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INORGANIC COMPOSITION OF SUSPENDED SEDIMENTS IN THE ACRE RIVER, AMAZON BASIN, BRAZIL

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Abstract: The purpose of this study was to determine the chemical and mineralogical composition of suspended sediments from the Acre River, located in the Purus Basin, upper Amazon basin, a region associated with the Fitzcarrald Arch. The elemental and mineralogical compositions of the sediments were assessed by using mass and atomic spectroscopy, and X-ray diffraction. A total of 46 samples were collected between 2008 and 2011 from four sites in the study area during wet and dry seasons. The suspended sediments contained feldspar, kaolinite, illite and quartz as well as the elements Hg, Zn, V, Ti, Si, Pb, Ni, Na, Mn, Mg, K, Fe, Cu, Cr, Cd, Ca, Al, S, and P in different proportions that were associated with the various weathering reactions linked to physical, chemical and biological processes in the region. The obtained results represent the first set of values and relationships regarding the mineralogy and chemical identification of the suspended sediments in the Acre River and can be used as a reference for the geochemical characteristics of the Purus Basin. Such regional studies will become increasingly necessary to observe the impacts of climate change and human activities on the suspended sediment load and composition of the Amazon River.

Keywords: chemistry of sediments, Amazon Basin, Acre River Basin.

INTRODUCTION

The Amazon River flows from the Andean Mountains to the Atlantic Ocean. The Amazon rainforest is the largest hydrographic basin in the world and has been described in terms of its dimension, biodiversity, floods, droughts, rainfall variability (Villar *et al.*, 2009) and projected climate change (Chen *et al.*, 2010; Fekete *et al.*, 2010; Salazar and Nobre, 2010). Suspended sediment (SS) composition and flux (Bouchez *et al.*, 2011), as well as water quality are highly important for ecological equilibrium (Berry *et al.*, 2003), which involves aquatic, terrestrial, atmospheric, oceanic and estuarine interactions.

The drainage area of the Amazon basin is $6.4 \cdot 10^6$ km^2 (Filho, 2005), and that of the Purus basin is 370,000 km^2 (Paiva and Collischonn, 2012). The Purus River begins in Peru at an altitude of 400 – 500 m a.s.l. and runs for 3,300 km with a mean water discharge of 10,499 $m^3 s^{-1}$ (ANA, 2011). The drainage area of the Acre River basin covers 35,000 km^2, and its discharge varies between 30 and 1,200 $m^3 s^{-1}$.

The Acre River basin is affected by forest fires, logging, agriculture and cattle production, which are the principal branches of the local economy. The annual average rainfall in the region is 1,956 ± 223 mm, according to 1971 – 2000 climatology (Duarte, 2006). The climate of the Amazon is characterized by the occurrence of two principal meteorological systems: the Intertropical Convergence Zone (ITCZ)

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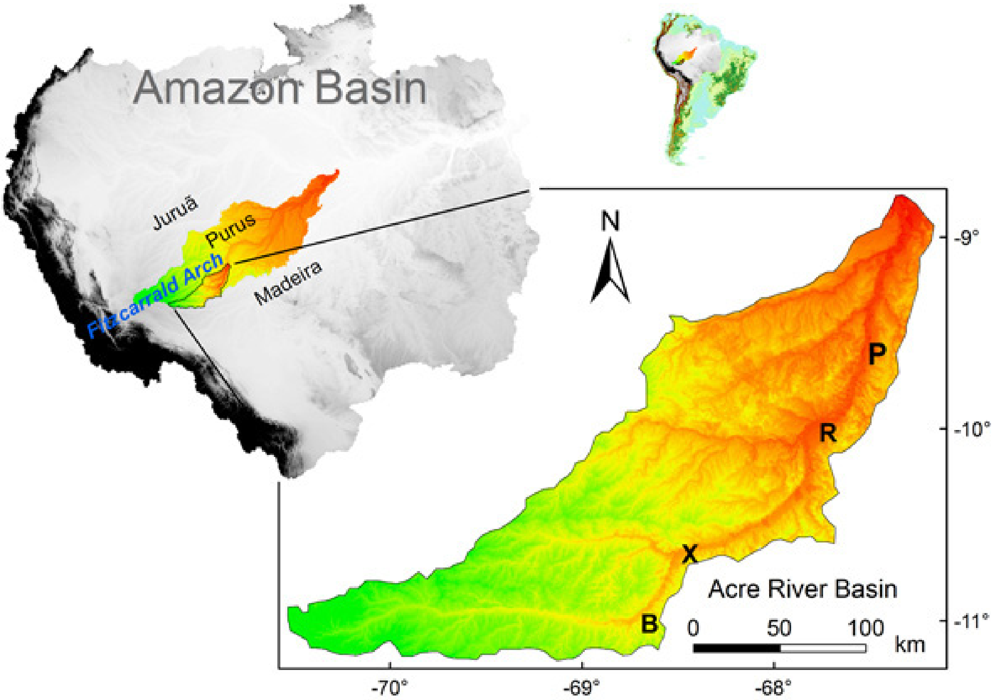

Figure 1. Map of the Amazon basin showing the Fitzcarrald Arch, Solimões (Juruá, Purus) and Madeira basins. Inset: Acre River basin is shown in detail. B, X, P, R refers to the sampling location: Brasileia (B, 11°1.4' S; 68°44.0' W), Xapuri (X, 10°38.9' S; 68°30.4' W), Rio Branco (R, 9°58.7' S; 67°48.4' W) and Porto Acre (P, 9°34.5' S; 67°31.9' W).

and the South Atlantic Convergence Zone (SACZ), which are modulated by the natural inter-annual variability related to El Niño and La Niña (Pizarro and Montecinos, 2004; Marengo, 2008; Chiessi *et al.*, 2009; Jury, 2009; Meehl *et al.*, 2009).

Townsend-Small *et al.* (2008) attributed the Andean sediment loads (particularly those of organic sediments) to episodic events of heavy rainfall or storms. The mechanical erosion rate and sediment fluxes due to weathering are related to precipitation, runoff, temperature, winds, humidity, basin morphology and other climatic and physical influences (Hurtrez *et al.*, 1999; Gartner *et al.*, 2008; Zoccatelli *et al.*, 2011; Govin *et al.*, 2012). Persson (2008) confirmed that as a general rule, sediment samples increase in roundness, sphericity and quartz content downstream from the Andes.

Elements such as Si, Mg, Fe, Al, Ca, Ti, and K are found in river bed and in the suspended sediment in different proportions (Mcdonough, 2000; Govin *et al.*, 2012), depending on geographical distribution and redistribution factors, such as geological formations, parental rocks, mineralogy, soils, topography, land use, land cover, climate and climate change (Zhang *et al.*, 1999; Liu *et al.*, 2007; Yoshikawa *et al.*, 2008; Wang *et al.*, 2011). Biomass burning, deforestation and fertilization produce materials entering the river system and contributing to the composition of the suspended sediment (Zhang *et al.*, 1999; Druffel *et al.*, 2005; Figueiredo *et al.*, 2010). In the upper Amazon basin and particularly in the Madeira basin, gold-mining operations release large quantities of Hg into the atmosphere, water and soils (Diaz, 2000; Maurice-Bourgoin *et al.*, 2000; Fillion *et al.*, 2006). Furthermore, the transport of particulate matter via rivers could be altered by dam constructions in the Amazon basin (Kemenes *et al.*, 2012).

The Acre River originates in Peru, then delimits Peru, Bolivia and Brazil and runs through the State of Acre to join the Purus River, which is the main river that drains the Fitzcarrald Arch (Fig. 1). Riverbank-erosion processes, transport and deposition of sediment in the floodplains and sediment re-entrance in the river flux play fundamental roles in the geochemistry of suspended matter due to the structural dynamics of the region. According to Guyot *et al.* (2007), most of the suspended sediment originates in the Andes Mountains and crosses the Amazon floodplains before reaching the Atlantic Ocean. The geological formation of the Purus basin corresponds to the Cenozoic Solimôes (sub-Andean trough and Andean foreland in Central Amazon). Thus, in this region, the mineralogical and chemical composition of the SS should have common characteristics. The SS particularities are better established for Solimões and Madeira Rivers than for the Purus River; therefore, the objective of the present paper was to determine the SS load, seasonality and, mineralogical and chemical composition of the Acre River (Purus basin) as well as its regional connection.

MATERIALS AND METHODS

The study area comprises the Acre River basin (part of the Purus basin, Fitzcarrald Arch), bordered by the Andean Mountains and the Juruá, Solimôes and Madeira Rivers (Fig. 1). The white waters of the Amazon River begin in the elevated parts of the Fitzcarrald Arch, initiating the erosion processes and high sediment load that muddies the rivers. The study area contains the following classes of soil: cambisols, vertisols, luvisols, acrisols, ferralsols and plinthosols (Amaral, 2003; EMBRAPA, 2006; FAO, 2007). The sampling procedures have been previously described (WMO, 1994). Surface water samples were collected during the wet (rainy) and dry seasons from four sampling sites (Fig. 1): Brasileia, Xapuri, Rio Branco and Porto Acre. The sampling points were located in a well-mixed reach of stream whose width, depth and velocity ranged from 100 to 200 m, 2 to 12 m, and 0.5 to 1.8 m s^{-1}, respectively. Samples were collected with 1-L plastic bottles that were immersed 15 to 30 cm under the water surface. Depth-profiling of SS was not measured. A total of 46 samples were obtained: 25 in the wet season and 21 in the dry season. The sediment yield QS (mega tons per year) was calculated using the following formula:

$$QS\ (Mt\ y^{-1}) = SS\ (g\ l^{-1})\ \ R\ (Gm^3\ y^{-1}) \qquad (1)$$

where: SS is suspended sediment concentration (grams per liter) and R is the integral water discharge (giga cubic meters per year).

The suspended sediment in the river water was dried (50 – 60ºC) for approximately 15 h. Next, the material was homogenized and weighed. The sediments were digested by adding 2.5 mL HNO_3, heating for 5 h at 80ºC and centrifuging. The resultant solution was diluted 5 to 100 times for elemental analysis (Tessier *et al.*, 1979; Gioda *et al.*, 2006; Gioda *et al.*, 2011). The chemical composition of the samples was determined using inductively coupled plasma mass spectroscopy (ICP-MS - Elan 6000, Perkin Elmer, USA) to measure the total Hg level and using inductively coupled plasma optical emission spectrometry (ICP-OES - Optima 4300 DV, Perkin Elmer, USA) for the other elements. Hg was measured as a total because this species is volatile, and certain losses could have occurred between sampling and analysis. For Ti, the acid digestion with HNO_3 was inefficient, extracting approximately 5%. Therefore, for these elements (Hg and Ti), the

	Wet	SS (mg L^{-1})		Dry	SS (mg L^{-1})
P	13/11/08	502	P	11/07/08	501
P	28/11/08	503	P	24/10/08	140
R	30/11/08	500	X	25/10/08	500
P	10/12/08	336	B	25/10/08	210
R	27/12/08	500	R	30/10/08	501
P	20/01/09	500	R	28/05/09	494
X	24/01/09	381	P	06/06/09	122
R	30/01/09	502	R	28/06/09	410
R	25/02/09	375	P	25/07/09	142
P	13/03/09	500	R	30/07/09	415
R	31/03/09	546	P	15/08/09	114
R	29/04/09	507	R	25/08/09	154
R	24/11/09	501	R	28/09/09	149
P	09/12/09	512	P	10/10/09	457
R	23/12/09	551	R	20/10/09	156
R	20/01/10	161	R	20/05/10	77
R	23/02/10	226	R	20/06/10	502
R	22/03/10	437	R	20/07/10	102
R	20/04/10	75	R	20/08/10	92
R	20/11/10	502	R	20/09/10	35
R	20/12/10	500	R	20/10/10	336
R	20/01/11	325			
P	24/01/11	354			
R	20/02/11	287			
R	20/03/11	227			

Table 1. Suspended sediment concentration in the Acre River in the dry and wet seasons between 2008 and 2011. B, R, P, and X as in figure 1.

detected concentrations may be underestimates. The accuracies of the employed methods were evaluated using spiked blanks of known metal concentration and a standard reference material (SRM, MESS-1, NRC Institute for National Measurement Standards). The recovery efficiency ranged from 40% (Mn and V) to 90 – 100% (Pb and Zn). The average recovery for most of the metals was 70 – 80%. A calibration check was performed after each set of 14 samples. The detection limit ranged from 0.02 to 0.80 ng L^{-1}.

The mineralogical composition of the samples was analyzed using X-ray powder diffraction (XRD - Diffractometer Ultima IV, Rigaku Americas Corporation, USA). Qualitative analysis of the samples was performed via continuous records ($5^o \leq 2\theta \leq 80^o$, $\Delta 2\theta = 0.05^o$) using Cu K_α radiation ($\lambda = 1.540562$ Å) and a K_β Ni filter. The minerals were identified by comparison of the XRD experimental patterns with standards in the Mineralogy Database (http://webmineral.com/) and the literature (Albers *et al.*, 2002).

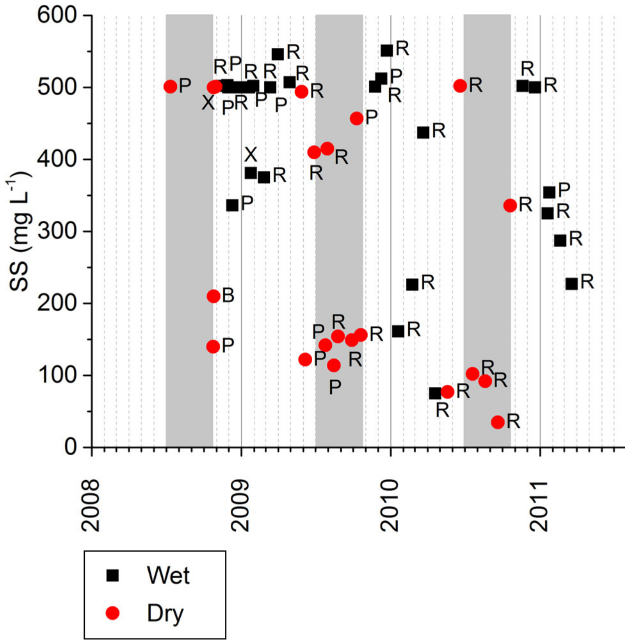

Figure 2. Seasonality of SS concentration in the Acre River from 2008 to 2011. Gray bars denote the dry season interval, from May to October, when the lowest SS concentrations were frequently observed.

RESULTS

The seasonal SS concentration values are shown in table 1. The SS was significantly greater during the wet season than in the dry season according to the results of a t-test at the 0.05 significance level. The seasonal behavior of SS concentration is not uniform as shown by the distribution of values in figure 2.

Chemical and mineralogical composition

The chemical composition of the suspended sediment of the Acre River is shown in table 2. The major elements were Fe, Al and Ca, with average concentrations of 27,232 mg kg^{-1}, 10,808 mg kg^{-1}, and 5,354 mg kg^{-1}, respectively. In contrast, the lowest concentrations were measured for Hg, Cd, and Ti with values of 1.54 mg kg^{-1}, 1.91 mg kg^{-1}, and 3.33 mg kg^{-1}, respectively. Other elements detected in high concentrations were Mg, K, Mn, Si, P, and S.

Strong correlations among certain elements suggest similar sources, as noted for P and S (r = 0.9), as well as for Ca and Mg (r = 0.9). Phosphorus in SS indicates anthropogenic origin. Fertilizers are a source of P to water courses through leaching and runoff, especially for Al- and Fe-rich soils, which are characteristic of the Purus Basin. Other elements also presented strong correlations: the Pb, V and Ni levels were correlated (r = 0.8), and the levels of V and Ni were also strongly correlated with Cr, Cd, and Cu (r = 0.6 – 0.9). However, Hg showed no correlations with these species. Fe, Al, Mg, and Si are predominant in silicate minerals, but there was no correlation among the concentration of these elements in the SS samples, with the exception of Mg and Al (r = 0.9).

For all the studied sites, the X-ray diffractograms of the SS samples display characteristic peaks of quartz, kaolinite, and illite, as illustrated in figure 3. Quartz, kaolinite and illite were previously found in suspended sediment, in the Purus and Juruá basins (Martinelli *et al.*, 1993; Carvalho *et al.*, 2005). Minerals as feldspar, Na-plagioclase, Ca-plagioclase and smectite-vermiculite were also found in the SS in Amazonian rivers (Allard *et al.*, 2002).

The ratio of X/Al (where X = Mg, Ca, Na and K) denotes the weathering index as a function of Al/Si, which exhibits the linear trend shown in figure 4, where the slopes of the lines are close to zero. The Pearson correlation coefficient indicates a strong association of the Mg/Al and Ca/Al ratios with the Al/Si and a weak association of the Na/Al and K/Al ratios with the Al/Si. Bouchez *et al.* (2011) had been explained the dilution processes in a mineralogical mixing with quartz and clay minerals, such as illite, kaolinite, alkali-feldspar and others.

DISCUSSION

Seasonality and composition of suspended sediment

The seasonal SS concentration in the Acre River follows the annual behavior of rainfall and water discharge. The maximum values ranges from 450 to 550 mg L^{-1} during the wet season when the water discharge ranges from 800 to 1200 m^3 s^{-1}, and the minimum values were measured during dry season, when the water discharge ranges from 30 to 450 m^3 s^{-1}. The high water discharge induces erosion of the river borders and soils and also promotes the re-entrance of the floodplain sediments into the river, increasing the SS load in the wet season. Lack of uniformity in SS seasonality had been noticed by Meade (1994) in relation to large rivers, but in the case of the Acre River, it can be influenced by anthropogenic movement of matter into the river system due to suppression of the vegetation in areas adjacent to the river (Machado, 2011). The reported mean yearly R values of the Acre River in Rio Branco and at the confluence with the Purus River are 8.9 and 13.7 Gm^3, respectively (Duarte, 2010). Using eq. (1), the QS in Rio Branco is 2.7 Mt y^{-1}, and at the confluence with Purus River, the QS is 4.1 Mt y^{-1}. The Purus River discharge is 10 – 15 times greater than that of the Acre River. According to the proportionality between the sediment load and discharge, the load of sediment carried by the Purus River is approximately 25 – 40 Mt y^{-1}. Observations conducted at the mouth of the Amazon River indicate a broad interval for estimated values between 0.6 and 1.3 Gt y^{-1} of sediment load (Filizola *et al.*, 2009; Villar *et al.*, 2011). Erosion of rocks containing quartz and clay minerals and weathering of cambisols, vertisols, luvisols, acrisols, ferralsols, and plinthosols, in conjunction with deforestation and use of slash and burning to transform vegetation into pasture for cattle and agriculture, as well as water transport, are the sources of the chemical composition and diversity of concentration of the SS, characterizing the sediment particles in the upper Amazon of the Acre River, Purus Basin.

The major elements present in the suspended sediment chemical concentration were Fe, Al, Ca, Mg, K, Mn, Si, P, and S. In contrast, the lowest concentrations were measured for Hg, Cd, and Ti. The measured concentrations of Hg, Pb, Fe, S, and P were significantly greater in the dry season than in the wet season. The high concentrations of elements in SS are evidence of severe weathering of Amazon soils. Weathering processes follow deforestation and burning with multiple responses. As referenced by Lindgren and Röttorp (2009) the influence of deforestation disturbances on soil erosion and leaching of substances are complex and dependent on each specific site and factors such as soil texture, topography, vegetation, land management history, climate, atmosphere deposition, etc. Forest dynamics in the Amazon show different influences on chemical element mobilization, such as slash and burn agriculture, intense rainfalls, forest to pasture conversion, leaching and surface runoff and erosion, elevated export of solids and solute, volatilization of S, alteration in the P cycle, reduced soil acidity and increased concentrations of Ca and of the trace elements Cu, Pb, Hg, and Ni (Lindell, 2011). It has been observed that Hg does not have an appreciable presence in the region (Mascarenhas *et al.*, 2004; Siqueira and Aprile, 2012). The Hg concentration in the SS of the Acre River could be a result of atmospheric deposition following the open-air amalgamation step of gold mining through which up to 170 t y^{-1} of Hg vapor is released to the Amazon atmosphere (Diaz, 2000). In addition, the

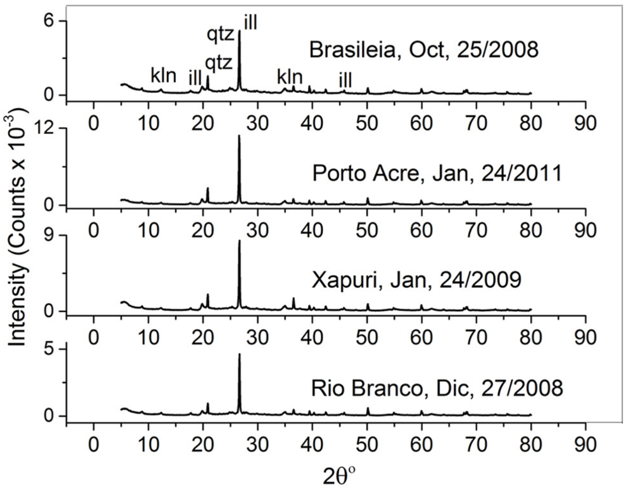

Figure 3. X-ray diffractograms of the Acre River SS with peaks of quartz (qtz), kaolinite (kln) and illite (ill). Identical patterns were obtained for all the sampling sites.

Table 2. Chemical concentration (mg kg^{-1}) of suspended sediment in the Acre River in the wet and dry seasons between 2008 and 2011. Note: ND – Not determined.

	Wet	Hg	Zn	V	Ti	Si	Pb	Ni	Na	Mn	Mg	K	Fe	Cu	Cr	Cd	Ca	Al	S	P
P	13/11/08	0.18	66.00	24.23	3.37	141.55	14.51	23.19	36.66	789.97	3045.00	1311.21	26007.10	18.92	15.32	2.42	5729.46	12519.20	238.00	506.27
P	28/11/08	3.66	54.33	24.17	4.38	146.23	11.05	18.74	80.33	580.81	2558.68	1427.40	34609.03	19.81	15.37	2.16	5353.84	12484.17	396.22	470.43
R	30/11/08	5.52	62.37	27.59	2.64	155.75	14.64	20.53	162.36	781.83	2621.09	1646.51	27777.77	23.96	14.60	2.04	6447.51	13222.07	467.47	609.09
P	10/12/08	2.43	70.36	28.90	4.17	112.18	17.52	23.10	106.85	1231.77	2193.75	4329.29	24191.14	22.05	12.87	2.62	5131.17	10617.39	920.13	878.84
R	27/12/08	0.80	59.01	23.46	2.82	114.95	13.08	24.22	16.62	1060.31	2788.90	1248.56	26712.89	19.67	15.27	2.06	5908.39	12406.09	154.22	427.13
P	20/01/09	0.02	64.21	23.59	2.67	125.62	15.74	23.20	40.10	929.08	2719.63	1152.11	25212.90	19.93	15.21	2.24	5393.12	11839.75	264.96	508.79
X	24/01/09	0.74	58.52	22.93	3.44	136.85	19.21	20.98	20.89	784.88	3126.07	1343.89	24182.17	18.11	15.31	1.80	6241.61	12656.22	130.24	339.47
R	30/01/09	0.36	52.92	21.26	3.11	129.28	11.12	19.37	137.70	646.79	2376.53	1064.05	21952.44	15.01	14.62	1.92	4527.05	10794.17	132.81	375.74
R	25/02/09	0.14	56.19	21.13	2.31	152.57	12.63	18.91	46.11	773.84	2675.87	1284.46	22753.72	19.31	12.46	1.17	5057.79	9897.58	276.43	465.46
P	13/03/09	0.02	68.87	24.64	2.80	144.42	11.21	23.74	134.66	1020.74	3777.66	1534.08	26331.38	22.73	14.57	2.05	7142.69	15089.98	194.48	469.75
R	31/03/09	0.96	68.19	25.36	3.10	115.87	12.21	22.01	133.98	741.03	2529.84	1296.84	25426.71	20.23	14.80	2.00	4841.66	11153.33	245.72	492.48
R	29/04/09	0.62	60.60	23.34	3.00	138.62	13.53	21.30	160.32	832.78	2506.29	1338.98	24934.11	18.91	15.65	2.02	4522.13	10656.39	216.94	518.25
R	24/11/09	ND	78.64	28.43	0.82	605.38	20.19	19.63	121.33	921.68	2566.53	2165.01	28000.71	32.96	12.29	1.40	5737.97	10259.81	445.44	576.17
P	09/12/09	1.24	68.02	28.39	3.36	97.06	16.89	21.68	88.40	751.85	3154.77	2565.99	37796.58	23.51	14.49	2.58	6399.34	13757.35	512.46	717.88
R	23/12/09	0.63	67.56	24.27	2.80	137.18	10.66	25.20	27.67	982.42	2801.04	1723.32	25723.32	22.02	15.21	2.33	5069.01	12252.59	259.04	540.24
R	20/01/10	0.71	68.13	25.73	2.54	158.48	15.04	22.52	132.55	973.34	2525.88	1175.59	28482.46	20.11	16.19	3.50	5181.10	12790.06	219.69	579.31
R	23/02/10	ND	51.35	19.62	1.46	122.09	11.56	15.86	39.76	643.47	2287.44	936.40	22305.72	18.54	10.35	1.13	4793.84	9075.72	238.30	464.93
R	22/03/10	0.02	52.45	20.54	1.64	124.41	11.84	16.86	36.39	883.35	2259.15	929.22	23618.71	17.21	12.27	1.22	4518.18	8739.16	238.01	498.28
R	20/04/10	1.71	55.46	20.42	2.28	111.24	13.16	20.55	124.31	849.70	2334.58	973.55	23130.31	15.04	13.61	1.95	4985.89	10572.30	14.36	83.42
R	20/11/10	ND	55.86	21.44	2.18	224.65	12.21	17.83	53.73	1173.43	2546.50	1018.69	24816.47	18.96	10.81	1.25	4917.37	9410.96	161.88	447.64
R	20/12/10	0.00	54.86	20.96	3.35	257.81	10.96	16.48	51.50	1056.74	2394.28	997.01	23479.03	17.94	10.34	1.21	4575.03	8989.38	200.08	450.51
R	20/01/11	ND	51.51	18.73	2.73	220.22	10.32	18.20	50.77	971.89	2259.99	982.13	22071.06	18.67	10.10	1.10	4351.09	8390.19	225.56	443.79
P	24/01/11	0.84	49.28	19.90	2.99	125.55	11.54	17.85	139.36	709.86	2500.54	1176.98	22666.56	16.79	13.51	1.47	4591.98	10804.25	335.86	498.54
R	20/02/11	1.77	54.98	20.51	23.49	703.50	10.86	19.27	43.75	976.07	2545.24	1035.10	21769.63	19.45	10.43	1.18	4770.76	9030.98	128.55	456.39
R	20/03/11	0.83	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	30290.48	ND	ND	ND	ND	ND	135.81	485.23

Table 2. *Continuation.*

	Dry	Hg	Zn	V	Ti	Si	Pb	Ni	Na	Mn	Mg	K	Fe	Cu	Cr	Cd	Ca	Al	S	P
P	11/07/08	3.43	91.31	39.68	5.38	172.94	20.19	28.65	133.66	1139.60	2236.15	1611.75	31624.72	33.87	15.14	3.48	6031.81	12077.99	929.84	1023.73
P	24/10/08	1.67	61.97	33.62	5.53	172.93	18.06	26.24	178.84	1364.09	2517.38	1883.16	28808.91	24.50	16.34	2.89	6727.93	11099.89	1553.50	984.70
X	25/10/08	4.00	60.68	31.40	5.05	135.17	14.39	24.30	166.83	898.93	2446.64	1818.37	25336.45	25.03	13.58	2.72	5293.54	10433.50	802.50	830.96
B	25/10/08	1.71	61.54	30.21	4.03	117.30	14.43	21.14	126.67	935.16	2491.93	1322.45	38587.39	25.11	13.75	2.65	5837.73	10704.70	791.92	607.46
R	30/10/08	2.26	8.68	6.43	0.84	28.99	3.10	2.45	27.93	176.25	474.69	282.19	36429.02	4.92	1.91	0.61	1165.68	2124.11	69.57	90.91
R	28/05/09	0.72	59.64	22.14	2.82	134.93	13.38	21.39	162.34	1021.40	2450.57	1469.52	24998.05	17.53	14.63	2.08	4542.34	9904.86	172.05	397.76
P	06/06/09	2.82	58.46	21.17	2.78	110.02	15.31	19.93	7.42	711.32	2805.25	1029.15	23649.40	16.93	13.62	1.21	5253.02	11732.07	127.59	366.56
R	28/06/09	0.02	51.27	20.77	2.11	160.24	11.96	14.75	55.98	800.45	2355.14	1045.05	22924.86	16.83	11.42	1.18	4951.52	8757.46	269.42	431.70
P	25/07/09	1.95	68.06	30.17	5.92	233.17	17.13	20.42	68.13	855.84	2509.24	1136.51	40033.25	18.94	14.24	3.14	5494.16	11296.52	463.65	711.26
R	30/07/09	ND	59.63	23.47	1.86	1810.82	15.80	15.83	76.11	903.93	2319.92	1311.71	27688.25	20.81	12.00	1.25	5043.03	8197.30	560.51	895.94
P	15/08/09	8.24	53.08	26.48	3.63	130.36	15.38	18.31	70.91	853.08	2144.27	1107.06	24745.02	18.15	12.47	2.49	5229.23	9449.53	555.54	726.51
R	25/08/09	ND	253.37	27.11	1.10	495.37	21.32	21.42	96.67	1236.42	2780.60	1568.68	30370.35	39.81	13.01	1.73	6201.40	10195.05	823.14	806.20
R	28/09/09	0.18	63.25	20.45	3.02	110.42	12.94	21.98	50.61	682.75	3813.41	1368.89	24359.91	19.14	14.53	1.61	6893.82	14287.41	121.36	375.47
P	10/10/09	1.95	67.51	26.33	2.99	190.36	18.26	21.66	89.52	754.01	3272.85	1886.85	27265.19	23.41	13.91	2.46	6633.28	13097.61	408.62	607.92
R	20/10/09	ND	55.04	26.04	2.06	136.52	12.06	15.38	55.30	647.00	2451.25	1114.65	26644.19	20.23	12.23	1.24	4796.31	10118.13	177.81	403.90
R	20/05/10	0.82	62.91	24.35	3.00	196.15	14.37	22.51	183.44	845.74	2889.57	1297.90	27326.01	20.35	14.31	2.09	5433.32	12352.51	213.04	492.04
R	20/06/10	ND	57.97	23.66	2.40	436.85	20.57	20.47	84.82	1291.03	2789.85	1907.58	31893.60	27.10	11.89	1.44	6112.09	9740.67	340.60	761.48
R	20/07/10	ND	62.12	27.25	2.69	622.09	18.94	17.88	80.61	1125.09	2527.51	1785.31	30704.35	32.41	12.74	1.60	5703.84	9367.85	388.87	624.19
R	20/08/10	ND	71.22	32.31	1.24	1688.23	28.43	29.30	123.08	2028.82	2998.65	2843.16	33227.27	47.49	13.17	1.52	6560.85	10779.13	623.13	657.97
R	20/09/10	ND	60.67	22.04	1.38	187.35	14.51	17.34	104.10	740.05	3092.65	1778.08	25933.88	21.89	12.06	1.32	5943.70	11362.03	529.28	736.16
R	20/10/10	0.97	58.46	25.65	2.63	136.14	13.04	18.43	128.59	776.41	2356.89	1295.48	25863.66	18.23	14.18	2.52	4881.61	11863.69	216.07	458.40

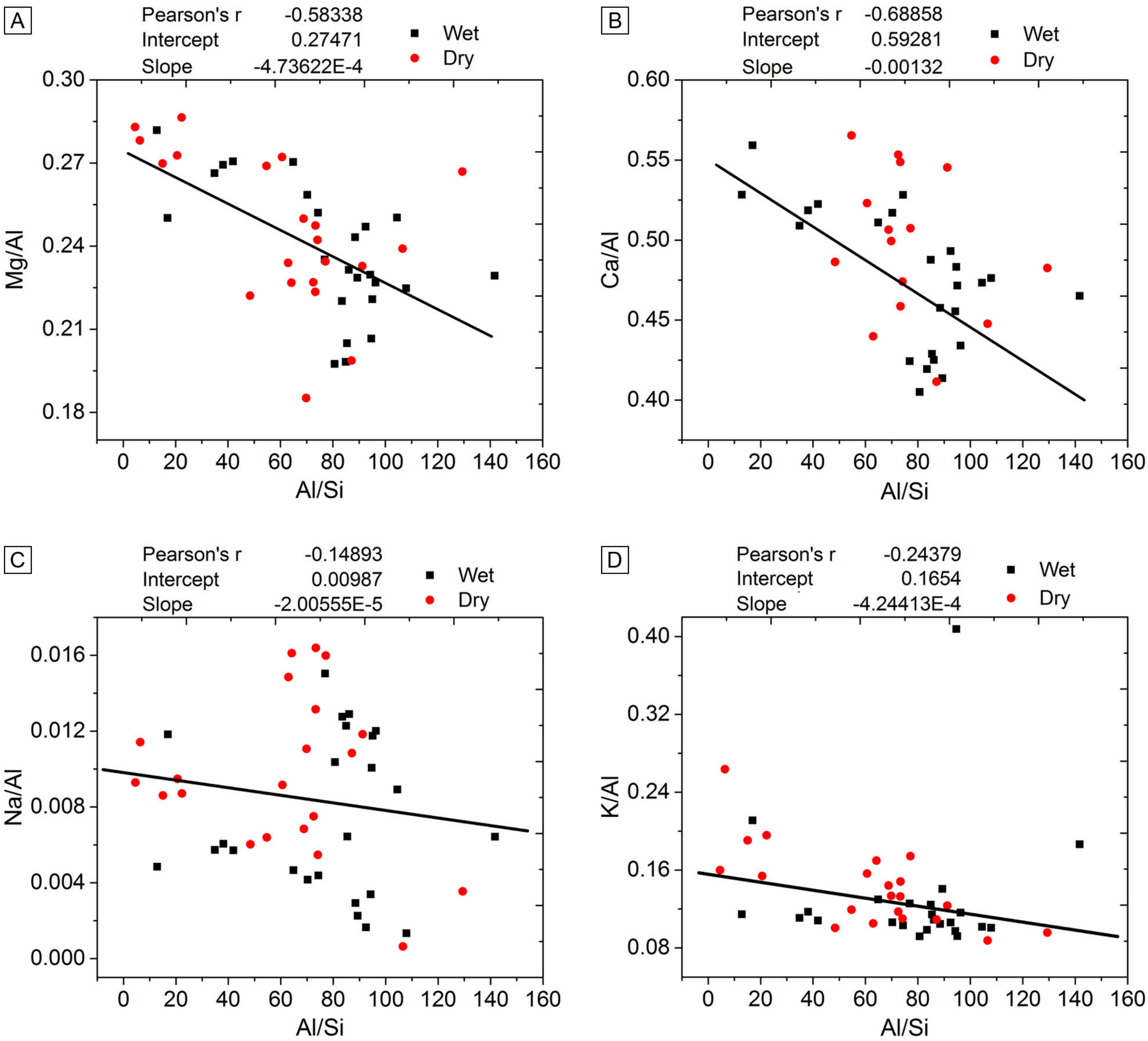

Figure 4. a) Mg/Al, b) Ca/Al, c) Na/Al and d) K/Al vs. Al/Si in the Acre River basin during the wet and dry seasons. The Pearson correlation coefficient, the intercept and slope of the linear trend lines are shown.

Hg is remobilized due to the cultural practices of deforestation in the Amazon. Slashing and biomass burning contribute to the atmospheric emission of Hg estimated by Michelazzo *et al.* (2010) of 6.7 t y^{-1} between 2000 and 2008 and by Roulet *et al.* (1999) of between 6 and 9 t y^{-1} from burning of primary forest.

Acre River and downstream suspended sediment

Weathering processes were extensively described by Bouchez *et al.* (2012), primarily in the context of the sediments of large rivers in the Amazon basin, by introducing a weathering index to measure the effects of weathering reactions that affect the soils and floodplains compared to reactions affecting the primary rocks. These authors report that little information is available to date on the potential contribution of weathering reactions during riverine transport and transient storage to global weathering fluxes and that weathering reactions were responsible for downstream chemical changes in sediments from the Solimões varzea (floodplain). These changes occurred through the loss of plagioclase, smectite and illite, the formation of kaolinite and a downstream shift in the mineral assemblage dominating the clay fraction of Amazon

	SSAc (mg kg^{-1})		SSAm (mg kg^{-1})		SSAm/SSAc
	Concentration	SD	Concentration	SD	Enrichment ratio
Na	90	49	7,955	1,830	88
Mg	2,596	492	8,219	2,271	3
Al	10,808	2,088	79,733	23,977	7
Si	265	355	301,394	45,918	1,139
K	1,456	627	18,732	4660	13
Ca	5,354	971	8,068	2,818	1.5
Ti	3	3	4,799	1,531	1,441
Cr	13	2	68	22	5
Fe	27,232	4,596	42,769	11,565	1.6
Ni	20	4	31	8	1.6
Cu	22	7	29	16	1.4
Zn	64	31	129	47	2

Table 3. Acre River Suspended Sediment (SSAc), and Solimões, Madeira and Amazon mainstreams SS (SSAm). Chemical mean concentration, standard deviation and enrichment ratio.

SS from illite-chlorite to kaolinite-smectite.

Comparison between the SS chemical concentrations from the Solimões, Madeira and Amazon mainstreams (SSAm) (Bouchez *et al.*, 2011) and that from the present study (SSAc), concerning an integrated size spectrum of particles, indicates the significant enrichment of Si, Ti, and Na, the moderate enrichment of K, Al, Cr, and Mg, and the low enrichment of Zn, Fe, Ni, Ca, and Cu in sediments in the course from Acre to Amazon mainstreams, as shown in table 3.

The major Si enrichment occurs in coarse sediments that are in deepest areas of the river. The relatively moderate content of Al in the Acre River SS is a characteristic property of fine particles in samples. Bouchez *et al.* (2011) conducted observations in river profiles up to 25, 30 and 60 m in depth, different from the Acre River depths between 2 and 12 m, where only surface samples were collected. This difference explains the high dispersion (SD) of values for the SSAm measurements compared to that encountered for the SSAc data. The relative enrichment in the chemical concentration of SS and the prevalence of coarse or fine particles in both of the compared areas is also revealed from the corresponding Al/Si values: between 1 and 160 for SSAc and between 0 and 0.5 for SSAm. For example, the concentration of Na in coarse particles (SSAm) was 88 times greater than its concentration in fine particles (SSAc); it was more than one thousand times for Si and Ti; and less than two times for Ca, Fe, Ni and Cu (Table 3). Apparently, the Acre River does not show a clear chemical and grain-size distribution of suspended sediment with river depth, i.e. the sediment-transport dynamics are essentially related to the movement of fine particles in a turbulent flow where the SS particles are almost randomly distributed. Figure 5 shows the relationship of the chemical concentration of the alkali metal Na and alkali-earth metal Ca with respect to Al/Si ratio for the case of (SSAm) (Bouchez *et al.*, 2011) and this study. The relationship indicates the distribution of elements in particles of various grain sizes, prevailing in the mixing of coarse SS (low Al/Si ratios) and fine surface SS (high Al/Si ratios), respectively. In the Amazon River, the Al/Si ratio points toward low values (silicon rich coarse sediments) in bottom SS and high values (aluminum rich fine sediments) in surface SS (Bouchez *et al.*, 2011). In the Acre River, no significant differences in grain size and chemical composition were observed, as evidenced by the nearly constant relationship of the weathering index values X/Al as a function of the Al/Si (Fig. 4).

Perspectives of suspended sediment modification

Amazon ecosystems are highly vulnerable to extreme events of climate and human interventions. Such impacts occur through deforestation, seasonal changes in atmospheric composition, floods and droughts. Moreover, the construction of highways (Maldonado *et al.*, 2012) and more than seventy dams for hydropower generation in the Brazilian Amazon (Kemenes *et al.*, 2007; Burger, 2011; Kemenes *et*

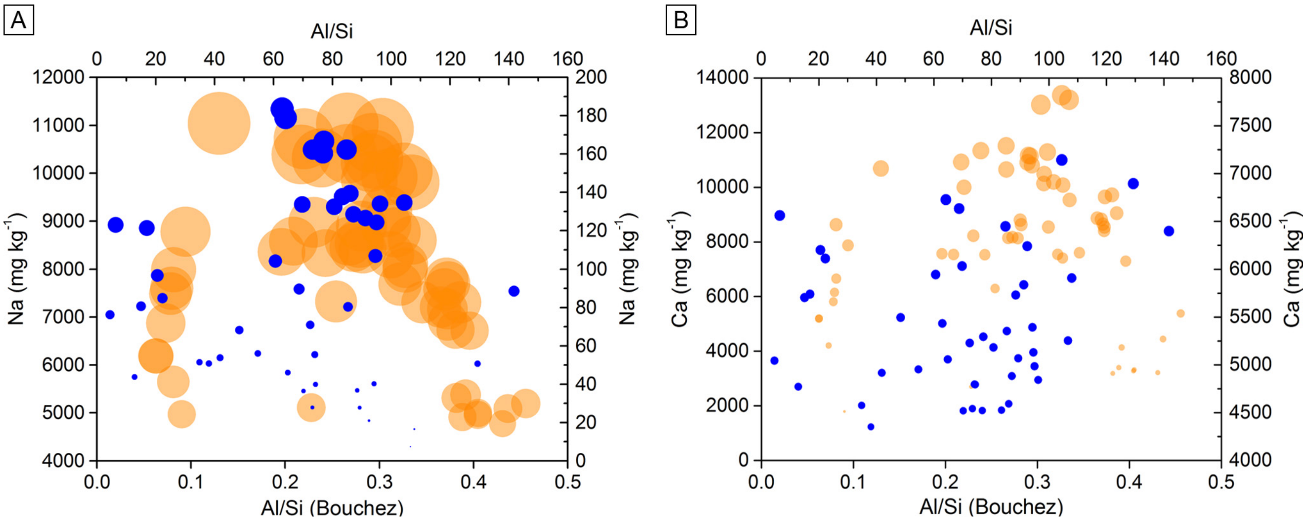

Figure 5. a) Downstream enrichment of Na concentration and b) of Ca concentration in SS. Comparison between SSAm from Bouchez et al. (2011) and SSAc (this paper). Circles represent grain size and element concentration: blue for SSAc and orange for SSAm.

al., 2011; Kemenes *et al.*, 2012; Pyper, 2012) and in the Andean Amazon (Finer and Jenkins, 2012) will have environmental impacts such as the release of significant amounts of methane and carbon dioxide to the atmosphere, with implications for climate change, natural cycles, soil loss, biodiversity loss and disturbances of river system loads and transport of sediments.

Influences on the suspended sediment load could be intensified due to the projected climate changes in Amazonia (Salazar *et al.*, 2007), which predict a loss of vegetation, a decrease in precipitation during longer dry seasons and higher temperatures and, as a consequence, additional droughts and fires. At the same time, during the shorter wet seasons, the rainfall is expected to intensify severe erosion events in a landscape with poor vegetation coverage (Saxena and Hildemann, 1996). These modifications could increase the redistribution of nutrients, such as P, and of contaminants, such as Hg and Pb, and increase the significance of water-sediment interactions and their influence on river water quality (Walling and Kane, 1982). Situations such as extreme floods and droughts in the Amazon (Collier and Webb, 2002) are predicted as new climate behavior for the 21th century.

CONCLUSION

The present study was developed in a portion of the Purus Basin that is the least studied area in the region. The seasonality of the suspended sediment (SS) from the Acre River was determined. The SS concentration of sediments was significantly greater during the wet season than during the dry season. In contrast, the concentrations of Hg, Pb, Fe, S, and P in the SS were significantly greater during the dry season than during the wet season. Quartz, kaolinite and illite were observed in all the sampling sites. The elements Zn, V, Ti, Si, Pb, Ni, Na, Mn, Mg, K, Fe, Cu, Cr, Cd, Ca, Al, S, and P derive from weathering reactions that affect the minerals and soils that are characteristic of the Fitzcarrald Arch geochemistry. A detailed chart of the geochemistry of the SS provides evidence of the distribution of element concentrations. Particles of various grain sizes, are present in the mixing of coarse SS (low Al/Si ratios) and fine SS (high Al/Si ratios), and a downstream enrichment of chemical concentrations was observed. It was assumed that Hg reaches the region via atmospheric transport and deposition and from gold mining in the Madeira basin. Erosion of rocks and clay minerals, soil weathering, practice of deforestation, use of slash and burning in agriculture, as well as water transport determine the chemical composition and diversity of concentrations of suspended sediment in the Acre River in the Purus Basin. The obtained results represent the first set of values and relationships regarding the mineralogy and chemical identification of the SS in the region and can be used as a reference for future efforts to add spatial and temporal information about the hydrological and geochemical characteristics within the Purus Basin, to observe, for example, possible impacts of climate change and human activities on the SS load and composition of the Amazon River.

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