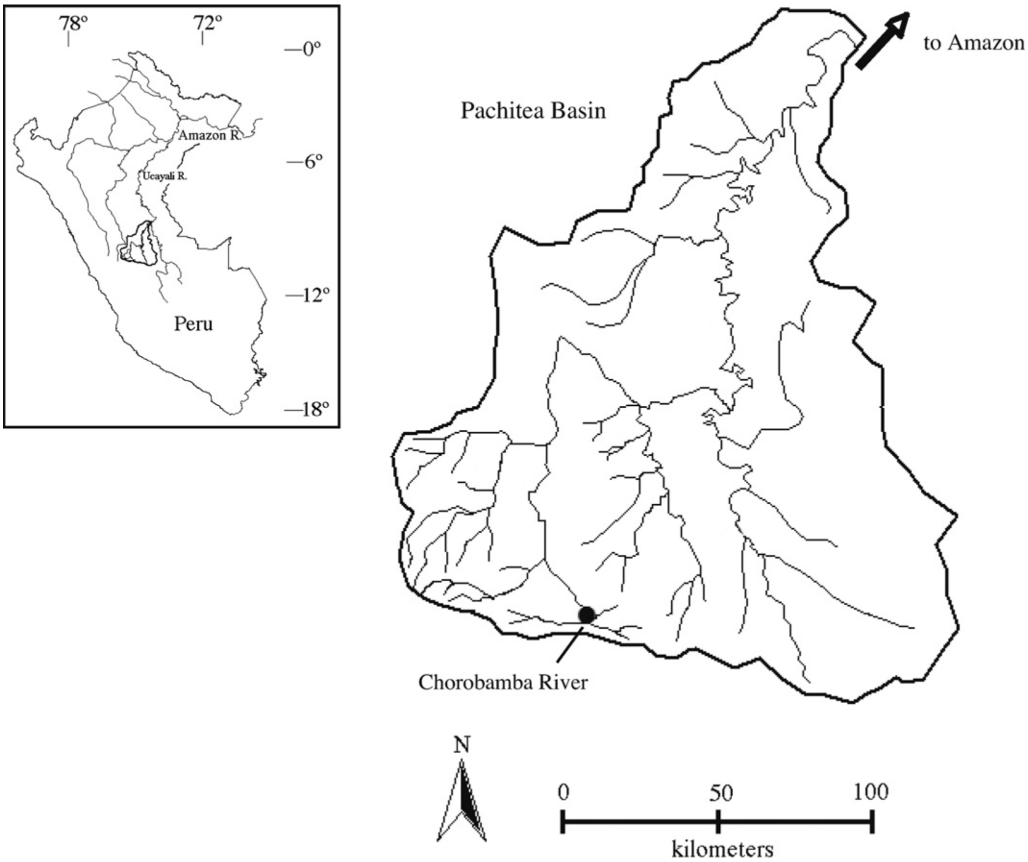

Fig. 1. Map of the study region. Map on right shows the location of the study area within Peru.

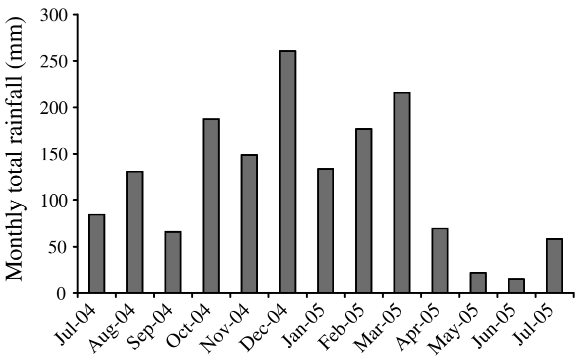

Fig. 2. Monthly rainfall amounts during the study period, as recorded at the Andean Amazon Research Station in Oxapampa.

2.3. Sample analysis

Stable isotopic and elemental composition ($\delta^{13}C$, $\delta^{15}N$, %OC, and %N) of suspended sediments was determined with a Carlo Erba NC 1500 elemental analyzer coupled to a Finnegan MAT DELTA plus continuous-flow isotope ratio mass spectrometer. Carbonates were removed from soils and sediments prior to $\delta^{13}C$ analysis by vapor-phase acidification with HCl for 24 h, followed by drying at 60 °C for 24 h. Coarse particulates were transferred onto glass fiber filters prior to analysis. All results were corrected for the filter blank.

2.4. River discharge and precipitation measurements

River discharge measurements and rainfall amounts are from Noguera (2007). Briefly, river stage was measured twice daily at the Chorobamba River and converted to discharge using a rating curve that was checked monthly for proper calibration. Rainfall was measured at the Andean Amazon Research Station in Oxapampa using a RainWise™ digital rain gauge.

2.5. Flux modeling

Previous, similar studies have relied on relationships between river constituents and discharge to evaluate daily sediment loads (e.g., Dalzell et al., 2007). In the Chorobamba, the relationship between suspended OM concentration and discharge is weak (Fig. 3) due to an unpredictable response of suspended sediments and organic matter to changes in discharge, such that a regression model based on the relationship between TSS and river discharge tended to greatly underestimate storm POM concentrations (Fig. 4A and B). To calculate fluxes of sediment, POC and PON in this system, we devised a simple quantitative model to predict daily concentrations. Our model used measured data when available, and repeated these measured concentrations on successive days until the next sample was taken. Storm concentrations were treated slightly differently. In this mod-

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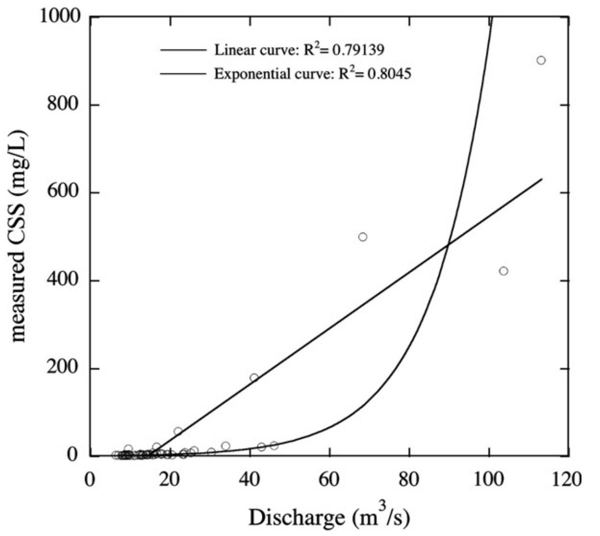

Fig. 3. Example of relationship between river constituents (CSS) and discharge.

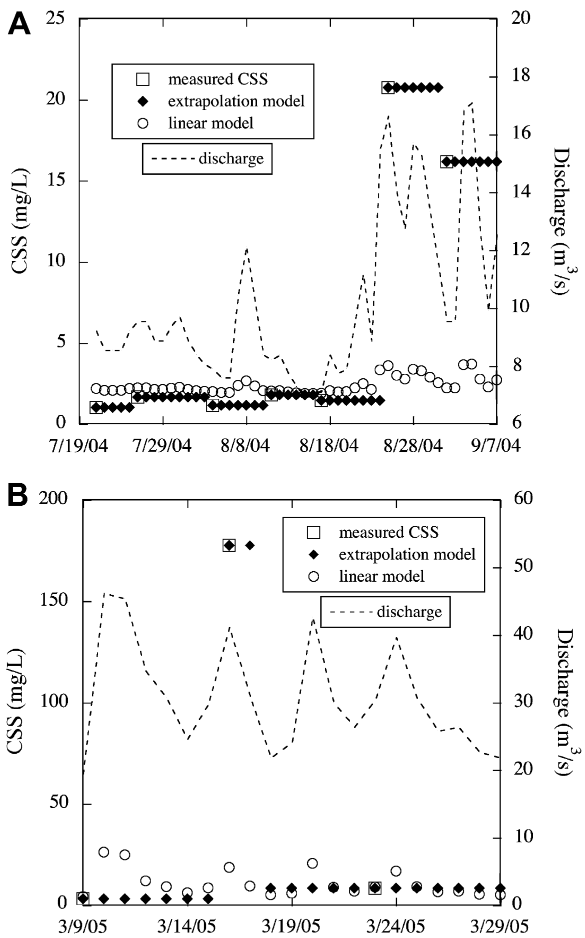

Fig. 4. Examples (using CSS) of two kinds of models used to calculate annual suspended sediment and organic matter loads in the Chorobamba River, shown with measured CSS concentrations and river discharge. The "extrapolation model" was chosen for use in the study. (A) Compares the two models during low water conditions and (B) during a storm event.

el, a storm occurred when the river discharge increased by more than 25% in one day and a sediment sample was taken on the same day. During the study period a total of five such storms occurred. For modeling purposes, storm sediment concentrations were repeated for 2 days (1 day after the event), with the sediment concentration from the next normal sampling day covering the days between the storm and the next sampling day. An example of this "extrapolation model" as compared to measured concentrations and a linear regression model is shown in Fig. 4A and B.

3. RESULTS

3.1. Relationship of constituents with discharge

As expected, river discharge was generally higher during the summer months, when rainfall was also highest (Fig. 2). River discharge increased by about a factor of 10 from the driest conditions to the largest storm events (Fig. 5). Concentrations of both coarse and fine suspended sediment were generally very low (<10 mg/L) throughout the study period, except during elevated discharge events (Fig. 5A), when concentrations often exceeded 100 mg/L. Concentrations of fine and coarse suspended sediment were consistently similar. Increases in river discharge during storms were also associated with increases in both coarse and fine POC (Fig. 5B) and PON (Fig. 5C).

Despite higher average river discharge observed in the rainy season, the concentration of suspended materials remained low. Concentrations became elevated during isolated storm events. Of the total estimated annual sediment load of the Chorobamba River for the study year, 81% was observed during these five storm events (85% of total CSS, 78% of total FSS; Table 2). Because of the decrease in %C and %N of suspended organic matter with increasing TSS concentration (e.g., Meybeck, 1982), storm events accounted for a slightly reduced proportion of total POM export as compared to TSS, but still accounted for 74% and 64% of the observed POC and PON exports, respectively, from the system (Table 2).

3.2. Seasonal variation in organic composition

The $\delta^{13}C$ of fine and coarse suspended sediment varied significantly with season (Figs. 4B and 6A, and Table 1). In both size classes, the $\delta^{13}C$ of POC was higher in the dry season (April–September). There was also a difference in annual average $\delta^{13}C$ of FPON vs. CPON. The average $\delta^{13}C$ (±standard deviation) of FPOC was -25.3 ± 0.7‰, significantly higher than the average for CPOC (-25.9 ± 1.5‰; $p = 0.03$). In April–June 2005, GF/F filters coated with a plastic binding resin were inadvertently used to sample fine suspended sediments. This resulted in a $\delta^{13}C$ value that could not be corrected for the filter blank (Fig. 4A), although it did not affect $\delta^{15}N$, %N, or %C (after correction).

The $\delta^{15}N$ of fine and coarse POM did not vary significantly with time of year (Figs. 5B and 7A). However, there was a significant difference in $\delta^{15}N$ with size class of suspended sediments. The average $\delta^{15}N$ (±standard deviation)

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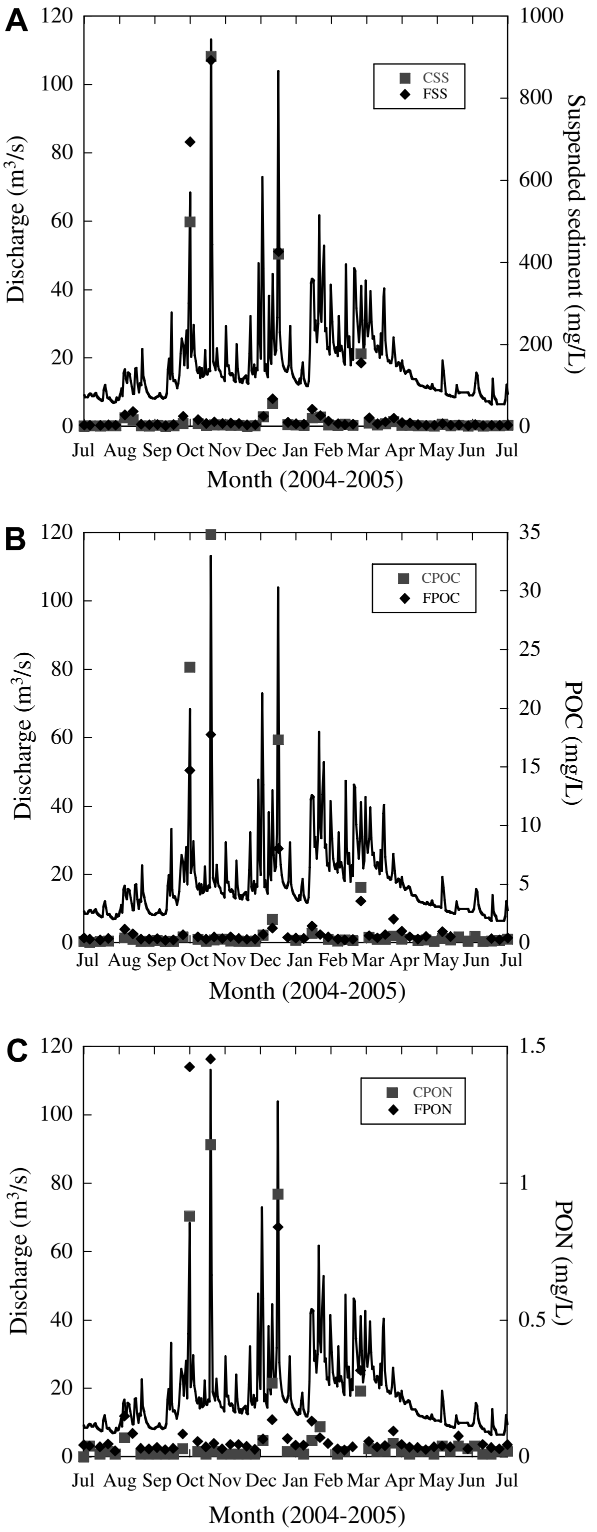

Fig. 5. River discharge in the Chorobamba River superimposed with concentrations of coarse and fine suspended sediment concentration (CSS and FSS; A), coarse and fine particulate organic carbon (CPOC and FPOC; B), and coarse and fine particulate organic nitrogen (CPON and FPON; C).

of FPON was 4.8 ± 1.1‰ as compared to 3.4 ± 1.2‰ for CPON ($p = 4.7 \times 10^{-8}$). In Figs. 6 and 7, shaded lines represent values observed during previous studies of organic composition of sediments in the Chorobamba River. Data from July 2002 are derived from Townsend-Small et al. (2005), while those from July 2004 are from Townsend-Small et al. (2007). In the study conducted during July 2002, $\delta^{15}N$ of CPOM was not measured.

4. DISCUSSION

Our results suggest that river systems in the Andean headwaters of the Amazon exhibit vastly different physical and biogeochemical properties than their lowland Amazon counterparts. The discharge hydrograph observed in the Chorobamba River is quite unlike that observed in the Amazon mainstem (Devol et al., 1995), which is regular and dampened. In small Andean rivers, gradual seasonal patterns in discharge are punctuated by spikes in flow during storm events, similar to other small mountain rivers (e.g., Masiello and Druffel, 2001; Dadson et al., 2005; Restrepo et al., 2006; and reviewed in Viviroli and Weingartner, 2004). Also unlike the mainstem Amazon (Devol et al., 1995), in Andean rivers neither FSS nor CSS show a regular seasonal concentration pattern (Fig. 5). These observations have major implications for our understanding of sediment and associated OM transport from the Andes to the lowland Amazon. Because the Andes are the major source of sediments to the Amazon (Gibbs, 1967), it was assumed that most of these sediments are transported during the rainy summer months (Devol et al., 1995). On a basin-wide scale this is true, but the integrated pattern consists of large short-term pulses. In the Chorobamba River, most sediments are transported during discrete storm events rather than distributed evenly over the entire season: sediment concentration in our study river decreases rapidly following each storm event, and average sediment concentrations are similar between the dry and wet seasons (not including storms, which are more frequent in the wet season).

The low median concentrations of CSS and FSS presented here indicate that, overall, these Andean rivers fall into the category defined by Meybeck (1982) as "less turbid" (5 < TSS < 5000 mg/L). The fact that Andean Amazon rivers are essentially clear during the majority of the year, with high turbidity occurring only rarely, indicates that lowland extensions of these Andean rivers must resuspend deposited sediment lower in the basin in order to consistently supply sediment to the mainstem Amazon (Aalto et al., 2003, 2006). This is reinforced with an examination of the distribution of sediment size classes. In the Chorobamba, patterns of CSS concentration are similar to those observed for FSS, and there is no significant difference between average annual FSS and CSS concentrations (Fig. 5, $p = 0.8$). This result is in contrast to observations in the lower Amazon (Devol et al., 1995), and also in other tributaries (Hedges et al., 2000; Bernardes et al., 2004), where CSS is generally lower than FSS. Andean rivers may supply similar proportions of coarse and fine sediment to the base of the mountains, but when combined with results from the Amazon mainstem (Devol et al., 1995), our results indicate that fine sediments are preferentially transported down-

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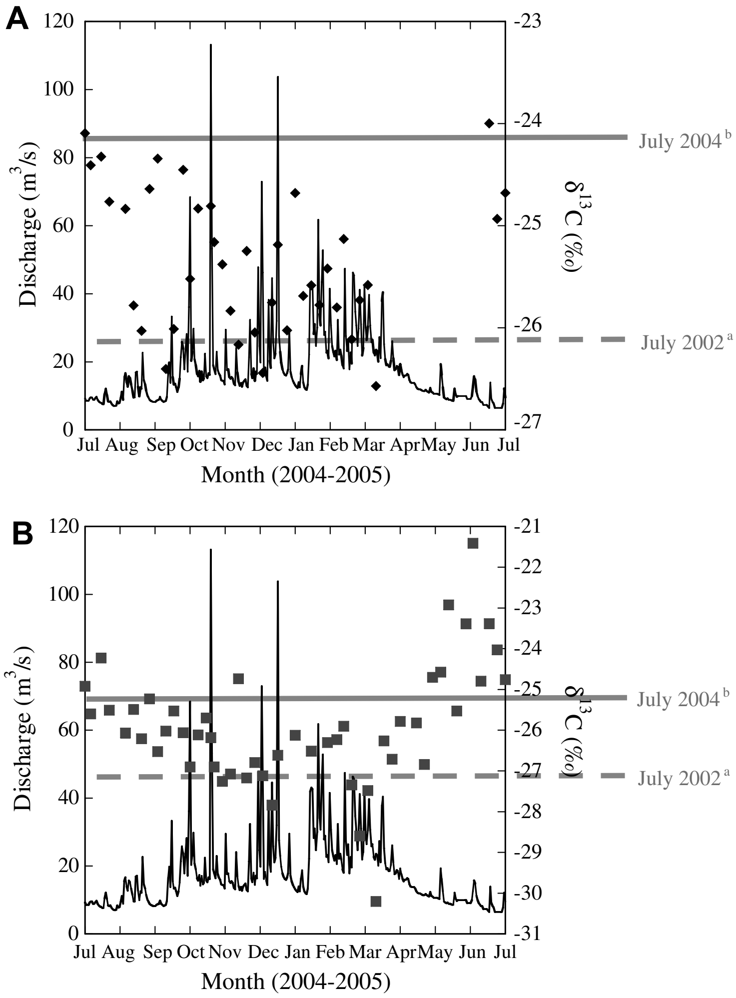

Fig. 6. Carbon stable isotopic composition ($\delta^{13}C$) of fine (A) and coarse (B) particulate organic carbon. Also shown are the same data observed in the Chorobamba region during previous studies (Townsend-Small et al., 2005, 2007).

Table 1
Measured parameters for which there is a significant difference in means (at the 95% confidence interval) between the dry and wet seasons (April though September, and October through March, respectively)

	Chorobamba
Discharge	*
CSS	*
FSS	*
$\delta^{15}N_{CSS}$	
$\%N_{CSS}$	**
$\delta^{13}C_{CSS}$	**
$\%OC_{CSS}$	**
$\delta^{15}N_{FSS}$	
$\%N_{FSS}$	**
$\delta^{13}C_{FSS}$	**
$\%OC_{FSS}$	**

The difference between means was assessed using Tukey's honestly significant difference test. Blank, no seasonal difference.
*Wet season is higher than dry season.
**Dry season is higher than wet season.

stream whereas coarse sediments are more or less permanently retained in the Andean foreland.

According to our calculations, the vast majority of TSS, POC, and PON export from the Chorobamba occurs during less than 3% of the year (Table 2), similar to other mountain river systems (Milliman and Syvitski, 1992; Milliman, 1995; Farnsworth and Milliman, 2003). The tight coupling between storms and sediment export has important implications for planning of future studies in the region, and casts results of prior research in a new light. While "snapshot" studies of organic composition of riverine material (e.g., Townsend-Small et al., 2005, 2007) have led to important biogeochemical findings in the region, the current study suggests that future studies should focus on sediment and OM dynamics during storm events, which likely link the Andes to the Amazon. For example, it is still unknown exactly what conditions are necessary to cause these mass transfers of sediment and OM from the landscape to rivers, as our data show that increases in river discharge do not always cause an increase in POM (Fig. 5). We need more information on the hydroclimatology of the re-

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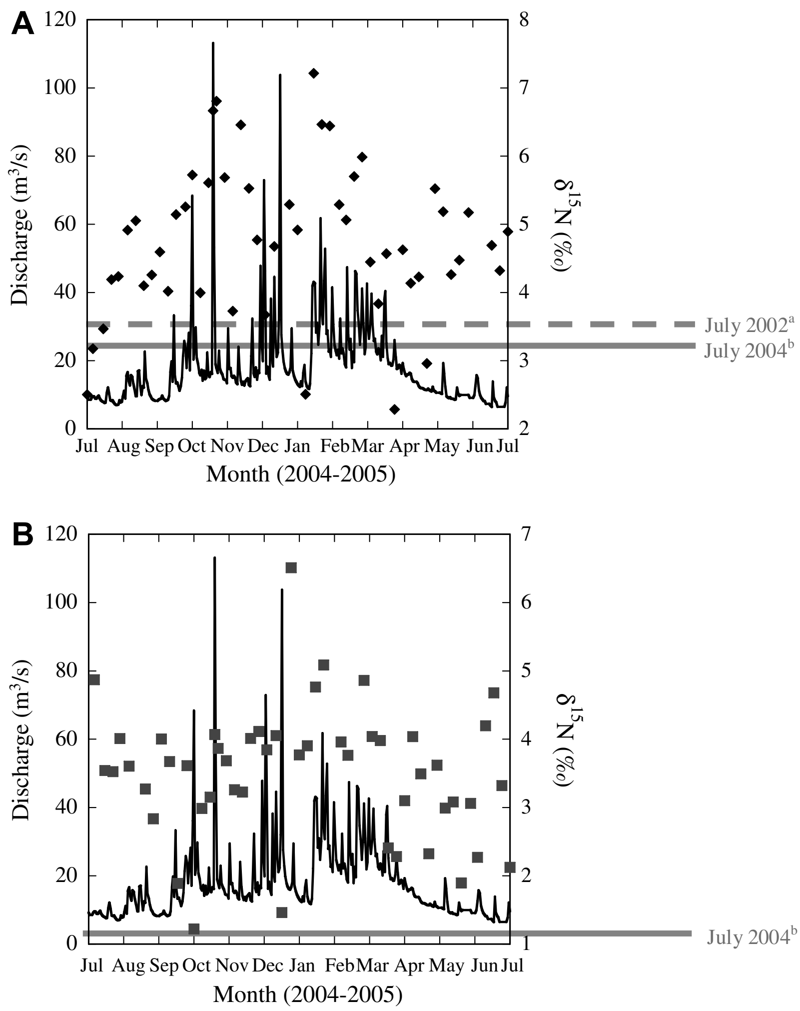

Fig. 7. Nitrogen stable isotopic composition ($\delta^{15}N$) of fine (A) and coarse (B) particulate organic nitrogen. Also shown are the same data observed in the Chorobamba region during previous studies (Townsend-Small et al., 2005, 2007).

Table 2
Percent of total suspended sediment and OC and N in suspension in the Chorobamba River during five 2-day storm events (or 2.7% of the study period) from July 20, 2004 through July 21, 2005

	Total	Coarse	Fine
TSS	81	85	78
POC	74	83	62
PON	64	68	61

gion in order to specifically link storm events to high suspended sediment concentrations. Also, more studies are needed on the impact of deforestation on sediment erosion in such high relief, naturally erodible basins.

The short time frame of sediment and POM loading to Andean rivers also has implications for Amazon biogeochemistry in the face of global climate change. If Amazonian deforestation and climate change lead to a decrease in rainfall in the Andean Amazon, as predicted by some climate models (Avissar and Werth, 2005; Chagnon and Bras, 2005), sediment transfer from the Andes to the Amazon will decrease. In five years of river monitoring at the Andean Amazon Research Station in Oxapampa (2001–2005), annual rainfall has decreased each year (Noguera, 2007). From 2003 to 2005, annual water discharge in the Chorobamba River decreased from 762 to 517 km^3 (a decrease of 32%), and sediment yield in the Chorobamba basin decreased as well, from 626 to 119 tons km^{-2} yr^{-1} (a decrease of 81%) (Noguera, 2007). For reference, the average sediment yield for the entire Amazon basin is 203 tons km^{-2} yr^{-1} (Ludwig and Probst, 1998). This has one important implication for our conclusions: we do not know if storm events would cause such a high proportion of sediment loading in a year with more consistent rainfall. However, if Andean precipitation and river discharge continue to decrease, so will sediment and associated OM export to the Amazon River. This is important because POM from upstream fuels Amazon food webs and provides substrate for soil formation in floodplain areas, and because the Amazon is a major source of terrestrial OC to the oceans (Richey et al., 1980).

Isotopic and elemental data as well as visual observation of the area indicate that suspended sediments in the Chor-

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obamba River are derived from soil erosion from the surrounding hillsides during storm events, and from localized channel erosion and/or resuspension during low flow. More information about the processes that influence the geochemistry and source of suspended particles in Andean rivers can be gleaned from seasonal differences in concentrations and chemical composition of FSS and CSS. A significant difference (at the 95% confidence level) was observed between the wet and dry seasons (October through March and April through September, respectively) for most of the measured parameters in the study river (Table 1). In almost all cases, the $\delta^{13}C$ of both FPOM and CPOM is significantly higher in the dry season than in the wet season. In contrast, there is no consistent seasonal offset of ^{15}N in either fraction. This corroborates our previous results from the region, where $\delta^{13}C$ observed during July of 2002 was about 2‰ less enriched than that observed during July of 2004. The 2002 sampling season was very wet, while 2004 was much drier. There are significant seasonal differences in the relative amounts of OC and N in each size fraction of organic matter as well (Table 1). The obvious decrease in OM content of suspended sediment in the wet season indicates that these sediments may be derived from mineral soils, whereas dry season sediments (with higher OM content) may be derived from surface soils. These seasonal differences may also be due to changes in sediment sources and hence surface area of suspended minerals, which would affect the degree of DOM sorption to suspended minerals, thought to be a major source of POM in the Peruvian Amazon (Aufdenkampe et al., 2001, 2007).

5. CONCLUSIONS

This study provides insight into temporal variations in C and N cycling in rivers of the Amazon headwaters, and supplies new information about mechanisms of sediment and associated OM transport from small headwater rivers in the Andean Amazon. Sediment concentrations in Andean rivers depend on storm events: outside of these events TSS concentrations are very low. Thus sediment transport to the lower Amazon is highly episodic, despite the fact that TSS concentrations in lowland Amazon tributaries are consistent throughout the year. Concentrations of coarse and fine sediments and CPOC and FPOC are similar, indicating that the Andes of central Peru supply equal quantities of each size fraction to the lower basin. There was a clear difference in isotopic composition of sediments in the dry and wet seasons, indicating a seasonal shift in the source of POC to Andean rivers. The dependence of sediment and POM on precipitation events indicates that imminent changes in local climate may have significant impacts on the quantity and quality of OM transport to the Amazon River.

The time series data emphasize the multiplicative nature of Andean rivers. During the majority of the year, river discharge and concentrations of suspended material are low, but under certain conditions, at some critical level of rainfall or storm intensity, a threshold is crossed, leading to exponential increases in POM export. The exact mechanism that leads to such high variability in sediment export patterns is unknown, but it is likely tied to massive movement of terrestrial soils during storms, or landslides. Spatial variability in tropical rainfall events and land cover also likely play a role in determining the response of riverine sediment concentration to increases in river discharge. Rain that falls on cleared land is more likely to cause mass wasting of soils, whereas forested areas are better able to retain sediments. More research on the response of Andean catchments to precipitation and deforestation is needed to understand the export of material from tropical mountain rivers.

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