

## A seasonal cycle in the carbon-isotope composition of organic carbon in the Sanaga River, Cameroon

**Abstract**—We report measurements of the carbon-isotope composition ( $\delta^{13}\text{C}$  value) of particulate organic carbon (POC) in the suspended sediment load of the Sanaga and Mbam Rivers, Cameroon. The results demonstrate that there is a seasonal cycle in  $\delta^{13}\text{C}$  value of 3.3‰ (–26.6 to –23.3‰) in the Sanaga River and 5.9‰ (–27.1 to –21.2‰) in the Mbam River that is directly related to seasonal changes in the discharge of the rivers. During periods of high discharge,  $\delta^{13}\text{C}$  values of POC are high, reflecting an increase in the proportion of POC derived from  $\text{C}_4$  plants, including  $\text{C}_4$ -derived carbon transported overland by wet season rains from savanna regions in the catchment hinterland. During periods of low discharge, the  $\delta^{13}\text{C}$  values of POC are low, reflecting derivation of the carbon primarily from  $\text{C}_3$  plants growing close to the riverbanks. Results suggest that the prime determinant of POC  $\delta^{13}\text{C}$  values in tropical rivers that carry a significant suspended sediment load is the  $\delta^{13}\text{C}$  value of the catchment vegetation.

Studies of the  $\delta^{13}\text{C}$  values and the abundance of lignin-derived phenols in riverine particulate organic carbon (POC) both suggest that a substantial proportion of the carbon in tropical rivers is derived from vegetation present in the catchments of the rivers (Hedges et al. 1986; Mariotti et al. 1991; Bird et al. 1992). The bulk  $\delta^{13}\text{C}$  value of vegetation in tropical regions is strongly dependent on the proportion of  $\text{C}_3$  ( $\delta^{13}\text{C}$  value of about –28‰) and  $\text{C}_4$  ( $\delta^{13}\text{C}$  value of about –12‰) plants in a given biome (Smith and Epstein 1971). Thus, woodland/savanna/grassland biomes have bulk  $\delta^{13}\text{C}$  values ranging from approximately –14 to –26‰ (McClaran and McPherson 1995; Bird and Pousai 1997), depending on the proportion of  $\text{C}_4$  grasses present, whereas closed forests have bulk  $\delta^{13}\text{C}$  values of approximately –28‰, reflecting the dominance of  $\text{C}_3$  plants in these biomes (e.g. Balesdent et al. 1993; Bird et al. 1996).

The observation that the  $\delta^{13}\text{C}$  value of riverine POC is dependent largely on terrestrial vegetation has led to the suggestion that long records of vegetation change in large river catchments in the tropics might be obtained from the carbon-isotope analysis of bulk organic matter (Mariotti et al. 1991) or terrestrially derived biomarker molecules (Bird et al. 1992) in the sedimentary sequences accumulated off the mouths of the major tropical rivers. To further test this hypothesis, Bird et al. (1994) analyzed bottom-sediment samples from along the length of the Sanaga River and its major tributary, the Mbam River, in Cameroon. These rivers have their sources in extensive savanna regions but later flow through tropical forest before joining and ultimately discharging into the Gulf of Guinea (see Bird et al. 1994 for detailed descriptions).

Bird et al. (1994) found that there was a large downstream decrease in the  $\delta^{13}\text{C}$  value of POC in the bottom sediments of both rivers, from values ranging from –16 to –23‰ in the savanna-covered headwaters of the rivers to values of

–24 to –27‰ in the lower reaches. Results were considered consistent with the gradual dilution of savanna-derived carbon by carbon derived from the forested regions in the lower parts of the catchment. An additional finding was that POC in the <63- $\mu\text{m}$  fraction of the sediments was enriched by 1–3‰ in  $^{13}\text{C}$  compared to POC in the 63–500- $\mu\text{m}$  fraction. This was attributed to increased erosion and overland transport of fine POC from  $\text{C}_4$ -rich regions away from the immediate riverbanks accompanying the runoff of precipitation during the wet season. During the dry season, only carbon from sources growing on the immediate riverbanks can reach the river.

The isotopic characteristics of the samples led to the prediction that a seasonal cycle in the  $\delta^{13}\text{C}$  value of POC exported from the catchments should exist, varying in response to seasonal changes in the amount and distribution of precipitation falling in the catchment. Our study sought to test this prediction by using approximately monthly suspended sediment samples collected between March 1995 and March 1996 from both the Sanaga and Mbam Rivers immediately upstream of their confluence (see Bird et al. 1994 for locations).

The suspended sediment concentrations for each sample, along with percentage POC and the  $\delta^{13}\text{C}$  value of POC in the samples, are presented in Table 1. The average hydrographs of both rivers (Figs. 1, 2) exhibit strong seasonal variation, with low flows occurring between January and April, then increasing gradually to peak flows in September before dropping rapidly after October. Nouvelot (1972) found that the peak in sediment load in the Sanaga–Mbam system slightly precedes the peak in discharge, a phenomenon typical of many rivers.

Comparison of the hydrographs of the two rivers with changes in suspended sediment load and percent POC (Fig. 3) indicate that during periods of high discharge, suspended sediment loads are high while POC percentages are low. During low discharge periods, suspended sediment loads are low while POC percentages are high. Suspended sediment loads in the Mbam during the wet season exceed those of the Sanaga by a factor of 4–5, reflecting both the comparative steepness of the Mbam catchment and its high population density.

The  $\delta^{13}\text{C}$  value of suspended POC in both the Mbam (Fig. 1) and the Sanaga (Fig. 2) increases dramatically immediately following the end of the dry season in April from values of around –27‰ in both rivers to values of –21 to –23‰, levelling out and/or decreasing well before the peak in discharge occurs. The  $\delta^{13}\text{C}$  values of suspended POC in the Mbam River remain high throughout the wet season, but drop slightly through June and August in the Sanaga before rising again as peak flows are approached in September.

The reason for the drop in the  $\delta^{13}\text{C}$  values of the Sanaga

Table 1. Results for suspended sediment (susp. sed.) samples from the Sanaga and Mbam Rivers, Cameroon.

Sample	Org. C (%)	$\delta^{13}\text{C}$ (‰)	Susp. sed. (mg liter <sup>-1</sup> )
<b>Mbam River</b>			
31 Mar 95	3.6	-26.8	32.3
5 May 95	6.2	-25.6	50.8
1 Jun 95	3.3	-22.5	65.6
28 Jun 95	3.1	-21.4	78.7
17 Aug 95	3.4	-22.2	120.5
5 Sep 95	3.3	-21.2	109.0
22 Dec 95	13.5	-27.1	11.4
3 Feb 96	10.5	-24.4	21.2
2 Mar 96	18.2	-26.1	23.4
<b>Sanaga River</b>			
31 Mar 95	4.2	-26.6	5.8
5 May 95	10.4	-23.8	9.0
1 Jun 95	5.1	-22.5	13.9
28 Jun 95	7.6	-24.6	12.5
17 Aug 95	5.4	-24.8	21.7
5 Sep 95	4.1	-23.3	21.6
22 Dec 95	17.0	-25.8	11.6
3 Feb 96	15.0	-25.9	5.0
2 Mar 96	12.3	-26.0	5.4

River samples cannot be definitively determined from the available data, but may be due to atypical behavior of the hydrograph over the sampling period (relative to the long-term average hydrograph presented in Fig. 2) or to modification of the natural hydrograph of the river by the Mbakaou Dam, which dams most of the savanna-covered portion of

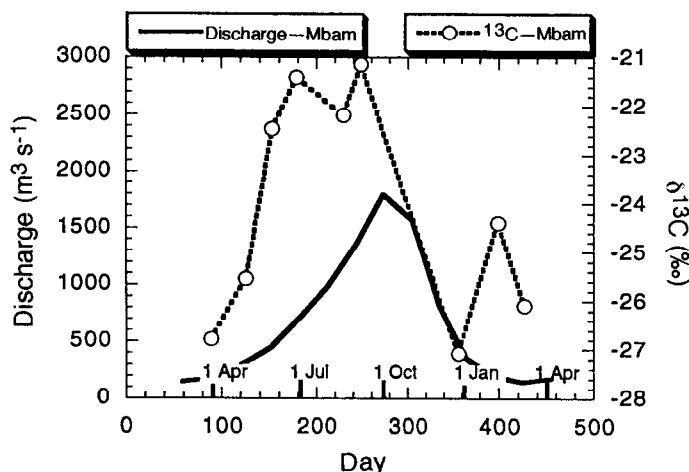


Fig. 1. Carbon-isotope composition of suspended POC in the Mbam River over a 1-year period from March 1995 to March 1996, as well as the 29-year average monthly discharge of the Mbam River at Goura (Olivry 1986). Suspended sediment samples were collected by bucket from a road bridge above the confluence of the Mbam and Sanaga Rivers and were concentrated by settling and decantation. The samples were prepared for analysis by using the techniques detailed in Bird et al. (1994). Carbon-isotope results are presented as per mil (‰) deviations from the international PDB standard, with an uncertainty of  $\pm 0.1\%$ .

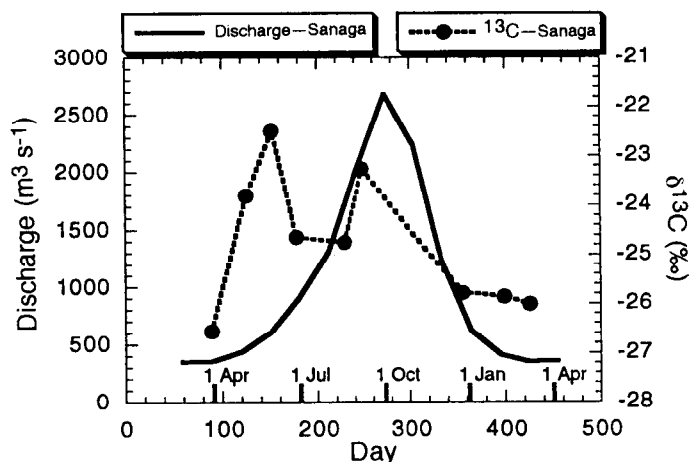


Fig. 2. Carbon-isotope composition of suspended POC in the Sanaga River over a 1-year period from March 1995 to March 1996, as well as the 29-year average monthly discharge of the Sanaga River at Nachigal (Olivry 1986). Sample details as for Fig. 1.

the Sanaga catchment (Bird et al. 1994). The  $\delta^{13}\text{C}$  values for the Sanaga tend to be 1–3‰ lower than for the Mbam during the wet season despite similar areas of savanna in both catchments. This is probably also due to the trapping of  $\text{C}_4$ -rich savanna-derived sediment and POC in the Sanaga River by the Mbakaou Dam. The results are consistent with the hypothesis that  $\text{C}_4$  detritus, accumulated on the soil surface away from the immediate river courses during the dry season, is washed into the rivers from the riverbanks by the rains of the wet season.

Unfortunately, logistic difficulties prevented sampling during peak flow in September–October in both rivers, but by January,  $\delta^{13}\text{C}$  values for suspended POC in both rivers had dropped again to values indicating a dominance of  $\text{C}_3$ -

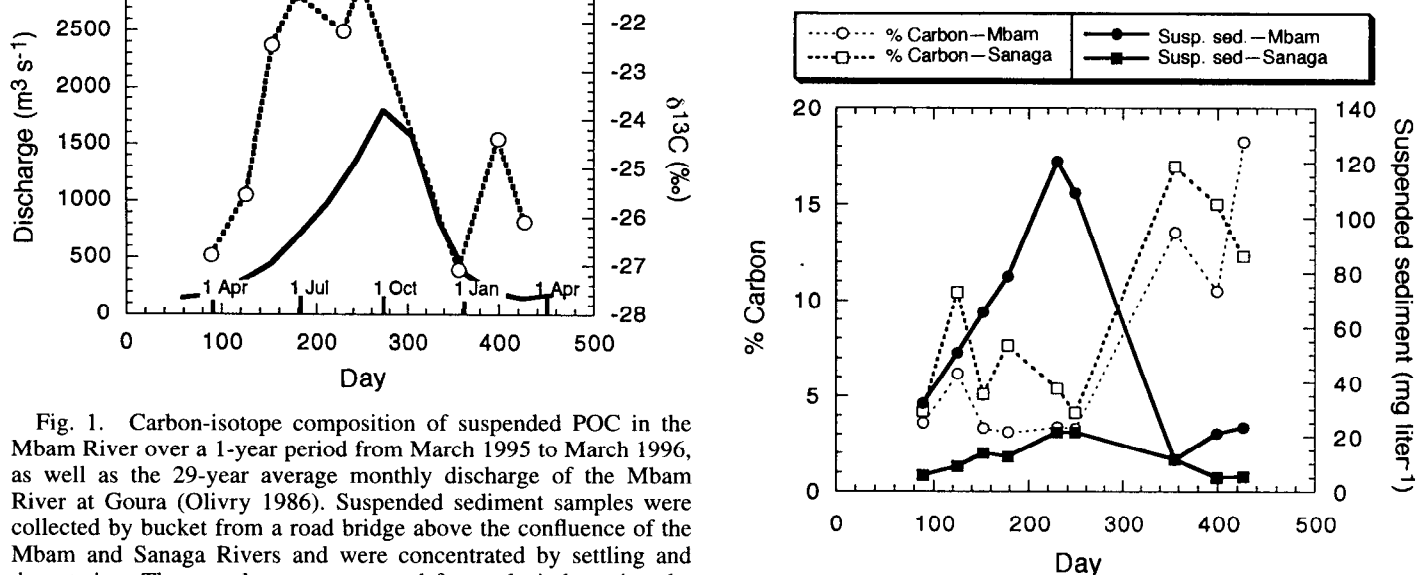


Fig. 3. Variations in the percentage of particulate organic carbon and suspended sediment concentrations in the Mbam and Sanaga Rivers over a 1-year sampling period.

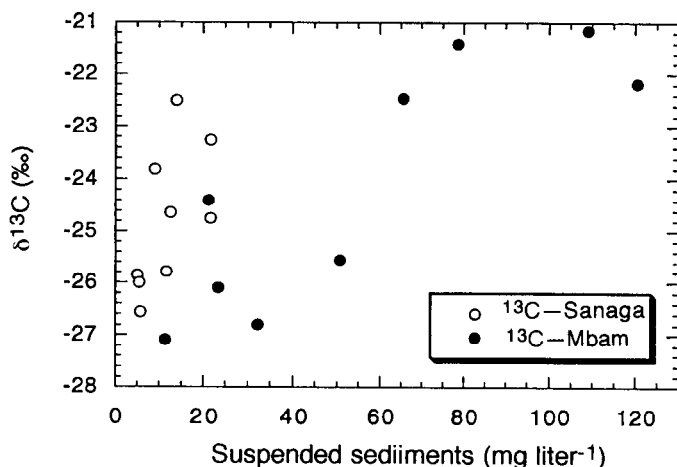


Fig. 4. Relationship between suspended sediment concentration and the  $\delta^{13}\text{C}$  value of POC in the suspended sediment for the Mbam and Sanaga Rivers.

derived detritus. The low  $\delta^{13}\text{C}$  values suggest that the bulk of the suspended POC in both rivers during the dry season is derived from fringing forests close to the riverbank and bank erosion, not from the savanna regions in the catchment hinterland (e.g. Marriotti et al. 1991; Bird et al. 1992, 1994). The observation that both bottom sediments and the suspended sediments show similar trends suggests that the trends do not result from the faster sedimentation of coarse particles. If this were the case, the fast-flowing waters of the wet season would be more able to carry dense  $\text{C}_3$ -derived woody detritus and the opposite trend would result to that which is observed (i.e. wet season POC would have lower  $\delta^{13}\text{C}$  values).

The suspended sediment concentrations and percentages of POC in the samples (Fig. 3) are consistent with the interpretation suggested above. During the dry season, the organic carbon contents of suspended sediment in both rivers are high (>10%), while suspended sediment loads are low. This reflects comparatively low erosion rates, with the POC derived from direct transfer from fringing forests into the river and from direct bank erosion. During the wet season, sediment loads increase and organic carbon contents decrease (<10%) due to the erosion of soils and organic detritus remote from the riverbank by runoff from precipitation, effectively diluting the component of carbon derived from close to the riverbanks. The POC percentages of suspended sediment in the Mbam during the wet season tend to be lower than sediments in the Sanaga, reflecting both the greater ability of the Mbam to transport coarser clastic sediment as well as the greater erodability of soils in the Mbam catchment as a result of intensive agriculture practised in the Bamileke region (Nouvelot 1972; Olivry 1977).

Figure 4 shows the relationship between the  $\delta^{13}\text{C}$  value and suspended sediment concentration, which suggests that sediment concentration is positively correlated with  $\delta^{13}\text{C}$  value. The relationship is particularly strong in the Mbam River ( $r^2 = 0.73$ ). Although some correlation is evident in the Sanaga River, the relationship is obscured by sediment being trapped by the Mbakaou Dam, such that the natural yearly

cycle in suspended sediment transport is modified, and POC from the savannas upstream of the dam are not effectively exported from the upper Sanaga catchment. The positive correlation between suspended sediment concentration and  $\delta^{13}\text{C}$  value of POC is again consistent with the hypothesis that the  $\delta^{13}\text{C}$  value of POC is controlled by the transport of terrestrially derived carbon to the rivers mediated by seasonal variations in precipitation.

The  $\text{C}_4$ -derived carbon exported to the river could have two sources. Tropical rivers commonly have a variable proportion of  $\text{C}_4$  grasses growing on exposed mudbanks, along the riverbanks, and on the adjacent floodplain. Such regions may be seasonally inundated, and must contribute to the observed wet season increases in POC  $\delta^{13}\text{C}$  value. Such a mechanism is not considered to be the major source of the very large variations observed in this study, as POC  $\delta^{13}\text{C}$  values obtained for the Amazon River, a tropical river with  $\text{C}_4$ -containing floodplains but with a mostly forested catchment, indicate seasonal variations generally <1‰ (Hedges et al. 1986; Quay et al. 1992). The changes observed in the Sanaga/Mbam samples are 3–6 times this magnitude. A more plausible explanation is that during the wet season, carbon is eroded from  $\text{C}_4$ -rich savanna regions remote from the immediate riverbanks—such regions contribute sediment to the rivers, so it is reasonable to expect they will contribute a proportionate amount of carbon as well.

It is also possible that algae may contribute carbon with a low  $\delta^{13}\text{C}$  value (<−30‰) to the POC load of the river. Although there is no analytical data available, analogy with other tropical whitewater rivers suggests that contributions from this source will be small (e.g. Hedges et al. 1986). The high turbidity of the Mbam River (generally 20–240  $\text{g m}^{-3}$ ; Olivry 1977) makes it unlikely that there could be a significant algal contribution. The Sanaga is less turbid (generally 5–140  $\text{g m}^{-3}$ ; Olivry 1977) and has a large dam in its headwaters that might provide a source of algal-derived carbon. However, the observations that dry-season  $\delta^{13}\text{C}$  values do not drop below −27‰ in either river and that dry-season  $\delta^{13}\text{C}$  values are similar in both rivers suggest that the proportion of algal-derived carbon in the Sanaga River is likewise small.

It is possible to construct a crude budget for suspended POC export from the Sanaga and Mbam catchments (based on the results in Table 1) and a knowledge of past seasonal variations in water discharge. Such a calculation suggests that 85–90% of POC exported annually by both rivers is transported during the 6 months that include the wet season (July–December). In addition, approximately one-third of the carbon exported to below the confluence of the rivers annually is derived from the Sanaga, while two-thirds comes from the Mbam. Although these figures are in general agreement with those derived by isotope mass balance by Bird et al. (1994), which suggested 60% derivation of POC from the Mbam and 40% from the Sanaga, note that the calculations are subject to large errors, as the samples used in this study were not depth integrated, and actual discharge data for the period when the samples were collected are not available.

The results presented above are consistent with the conclusion of Bird et al. (1994) that the prime determinant of riverine POC  $\delta^{13}\text{C}$  values in the Sanaga/Mbam catchment is

the bulk  $\delta^{13}\text{C}$  value of vegetation in the river catchment. The bulk  $\delta^{13}\text{C}$  value of POC delivered to the river is a function of vegetation type and rainfall distribution in the catchment as well as topography and season. The large range of values encountered during a single seasonal cycle suggest that caution should be exercised in interpreting POC  $\delta^{13}\text{C}$  values from a single sampling of suspended sediment and from tropical rivers with a substantial proportion of  $\text{C}_4$  plants in the catchment. Where only a single sampling is logistically possible, bottom sediments are more likely to provide a better integrated value for the average  $\delta^{13}\text{C}$  value of POC in the river.

*Michael I. Bird*

Research School of Earth Sciences  
The Australian National University  
Canberra 0200, Australia

*Pierre Giresse*

Lab de Sédimentologie et  
Géochimie Marine  
66860, Perpignan, France

*Simon Ngos*

Geology Department  
Yaounde University  
BP 812 Yaounde, Cameroon

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## Photoadaptive response during the development of a coastal Antarctic diatom bloom and relationship to water column stability

**Abstract**—The ratio of the xanthophyll pigments diadinoxanthin and diatoxanthin to chlorophyll *a* [(DD + DT):Chl *a*] was used as a photoadaptive index during the development of a large Antarctic diatom bloom. This index was found to track fluctuations in the incident solar irradiance and the in situ light field over a 3-order-magnitude change in the water column biomass. Depth profiles of the (DD + DT):Chl *a* ratio show that the upper mixed layer, assessed by physical data, was in fact stable over the course of the month. Diel experiments conducted over the same period showed a delayed (5–8 h) response of the DD + DT pool to the instantaneous  $Q_{\text{par}}$  (400–700 nm) irradiance. These time-series results illustrate the potential use of xanthophyll pigments in assessing phytoplankton light histories and the degree of water column stability.

The Southern Ocean supports a rich biotic ecosystem and has been recognized as playing an important role in many global processes, such as biogeochemical cycling (Nelson and Smith 1991) and the sequestration of atmospheric  $\text{CO}_2$  (Siegenthaler and Sarmiento 1993). These processes are ultimately dependent on autotrophic production by phytoplankton. Although a continued subject of debate (Chisholm and Morel 1991), the primary mechanism controlling phytoplankton production over much of the Southern Ocean is thought to be light limitation as a result of the deep vertical mixing, characteristic for the region (Mitchell et al. 1991; Nelson and Smith 1991; Sakshaug et al. 1991). This is especially true in neritic and shelf water where potentially lim-