Biogeochemistry of Carbon in the Amazon River

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Biogeochemistry of carbon in the Amazon River

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Abstract

Depth-integrated, discharge-weighted water samples were collected over 1,800 km of the Amazon River on eight cruises at different stages of the hydrograph, 1982–1984. Fine (FPOC, <63 μm) and coarse (CPOC, >63 μm) particulate organic carbon as weight percentage of suspended sediment varied between 0.9–1.5% for FPOC and 0.3–3.4% for CPOC. Concentrations of FPOC ranged from 5 mg liter⁻¹ upriver to 2 mg liter⁻¹ downriver in the mainstem and from 6 mg liter⁻¹ in the Rio Madeira to <1 in the Rio Negro. CPOC had similar distribution patterns, but with concentrations 15–30% those of FPOC. Dissolved organic carbon (DOC) averaged 4–6 mg liter⁻¹ in the mainstem and up to 12 mg liter⁻¹ in the Rio Negro. Upriver dissolved inorganic carbon (DIC) concentrations of about 1,200 μM were diluted by tributaries and floodplain drainage to 600 μM at the most downriver site. Evasion of CO₂, invasion of O₂, and in situ oxidation were of comparable magnitude, 3–8 μmol m⁻² s⁻¹.

The average export of total organic carbon (TOC) was 36.1 Tg yr⁻¹ (8.5 g m⁻² yr⁻¹), of which 62% was DOC, 34% was FPOC, and 4% was CPOC. TOC inputs were insufficient to support in situ oxidation by a factor of at least two. A relatively small, rapidly cycling pool of labile organic matter may coexist with a much larger pool of more refractory material.

A central problem in riverine ecology is to determine how the dynamics of carbon vary as flowing waters increase in size from first-order springs and seeps to the world’s great rivers. With the advent of the energy

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Contribution 32 from the CAMREX project and 1824 from the School of Oceanography, University of Washington.

budget approach (Odum 1957; Teal 1957), riverine research has focused on measuring the origin, amount, and form of organic matter that enters a stream segment, the groups of organisms that selectively process this material, and the material that is ultimately exported via oxidation and downriver transport (e.g. Fisher and Likens 1973; Hynes 1975; Minshall et al. 1983; Cummins et al. 1983; Elwood et al. 1983). Changes in chemical and biological processes along a river network have been viewed as a continuously integrated series of adjustments to the physical constraints imposed by fluvial geomorphology (Vannote et al. 1980; Statzner and Higler 1985). Although intended to be universal, these approaches have been developed primarily for unperturbed, temperate streams of sixth order or less. Little is known of metabolic patterns in larger rivers (Degens 1982; Naiman 1983).

Tropical floodplain rivers drain vast rain forest and savannah environments and account for >30% of the freshwater discharge
to the oceans (Meybeck 1982). Of the continuum of rivers, such continental scale systems represent the end-members, without which no theory of river function is complete. Carbon fluxes in these systems represent an extension of the properties of the smaller rivers that form them; their main channel acts as an “integrator” of basin-wide properties (Welcomme 1979; Richey et al. 1980). Carbon in transport is a mixture of materials ranging from those introduced continuously from the adjacent floodplain to those originating thousands of kilometers away in upland regions. From Vannote et al. (1980) and Minshall et al. (1985) it may be inferred that forests of headwater regions quantitatively dominate the C input to the main channel of large rivers in the form of refractory particulate and dissolved organic materials, which are oxidized at low and constant rates. Sedell et al. (1989) concluded, however, that it may not be possible to extrapolate the concepts of the longitudinal continuity of upland streams to large rivers and that a biogeochemically based ecosystem approach to large rivers is necessary.

In this paper, we analyze the spatial and temporal dynamics of particulate and dissolved organic and dissolved inorganic carbon and oxygen over 1,800 km of the Amazon River between Vargem Grande and Obidos, Brazil (Fig. 1). Our intent is to test and revise as needed the hypothesis of Richey et al. (1980) that while respiration is constant throughout the Amazon at any one time, there are two annual peaks of respiration and that the net export of total organic carbon is constant throughout the hydrological cycle. The analysis is placed within the context of the carbon dynamics of large rivers in general.

This research is part of the CAMREX (Carbon in the Amazon River Experiment) project, the first systematic analysis of the biogeochemistry of a very large river. Previous research on the Amazon River system had been restricted to isolated sites or time periods (Gibbs 1972; Schmidt 1973; Fisher and Parsley 1979; Stallard and Edmond 1983).

The Amazon River system and analytical framework

The Amazon basin, with an area of $6 \times 10^6$ km$^2$, contains the largest stand of tropical rainforest in the world and contributes 20% of the world’s river discharge to the oceans. (General biogeochemical and hydrological properties of the basin have been reviewed by Sioli 1983.) The main channel
of the Amazon River receives input from major and minor tributaries, and exchanges water and elements with an annually inundated floodplain, or "varzea." The varzea acts as a large reservoir (50,000 km² in the reach between Vargem Grande and Obidos) for flood discharge and local precipitation. Depending on the season, up to 30% of the flow in the mainstem is derived from water that has passed through the floodplain (Richey et al. 1989). Aquatic primary production occurs on the banks of the river and in the varzea; there is essentially no primary production in the main channel (Wissmar et al. 1981; Devol et al. 1987).

**Study reach: Vargem Grande–Obidos**—The 1,800-km reach of the Amazon selected for this study includes most of the important tributaries and floodplain of the Brazilian Amazon (Fig. 1). The reach can be divided into three geomorphically distinct regions (Melack 1984; Mertes 1985). The upstream reach (Vargem Grande to Itapeua) is characterized by deposition of sand in the main and floodplain channels, with subsequent rapid migration of these channels to produce an intricate scroll-bar topography with hundreds of long, narrow lakes. The Amazon at Vargem Grande carries primarily water from the Andes, while the Rios Içá and Japurá originate in the Andes and cross the lowland plains to the mainstem, and the Rios Jutaí and Juruá drain the sub-Andean trough and the central plain. The middle reach, between Itapeua and São José do Amatari, is controlled by structural features that constrain the river and allow almost no morphological change. The floodplain is narrow and lakes are less numerous. The Rio Purús drains the sub-Andean trough and central plain, while the Rio Negro drains primarily the caatinga forest on the Planalto das Guianas, and its major tributary, the Rio Branco, drains a drier savannah region.

In the downstream reach, São José do Amatari–Obidos, an incomplete levee system provides free access for overbank flows to a wide floodplain of relatively flat-lying topography and a patchwork of wide, shallow lakes. The Rio Madeira is the primary tributary; it originates in the Bolivian Andes and then passes across the Planalto Brasileiro and the central plain.

**Experimental design**—The basis for our analysis is a mass-balance model in which the river is treated as a series of linked reaches (Richey 1983). All parameters discussed in this paper are identified in the list of symbols. For each reach, the flux balance for particulate organic species is

\[
\Delta F = F_{\text{in}} + F_{\text{tr}} + F_{\text{fp}} - F_{\text{ot}} - F_r. \tag{1a}
\]

Flux balances for CO₂ and O₂ include in addition diffusive gas exchange (negative for CO₂, positive for O₂), and F₉ is negative for O₂.

\[
\Delta F = F_{\text{in}} + F_{\text{tr}} \pm F_e + F_{\text{fp}} - F_{\text{ot}} \pm F_{\text{ex}}. \tag{1b}
\]

Changes in volume within the river channel are small relative to the inputs and outputs listed in Eq. 1 (Richey et al. 1989) and are neglected here.

We measured the terms of Eq. 1 at intervals of 100–200 km and 3–4 months. The overall reach was defined by 18 sampling stations, 11 stations located in the mainstem just upstream of tributary confluences and 7 in major tributaries (Fig. 1). The data were collected primarily on a series of eight cruises between 1982 and 1984, each at a different stage of the hydrograph. On each cruise of the LM Amanai we sampled from the uppermost station, Vargem Grande, down to the last station, Obidos, in a quasi-Lagrangian mode (current and effective boat velocity were roughly comparable at 1–2 m s⁻¹).

**Field sampling and chemical methods**—To obtain horizontally and vertically integrated measurements of overall material transport, we used a modified equal-width-increment procedure with vertical integration (see Richey et al. 1986). A variable-speed hydraulic winch was used to deploy an instrument array consisting of a 130-kg sounding weight, a Price AA current meter, and a collapsible-bag sampler by lowering it from the surface to the bottom and back at a constant velocity. Eighteen equidistant vertical sampling profiles were taken at each mainstem station (fewer on tributaries) with positioning determined by shipboard monitoring of a 3-marker baseline on shore.
Fifty-one floodplain lakes and river side-channels ("paranas") were sampled from a small boat concurrently with the mainstem sampling (Forsberg et al. 1988; Richey et al. 1988). Most lakes were located within 5 km of a navigable river and were connected to it by a channel at the time of sampling. Surface and bottom samples were collected with a Niskin bottle near the center of smaller lakes, near the connecting channel in very large lakes, and at the surface near mid-channel in the paranas.

Samples of fine (<63 μm) and coarse (>63 μm) suspended sediments were separated by sieving and the fine fraction was recovered by continuous centrifugation (Hedges et al. 1986a). Both size fractions were dried (50°C) aboard ship and returned to Seattle for analysis of organic C and total N with a Carlo Erba CHN analyzer (model 1106) (Hedges and Stern 1984; Hedges et al. 1986a). Concentrations of POC were then calculated as the product of the wt% and suspended sediment concentrations (from Richey et al. 1986) and reported as FPOC and CPOC. DOC samples were isolated aboard ship by filtration through precombusted Gelman GFF glass-fiber pads and preserved with 0.1 ml of saturated HgCl₂ (60 ml⁻¹) per sample. Samples were returned to Seattle and analyzed by ultraviolet-catalyzed persulfate oxidation on a Dohrmann DC-80 organic carbon analyzer.

Because of the slight mixing generated by the collapsible-bag sampler, samples for dissolved gases were taken with a Niskin bottle at five points (3-m depth) across mainstem sections. Samples for pH determination were analyzed immediately after collection in a closed container with a Corning model 130 pH meter and an Orion Ross electrode. Alkalinity was determined by micro-Gran titration (Edmond 1970); DIC and CO₂ were calculated from pH and alkalinity (Skirrow 1975). Stallard (1980) showed that these calculated values agreed with those measured by infrared CO₂ analysis for a variety of Amazon waters, and we have comparable results with gas chromatography (unpubl. data). Samples for SiO₄ were measured colorimetrically aboard ship (Strickland and Parsons 1972) and for Ca were analyzed by plasma induction (Jarrel-Ash) at the Centro de Energia Nuclear na Agricultura (CENA).

Ambient oxygen concentrations were determined with a YSI (model 58) or a Radiometer oxygen meter. Oxygen consumption rates were determined directly on aliquots of composite samples from measured changes in O₂ concentration in samples incubated in 60-ml BOD bottles at in situ temperatures (28°±2°C) (Devol et al. 1987).

**Flux calculations**—The fluxes \( F_{\text{in}} \), \( F_{\text{ex}} \), and \( F_{\text{tr}} \) for each reach were calculated as the product of the respective concentrations for each species at each reach boundary and water discharge for that site (Richey et al. 1986; Richey et al. 1989). The floodplain input was calculated as the product of the mean concentration for that species on the floodplain in that reach (from the discrete floodplain sampling) and the flux of water between the mainstem and the floodplain (Richey et al. 1989). We assumed that the

<table>
<thead>
<tr>
<th>Significant symbols</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{in}} ), ( F_{\text{ex}} ), ( F_{\text{tr}} )</td>
<td>Flux in from upstream, major tributaries, and local channels and net exchange with the floodplain, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>( F_{\text{et}} )</td>
<td>Flux out downstream, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>( F_{r} )</td>
<td>Respiration, μM h⁻¹, μmol m⁻² s⁻¹, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>( F_{\text{ex}} )</td>
<td>Diffusive gas exchange, μmol m⁻² s⁻¹, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>( F_{mb} )</td>
<td>Mobilization of particles, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>( \Delta F )</td>
<td>Cumulative imbalance due to measurement uncertainty and unidentified fluxes, kg s⁻¹, Tg yr⁻¹</td>
</tr>
<tr>
<td>wt%</td>
<td>Carbon wt% of suspended sediment, %</td>
</tr>
<tr>
<td>POC</td>
<td>Particulate organic carbon, mg liter⁻¹</td>
</tr>
<tr>
<td>FPOC, CPOC</td>
<td>Fine (&lt;63 μm) and coarse (&gt;63 μm) particulate organic carbon, mg liter⁻¹</td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved organic carbon (passes GFF filter), mg liter⁻¹</td>
</tr>
<tr>
<td>DIC</td>
<td>Total dissolved inorganic carbon, μM</td>
</tr>
<tr>
<td>CO₂</td>
<td>Free dissolved carbon dioxide, μM</td>
</tr>
<tr>
<td>CO₃⁻</td>
<td>Dissolved oxygen, μM</td>
</tr>
<tr>
<td>D</td>
<td>In-water molecular diffusion coefficient (=2.1 for CO₂; =2.6 for O₂), 10⁻³ cm² s⁻¹</td>
</tr>
<tr>
<td>( z )</td>
<td>Empirical thickness of a hypothetical stagnant boundary layer (=50), μm</td>
</tr>
<tr>
<td>( C_{\text{eq}} )</td>
<td>Gas concentration at equilibrium with the atmosphere, μM</td>
</tr>
<tr>
<td>C</td>
<td>Bulk concentration of the respective gas (mean of the measurements at the reach boundaries), μM</td>
</tr>
</tbody>
</table>
particulate concentrations in the floodplain waters were negligible.

The diffusive fluxes of CO₂ and O₂ between the atmosphere and water for each reach were calculated with a stagnant film gas transfer model,

\[ F_{\text{ex}} = D(C_{\text{eq}} - C)/z \]  
(Devol et al. 1987, 1988; Richey et al. 1988).

Respiration rates within a sampling reach were calculated in two different ways. Respiration per unit of volume was determined as the mean time rate of change of oxygen from the incubation measurements at the reach boundaries. Respiration per unit of surface area of a reach was calculated indirectly from the O₂ mass balance (Eq. 1b) as (assuming \( \Delta F = 0 \))

\[ F_r = F_{\text{in}} + F_{\text{ir}} + F_{\text{fp}} + F_{\text{ex}} - F_{\text{ot}}. \]  
(3)

Statistical tests — The Mann-Whitney test (Sokal and Rohlf 1981) was used to identify statistically significant differences in a parameter between time periods. The Spearman’s rank correlation procedure (Zar 1974) was used to identify upstream–downstream gradients in a parameter. Significant relations are indicated in the text by the abbreviation of the test statistic (M.W. for Mann-Whitney or \( r_s \) for Spearman’s rank correlation) and the significance level.

Spatial and temporal variability of carbon and oxygen

The CAMREX cruises result in eight synoptic “snapshots” of the spatial and temporal variability of the chemical species measured. Daily hydrograph records (Richey et al. 1989) at four stations along the sampling reach set our measurements in the context of the overall hydrograph for 1982–1984 (Fig. 2). Cruise 1 was near peak high water, cruises 3 and 7 were on the ascending limb of the hydrograph, and cruise 4 followed a brief reduction in discharge. Cruises 5 and 8 were on the early descending limb of the hydrograph and cruise 2 was on the late descending limb; cruise 6 was immediately past low water. For the discussion below, cruises 1, 3, 4, 6, and 7 are aggregated as rising-water and cruises 2, 5, and 8 as falling-water periods.

Organic carbon distributions — The overall mean wt% of FPOC in the Amazon River was 1.2%; the rising-water mean of 1.1% was significantly less than the falling-water mean of 1.3% (M.W. \( P < 0.01 \)) (Fig. 3). During rising water, the wt% of FPOC did
not change significantly over the length of the reach, whereas there was a significant increase downstream at falling water \((r_s P < 0.01)\). Downstream increases were the most pronounced during the period of rapidly falling water, reaching 1.6\% (cruise 2). In contrast, the wt\% of CPOC (overall mean of 1.1\%) did not significantly differ between rising and falling water. From Vargem Grande (km 0) to Manacapuru (km 1,000), the mean wt\% of CPOC was 0.9\%. At rising water, however, there were dramatic increases in wt\% CPOC at Sao Jose do Amatari (km 1,200), immediately below the confluence of the Rio Negro with the mainstem, with values approaching 3.4\%.

With FPOC and CPOC being relatively constant in wt\%, the POC distributions closely tracked the respective suspended sediment distributions (Richey et al. 1986) (Fig. 4). Overall mean FPOC concentration was 2.7 mg liter\(^{-1}\), with the rising-water mean of 3.1 mg liter\(^{-1}\) being significantly greater than the falling-water mean of 2.1 mg liter\(^{-1}\) (M.W. \(P < 0.01\)). With inputs from the generally more dilute tributaries, there was a pronounced decrease in FPOC downstream from Vargem Grande to Sao Jose do Amatari during rising water, from 4.6 to 3.0 mg liter\(^{-1}\) \((r_s P < 0.01)\). During rising water, the Rios Icá, Jutaí, Juruaí, Japurá, and Purús were comparable to each other, 1–2.5 mg liter\(^{-1}\), and 2–3 mg liter\(^{-1}\) more dilute than the mainstem, while the Rio Negro had the lowest concentrations, <1 mg liter\(^{-1}\). After input from the sedi-
ment-rich Rio Madeira, 4–6 mg liter\(^{-1}\), FPOC remained constant or increased to Obidos. During falling water, there was no significant downstream trend; all tributaries, including the Rios Madeira and Negro, were 1–2 mg liter\(^{-1}\) more dilute than the mainstem.

CPOC exhibited similar distribution pat-
terns to FPOC, but concentrations were considerably lower, averaging <15–30% of the fines, with an overall mean of 0.5 mg liter⁻¹. The rising-water mean of 0.6 mg liter⁻¹ was significantly greater than the falling-water mean of 0.4 mg liter⁻¹ (M.W. $P < 0.01$). Unlike FPOC, CPOC decreased downstream at both rising and falling water ($r_s P < 0.01$). At rising water, CPOC decreased from about 1.0 mg liter⁻¹ upstream to 0.1–0.4 mg liter⁻¹ downstream (in the midreaches on cruise 3, CPOC increased to between 0.9 and 1.2 mg liter⁻¹). The Rios Japurá and Madeira had a wide range of concentrations, depending on cruise, up to 1.2 mg liter⁻¹. All other tributaries were at ≈0.3 mg liter⁻¹. At falling water, CPOC went from 0.6 mg liter⁻¹ upstream to 0.3 downstream. In all cases, tributary concentrations were less than the mainstem, from 0.5 mg liter⁻¹ in the Rio Içá to <0.1 in the Rios Jutaiá, Juruá, Purús, Negro, and Madeira.

DOC accounted for ~50% of the total organic matter transported by the Amazon and was by far the predominant form of organic matter in most tributaries. The overall mainstem mean was 3.6 mg liter⁻¹, with no significant differences between rising and falling water. At rising water there was no significant downstream trend, but at falling water DOC increased downstream ($r_s P < 0.01$), particularly below the Rio Negro. At rising water, the upriver tributaries were on average 1.5–2 mg liter⁻¹ more enriched in DOC than the mainstem (5–7.5 mg liter⁻¹). The Rio Negro ranged from 7 to 10 mg liter⁻¹, while the Rio Madeira concentration was essentially the same as the mainstem. At falling water, DOC concentrations in tributaries were comparable to the mainstem, with only the Rio Negro maintaining higher values.

**Dissolved inorganic C and O₂ distributions**—Overall DIC concentrations are established by lithology and weathering of the respective tributary basins (Stallard and Edmond 1983). About 60–90% of the DIC exists as bicarbonate at the average Amazon pH values of 6.5–7.2, with the balance being dissolved CO₂ gas; carbonate alkalinity is virtually zero. Overall, the mean DIC of 780 μM was comparable to the concentration of TOC (Fig. 5). Dilution of DIC was evident ($r_s P < 0.01$), from ~1,100 μM upstream to 500–600 μM downstream; DIC was slightly greater during rising water (mean 830 μM) than during falling water (mean 720 μM) (M.W. $P < 0.05$). During rising water, DIC was more dilute in all tributaries than in the mainstem. The Rio Juruá had the highest DIC (700–900 μM), the Rios Jutaiá, Purús, and Madeira were comparable (300–600 μM), and the Rios Içá, Japurá, and Negro had the least (<300 μM). During falling water, DIC in the Rio Juruá was elevated relative to high water (900–1,200 μM), while the remaining tributaries maintained concentrations comparable to those at rising water.

The mainstem was supersaturated in CO₂ with respect to the atmosphere by 10–20 times, with an overall mean of 130 μM. In contrast to DIC, CO₂ did not change downstream at rising water (mean 100 μM) and increased downstream at falling water from 110 to 180 μM ($r_s P < 0.01$); downstream increases in CO₂ were accompanied by decreases in pH. At rising water, the tributaries were either comparable in CO₂ to the mainstem (Rios Madeira, Negro, Japurá), up to 200 μM more enriched (Rios Içá, Juruá, and Purús), or from 200 to 400 μM more enriched (Rio Jutaiá). At falling water, the maxima for the Rios Jutaiá and Purús were comparable to rising water, while the Rios Içá, Juruá, and Japurá increased by 100–150 μM. The Rio Negro increased slightly and the Rio Madeira decreased slightly.

Mainstem dissolved O₂ was 50–80% undersaturated relative to the atmosphere, averaging overall 164 μM. As with CO₂ at rising water, O₂ did not change downstream and averaged 164 μM. Concentrations were significantly (M.W. $P < 0.01$) lower at falling water, averaging 158 μM, and decreased downstream ($r_s P < 0.01$). Tributary O₂ concentrations were comparable to the mainstem, except for lower concentrations in the Rios Jutaiá, Juruá, and Purús at falling water.

**Gas exchange and respiration**—The concentrations of dissolved CO₂ and O₂ gases in the mainstem indicated net evasion of CO₂ and invasion of O₂ (Fig. 6). The overall mean evasion of CO₂ was ~5.0 μmol m⁻²
s⁻¹ (negative values indicating loss from the river to the atmosphere). At rising water, the mean was −3.9 μmol m⁻² s⁻¹, with no significant gradient over the sampling reach. The falling-water mean was −6.5 μmol m⁻² s⁻¹, however, with 50–100% increases downriver (r, P < 0.01). The invasion rate of O₂ essentially mirrored the evasion of CO₂ with an overall mean of 4.6 μmol m⁻² s⁻¹, and no significant downstream trend at rising water (mean 4.3 μmol m⁻² s⁻¹). At falling water, there was also a pronounced
downstream increase in O$_2$ invasion rate ($r_2$, $P < 0.01$), but the mean of 5.0 $\mu$mol m$^{-2}$ s$^{-1}$ was slightly less than CO$_2$ evasion rate (M.W. $P < 0.01$).

For comparison with the incubation-derived respiration measurements, the areal respiration rates derived by O$_2$ balance (Eq. 3) were divided by the mean depth of each reach. In neither case was there a significant upstream–downstream gradient; hence results are presented as cruise means (Table 1). Except for the unusually high rates measured on the early cruises (especially cruises 3 and 4), the two independent calculations yielded comparable results, with overall means for the incubations of 2.2 $\mu$M h$^{-1}$ (all cruises) and 1.4 $\mu$M h$^{-1}$ (excepting cruises 3 and 4) and 1.1 $\mu$M h$^{-1}$ for the O$_2$ balance.

We suspect that problems in sampling and incubation techniques account for the high values in the incubation measurements obtained on the early cruises. The O$_2$ balance calculations assume a constant boundary-layer thickness, which may in fact vary with river stage. Calculations of volumetric respiration rates include mean reach depth, which varies with stage and is difficult to estimate. That two methods crossing such different time and space scales yield comparable results indicates, however, that the methods provide reasonable measures of in situ respiration.

We use the O$_2$ balance method on the areal basis for comparison to the other gas exchange fluxes because it is not dependent on mean depth and problems in incubation, and it is consistent with the use of gas exchange and mass balance methods to estimate oxidation rates of Devol et al. (1987, 1988) and Richey et al. (1988). In situ res-
Table 1. Cruise average (a/n) respiration rates derived from incubation measurements, \( F(a) \) and areal \( \text{O}_2 \) mass balance, \( F(a) \), normalized per unit of depth of the reach, \( F(a) \). Overall averages were calculated with (avg 1) and without (avg 2) cruises 3 and 4.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>( F(0) ) (( \mu \text{mol h}^{-1} ))</th>
<th>( F(a) ) (( \mu \text{mol h}^{-1} ))</th>
<th>( F(a) ) (( \mu \text{mol m}^{-2} \text{s}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.6 (0.1)</td>
<td>1.0 (0.1)</td>
<td>4.6 (0.5)</td>
</tr>
<tr>
<td>3</td>
<td>5.5 (0.5)</td>
<td>0.9 (0.1)</td>
<td>3.9 (0.2)</td>
</tr>
<tr>
<td>4</td>
<td>3.2 (0.2)</td>
<td>0.9 (0.1)</td>
<td>6.0 (0.2)</td>
</tr>
<tr>
<td>5</td>
<td>2.1 (0.2)</td>
<td>1.6 (0.2)</td>
<td>6.5 (0.6)</td>
</tr>
<tr>
<td>6</td>
<td>0.9 (0.1)</td>
<td>0.9 (0.1)</td>
<td>3.1 (0.04)</td>
</tr>
<tr>
<td>7</td>
<td>1.4 (0.1)</td>
<td>1.0 (0.1)</td>
<td>4.4 (0.3)</td>
</tr>
<tr>
<td>8</td>
<td>0.8 (0.04)</td>
<td>1.1 (0.1)</td>
<td>4.9 (0.4)</td>
</tr>
<tr>
<td>Avg 1</td>
<td>2.2 (0.2)</td>
<td>1.1 (0.04)</td>
<td>4.9 (0.2)</td>
</tr>
<tr>
<td>Avg 2</td>
<td>1.4 (0.1)</td>
<td>1.1 (0.04)</td>
<td>4.9 (0.2)</td>
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Respiration rates were of comparable magnitude to the \( \text{CO}_2 \) evasion and the \( \text{O}_2 \) invasion rates, with an overall mean of 4.9 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) (Table 1). Rates varied with the hydrograph; respiration was significantly higher (M.W. \( P < 0.01 \)) at falling water (mean 5.6 \( \mu \text{mol m}^{-2} \text{s}^{-1} \)) than at rising water (mean 4.3 \( \mu \text{mol m}^{-2} \text{s}^{-1} \)).

Seasonal and annual fluxes—Because distributions of carbon and oxygen on any one cruise changed only gradually between stations, we calculated advective fluxes, gas exchange, and respiration over the three geomorphologically distinct reaches identified above, Vargem Grande—Itapeua (reach 1), Itapeua—São José do Amatari (reach 2), and São José do Amatari—Obidos (reach 3) (Fig. 7). Perhaps the common denominator used most frequently for comparing river systems of widely varying properties is the annual export of \( C \), both on an absolute scale and per unit of area of drainage basin (Table 2).

The advection of FPOC from upstream dominated the total inputs to reach 1 and were greater during mid-to-late rising water (250 kg s\(^{-1}\)) than during early rising (80 kg s\(^{-1}\)) or falling water (120 kg s\(^{-1}\)). Tributaries averaged 40 kg s\(^{-1}\). Similarly, upriver inputs were the primary source of FPOC to reach 2, averaging 250 kg s\(^{-1}\) at rising water and 200 at falling water; tributaries contributed <40 kg s\(^{-1}\). In turn, advective input from reach 2 to reach 3 was the major input only during falling water, averaging over all stages 250 kg s\(^{-1}\). At rising water, the tributary input (the Rio Madeira) was comparable.

Of the total upstream and tributary FPOC input of 11.5 Tg yr\(^{-1}\), 49% enters the overall reach at Vargem Grande and 33% via the Rio Madeira. The fluxes averaged annually per unit of basin area of the Rios Içá, Jutai, Juruá, Japurá, and Purús were 20–40% that of Vargem Grande. The area-normalized flux of FPOC in the Rio Madeira during high discharge was comparable to that of Vargem Grande, and overall it was comparable to the other tributaries, whereas the Rio Negro had the lowest areal flux.

Input advective fluxes of CPOC at Vargem Grande ranged from 20 kg s\(^{-1}\) at lowest water to 50 kg s\(^{-1}\) at high rising water, increased at reach 2 to a high-water maximum of 70 kg s\(^{-1}\), and averaged 50–60 kg s\(^{-1}\) into reach 3 on all cruises except 6. The primary tributary inputs were from the Rio Madeira at high water, when they were comparable to combined upstream inputs.

The annual average CPOC export flux of 1.6 Tg yr\(^{-1}\) at Obidos was 13% of the FPOC flux. Of the upstream and tributary inputs, CPOC was derived principally from Vargem Grande (60%) and the Rio Madeira (30%). Areal fluxes of CPOC in the Rios Içá, Japurá, and Madeira were 30–64% that of Vargem Grande, and <10% in the other tributaries.

Average DOC inputs to reach 1 of 400 kg s\(^{-1}\) were divided among upstream, tributary, and varzea sources. Varzea drainage was the dominant input at falling water, with a maximum of 400 kg s\(^{-1}\). In the midreach, the varzea contribution was negligible, while the tributary inputs, primarily the Rio Negro, were comparable to the upstream input, averaging 300 kg s\(^{-1}\). Finally, the downstream reach was dominated by the upstream input, averaging 700 kg s\(^{-1}\) during falling and late rising water and 400 kg s\(^{-1}\) during the other stages; contributions from the Rio Madeira and varzea averaged 60–120 kg s\(^{-1}\).

The annual average export of DOC at Obidos was 22.1 Tg yr\(^{-1}\). Of the total upstream, tributary, and varzea input of 26.1 Tg yr\(^{-1}\), 31% was from the Rio Negro, 20% was from Vargem Grande, and 17% was from varzea drainage. Area-normalized fluxes of DOC were greatest at falling water. Relative to Vargem Grande, the Rio Negro
had the greatest export of DOC per unit of area (250%), followed by the Rio Jutaí (180%) and the Rio Purús (100%). Curiously, the Rio Juruá, in between the Rios Jutaí and Purús, had the lowest fluxes (70%). The Rios Içá and Japurá had fluxes comparable to Vargem Grande.

Reach 1 rising-water DIC fluxes were primarily from upstream, averaging 600 kg s\(^{-1}\), while at falling water, inputs of 500 kg s\(^{-1}\)
Table 2. Average annual fluxes (F, Tg yr\(^{-1}\)) and average annual fluxes per unit of drainage basin area (F/A, g m\(^{-2}\) yr\(^{-1}\)). (Obidos and Rio Madeira from cruise 1 estimated.)

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>F/A</th>
<th>F</th>
<th>F/A</th>
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</tr>
<tr>
<td>Vargem Grande</td>
<td>5.6</td>
<td>5.1</td>
<td>1.2</td>
<td>1.1</td>
<td>5.3</td>
<td>4.8</td>
<td>12.1</td>
<td>11.1</td>
</tr>
<tr>
<td>Rio Içá</td>
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<td>2.1</td>
<td>0.0</td>
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<td>0.8</td>
<td>5.6</td>
<td>1.1</td>
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</tr>
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<td>0.1</td>
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<td>8.7</td>
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</tr>
<tr>
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<td>0.0</td>
<td>0.1</td>
<td>0.6</td>
<td>3.2</td>
<td>0.8</td>
<td>4.2</td>
</tr>
<tr>
<td>Rio Japurá</td>
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<td>1.7</td>
<td>5.1</td>
<td>2.6</td>
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</tr>
<tr>
<td>Rio Purús</td>
<td>0.4</td>
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<td>0.0</td>
<td>0.1</td>
<td>1.7</td>
<td>4.8</td>
<td>2.1</td>
<td>5.9</td>
</tr>
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<td>Rio Negro</td>
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<td>0.6</td>
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<td>8.1</td>
<td>12.0</td>
<td>8.5</td>
<td>12.6</td>
</tr>
<tr>
<td>Rio Madeira</td>
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<td>?</td>
<td>4.4</td>
<td>3.5</td>
<td>6.5</td>
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</table>

included more tributary and varzea sources. Reach 2 and reach 3 sources were dominated by upstream inputs of 700–1,200 kg s\(^{-1}\), following the input of low-alkalinity tributary waters.

Fluxes of CO\(_2\) were greatest during falling water. In reach 1, upstream inputs of CO\(_2\) were less than individual tributary, varzea, or respiratory inputs of 50–250 kg s\(^{-1}\). Outputs were evenly divided between evasion and advection. In the middle reach, varzea influence diminished, with upstream, tributary, and respiratory fluxes being roughly comparable. Finally, in the downstream reach, advection of 300–500 kg s\(^{-1}\) from upstream was larger than the other sources at falling water and comparable to respiration at rising water. Export of CO\(_2\) was greatest at falling water, with evasion of 250 kg s\(^{-1}\) and advection of 300–500; rising-water losses via evasion and advection were about 200–300 kg s\(^{-1}\).

The average annual efflux of DIC (35 Tg yr\(^{-1}\)) at Obidos was comparable to that for TOC. Of the total upstream, tributary, and floodplain inputs, 50% entered at Vargem Grande, 16% from the varzea, 20% from the Rios Madeira and Purús, and the remainder from the other tributaries. The area-normalized DIC flux at Vargem Grande (18.2 g m\(^{-2}\) yr\(^{-1}\)) was at least twice that of the tributaries. The total annual evasion of CO\(_2\) was about 50% of total DIC export, derived in large part from in situ respiration.

The annual export of TOC from Obidos was 36.1 Tg yr\(^{-1}\), of which 62% was DOC, 34% was FPOC, and 4% was CPOC. It compares to the estimate of 60 Tg yr\(^{-1}\) of Richey et al. (1980), based on two sampling cruises and different sampling methodologies. Per unit of drainage basin area, TOC export ranged from 3.6 g m\(^{-2}\) yr\(^{-1}\) in the Rio Madeira to 12.6 in the Rio Negro; the total export from Obidos was 8.5 g m\(^{-2}\) yr\(^{-1}\).

Comparison with other large rivers—The carbon distributions observed in the Amazon mainstem are not extraordinary relative to other river systems; knowledge of the C composition of major world rivers has increased recently (Degens et al. in press). Meybeck (1982) calculated global averages for DOC (5.8 mg liter\(^{-1}\)), wt% POC (1%), and estimated riverine TOC export as 1–2% of net basin primary production. Concentrations of DOC in other South American tropical rivers are comparable. In the Orinoco River system, DOC concentrations are in the range of 1.6–6.3 mg liter\(^{-1}\) and in the Parana, 9 mg liter\(^{-1}\) (Lewis et al. 1986; Depeetris and Paolini in press). Tropical African rivers cover a similar range, 2.4–8.5 mg liter\(^{-1}\) (Martins and Probst in press). Schlesinger and Melack (1981) summarized the rate of loss of organic C by world ecosystem types. They calculated mean TOC as 10 mg liter\(^{-1}\) and reported a mean export rate of 7.2 g m\(^{-2}\) yr\(^{-1}\), yielding a global export of 400 Tg yr\(^{-1}\) to the oceans.

Based on more detailed data for rivers of Asia and South America, Degens and Ittekot (1985) found that previous assumptions that the wt% of POC decreased with increased suspended sediment concentrations
were not true across seasons and that the total riverine flux of TOC was 600–900 Tg yr\(^{-1}\). This latter estimate is very close to the estimate of 1,000 Tg yr\(^{-1}\) of Richey et al. (1980), which included in situ oxidation (\(~50\%\) of the TOC flux). That CO\(_2\) is maintained considerably in excess of atmospheric equilibrium and O\(_2\) is maintained at less than equilibrium in many world rivers (Kempe 1982) implies that relatively high respiration may be common in large river systems.

**Organic composition and flux mass balance**

*Organic carbon composition—*Changing chemical composition and patterns of fluxes are indicative of the processes which control the distributions of the various carbon species. In previous papers, we have discussed some of the compositional characteristics of the organic C in transport, based on analyses of \(\delta^{13}\)C, \(\Delta^{14}\)C, C:N ratios, and lignin compositions characteristic of particular tissue types.

Hedges et al. (1986a) found that the FPOC in transport is characterized by high N content (low C:N) and low concentrations of lignin that apparently have been extensively degraded by microorganisms; Hedges et al. (1986b) determined an upper bound on average residence time of FPOC in the basin of \(<600\) yr. These uniform compositional features and the near-conservative behavior of FPOC in transport relative to sediment suggests that the bulk of this organic matter is soil derived and refractory within the river. The coexisting CPOC fraction is compositionally distinct and predominantly a mix of leaf (\(~80\%\)) and wood (\(~20\%\)) remains, which are less diagenetically altered than the FPOC and much more recent in origin. Varzea grass remains are apparently minor (\(<10\%\)) components of this mixture.

The dramatic increase in wt% of CPOC at São José do Amatari during rising-water cruises (Fig. 3) may be indicative of the interplay between the transport dynamics of suspended particles and their different compositions. With the increase in wt%, total concentrations of CPOC decreased, indicating the absence of a large CPOC source between the Rios Negro and Madeira; usual elemental or molecular compositions of the CPOC were not observed (Hedges et al. 1986a). The lower Amazon mainstem is effectively dammed during early rising water by previous cresting of the Rio Madeira; this impedance slows the flow of the mainstem, thereby reducing its capacity to transport suspended particles (Meade et al. 1985). This phenomenon is clearly indicated by pronounced decreases in the ratio of coarse to fine total suspended sediment at São José do Amatari during periods of rising water (Meade et al. 1985; Richey et al. 1986).

The greatest effect of differential particle settling on wt% of organic C should be observed in the coarse size fraction, which consists primarily of sand grains and physically separate coarse plant debris (Hedges et al. 1986a). Less dense plant debris settles more slowly than sand (J. Hedges pers. obs.) and therefore concentrates in suspension when river velocity decreases. These observations are consistent with a model of the preferential removal of sand vs. coarse plant debris with a reduction in current velocity, leading to the elevated wt% of CPOC without changes in its sources or compositions.

Dissolved humic substances average 60% of total riverine DOC, with slightly higher values for blackwater tributaries (Ertel et al. 1986). The lignin component of the dissolved humic substances is relatively uniform in the mainstem and has undergone a much greater degree of oxidative degradation than lignin in the coexisting particulate fractions. The humic fraction has an upper bound on average residence time within the basin of \(<150\) yr (Hedges et al. 1986b). These data indicate that the diagenetic transformation of dissolved humic substances also has occurred predominantly in the terrestrial environment.

These results are consistent with data from other rivers. Dahm (1981) concluded that the constancy of TOC flux in the Columbia River was indicative of the refractory nature of the (dominant) dissolved load. Ittekot et al. (1985) found that the organic matter associated with peak sediment discharge in the Ganges River was dominated by degraded fine materials; Ittekot (1988) estimated that only 15% of POC in high-sediment rivers in general is potentially labile.
Table 3. Mass balance anomalies (ΔF%, Eq. 4, text) for reaches 1 (Vargem Grande–Itapeua), 2 (Itapeua–São José do Amatari), 3 (São José do Amatari–Obidos), and overall (Vargem Grande–Obidos) for rising- and falling-water cruises. Data for fine and coarse suspended sediments (FSS and CSS) from Richey et al. (1986). TOC (−r) an TOC (+r) are the TOC balances without and with respiration.

<table>
<thead>
<tr>
<th></th>
<th>Rising</th>
<th></th>
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<tbody>
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<tr>
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<td>38</td>
<td>14</td>
<td>47</td>
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<td>−32</td>
<td>−32</td>
<td>26</td>
<td>39</td>
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<td>−34</td>
<td>−54</td>
<td>106</td>
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<td>13</td>
<td>237</td>
<td></td>
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<tr>
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<td>−7</td>
<td>−4</td>
<td>−16</td>
<td>−25</td>
<td>−2</td>
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<td>4</td>
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<td>1</td>
<td>−10</td>
<td>−6</td>
<td>−12</td>
<td>−8</td>
<td>3</td>
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<tr>
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<td>306</td>
<td>30</td>
<td>16</td>
<td>157</td>
<td>22</td>
<td>20</td>
<td>24</td>
<td>73</td>
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Flux mass balance—Differences between the fluxes observed in a reach and the fluxes expected in a reach can provide insight into not only uncertainties in the mass balances, but also in processes not accounted for in the initial mass balance (Table 3). To identify possible flux anomalies on a comparative basis, we express ΔF (Eq. 1) as

$$\Delta F\% = \left[ \frac{(F_{\text{out}} + F_{\text{r}} - F_{\text{in}} - F_{\text{v}} - F_{\text{p}})}{F_{\text{in}} + F_{\text{v}} + F_{\text{p}}} - 1 \right] \times 100$$

(4)

(ΔF% for CO₂ and O₂ would include Fᵣ in the denominator). A positive ΔF% (in excess of measurement uncertainty) implies that there is a source not accounted for in the model for that reach; a negative ΔF% (in excess of measurement uncertainty) implies that there is a sink unaccounted for.

We estimated the error associated with the flux mass balances of the respective C species empirically from the fluxes of the chemically conservative constituents alkalinity, Ca, and SiO₄. These mass balances were calculated for the up-, mid-, and downriver reaches (Fig. 8). Mean ΔF% for Si averaged 2% and for Ca averaged 5%; ΔF% for alkalinity averaged 6% for each reach. These values are comparable to the estimates for the error (1σ) associated with the water discharge measurement of 2.5% and with dissolved chemical fluxes of 5% reported by Richey et al. (1986). Hence, we will take 10% as the 2-σ C.I. for the uncertainty in the DOC and DIC flux balances. Fluxes of particulate species could have a greater uncertainty, due to the problem of sampling more heterogeneous distributions. We will, therefore, assume overall measurement errors of 15% for FPOC and 20% for CPOC flux balances (Richey et al. 1986). Because of the uncertainty associated with gas exchange and respiration measurements relative to the magnitude of the advective fluxes, we take 35% as the uncertainty in CO₂ mass balances (Devol et al. 1987).

During rising water, FPOC fluxes essentially balance. At falling water, however, there is a significant internal source of FPOC (ΔF% = 121%) in both reach 1 and 3. This anomaly in FPOC closely mirrors that of fine suspended sediments. Patterns of flux mass balance for CPPOC were similar to FPOC during falling water (ΔF% = 93%), with reaches 1 and 2 being the sources. During rising water, there was a net sink of CPPOC, with upriver being a source and reaches 2 and 3 being sinks. As with the fine fraction, flux anomalies for CPPOC were comparable to those of coarse suspended sediments, except that they were more pronounced during rising water in reach 2 and during falling water in reach 1.

Flux mass balances showed that there was a net sink of DOC over the entire study reach at rising (ΔF% = −16%) and particularly at falling (ΔF% = −24%) water; losses were greatest upstream. In contrast to the organic species, DIC and CO₂ fluxes were in balance, within measurement uncertainty.

Including only the advective fluxes of FPOC, CPPOC, and DOC over the entire reach, the TOC pool balances within <12%.
To calculate the respiratory demand on organic C in the river, we assume first that respiration is derived entirely from the measured TOC and that all of the TOC is available. Then, the calculation of the expected TOC must include a loss term for respiration. In this case, there is a shortfall of TOC over the entire reach of a factor of about two ($\Delta F\% = 73\%$ at falling water and $157\%$ at rising water); i.e., respiratory demand is about equal to TOC inputs. If much of the measured POC and DOC in transport has been diagenetically altered before introduction to the river and is mostly recalcitrant material, as suggested by the compositional indices, the shortfall of labile TOC is proportionately greater.

**TOC and oxidation potential**—The immediate conclusion to be drawn from the TOC imbalance when respiration is included as a loss term is that there is not nearly enough organic carbon observed in transport to support in situ oxidation. Organic matter sources of the magnitude required to sustain the measured oxidation must exist that could continuously supply C to the river by lateral exchange. They occur on time and space scales shorter than we have measured to date.

POC transport is to a large extent dependent on the physical processes governing sediment dynamics. That erosion-deposition cycles can mobilize POC within a reach can be deduced from the concurrent patterns of flux anomalies for POC and bulk suspended sediments (cf. Meade et al. 1985; Mertes 1985). During the temporary residence of sediment deposited on the floodplain, carbon new to the river could be added through local primary production, with the enriched particles cycled back into the river through erosion. Our original assumption that the concentration of particulate matter in draining floodplain waters was negligible would appear to be incorrect. An additional term for remobilization ($F_{mb}$) should be included.

DOC was not transported conservatively within the river; there was a sink (possibly respiration) for DOC omitted from the original mass balances. Labile dissolved organics supplied laterally from the varzea are a potential substrate for in-channel respiration. Richey et al. (1988) measured significant cross-channel gradients of dissolved CH$_4$ at falling water. (Such gradients were also observed in detail at high water, May 1987, J. Richey unpubl. data.) Input of waters with CH$_4$ levels typical of the varzea (>10 $\mu$M) at water fluxes of 100–1,000 m$^3$ s$^{-1}$ are sufficient to supply the CH$_4$ levels of 0.01–0.1 $\mu$M observed in the mainstem. Al-
though CH₄ itself constitutes only a minor source of labile organic C, the distinct gradient of CH₄ indicates the potential for a similar gradient of other labile organic molecules of varzea origin.

These calculations influence the interpretation of indices of transport and metabolism that have been used to compare fluvial ecosystems. With annual averages at Vargem Grande of TOC concentration (9.5 mg liter⁻¹), current velocity (1.5 m s⁻¹), and respiration (5 μmol m⁻² s⁻¹), the spiraling length (sensu Newbold et al. 1982) of TOC is about 4,000 km. If, for example, 90% of the TOC is refractory, then the spiraling length of the labile TOC would be 400 km, while that of the refractory fraction would be much greater. By comparison, Newbold et al. (1982) calculated spiraling lengths of 3–40 km for small, temperate streams and rivers. The ratio of respiration to lateral inputs—the stream metabolism index (SMI) of Fisher (1977)—would approach 1.0 if most respiration is supplied from floodplain inputs. This result would agree with the assertions of Newbold et al. that the SMI should approach 1.0 in the downstream reaches of river systems.

The overall implication is that a relatively small, rapidly cycling pool of labile organic matter coexists with the much larger pool of more refractory material that accounts for the bulk of organic matter in transport. The high measured rates of in situ respiration necessitate rapid turnover of this small pool to account for the large fluxes through it. The source of such material(s) would have to be local; such reactive material could not be transported efficiently for long distances. Future research in the Amazon, as well as in other river systems, must address the issue of exactly what materials are being produced and oxidized over short scales.

A model of the Amazon and other very large rivers

The results presented here allow a considerable refinement of previous models of large rivers (Richey et al. 1980; Vannote et al. 1980; Minshall et al. 1985; Sedell et al. 1989). As the Amazon hydrograph is damped and relatively uniform from one year to the next, we assume that our eight cruises constitute sufficient temporal resolution to define the general properties of organic carbon transport.

If so, we can construct a general sequence of C fluxes key to the hydrograph (Fig. 9). Forests of headwater regions do supply carbon at relatively constant rates to the head of the reach; tributaries draining both lowlands and highlands supply the time-varying amounts of C. The FPOC is largely refractory, soil-derived material, but the CPOC is potentially labile, nonwoody, vascular plant debris. Neither component undergoes extensive within-channel modification. Over half of the DOC is humic material, the bulk of which is refractory. Tributary inputs diminish with falling water; but mobilization of POC via erosion and varzea drainage of DOC maintain export rates, particularly in the geomorphologically active upriver reach. Within-channel oxidation does not significantly utilize the bulk of organic C in transport. Rather, labile (probably dissolved) organic substrates supplied laterally from the floodplain on short space scales fuel respiration within the mainstem at a rate higher but more damped than hypothesized by Richey et al. (1980).

Dissolved CO₂ in the river is maintained at high levels predominantly by respiration at rising water and by a combination of respiration and varzea drainage at falling water. At falling water, CO₂ concentrations increase downstream because the level of respiration augmented by varzea inputs is greater than can equilibrate with the atmosphere. Rather than being constant, as initially hypothesized by Richey et al. (1980), total TOC export (at Obidos) tracks the hydrograph, increasing on the rising limb and decreasing with falling discharge. Residence time of TOC in the reach is not sufficient to buffer export to a uniform rate.

We conclude that the biogeochemistry of C in the mainstem carries signals of drainage basin processes operative at several different time and space scales. Variations in discharge and concentrations of dissolved and particulate materials in transport occur on a relatively damped and predictable basis, with changes over several weeks and tens to hundreds of kilometers. This inter-
mediate signal, however, also seems to be affected by processes operating on very different scales. The chemical compositions of the bulk organic matter in transport appear to be established on a decadal basis or longer over large areas of the Andean and tributary basins (and perhaps on the floodplain). Conversely, the level and dynamics of in situ oxidation indicate that there are important processes occurring over hours to days with distances of several kilometers or less.

References


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