CHAPTER 17

Organic Carbon Transported by the Equatorial Rivers: Example of Congo-Zaire and Amazon Basins

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17.1 INTRODUCTION

The consequences of deforestation and land management of equatorial rainforests extend beyond the regional issues of conservation and sustainable land use to global issues of climate change. With CO_2 and CH_4 levels continuing to rise in the atmosphere, many scientists consider the tropical forests as one of the key issues in the global carbon (C) budget. Do the tropical forests act as a source or a sink for atmospheric C? The answer to this question warrants evaluating precisely how much C is retained in soils and vegetation and how much is emitted into the atmosphere and transported to oceans by rivers.

The erosion of C from land to sea via rivers represents a major pathway in the global C cycle (Kempe, 1979; Degens et al., 1984). With respect to the total flux of C and that carried by world rivers (G t yr^{-1}), the contribution of organic C is estimated to represent ~40%, with 16% being exported from the tropical rain forest environment (see Meybeck et al., this volume). Investigations conducted by SCOPE/CARBON program since 1980 (Degens, 1982), have substantially improved our knowledge of the fluvial C fluxes (Degens et al., 1984; 1985; 1991; Kempe et al., 1993; Lewis and Saunders, 1989; Richey et al., 1990; 1991; Paolini, 1995). However, even if the global figures are more precise today, important gaps persist, mainly due to the lack of data for some rivers (Meybeck, 1982; 1993b; IGBP, 1995; Billen et al., 1998), and the scarcity of river sampling unsuited to compute realistic riverine C fluxes. This chapter is concerned with the determination of fluxes of organic C in the two largest rivers in the world: the Congo-Zaire River and the Amazon River, which are both responsible for almost 50% of the freshwater inputs into the Atlantic Ocean (Degens et al., 1991; Probst, 1990). Whereas a large amount of data has been published concerning the Amazon, including the cycling and fluxes of bioactive organic compounds (Richey et al., 1980; Junk, 1985; Ertel et al., 1986; Hedges et al., 1986; Quay et al., 1992; Hedges et al., 1994; Mounier et al., 1998; Patel et al., 1999; Moreira-Turcq et al., 2003), almost nothing has been published on the Congo-Zaire basin with a few exceptions (Martins and Probst, 1991; Seyler et al., 1995). Consequently, comparisons between these two vast rivers draining the largest rainforest areas of the world, and — up to now — weakly impacted by anthropogenic perturbations have not been done.

This chapter considers the organic C species distributions in the two mainstreams and their tributaries, to compare levels and yields between the two basins and to present quantitative estimates of organic fluxes from Congo-Zaire and Amazon rivers entering the Atlantic Ocean.

17.2 METHODOLOGY

17.2.1 General Characteristics of the Studied Basins

17.2.1.1 The Congo-Zaire Basin

The Congo-Zaire basin lies at the center of equatorial Africa (Figure 17.1) and is the second largest basin in the world. Its watershed (3.8×10^6 km^2) is mostly constituted by a large peneplain (altitudes lower than 400 m) surrounded by highlands to the north and the south and by the mountainous chain of the East African valley to the east. Lake Tanganyika and its drainage basin are also part of the Congo-Zaire basin. Its central region is covered by an evergreen forest (50% of the total area) surrounded by tree savannahs (De Namur, 1990). The Congo-Zaire basin is characterized by a wet tropical climate. The mean annual rainfall calculated for the 1980s (Mahe, 1993) is 1550 mm yr^{-1}, and the mean temperature is > 20°C. The hydrological regime of the Congo-Zaire River is mainly pluvial and discharge fluctuations are due to the distribution of its tributaries on both sides of the equator resulting in an annual hydrologic cycle with two maxima in December and May, and minimum flows in August and March. Long-term average discharge at the Kinshasa-

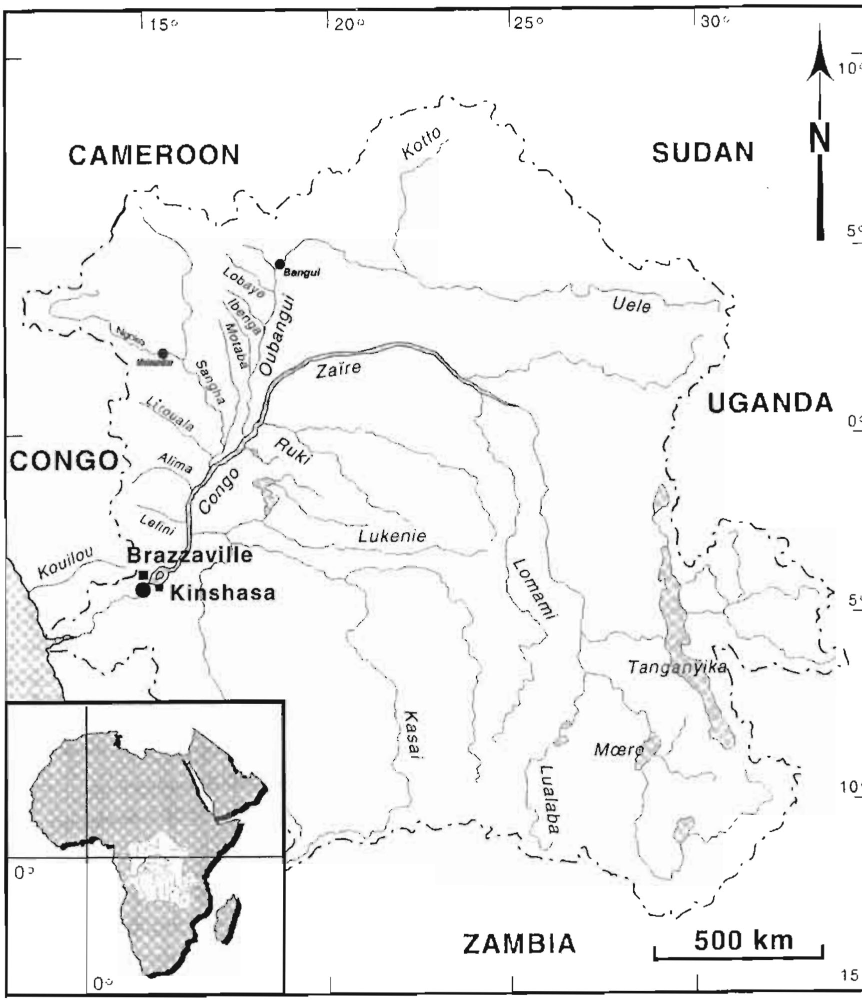

Figure 17.1 Map of the Congo-Zaire basin showing the location of collection sites.

Brazzaville hydrological station is about 40,600 $m^3 s^{-1}$, and average discharge during the study period was 37,700 $m^3 s^{-1}$ or 11 l $s^{-1} km^{-2}$ (Bricquet, 1995). The Congo-Zaire hydrological regime is one of the most steady in the world (irregular interannual ratio = 1.43).

Among the main tributaries of the Congo-Zaire River (Upper Zaire, Oubangui, Ngoko-Sangha, Likouala Mossaka, and Kasaï rivers), the Oubangui and the Ngoko-Sangha are the focuses of the present chapter.

With a drainage basin of about 489,000 km^2 and a mean flow of about 4,200 $m^3 s^{-1}$ (5.8 l $s^{-1} km^{-2}$) at the Bangui gauge station, the Oubangui River is the second most important tributary of the Congo-Zaire River system. The mean annual rainfall of the Oubangui drainage basin is 1,540 mm yr^{-1} and its vegetation mainly comprises dry tree savannah (Boulvert, 1992).

The Ngoko-Sangha River constitutes the upper part of the Sangha River, a right bank tributary of the Congo-Zaire River. It drains an homogeneous forested basin which covers 67,000 km^2. The average rainfall extends upward of 1,700 mm yr^{-1}. The hydrological regime is mainly pluvial, with maximum discharge observed in October and minimum in March through April. A secondary discharge peak occurs in July. The mean annual discharge is 713 $m^3 s^{-1}$ (11.3 l $s^{-1} km^{-2}$). Humid evergreen forest covers 95% of the basin.

Table 17.1 Physical Characteristics of the Congo–Zaire River and Its Tributaries

River	Station	Basin Area km²	Mean Annual Discharge $m^3 s^{-1}$	Runoff $l\ s^{-1}\ km^2$	Forested Area in the Basin %
Oubangui	Bangui	489,000	3,750	7.7	22
Ngoko-Sangha	Moloundou	67,000	715	10.7	95
Congo-Zaire	Kinshasa-Brazzaville	3,500,000	40,600	11.6	50

Major features of the Congo and its tributaries are shown in Table 17.1. More complete information about morphology, lithology, and vegetation of the watersheds has been published by Bricquet (1995), Olivry (1986), Orange et al. (1999), Seyler et al. (1993), and Sigha Nkamdjou et al. (1995).

17.2.1.2 The Amazon Basin

The Amazon basin (Figure 17.2) covers 6.4×10^6 km² and has an average discharge of 209,000 $m^3 s^{-1}$, supplying up to 20% of all the river water discharged into the ocean (Molinier et al., 1997). The basin is bordered by the Andes Cordillera and the sub-Andean region in the west, and by Guyana and Brazilian Shields to the north and south, respectively. The entire Amazon basin is covered by tropical rainforest (71%) and savannas (29%; Sioli, 1984). Native vegetation in the forested basins is classified as moist open tropical forest and consists of perennially evergreen broadleaf trees with a high number of Palms (Pires and Prance, 1986). An inundated forest predominates in the lowest part of Negro River basin.

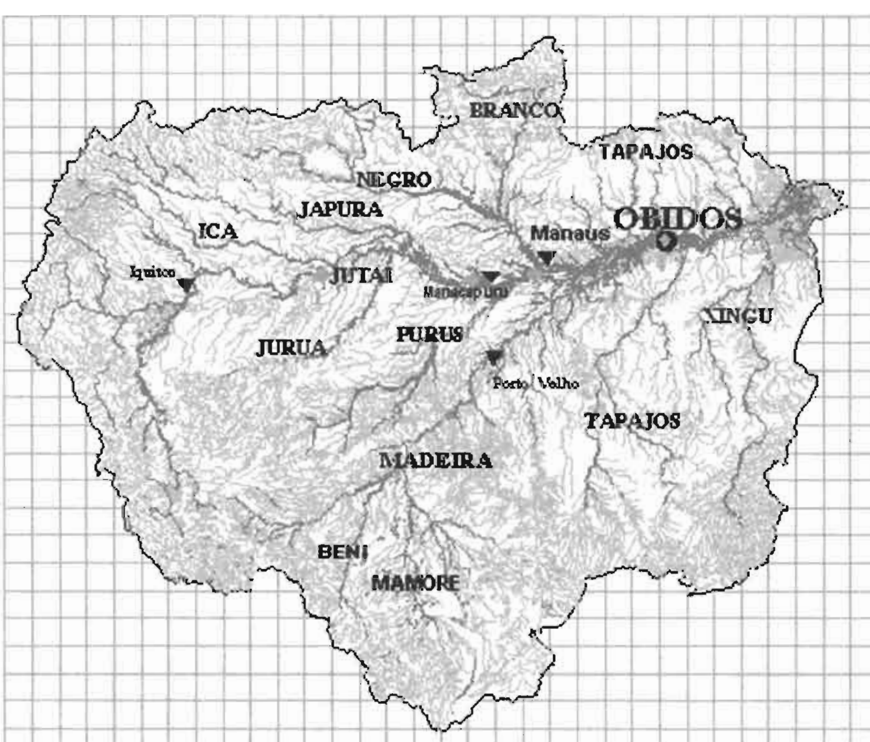

Figure 17.2 Map of the Amazon basin.

Table 17.2 Physical Characteristics of the Amazon River and Its Tributaries

Basin	River	Station	Basin Area km²	Mean Annual Discharge m³ s⁻¹	Runoff l s⁻¹ km²
Negro	Negro	Manaus	689,810	28,400	40.8
Solimoes	Solimoes	Manacapuru	2,147,740	103,000	48.0
Madeira	Beni	Villabela	282,500	8,920	32
	Mamore	Guajaramerin	599,400	8340	14
	Madeira	Foz	1,420,000	31,200	22.0
Amazon	Trombetas	Oriximina	128,000	2555	20.0
	Tapajos	Santarem	490,000	13,500	27.6
	Xingu	Porto de Moz	504,300	9,700	19.2
	Amazon	Obidos	4,618,750	168,000	36.5

In Brazil, the Amazon River refers to the mainstream channel downstream from the confluence of the Solimões and Rio Negro Rivers. Mean annual rainfall in the basin is about 2,000 mm yr^{-1}, and the water regime of the main channel is characterized by one high water stage and one low water stage, which occur between May and August and September and December, respectively. The main tributaries are the Solimões, the Negro, and the Madeira rivers. Its tributaries are classified according to their color, which varies depending on whether dissolved organic matter (black water tributaries) or suspended sediment (white water tributaries) predominates. The Solimões River is formed by the confluence of the Ucayali and Maranõn rivers, which originate from the Andes, and has a surface area of 2,240,000 km^2. It receives a mean rainfall of 2,900 mm yr^{-1} and has a mean discharge of 103, 000 $m^3 s^{-1}$. The Negro River, archetype of the blackwater rivers, is volumetrically the largest tributary of the Amazon with a surface area of 686, 810 km^2, a mean discharge of 28,400 $m^3 s^{-1}$, and a mean rainfall of 2,566 mm yr^{-1}. From its left bank it receives the Branco River, a typical white water river, draining a dry savannah region situated in the north hemisphere, whereas the Negro River drains the densest part of the rain forest.

Two hundred kilometers downstream of the Solimões-Negro confluence, the Amazon River receives water from the Madeira River, which comes from the Bolivian Andes and passes through the central Amazon plain. The Madeira mainstream is formed by the confluence of the Mamore and Beni Rivers in Bolivia. The entire basin has a surface area of 1,420,000 km^2 and is characterized by a mean rainfall of 1,940 mm yr^{-1}, and a mean discharge of 31,200 $m^3 s^{-1}$. The main tributaries of the lower course, the Trombetas, Tapajós, and Xingú rivers drain the Brazilian shield. Tapajós (area, 490, 000 km^2; mean rainfall, 2,250 mm yr^{-1}; mean discharge, 13,500 $m^3 s^{-1}$), Xingú (area, 504,300 km^2; mean rainfall, 1,930 mm yr^{-1}; mean discharge, 9,700 $m^3 s^{-1}$) and Trombetas (area, 128,000 km^2; mean rainfall, 1,822 mm yr^{-1}; mean discharge, 2,555 $m^3 s^{-1}$) are known as the clear water rivers of the Amazon basin (Sioli, 1984).

One of the largest riverine wetlands in the world is the floodplain of the Amazon River and its tributaries (Junk 1997). Estimates vary between 100,000 (Junk, 1985) to 300,000 km^2 (Junk, 1997). In the depressions of the terrain, covering a considerable area, the floodplain oxbow lakes called "várzeas" are formed, characterized by a high production of phytoplankton (Richey et al., 1990; Junk, 1997).

Major features of the Amazon basin are shown in Table 17.2. Additional details about main characteristics of the Amazon basin are reported by McClain et al. (2001).

17.3 SAMPLING AND ANALYTICAL METHODS

This chapter is based on an extensive dataset of analyses conducted for the Congo-Zaire basin between 1990 and 1996 by the PIRAT/PEGI program supported by INSU/CNRS, and for the Amazon basin between 1994 and 2000 by the HyBAm (Hydrology and geochemistry of the Amazon basin) project supported the IRD (French Research Institute for Development). The Following abbreviations are used throughout the text:

TSS: Total suspended solids (expressed in mg l^{-1})
POC: Particulate organic carbon (expressed in mg l^{-1})
POC%: Particulate organic carbon (expressed as a percentage of TSS)
DOC: Dissolved organic carbon (expressed in mg l^{-1})
TOC: Total organic carbon, i.e., sum of the DOC and the POC (expressed in mg l^{-1})

17.3.1 Sampling Frequency

With regard to Congo-Zaire River, samples were collected during various cruises carried out between Bangui (Central African Republic) and Brazzaville (Republic of Congo) during low and high water stages. Moreover, three "key stations" where monthly time series were carried out, have been selected on the basis of their particular characteristics (hydrology, vegetation type) in order to highlight the factors influencing the temporal distribution of organic C.

- Bangui station on the Oubangui River (savannah region) was sampled monthly between November 1990 and September 1996.
- Moloundou station on the Ngoko-Sangha River drains a basin, which is 95% tropical rain forest, and was sampled between January and December 1991.
- Brazzaville/Kinshasa station, which covers almost the entire Congo-Zaire basin, was sampled between November 1990 and October 1993.

In the Amazon basin, samples were collected during twelve cruises. During each cruise, one river was generally sampled preferentially, but all of the other key stations corresponding to the outlet of each sub-basin (Solimões, Negro, Branco, and Madeira rivers) were routinely sampled at least four times per year as well as the Óbidos station which controls 95% of water and 99% of the sediment discharge in the Amazon River (Callède et al., 2002; Filizola, in press). The key stations were hydrologically instrumented, and discharge data were collected on a daily basis.

17.3.2 Sampling and Analysis Procedures

A 1 liter sample was taken in the center of the river cross section in sterilized containers. After homogenization, precise volume of water was filtered through preheated and preweighed 0.70 µm Whatman GF/F fiberglass filters under reduced pressure to separate dissolved and particulate matters.

The filters were dried in an oven at 50°C for 24 h and weighed to determine TSS concentrations. Then filters were decarbonated with 2N HCl to eliminate carbonates, and dried at 60°C for 24 h. The POC contents were measured on a LECO CS 125 analyzer. Detailed description of POC analysis is reported by Etcheber (1986).

The water-fractions passing through the filter were acidified on a board with ultrapure H_3PO_4 and analyzed in the laboratory by high-temperature catalytic oxidation method (HTCO) using a Shimadzu TOC-5000 Instrument to determine DOC concentrations (Abril et al., 2002).

17.4 RESULTS

17.4.1 Spatial Variations of TSS, POC, and DOC Concentrations in the Congo-Zaire River and Tributaries

Analytical data for the Congo-Zaire basin are reported in Table 17.3.The mean concentration of TSS is relatively low, and ranges from 6 to 36 mg l^{-1} for three key stations. These concentrations

Table 17.3 Average Concentrations of TSS, POC, and DOC in the Oubangui, Ngoko–Sangha, and Congo–Zaire Basins

Rivers	Hydrological Stages	Water Discharges ($m^3 s^{-1}$)	Specific Water Discharges ($l s^{-1} km^{-2}$)	TSS ($mg l^{-1}$)	POC (%)	POC ($mg l^{-1}$)	DOC ($mg l^{-1}$)	DOC/TOC (%)
Oubangui at Bangui	Average	3,005	6.2	18.9	6.3	1.2	5.0	81.0
	High waters	4,556	9.3	28.1	5.7	1.6	6.1	79.0
	Low waters	834	1.7	6.1	11.5	0.7	3.5	83.0
Ngoko-Sangha at Moloundou	Average	862	12.9	28.8	6.9	2.0	10.5	84.0
	High waters	1,012	15.1	33.6	6.8	2.3	11.8	84.0
	Low waters	412	6.1	16.7	7.8	1.3	3.8	75.0
Congo-Zaïre at Brazzaville	Average	37,047	10.6	27.1	6.3	1.7	9.8	85.0
	High waters	41,232	11.8	24.6	6.1	1.5	11.0	88.0
	Low waters	32,861	9.4	29.5	6.4	1.9	8.6	82.0

are among the lowest reported in river water, and attributed to three factors: (1) flat terrain, (2) good vegetal cover, and (3) lack of highly erodible soils. The TSS values are higher in high water than low water stage, except for Congo-Zaire at the Brazzaville station where the difference is not significant due to the low seasonal variability of the hydrograph. The annual average concentration of POC varies from 1.2 mg l^{-1} (at Bangui station) to 2.0 mg l^{-1} (at Moloundou station) and follows the same pattern as the TSS with the maximum concentrations during the high water stages, except for the Brazzaville station as has been discussed before. The percentage of C contained in TSS (POC%) is relatively high as compared to temperate rivers (Meybeck, this volume), ranging from 5.7 to 11.5% in the Oubangui River, 6.8 to 7.8% in the Ngoko/Sangha River, and 6.1 to 6.3% in the Congo-Zaire River, for low and high water flows, respectively. Comparing these data obtained in the Congo-Zaire River with those already published and obtained in general from a small set of data, there exists a good agreement (6%, Cadet, 1984; 7%, Kinga Mouzeo, 1986). Comparing the mean POC values of the Oubangui River (1.2%) with others flowing in African savannah, an excellent agreement is observed with the Senegal (1.2%, Orange, 1990) and Gambia rivers (Lesack et al., 1984).

The concentration of dissolved organic carbon (DOC) differs between the Bangui station on the Oubangui River and Moloundou station on the Ngoko/Sangha River. At Bangui station, or the "Savannah observatory," the DOC concentrations ranged from 3.5 mg l^{-1} during the periods of low flow to 6.1 mg l^{-1} during the flood period with an annual average value of 5 mg l^{-1}. At Moloundou Station, or the "forest observatory," DOC concentrations ranged from 3.8 mg l^{-1} to 11.8 mg l^{-1}, with an annual average of 10.5 mg l^{-1}, i.e., three times higher than the former. Concerning the other main tributaries of the Congo-Zaire River, the highest DOC concentrations are found in the Upper Zaire at Mbandaka (18.1 mg l^{-1}, n = 5) and in the Ruki River (18.9 mg l^{-1}, n = 2), the latter draining the marshes and inundated forest zone situated in the center of the basin (Seyler et al., 1995). The right bank tributaries of the lower Congo-Zaire River upstream Kinshasa/Brazzaville, called Bateke Rivers (Djiri, Lefini, Nkeni, and Alima rivers), have an average DOC concentrations of 3.5 mg l^{-1} (Seyler et al., 1995).

It is also interesting to compare DOC/TOC ratio for each river, which is related with the specific phase (particulate or dissolved) on which organic C is primarily transported to the ocean. For the three key stations, DOC is apparently the dominant form with a mean concentration of 0.79 mg l^{-1} in the Oubangui River, 0.84 mg l^{-1} in the Ngoko-Sangha River, and 0.85 mg l^{-1} in the Congo-Zaire River.

17.4.2 Spatial Variations of TSS, POC, and DOC Concentrations in the Amazon River and Tributaries

Results for the Amazon basins at Óbidos station and for the sub-basins at the confluences with the main channel are shown in Table 17.4 and Figure 17.3. In the Negro basin, lower concentrations

Table 17.4 Average Concentrations of TSS, POC, and DOC in the Amazon River and Its Main Tributaries

Basin	River	TSS (mg l^{-1})	POC (mg l^{-1})	POC (%)	DOC (mg l^{-1})	DOC/TOC (%)
Negro	Negro	5	0.72	13.6	10.25	93%
Solimões	Solimões	81	1.3	1.6	4.5	78%
Madeira	Béni	451	2.9	0.6	4.11	59%
	Mamoré	109	1.12	1	7.68	87%
	Madeira	233	2.1	0.9	3.8	64%
Amazon	Trombetas	6	0.65	10.3	5.75	90%
	Tapajos	6	0.44	7.5	4.45	91%
	Xingu	9	0.95	10.7	3.4	78%
	Amazon	61	1.08	1.8	6.94	87%

of TSS (about 3.7 mg l^{-1}) were observed in low water period, whereas higher concentrations (up to 17 mg l^{-1}) were observed during the peak discharge. The same trend was observed for POC concentrations. The POC in the Negro represents only 9% of the TOC, and concentrations were relatively low (mean = 0.86 mg l^{-1}). However, the POC contents in terms of percentage of TSS are high, ranging from 5.4 to 31%, with a mean of 13%. The minimum POC corresponding to low waters is probably linked to the acidic and oligotrophic nature of the Negro River waters. This trend is one of the major differences with the POC pattern in the Congo-Zaire River. The organic C data obtained in the Negro River, confirmed that the entire Negro River basin contains large amounts of DOC and a low content of suspended matter. The concentrations of DOC ranges between 3 and 18 mg l^{-1} and the mean DOC concentration in the Negro basin is 12.7 mg l^{-1}. The lowest concentrations are observed during a rising water period. The DOC values represent an average of 93% of the TOC, whose contribution to Amazon does not vary much with different water levels. The DOC was always the principal component of TOC. Concerning the major tributary of the Negro River, the mean concentration of suspended solids in the Branco basin during peak discharge was about 22.7 mg l^{-1}, which is three times higher than that during the periods of low water level (7.5 mg l^{-1}). The Branco River contribution of organic C to Negro River is small, and represents the major contribution in TSS for the lower reach of the Negro basin. The POC concentrations are similar to those in other white rivers (0.31 to 2.67 mg l^{-1}) and seem to follow the same pattern as TSS. The POC does not vary significantly between different periods of low water and represented in average 5% of the TSS. As in the Negro river, the DOC fraction is also the main C fraction, representing around 80% of the TOC. The DOC concentrations are variable along the Branco River, with a mean of 3.5 mg l^{-1}, or four times the concentration of the Negro River. Already pointed out for the Congo basin, there is a strong influence of the vegetation cover on the POC concentration of riverine C.

In the Solimões River, the TSS concentrations obtained at the Manacapuru station for the entire hydrological cycle show that peak sediment discharge occurs when the water level begin to rise two months before the maximum flow (Filizola, 2003). The POC concentrations vary between 0.60 and 2.16 mg l^{-1} in July and April, respectively. With regard to the POC, it varies between 0.6 in March at the time of the high TSS discharge (141 mg l^{-1}) and 3.7 in July at the time when TSS concentrations are lowest (10 to 20 mg l^{-1}; Filizola, 2003). As in the Negro River, DOC was the dominant form of organic C, corresponding to about 76% of TOC. This percentage increases during low water periods when DOC concentrations are high. The mean DOC concentration was 5.88 mg l^{-1} for the whole of the Solimões basin, whereas the mean POC concentration was 1.19 mg l^{-1} and the mean POC% was 4.6%.

In the Madeira River, the concentration of TSS was correlated with river discharge. The highest concentrations (up to about 500 mg l^{-1}) were observed in April and the lowest concentrations (about 18 mg l^{-1}) in June. The POC concentration closely follows the same pattern. The POC concentration ranged between 0.17 and 4.46 mg l^{-1} in September and April, respectively. With regard to the POC,

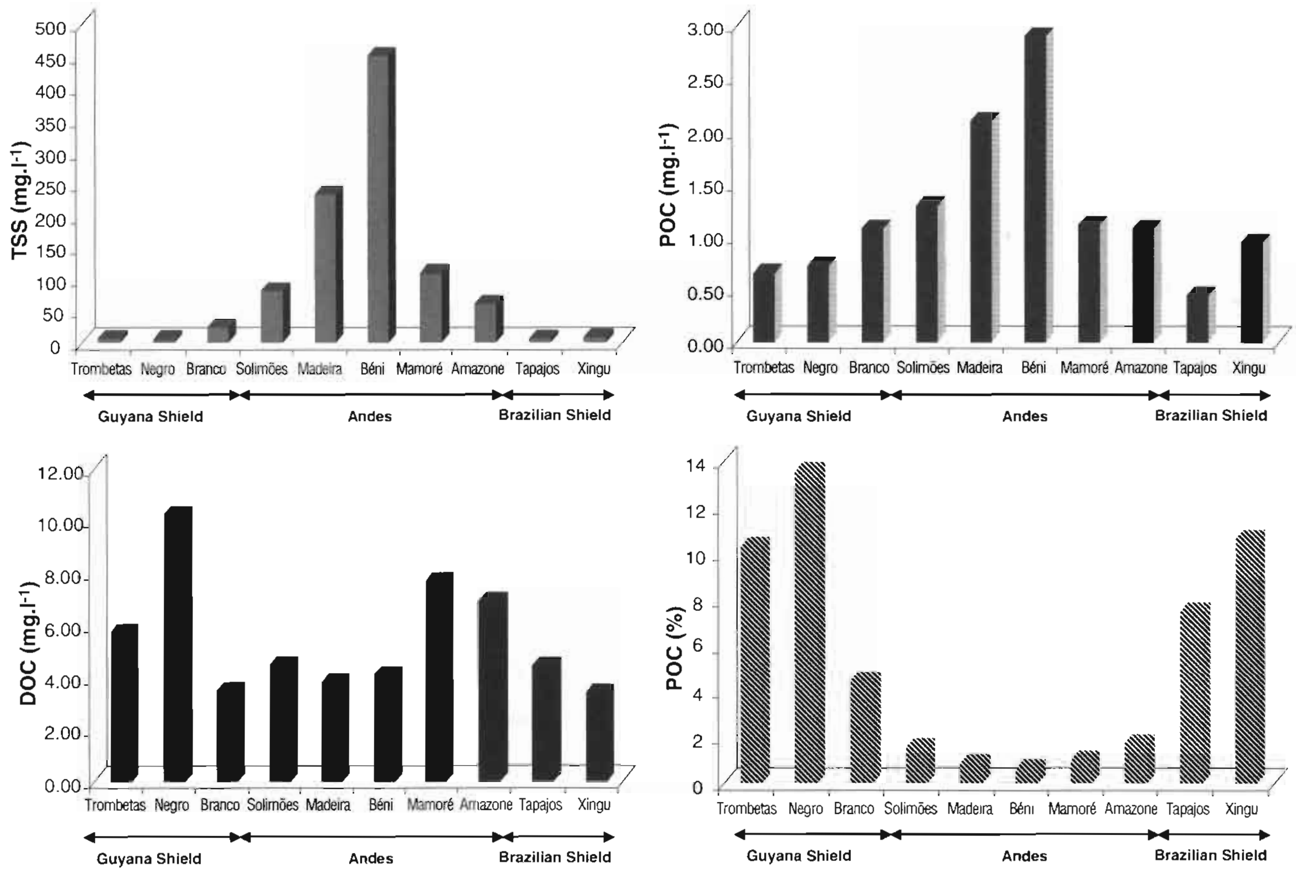

Figure 17.3 Average values of TSS, POC (mg l^{-1}), POC%, and DOC in the Amazon basin and its main tributaries.

it ranged between 3.3% in July during low waters and 0.8% in April at the time of the maximum TSS. The positive relations between TSS/POC/Water discharge and the opposite TSS/POC were also observed in the Congo-Zaire basin. During high flow period DOC concentrations ranged from 7.6 mg l^{-1} at the boundary between Bolivia and Brazil to 3.9 at its confluence with the Amazon River. The lowest concentrations were observed during the low stage (1.7 to 1.9 mg l^{-1}). The DOC/TOC ratio was generally close to 0.5, indicating that the C was transported as much in the dissolved form as in the particulate form.

Clearwater rivers (Tapajós, Xingú, and Trombetas) are characterized by intermediate concentrations of TSS and organic C compared to black and white rivers. The Tapajós River had a mean TSS concentration of 7.2 mg l^{-1}, a mean POC of 3.6 mg l^{-1} (POC% of 12.8%), and a mean DOC of 4.2 mg l^{-1} The concentrations of TSS, POC, and DOC are in the same range as those for the Xingú River (2.8 to 3.4 for the DOC mg l^{-1}, 10% for the POC). The ratio of DOC/TOC was similar in the Tapajós and the Xingú rivers (about 85%). In the Trombetas River the mean TSS concentration was 8 mg l^{-1}, the mean POC concentration was 0.69 mg l^{-1}, the mean POC% was 9.8%, and the mean DOC concentration was 5.5 mg l^{-1}.

Results obtained in these two large tropical basins indicate C dynamics. The main factors that explain the distribution of organic C in the different rivers of Congo-Zaire and Amazon basins are discussed below.

17.5 DISCUSSION

The results obtained show the impact of different parameters affecting the distribution of organic C concentrations, TSS, POC, and DOC in these rivers, and comparison of these data with other rivers of the world.

17.5.1 Factors Controlling the TSS, POC, and DOC Concentrations in the Congo-Zaire and Amazon Basins

The study of the Congo-Zaire tributaries and Amazon basin rivers show that the fluctuations in the TSS and POC concentrations are closely related to the hydrological factors. An increase in mechanical erosion is expected with increase in water discharge from the basin, leading to the mobilization by runoff of a huge POC stock associated with the mineral matrix of eroded soils and clay minerals but also contained in the litters of the topsoils of the basin and riparian zones. During the falling stage, POC concentrations decrease with the decrease in TSS, due to the progressive decline of the erosion processes. Such pattern is not typical of tropical rivers, but has been described for other major rivers (Telang et al., 1991; Kaplan et al., 1980; Colas, 1994; Maneux, 1998; Veyssy, 1998; Zhang et al., 1992).

For the entire data set, an inverse relation was observed between POC and TSS (Figure 17.4), which fits a logarithmic model with a correlation coefficient of 0.96. River erosion can be grouped into two categories: predominately chemical (weathering) or mechanical erosion processes. For the high turbid rivers, the mechanical erosion process dominates (TSS high and POC low) whereas for the low turbid rivers, the chemical weathering process is dominant. This distinction is independent of the type of basin since Ngoko/Sangha, Congo-Zaire, and Oubangui have the same characteristics as Tapajós (Amazon basin; Figure 17.4).

For the Amazon basin, the effect of altitude on organic C loads is shown in Figure 17.3, which compares concentrations of TSS, POC (mg l^{-1} and %), and DOC with the geographical parameters of the sub-basins. For instance, high concentrations of TSS and POC (mg l^{-1}) contents were observed in the rivers flowing from the Andean region, whereas high concentration in DOC and POC (%) were observed for lowland rivers draining the Shields. These observations are in agreement with the results obtained by other investigators (Milliman and Meade, 1983; Ludwig et al., 1996; Guyot

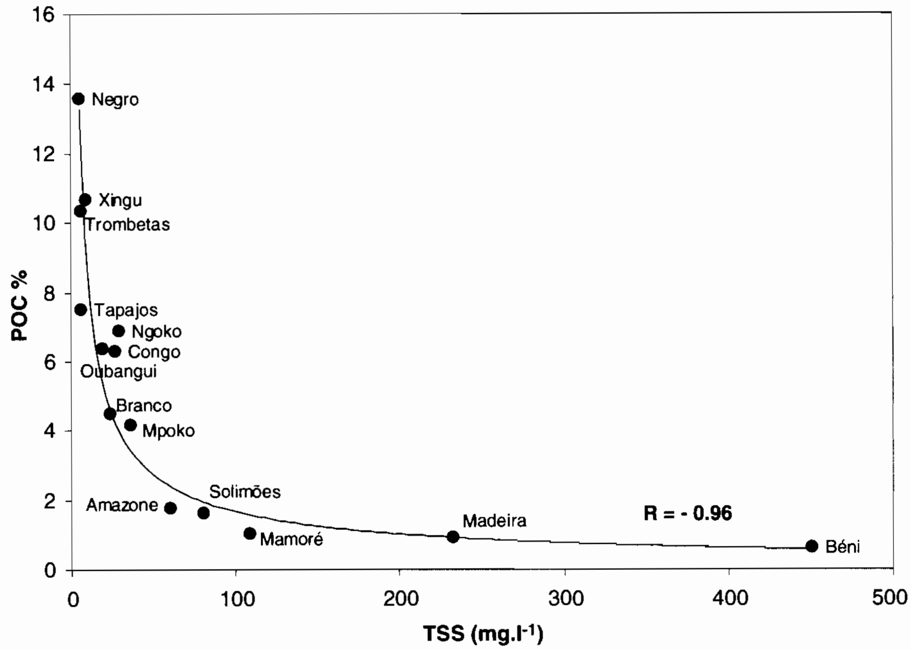

Figure 17.4 Variation of organic carbon content in river particulate matter (POC in %) for Congo-Zaire and Amazon sub-basins. Best fit is obtained with a logarithmic model (coefficient correlation = 0.92).

and Wasson, 1994), and show the importance of the contribution of the mountainous basins to the global fluxes of TSS and POC. The large and highly contrasting, and still relatively pristine basin of the Madeira River constitutes a suitable study area to test the impact of altitude on the riverine organic C concentration. The altitude decreases from 5,500 m at the summit of the basin to 120 m at the piedmont of the Andean Cordillera. The DOC concentrations vs. the altitude of sampling points are plotted in Figure 17.5. A marked enrichment in DOC was observed at 250 m altitude where the Madera River enters the flat plain. These results corroborate the observations made by Hedges et al. (2000) and Guyot and Wasson (1994), who also observed a strong contrast in DOC river concentrations between the Andean mountainous region (average of 2.2 mg l^{-1}) and the lowlands (average of 5.7 mg l^{-1}).

Whereas an "altitude effect" was observed in the distribution of organic loads of rivers, some variations in POC and DOC contents in lowlands rivers (e.g., Oubangui vs. Ngoko/Sangha rivers or Negro vs. Branco rivers) suggest that other key parameters such as the vegetative cover may explain these differences. The effect of the vegetation on the DOC river contents can be observed plotting the DOC concentrations and the percentage of forest cover in the basins of the Madeira River and the Congo-Zaire (Figure 17.6). This percentage was calculated for each sampling station watershed with the vegetation map of Africa and South America (Global Land Cover 2000 project EEC, 2003). The concentrations of DOC increased in both cases with an increase in the percentage of forested area in each basin. The comparison of the two basins shows two distinct trends with higher values observed for the Congo-Zaire River system. As previously mentioned, the higher altitude of the Madeira basin may explain lower DOC contents than those observed in the Congo-Zaire River for a similar vegetation cover.

17.5.2 Organic Carbon Flux from Congo-Zaire and Amazon Basins

To compute the organic C flux of the rivers, a monthly average was first calculated when more than one value was available by month (case of the Congo-Zaire basin). When just one value was

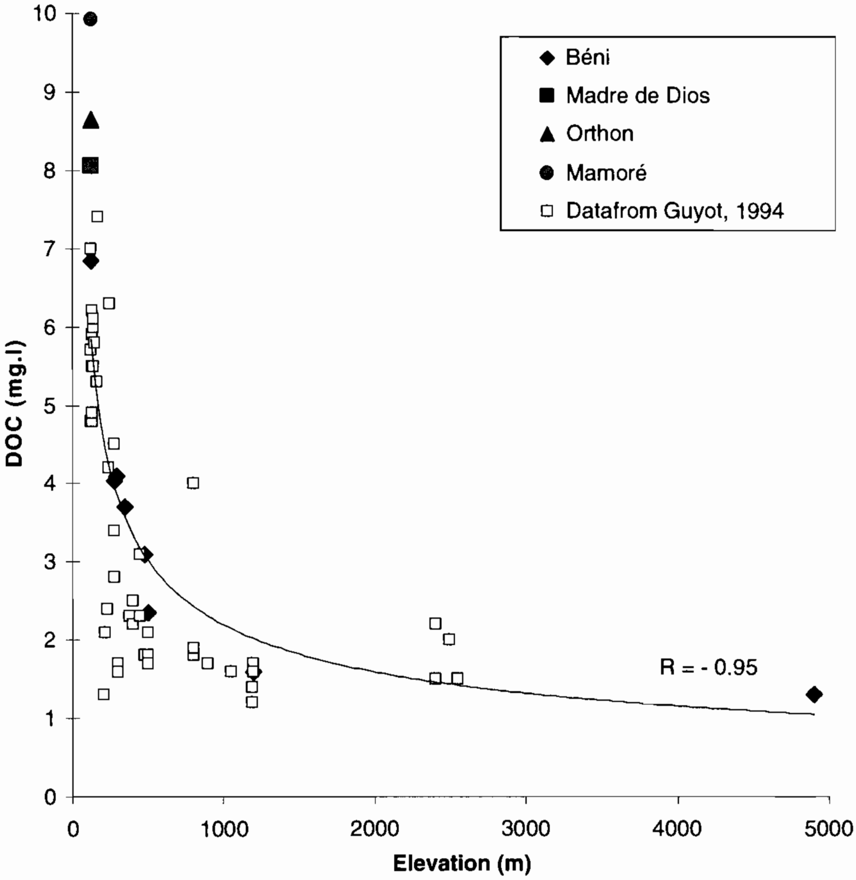

Figure 17.5 Mean DOC value vs. sampling point altitude (m above sea level); data from Guyot and Wasson, 1994 are also reported.

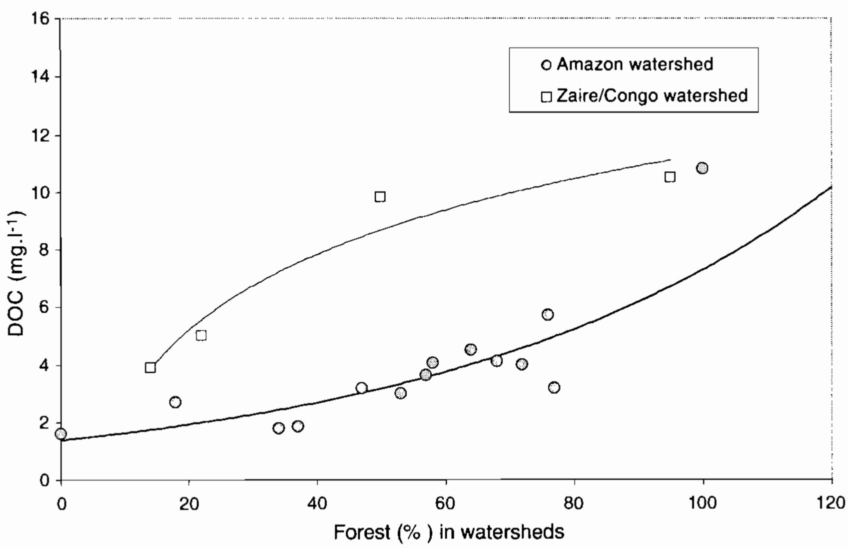

Figure 17.6 Mean DOC concentrations (mg l^{-1}) as a function of the forested area (%) in the Congo-Zaire and Madeira basins.

Table 17.5 Carbon Budget of the Congo–Zaire Basin

Basin	Annual Discharge[a] $m^3 s^{-1}$	POC Flux $Tg\ yr^{-1}$	DOC Flux	TOC Flux	DOC Flux/ TOC Flux %
Oubangui	4,000	0.2	0.4	0.6	67
Ngoko/Sangha+Likouala	2,200	0.2	1.2	1.4	86
Kasai	8,500	0.4	3.1	3.5	89
Upper Zaire	16,960	1	6.5	7.5	87
Bateke Rivers	2,400	0.1	0.3	0.4	75
Congo-Zaire[b]	42,000	1.9	11.5	13.4	86

[a] Water discharge at the confluence with the main stream.
[b] Data for Kinshasa-Brazaville Station.

available during a given month, this value was considered representative for the month. The mean annual flux of DOC, POC, and TSS were then computed by the summation of the 12 interannual monthly values.

17.5.2.1 Congo-Zaire Basin

Based on annual flux computed for the key stations and at the confluence of other tributaries (Upper Zaire, Kasai, Likouala, and Bateke rivers), a budget of the C species is presented for the Congo-Zaire basin (Table 17.5 and Figure 17.7). The data show the following: irrespective of the type of vegetation in the sub-basins, the dissolved C flux is a major component of the total flux. However, a marked difference is observed between the savannah and the forested basins. The ratio dissolved flux/particulate flux is 70% in the former and always up to 86% in the latter (Table 17.5). Since the savannah covers half of the basin (Global Land Cover 2000 project EEC, 2003), about 12.5% of TOC is produced by the savannah and 87.5% by the forested areas. Finally, considering the fluxes calculated at Kinshasa-Brazzaville station representative of the total flux

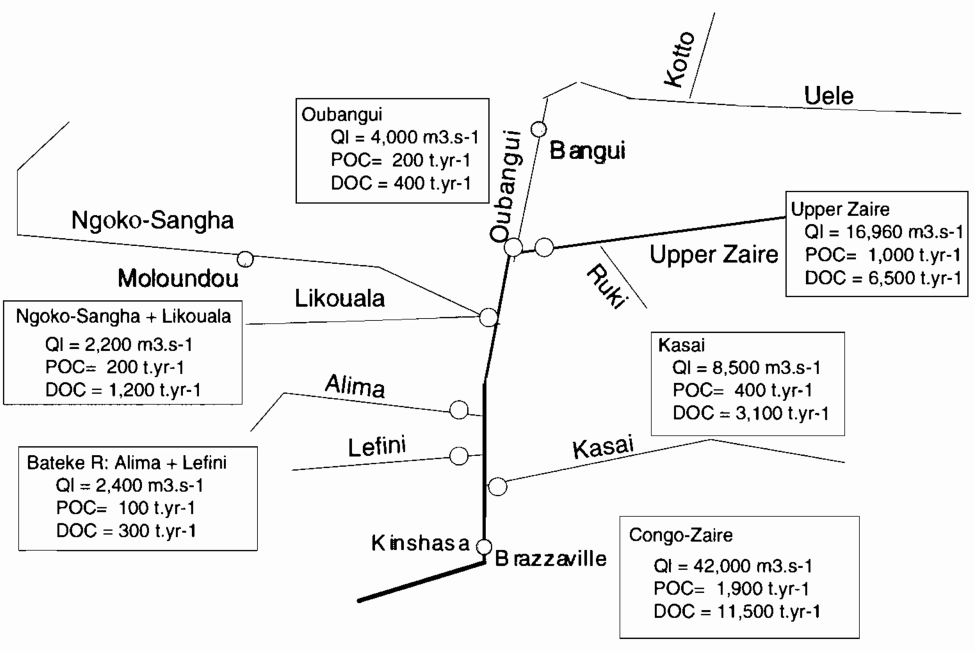

Figure 17.7 Fluvial budget of DOC and POC in the Congo-Zaire basin.

Table 17.6 Carbon Budget of the Amazon Basin

Basin	River	POC Flux Tg yr^{-1}	DOC Flux Tg yr^{-1}	TOC Flux Tg yr^{-1}	DOC Flux/ TOC Flux %
Negro	Negro	0.67	6.00	6.67	90
Solimões	Solimões	4.00	15.00	19.00	79
Madeira	Béni	0.80	1.10	1.90	58
	Mamoré	0.30	2.00	2.30	87
	Madeira	1.50	4.30	5.80	74
Amazon	Trombetas	0.05	0.50	0.55	91
	Tapajos	0.15	1.50	1.65	91
	Xingu	0.26	0.95	1.21	79
	Amazon	5.80	35.00	40.80	86

of the Congo-Zaire River to the Atlantic Ocean, this river contributes 1.9×10^6 t yr^{-1} of POC and 11.5×10^6 t yr^{-1} of DOC. Solid discharge makes up 30.6×10^6 t yr^{-1}. These values are similar to those reported by Probst et al. (1993) comprising 1.2×10^6 t $yr^{-1}$of POC and 9.6×10^6 t $yr^{-1}$of DOC, and Seyler et al. (1995) comprising 1.6×10^6 t yr^{-1} and 11.4×10^6 t yr^{-1} for the 1992 hydrological year, respectively.

17.5.2.2 Amazon Basin

The major contributors of organic C to the Amazon (Table 17.6, Figure 17.8) are the Solimões and Negro rivers. The Madeira River seems to contribute a relatively high amount of organic C to the Amazon River during high water periods. The present study shows that the Solimões River contributed about 40% of the TOC flux of the Amazon River. The Negro River also contributed 40%, the Madeira River ~14%, and the clear water rivers ~6%.

The Óbidos station is located upstream from the confluence of the Xingú and Tapajós rivers, but their water input (~3%) is low compared to other tributaries. The mean annual DOC flux was $35 \pm 4 \times 10^6$ t yr^{-1} and the mean annual POC flux was $5.8 \pm 0.3 \times 10^6$ t yr^{-1}. POC flux was lower and DOC flux was higher than those reported by Richey et al. (1990). This discrepancy may be

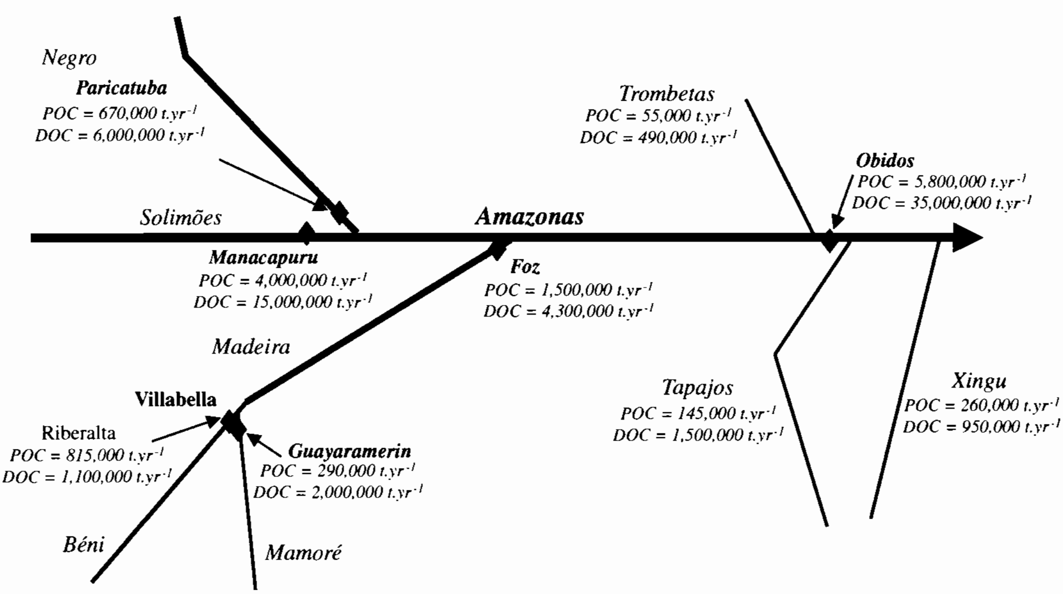

Figure 17.8 Fluvial budget of DOC and POC in the Amazon basin.

due to a difference in sampling separation procedure. Richey et al. (1990) estimated an annual TOC flux at the Óbidos station of 36.7×10^6 t yr^{-1}, which is similar to that of $40.8 \pm 4.3 \times 10^6$ t yr^{-1} reported in the present study. Nevertheless, the annual average TOC input from the principal Amazon tributaries (Negro, Solimões, Madeira, and Trombetas) was $36.9 \pm 3.3 \times 10^6$ t yr^{-1}. Comparing these inputs (36.9×10^6 t yr^{-1}), with the C flux in Óbidos (40.8×10^6 t yr^{-1}), a gain in organic C (about 4×10^6 t yr^{-1}) is observed which indicate, other important sources of organic C. These inputs are attributed to várzea systems. During the period in which the water level decreases, Richey et al. (1990) estimated that up to 400 kg s^{-1} of organic C came from the várzea lakes and between 60 and 120 kg s^{-1} of organic C came from other water stages associated with the Madeira River input. These additional inputs from floodplains to the mainstream are sufficient to account for the gain in C observed in Óbidos.

As mentioned above, two other large tributaries (Tapajós and Xingú rivers) flow through the Amazon River between Óbidos gauging station and the ocean. Taking into account the fluxes of these tributaries, up to 42×10^6 t of C is discharged each year into the Atlantic Ocean by the Amazon River.

17.5.3 Congo-Zaire and Amazon Organic Carbon Yields: Comparisons with World Ranges

Annual specific rates or yields of TSS (Figure 17.9) are of more than 100 g m^{-2} yr^{-1} for the basins in Andean ranges whereas these are about 10 g m^{-2} yr^{-1} for the stations corresponding to Congo-Zaire and Rio Negro basins. Specific rates of POC also show similar trends, i.e., a more significant flux for the Andean system than for Congo-Zaire and Negro basins. The values range between 0.2 and 2 g m^{-2} yr^{-1}. With regard to the DOC, there is a clear distinction between savannah and forest basins: the fluxes for Oubangui River draining savannah are 1 g m^{-2} yr^{-1} compared to 10 g m^{-2} yr^{-1} for the Amazon, Solimões, and Negro basins. Intermediate values of 4 g m^{-2} yr^{-1} were observed for Madeira, Congo-Zaire, and Ngoko.

The data in Figure 17.10 compare the computed yields of POC for Congo-Zaire and Amazon rivers along with those of others major world rivers. At the global scale, the relation between POC (%) concentration and TSS is not trivial. As discussed above, POC flux is directly linked to the sediment yield. The most turbid rivers are mountainous rivers such as the Beni, Mamore, and Madeira rivers. These rivers are in the same quadrant of Figure 17.10 as the temperate and semiarid rivers with a limited vegetation cover. Conversely the lowland rivers of the lowland regions of Congo-Zaire and Amazon basins fall among the "cold river" basins in which the large amount of POC may be eroded from organic-rich soil layer.

17.6 CONCLUSIONS

The extensive database of the organic C species in Congo-Zaire and Amazon rivers and its main tributaries allows us to determine factor controls and a quantitative estimate of TSS, DOC, and POC fluxes in the two major rivers of the world whose basin areas together cover ~70% of the world's humid tropics.

The common pattern observed in the rivers studied and other rivers of the world (Ittekkot et al., 1985; Meybeck, 1982; Spitzy and Ittekkot, 1991; Telang et al., 1991) shows that variation in POC is related to an increase in total suspended solids. This trend is attributed to the dilution of organic matter by mineral matter (Ittekkot et al., 1985; Meybeck, 1982). Reduced autochthonous production, due to a lack of light penetration at high sediment concentrations (Thurman, 1985), and differences in the sources and biogeochemical processes, affect the nature of organic matter at various stages of the hydrographic regime (Spitzy and Ittekkot, 1991; Wallace et al., 1982). While the highest contents of POC and DOC were observed during high water periods, the least

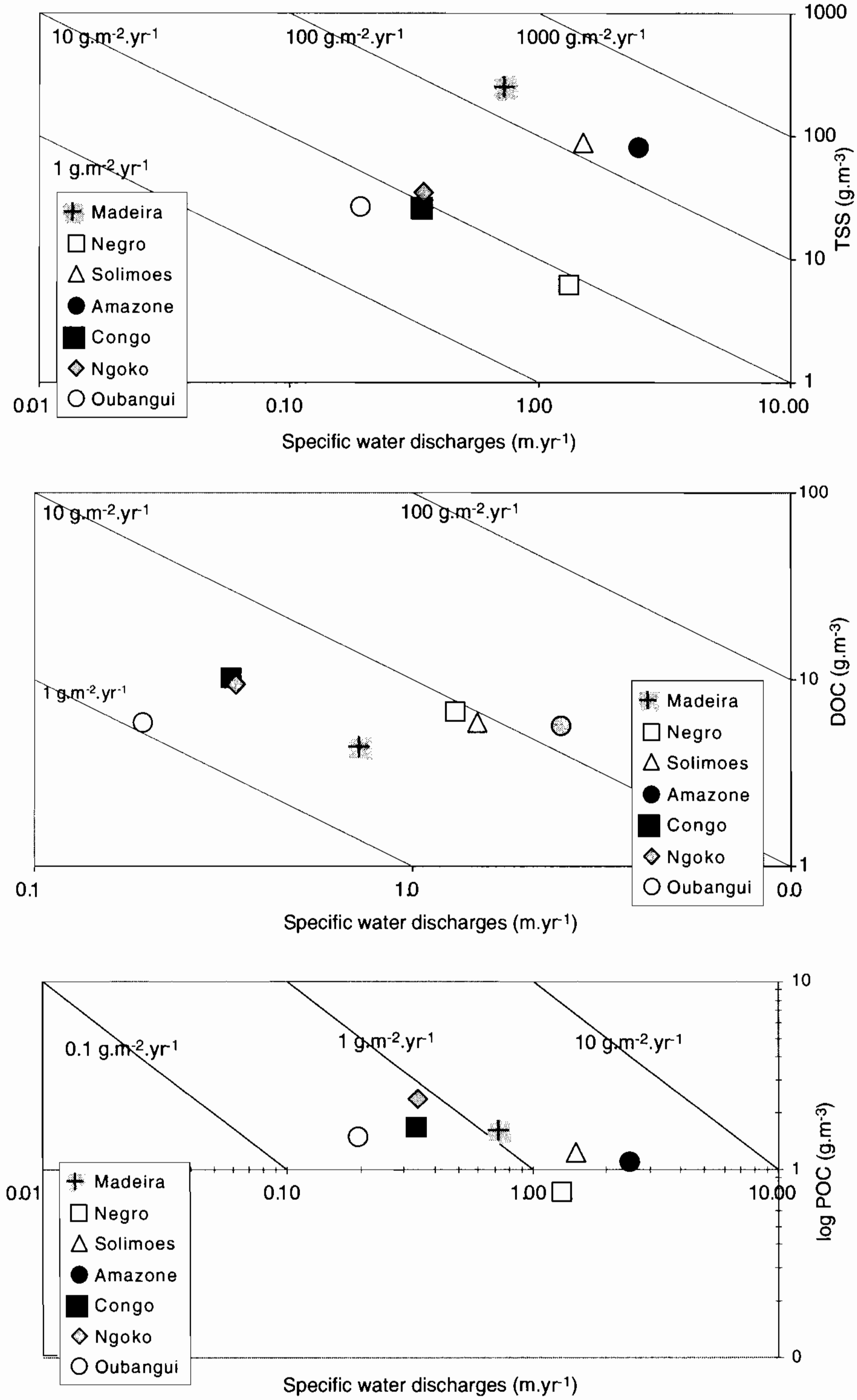

Figure 17.9 Annual specific rates of TSS, POC, and DOC in Congo-Zaire and Amazon basins (g m^{-2} yr^{-1}).

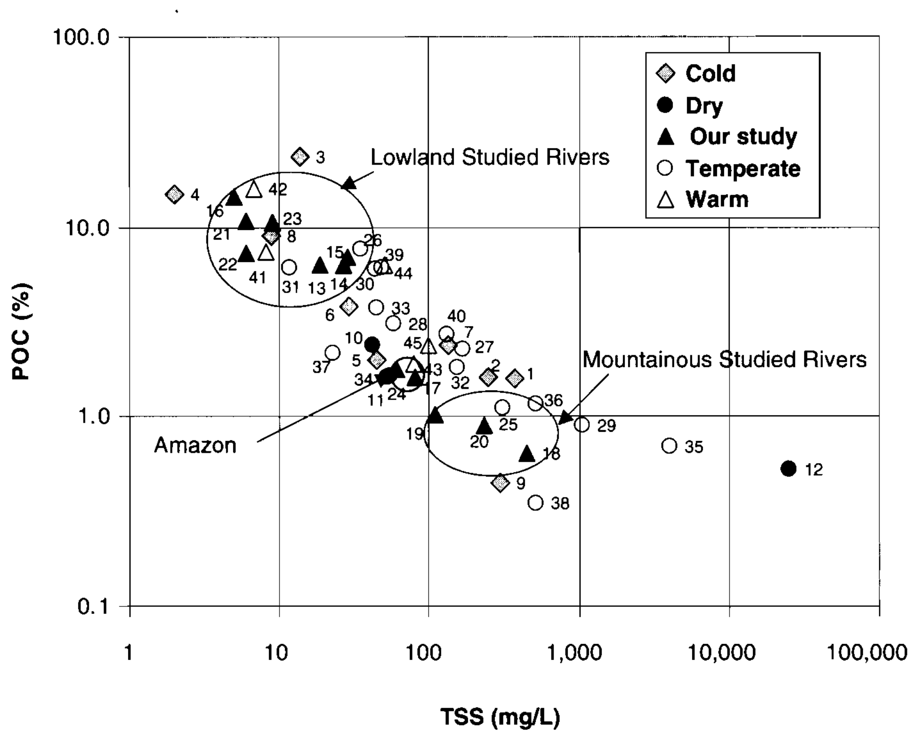

Figure 17.10 Relationship between annual average particulate organic carbon concentrations (POC in %) and total suspended solids (in mg/L) in rivers of Congo-Zaire and Amazon basins (our study) and major word river basins. **Cold** = (1) Mackenzie, (2) alpine Rhône, (3) N. Dvina, (4) Pechora, (5) Ob, (6) Lena, (7) Mackenzie, (8) Moose, (9) Yukon; **Dry** = (10) Gambia, (11) Orange, (12) Huang He; **Our study** = (13) Oubangui, (14) Ngoko, (15) Congo-Zaire, (16) Negro (17) Solimoes, (18) Beni, (19) Mamore, (20) Madeira, (21) Trombetas, (22) Tapajôs, (23) Xingu, (24) Amazone, **Temperate** = (25) Danube (26) Loire, (27) Mississippi, (28) Ohio, (29) Peace, (30) Rhine, (31) St. Lawrence, (32) Kuban, (33) Don, (34) Dniepr, (35) Choroch, (36) Changjiang, (37) Pee dee, (38) Rioni, (39) Seine, (40) Rhône; **Warm** = (41) Caroni, (42) Caura, (43) Orinoco, (44) Sanaga, (45) Tuy. (From Meybeck, M. 1993a. Riverine transport of atmospheric carbon: Sources, global typology and budget. *Water, Air, and Soil Pollution* 70:443; Meybeck, M. 1993b. C, N, P, and S in rivers: From sources to global inputs, In R. Wollast, F. T. Mackenzie, and L. Chou, eds., *Interactions of C, N, P, and S in Geochemical Cycles and Global Change*. Springer-Verlag, New York, p. 163. With permission.)

concentrated were observed during the low water periods. Thus, the main part of the organic C in these rivers is of terrestrial origin (allochtonous component) and in situ phytoplanctonic production (autochtonous component) is of limited significance in these rivers (Moreira-Turq et al., 2003). Both POC and DOC contents in the rivers studied were directly linked to weathering intensity, and their origin was associated with leaching of soils litter and humic layers (when DOC and POC% concentrations are high) and to the sedimentary rock containing fossil organic C (when POC% is low; Meybeck et al., this volume).

The distribution of organic C in different rivers of Congo-Zaire and Amazon basins depends on the mean altitude of the basins and the vegetation cover (%). With regard to the Congo-Zaire basin, Oubangui River draining mainly a savannah region, contained three times lower DOC than the Ngoko/Sangha River draining mainly a forested region. The trend is not clear for the POC. With regard to the Amazonian basin, the detailed study of the Madeira sub-basin indicated the role of vegetation type which itself depends on the mean altitude of the basin.

Computation of inputs to Atlantic Ocean show that the Congo-Zaire River contributes 13.4 × 10^6 t yr^{-1} of TOC of which 11.5 × 10^6 t yr^{-1} is DOC and 1.9 × 10^6 t yr^{-1} is POC. The Amazon contributed 42 × 10^6 t yr^{-1} of TOC of which 37 × 10^6 t yr^{-1} is DOC. Based on this study and the most recent estimate of the annual amount of organic C transported into oceans by rivers (500×10^6 t yr^{-1}; Spitzy and Ittekkot, 1991), it is concluded that the Congo-Zaire and Amazon rivers contribute a mean organic C flux of about 10 to 12% of the world's total.

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On the cover: A typical landscape of red ferrallitic soils on the high plateau of central Madagascar near Antananarivo during the rainy season. The hilltop is covered by overgrazed grassland deeply eroded around the cattle trails which join the village and the springs in the valley. The hills lose carbon, nutrients, soil, and water, but might be nourishing the rice paddies below.

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SOIL EROSION AND CARBON DYNAMICS

In addition to depleting nutrients necessary for healthy crops, soil erosion processes can affect the carbon balance of agroecosystems, and thus influence global warming. While the magnitude and severity of soil erosion are well documented, fluxes of eroded carbon are rarely quantified. **Soil Erosion and Carbon Dynamics** brings together a diverse group of papers and data from the perspectives of world-renowned soil scientists, agronomists, and sedimentologists to resolve whether soil erosion on carbon is a beneficial or destructive process.

This book collects quantitative data on eroded organic carbon fluxes from the scale of the agricultural plot to that of large basins and oceans. It quantifies the magnitude of eroded carbon for different soil management practices as compared to normal carbon sequestration and discusses the fate of the eroded carbon and whether or not it is a source or sink for atmospheric CO_2. Finally, the book offers data reflecting the impact of soil erosion on soil, water, and air quality. Other important topics include solubilization, carbon transfer, and sediment deposition, as well as carbon dioxide emissions, global warming potential, and the implications of soil erosion on the global carbon cycle and carbon budget.

Features

- Defines basic concepts and general approaches to the global carbon cycle, carbon sequestration, erosion, and eroded carbon
- Addresses the great debate on "missing" or "fugitive" carbon
- Includes arguments and data that support contrasting viewpoints on the effects of the carbon cycle
- Offers a meaningful look at the impact of soil erosion on the global carbon cycle and the global carbon budget
- Covers solubilization and carbon transfers in rivers and deposition in sediments
- Addresses the impact of soil erosion on crop production systems
- Elucidates the CO_2-to-carbon relationship and organic carbon fluxes

Based on the first symposium of the international colloquium *Land Uses, Erosion and Carbon Sequestration* held in Montpellier, France, **Soil Erosion and Carbon Dynamics** provides data that link soil erosion to the global carbon cycle and elucidates the fate of eroded carbon at scales ranging from plot to watershed.

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