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Regional pattern of riverine dissolved organic carbon in the Amazon drainage basin of Bolivia

Abstract—Dissolved organic carbon (DOC) was analyzed at 11 hydrometric stations and 41 Andean and lowland sites in the upper Rio Madeira drainage basin where anthropogenic alteration is low. The two regions, Andes and Llanos, behave very differently. Mean DOC is 2.2 mg liter^{-1} (range, 1.2–4.2 mg liter^{-1}) in the Andes and 5.7 mg liter^{-1} (range, 4.8–7.4 mg liter^{-1}) in the Llanos. DOC enrichment may occur rapidly as Andean rivers enter the Llanos. The specific DOC export is correlated with the watershed forested area in the Andes but not in the Llanos. Specific DOC yield for a given water runoff is 3 times higher in the Llanos. Regionalization seems important for predicting DOC dynamics in such a large basin.

The biogeochemistry of organic C in the Amazon River has been extensively investigated with regard to origin, processes, and budgets (e.g. Richey et al. 1990). Richey et al. sampled Amazon tributaries near their confluence to determine their contribution to mainstem functioning. However, little is known about the origin of organic C in the upper drainage basins of the Amazon. The relative contribution of the different regions and landscapes to riverine carbon yields remains poorly documented. Although increasing colonization is leading to rapid landscape alterations in some

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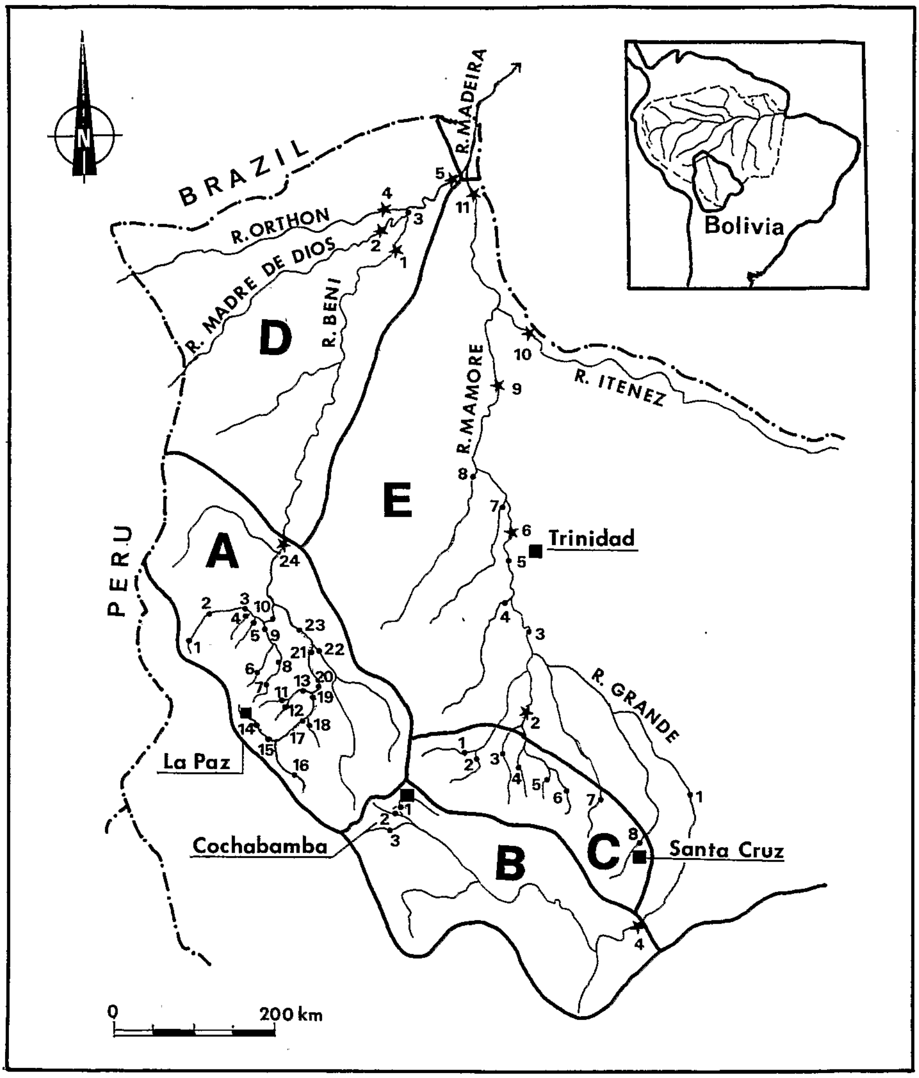

Fig. 1. Map of the Amazon drainage basin of Bolivia: sampling points—●; PHICAB gauging stations—★; major cities—■. Letters refer to the five regions: A—upper Rio Beni; B—Rio Grande; C—Chapare, for the Andes; D—Rio Beni; E—Rio Mamore, for the Llanos. Stations codes given in Table 1.

regions, the global impact of such development on the organic C fluxes in these rivers is hardly predictable.

The drainage basin of the Rio Madeira upstream of the Brazilian frontier extends over 900,000 km^2 and supplies on average 18,000 m^3 of water s^{-1}. Andean tributaries are known to provide most of the yields for both dissolved and sediment loads (Roche and Fernandez 1988; Guyot et al. 1988), but nothing is known about organic C. This large, highly contrasted, and still relatively pristine tropical basin now constitutes a study area of high interest, inasmuch as it is covered by the PHICAB hydrological network which has been providing daily data on discharge and total dissolved and suspended solids (TDS and TSS) at 11 gauging stations since 1983. Our study was designed to investigate the spatial pattern of riverine dissolved organic C (DOC), to identify possible causes of variation, and to propose a framework for the regionalization of the DOC dynamics.

The Bolivian portion of the upper Rio Ma-

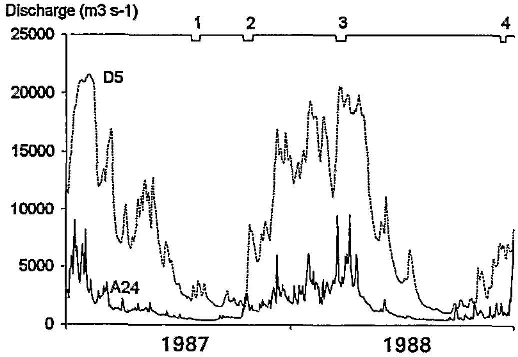

Fig. 2. Mean daily discharge of Rio Beni at Angosto del Bala (A24) and Cachuela Esperanza (D5), 1987–1988. Numbers on upper axis (1–4) indicate sampling periods at the PHICAB stations.

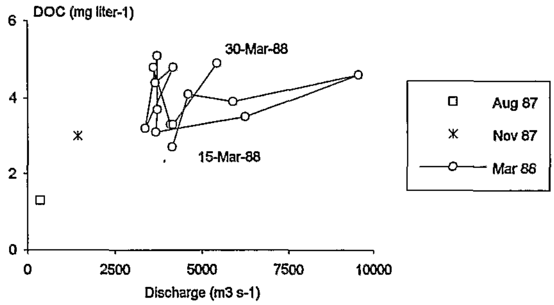

Fig. 3. DOC vs. discharge on the Rio Beni at Angosto del Bala (A24).

deira drainage basin (74% of the total basin area) is clearly divided into two geographic zones: the eastern slope of the Andes, ranging from 6,500 to 250 m, and the plain ("Llanos"), extending from the piedmont of the Andes to the Brazilian shield (Fig. 1). Individual watersheds in the Andes are heavily contrasted; they range from semiarid basins on the Altiplano quaternary sediments to densely vegetated hyper-humid basins on Paleozoic rocks. That large zone has been subdivided into three regions. The upper Rio Beni drainage basin (A on Fig. 1) is made up of deeply incised, humid (rainfall, 1,500–3,000 mm yr^{-1}), forested valleys: the "Yungas" and the Alto-Beni foothills; it also includes some semiarid (rainfall, <800 mm yr^{-1}), highly erodible basins (Rios La Paz-Boopi and Consata). The Rio Grande drainage basin (B), which culminates at 5,100 m, is entirely semiarid. The Chapare region (C) is made up of densely forested mountains and reaches 4,500 m; in this region, as in other peripheral parts of the Amazon basin, precipitation is maximal (5,000–7,000 mm yr^{-1}) at very low elevations in the contact zone between the Andes and the Llanos and decreases to 2,000 mm yr^{-1} with increasing altitude. The extreme variability of mechanical erosion rates in adjacent basins must be emphasized (1,000–20,000 t km^{-2} yr^{-1}, Guyot et al. 1988). Highly turbid rivers flowing out from the Andes (Madre de Dios, Beni, and Mamore) correspond to white-water rivers.

The Llanos is a nearly flat plain of recent alluvial sediments whose level is controlled by the Precambrian Brazilian Shield outcrop near Cachuela Esperanza (D5) and Guayaramerin (E11). About 150,000 km^2 are flooded annually in this region, inducing the development of savannah patches. Annual rainfall is ~2,000 mm in the Rio Beni catchment (D), which is covered mainly by tropical evergreen to seasonal forest. In region E, rainfall ranges from 2,000 mm yr^{-1} in the north to 1,100 mm yr^{-1} in the southeast where a tropical seasonal forest progressively gives place to tropical savannah.

Human densities are low, ~7 inhabitants km^{-2}, including major cities, and ~1 inhabitant km^{-2} in the Llanos. Accessibility to most rivers is difficult. Pollution is restricted to some large cities. Hydroelectric reservoirs are small and located at high altitude; channelization is unknown. Agriculture is traditional with many sites of active rural colonization in the Chapare, Alto-Beni, and Llanos.

The 11 PHICAB gauging stations located in the Andean piedmont and the Llanos were sampled 2–4 times, corresponding to different

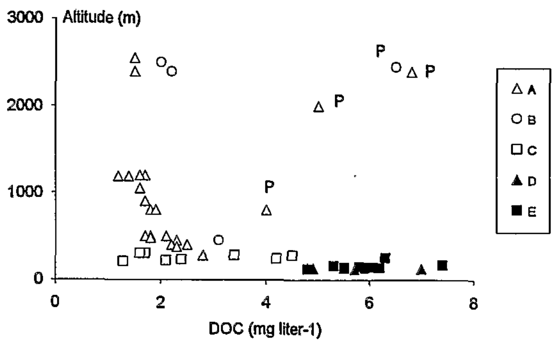

Fig. 4. Mean DOC value vs. sampling point altitude. Points referenced by region (Table 1, Fig. 1); P indicates a polluted river.

Table 1. Data for rivers of the Amazonian drainage basin of Bolivia. River sample points, characteristics, and mean results. Alt.—sample point altitude (m); *A*—drainage basin area (km^2); *qs*—specific discharge or runoff (liter s^{-1} km^{-2}); F—forested area (%) in the watershed ([·] = % of forested area for Bolivian area only); *n*—number of organic C samples; DOC—average values (mg $liter^{-1}$); *qs* × DOC—DOC-specific yields (g m^{-2} yr^{-1}).

Code	River	Alt.	*A*	*qs*	F	*n*	DOC	*qs* × DOC
A1	San Cristobal	2,400	110	16	0	1	1.5	0.8
A2	Consata	900	2,400	16	0	1	1.7	0.9
A3	Mapiri	500	10,100	18	47	2	1.8	1.0
A4	Tipuani	500	1,400	26	34	2	1.7	1.4
A5	Challana	500	1,900	55	66	1	1.8	3.1
A6	Zongo	1,200	330	50	15	1	1.7	2.7
A7	San Juan	1,200	100	50	4	1	1.6	2.5
A8	Coroico	800	610	43	34	1	1.8	2.4
A9	Coroico	500	5,400	33	77	2	1.7	1.8
A10	Kaka	480	18,800	26	57	2	1.8	1.5
A11	Unduavi	1,200	280	19	0	1	1.2	0.7
A12	Taquesi	1,200	620	19	0	1	1.4	0.8
A13	Tamampaya	500	2,100	19	15	1	1.6	1.0
A14	La Paz*	2,400	930	11	0	1	6.8	2.4
A15	La Paz*	2,000	1,100	11	0	1	5.0	1.7
A16	Luribay	2,550	810	11	0	1	1.5	0.5
A17	La Paz*	800	5,200	11	0	1	4.0	1.4
A18	Miguillas	800	1,000	11	0	1	1.9	0.7
A19	La Paz	500	7,400	11	2	1	2.1	0.7
A20	Boopi	450	10,900	13	11	1	2.3	0.9
A21	Boopi	400	12,500	15	22	1	2.5	1.2
A22	Cotacajes	400	16,000	20	46	1	2.2	1.4
A23	Alto Beni	380	29,100	21	37	2	2.3	1.5
A24†	Beni	280	67,500	30	58	17	2.8	2.6
B1	Rocha*	2,450	3,600	5	1	1	6.5	1.0
B2	Tapacari	2,500	940	5	0	1	2.0	0.3
B3	Arque	2,400	2,300	5	0	1	2.2	0.3
B4†	Grande	450	59,800	5	18	3	3.1	0.5
C1	Esperitu Santos	300	2,700	70	76	1	1.7	3.8
C2	San Mateo	300	2,400	70	77	1	1.6	3.5
C3	Chimore	210	1,900	70	100	1	1.3	2.9
C4	Sajta	220	2,100	70	97	1	2.1	4.6
C5	Ichoa	230	670	70	100	1	2.4	5.3
C6	Ichilo	240	2,100	70	100	1	4.2	9.3
C7	Yapacani	280	6,900	13	77	1	3.4	1.4
C8	Piray*	280	4,100	13	63	1	4.5	1.8
D1†	Beni	130	119,000	24	62	3	4.8	3.6
D2†	Madre de Dios	130	124,200	41	[89]	3	4.9	6.3
D3	Beni	125	243,000	34	[68]	1	4.8	5.1
D4†	Orthon	120	32,300	14	[100]	3	7.0	3.2
D5†	Beni	110	282,500	32	[72]	3	5.7	5.7
E1	Grande	250	67,000	8	27	1	6.3	1.6
E2†	Ichilo	190	7,600	78	99	2	7.4	18.2
E3	Ichilo-Mamore	175	124,000	30	49	2	5.3	5.0
E4	Secure	165	17,000	30	77	1	5.8	5.5
E5	Mamore	150	144,000	22	53	1	6.0	4.2
E6†	Mamore	145	159,100	20	52	3	6.1	3.8
E7	Tijamuchi	140	7,600	30	15	1	5.5	5.2
E8	Apere	135	17,000	30	60	1	6.2	5.9
E9†	Mamore	120	216,200	25	48	4	5.5	4.3
E10†	Itenez-Guapore	115	354,300	6	[74]	2	5.9	1.1
E11†	Mamore	110	599,400	14	[62]	3	4.8	2.1

* Polluted river.
† PHICAB gauging station.

Table 2. Minimum, average, and maximum values of mean DOC contents (mg liter^{-1}) in unpolluted stations of the five regions. (Regions identified in Fig. 1.) No.—number of stations by region.

Domain	Region	No.	Min	Avg	Max
Andes	A	21	1.2	1.9	2.8
	B	3	2.0	2.4	3.1
	C	7	1.3	2.4	4.2
Llanos	D	5	4.8	5.4	7.0
	E	11	4.8	5.9	7.4

hydrological phases (Fig. 2): low flow (July–August 1987), rising levels (November 1987, December 1988), and high flows (March 1988). Major rivers in the Andes were sampled once in March, April, or June 1988, and a 15-d flood episode was studied at one station. In the turbulent Andean rivers, samples were taken at the river's edge. In the Llanos, surface samples were taken in the middle of the river. Measurements made with depth-integrating samplers (USD 49) at gauging stations exhibited very good homogeneity of TDS over the whole cross-section, the C.V. being ≤0.05 for 95% of the trials.

Samples were passed, on location, through a glass-fiber filter (GF/C) previously heated at 550°C. The samples were then acidified (H_3PO_4, pH 2), stored in the dark, and sent to the CEMAGREF laboratory in Lyon (France). DOC determinations were performed with a nondispersive infrared analyzer (Dhormann DC80). Ninety-three samples from 52 sites were processed. Percentage of forested area was calculated for each station watershed with a vegetation map of Bolivia (Brockmann 1978), assuming that no significant large-scale alteration of the vegetative cover has occurred in the past 15 yr. Five stations contaminated by the cities of La Paz (A14, A15, A17), Cochabamba (B1), and Santa Cruz (C8) were not used.

DOC was measured daily during an annual flood episode at the Angosto del Bala gauging station (A24) which controls the Rio Beni output from the Andes. DOC contents varied between 2.7 and 5.1 mg liter^{-1}, but with no direct relation with either discharge (Fig. 3) or TDS during such events. The flushing effect (i.e. increased DOC with increased discharge) observed by various investigators therefore seems limited. Still, the lowest value for this station (1.3 mg liter^{-1}, 28 August 1987) corresponds

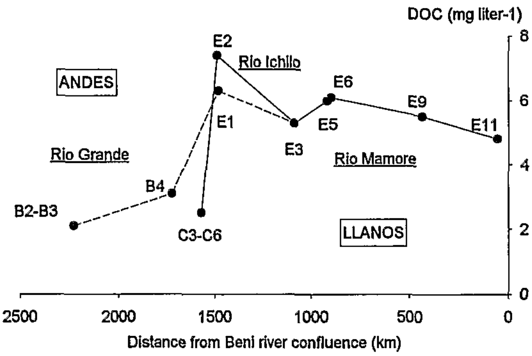

Fig. 5. Downstream evolution of mean DOC content along the Rio Mamore and its Andean tributaries. Stations identified in Table 1.

to the lowest flow situation observed in the 1983–1989 period. Thus, as previously observed in tropical South America (Lewis et al. 1986; Richey et al. 1990) and in the Gambia River (Lesack et al. 1984), DOC values for a particular river seem to have limited variations (1–3-fold) on a broad temporal scale. Consequently, we used average values to characterize spatial variations.

Detailed results are given in Table 1. By plotting DOC values vs. altitude (Fig. 4), the contrast between the Andes (A, B, C) and Llanos (D, E) is immediately apparent. Mean DOC content is 2.2 mg liter^{-1} for unpolluted Andean stations and 5.7 mg liter^{-1} for the Llanos below 200 m. Data for each region are summarized in Table 2. The ranges for Andes and Llanos do not overlap and correspond to the world DOC distribution proposed by Meybeck (1982). Extreme values measured in the Llanos are 3.6 and 9.4 mg liter^{-1}. These values are in the same range as the data from Amazonian rivers in Brazil (Richey et al. 1990) and from the Orinoco basin (Lewis et al. 1986; Depetris and Paolini 1991).

But the salient feature of this pattern is the evidence of a DOC enrichment of the whitewater rivers (Rios Beni and Mamore) as they enter the Llanos. This transition can be fast, as illustrated by the evolution of DOC along the Rio Mamore, coming from the B and C regions (Fig. 5). The Rio Ichilo, sampled at 30 km from the Chapare foothills (E2) has the highest DOC content (7.4 mg liter^{-1}) while the mean DOC value of its four tributaries (C3–C6) is only 2.5 mg liter^{-1}. The same phenom-

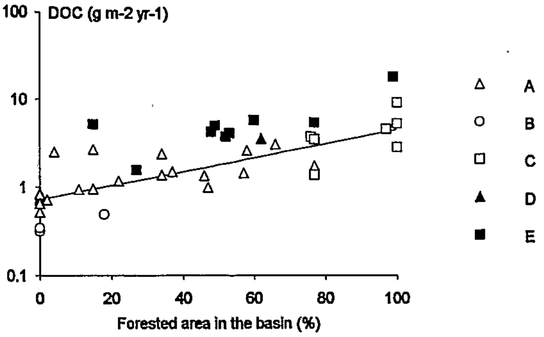

Fig. 6. Mean DOC-specific yield vs. forested area in the drainage basin. For Andean rivers (A, B, C) $n = 31$, $r^2 = 0.664$, $P < 0.001$, $qs \times \text{DOC} = \exp(0.018 \times F - 0.327)$. D, E—Llanos rivers. Points referenced by region (Table 1, Fig. 1).

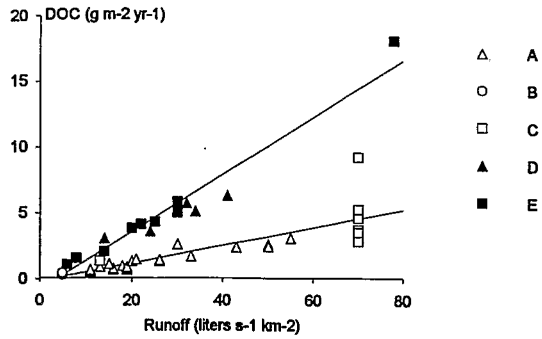

Fig. 7. Mean DOC-specific yield vs. runoff. For Andean rivers (A, B, C) $n = 31$, $r^2 = 0.704$, $P < 0.001$, $qs \times \text{DOC} = 0.068 \times qs - 0.109$. For Llanos rivers (D, E) $n = 16$, $r^2 = 0.931$, $P < 0.001$, $qs \times \text{DOC} = 0.218 \times qs - 0.767$. Points referenced by region (Table 1, Fig. 1).

enon is observed along the Rio Grande between stations B4 and E1 with DOC contents of 3.1 and 6.3 mg liter^{-1}. In both cases, this enrichment occurs in a short distance at the beginning of the floodplain and can be related to the presence along the piedmont of extensive swamps and riparian forests in zones of active fluvial dynamics that maximize the connectivity between rivers and wetlands. At the Chapare (C), this phenomenon may be intensified by huge local rainfalls.

The DOC-specific export rate (mean DOC × specific discharge) has been plotted vs. total forested area for each watershed. These two parameters exhibit a good correlation, but that is exclusively due to the Andean stations. The correlation is significant for regions A, B, and C but not for the Llanos (Fig. 6). Thus, the role of forested areas in river DOC production seems to be different depending on the geographical context. The relationship between forest area and DOC production is poorly documented and principally in relation to forestry practices (Collier et al. 1989). Our results indicate that in the deeply incised and humid Andean valleys (Yungas and Chapare), the valleyside forests of the watershed are involved in DOC production. Conversely, the importance of carbon inputs from the floodplain has been emphasized (Ittekkot and Arain 1986; Richey et al. 1990). In the Bolivian Llanos, high DOC production may be achieved in the floodplain, and the contribution of the whole-basin forest seems to be of minor importance.

As observed by Spitzy and Leenheer (1991), DOC production increases linearly with increasing runoff. DOC specific yield is obviously correlated with specific discharge, as DOC contents exhibit limited variations during the hydrological cycle. But the salient feature of the Bolivian data (Fig. 7) is once more the clear separation between the Andes and the Llanos, the regression coefficients for both zones being significantly different. The DOC production for a given runoff is ~3 times higher in the Llanos than in the Andes, suggesting that different processes prevail in each region.

Despite the relatively small number of samples, the first insight into the DOC spatial pattern in the Amazonian basin of Bolivia has shown a clear distinction and a rapid transition between two domains: the Andes and the Llanos. This difference in DOC content seems to correspond to a distinct origin of DOC production: the valleyside forests in the Andes and, presumably, the floodplain wetlands in the Llanos. As a consequence, deforestation should not have the same impact on DOC dynamics in these two domains.

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