Biogeosciences Discussions, 2, 1159–1196, 2005
www.biogeosciences.net/bgd/2/1159/
SRef-ID: 1810-6285/bgd/2005-2-1159
European Geosciences Union

Biogeosciences Discussions is the access reviewed discussion forum of *Biogeosciences*

Sources and transfers of particulate organic matter in a tropical reservoir (Petit Saut, French Guiana): a multi-tracers analysis using δ^{13}C, C/N ratio and pigments

A. de Junet[1,*], G. Abril[1], F. Guérin[1], I. Billy[1], and R. de Wit[1,]**

[1]Environnements et Paléoenvironnements Océaniques (EPOC), UMR CNRS 5805, Université Bordeaux 1, Avenue des Facultés, 33405 Talence, France
[*]now at: Institut de Recherche et Développement (IRD), Université de La Réunion, BP 172 97492 Sainte Clotilde Cedex, France
[**]now at: Écosystèmes lagunaires, Université Montpellier II,Case 093,Place Eugène Bataillon, 34095 Montpellier Cedex 05, France

Received: 21 July 2005 – Accepted: 9 August 2005 – Published: 30 August 2005

Correspondence to: G. Abril (g.abril@epoc.u-bordeaux1.fr)

Abstract

Carbon cycling and organic matter transfers in the tropical Sinnamary river system (French Guiana), including a mid-stream reservoir (Petit Saut) and its estuary on the Atlantic coast, were studied during the dry season by analyzing the organic carbon isotopic ratios (δ^{13}C-OC), C/N ratios and pigments contents of suspended matter, sediments, sediments traps and epiphytic and epilithic biofilms. In the River upstream as well as in surface sediments at the entrance of the reservoir and at the littoral zone of the reservoir, particulate organic matter (POM) was in majority of terrestrial origin, with a δ^{13}C-C/N signature close to the one of soil and litter collected in the surrounding forest and with high OC/total pigments ratios. High concentrations of Pheopigments *a* and *b* in these surface sediments showed that this terrestrial POM, either carried by the river and eolian transport or present in the soil before flooding, undergoes intense degradation. Deeper in the sediment, the δ^{13}C profile showed a decreasing trend with depth typical of what is found in soils, showing that the flooded soil still remains present at the reservoir bottom 10 years after flooding. At the center of the reservoir, POM in the water column, in sediment traps and in surface sediments was in majority of aquatic origin with low C/N and OC/total pigments ratios. In the oxic epilimnion at 3 m depth, Chl *a*, Chl *b* and Lutein showed the predominance of Chlorophyceae to the phytoplankton community. At this depth, a C/N ratio of 21 suggests a large contribution of transparent exopolymeric particles to the bulk POM, which, in addition, was ^{13}C-depleted due to a significant contribution of methanotrophic bacteria. At 7 m depth, below the oxicline, high concentrations of BChl *d* and occasionally BChl *c* revealed the presence of anoxygenic phototrophic bacteria, namely Chlorobiaceae. In the sediment traps, Chl *a*, Chl *b*, Lutein and BChl *c* and BChl *d* confirmed the contribution of plankton to the sedimentary POM. This material was undergoing intense degradation as revealed by high concentration of pheopigments and by an increase in C/N ratio and an increase in δ^{13}C-OC with trap depth. Scytonemin was found in a biofilm developed on tree trunks at the reservoir surface and in all sediment traps. Other tracers

BGD

2, 1159–1196, 2005

showed however that the contribution of the biofilm to the sedimentary POM was minor compared to the planktonic source. In the Sinnamary downstream of the dam, POM became more ^{13}C-depleted showing a larger contribution of methanotrophic bacteria. Chl *b*, Lutein and BChl *c*+BChl *d* originating from the reservoir progressively decreased downstream as the result of mineralization. At the estuarine mouth, fucoxanthin showed the presence of diatoms and the δ^{13}C-C/N signature matched the one of POM carried by the Amazonian coastal mobile mud belt.

1. Introduction

Understanding the carbon cycle and organic matter (OM) sources, transfers and transformations in terrestrial and aquatic ecosystems is fundamental in the context of global change (Houghton et al., 2001). Among aquatic systems, artificial reservoirs have been recently identified as potentially significant source of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere (Galy-Lacaux et al., 1999; St Louis et al., 2000). Reservoirs are particularly complex systems where multiple sources of OM coexist. First, the terrestrial OM initially flooded composed of soils, litter, leaves and trunks may remain for a long time in the system; second, terrestrial OM is carried by the rivers or by eolian transport and might settle in the reservoir, being buried or recycled; third, autochthonous OM is produced in the reservoir by phytoplankton, bacteria, macrophytes and/or biofilms. Furthermore, all these sources of OM may have very different residence time in the system, depending on their transport, bioavailability and recycling. Owing to this complexity, the origins and transfers of OM are poorly documented in reservoirs, particularly in the tropics. Most studies focus on net CO_2 and CH_4 emissions (Galy-Lacaux et al., 1999; St Louis et al., 2000; Abril et al., 2005). Little is generally known on the internal processes involved in the C cycles of reservoirs including riverine inputs, sedimentation, primary production, degradation and export downstream.

The carbon isotopic composition (δ^{13}C) of OM can be used to identify its origin in

waters and sediments. (Mook and Tan, 1991; Lonchouarn et al., 1999; Onstad et al., 2000). The $\delta^{13}C$ of terrestrial OM allows to differentiate OM from plants using the C3 pathway of CO_2 uptake ($\delta^{13}C \approx -25$ to -28 per mil) against OM from plants employing the C4 pathway ($\delta^{13}C \approx -10$ to -14 per mil). The $\delta^{13}C$ of aquatic autotrophic microorganisms depends on the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) they take up from the water, and on the isotopic fractionation during CO_2 fixation. Since $\delta^{13}C$-DIC is much more negative and variable in freshwaters than in marine waters, $\delta^{13}C$-POC varies from -23 to -44 per mil in freshwater phytoplankton (Mook and Tan, 1991). In the case of methane-rich environments like organic-rich freshwater sediments (Boschker and Middelburg, 2002) or the water column of tropical reservoirs (Dumestre et al., 2001), the dense population of methanotrophic bacteria may significantly decrease the $\delta^{13}C$ of the bulk POM. Indeed, methanotrophic bacteria have a carbon isotope ratio between -60 and -110 per mil (Blair, 1998; Boschker and Middelburg, 2002). Finally, in environments with an anoxic water body, strictly anaerobic and photoautotrophic bacteria that use H_2, H_2S or another reduced sulfur compound as electron donors for anoxygenic photosynthesis can also become a significant contributor to the POM pool. Sirevåg et al. (1977) have described a $\delta^{13}C$ for the bulk biomass of *Chlorobium limicola* (Chlorobiaceae) of -12.2 per mil, which is explained by the fact that Chlorobiaceae use the reverse TriCarboxilic Acid (TCA) cycle for the fixation of CO_2 (Buchanan and Arnold, 1990). Accordingly, Chlorobiaceae in fresh water systems are expected to be isotopically heavier ($\delta^{13}C$) than phytoplankton species by about 10 per mil.

The C/N ratio of OM also allows to distinguish between terrestrial and aquatic OM, as well as their decomposition states. Elser et al. (2000) have shown that terrestrial plants have an average C/N ratio of 32 whereas freshwater phytoplankton has an average C/N ratio near the Redfield value of 7 and bacteria have a C/N ratio around 4 (Lee and Furhman, 1987). Furthermore, microbial decomposition of organic matter tends to increase its C/N ratio (Lehmann et al., 2002), nitrogen being mineralized faster than carbon.

BGD
2, 1159–1196, 2005

Pigments and carotenoids are present in both terrestrial and aquatic photosynthetic organisms and can also be used as tracers of OM origins in aquatic systems. Some phytoplankton and bacterioplankton groups contain specific pigments that can be used as unequivocal tracers. For instance, diatoms are revealed by the presence fucoxanthin (Jeffrey et al., 1997), cyanobacteria by scytonemin, myxoxanthophyll and echinenone (Sinha et al., 1998; Hunsucker et al., 2001) and Chlorobiaceae by chlorobactene (Schouten et al., 2000). Chlorophyll *b* and lutein are found in Chlorophyceae but also in terrestrial plants and aquatic macrophytes (Bianchi et al., 1993a). In such a case, the carbon/pigment ratio which is much lower in phytoplankton than in higher plants, can still allow the differentiation between these two kinds of OM sources. Finally pheopigments can be used for tracing the degradation of OM from a specific origin in the aquatic system.

In the present study, we have combined these three kinds of tracers (δ^{13}C, C/N and pigments) in order to characterize the OM origins and major transfers in a 10-years old tropical reservoir and its river upstream and downstream. Many organic matter pools of different origins coexist in such system. Different compartments of the system were analyzed: particulate matter in the water column, sediment traps, sediments and biofilms upstream and downstream of the dam. The combination of these three kinds of tracers allows us to differentiate allochthonous (flooded soil and river sediment load) and autochthonous OM (phytoplankton, bacteria and biofilms) and to obtain a general and semi-quantitative picture of OM cycling in the reservoir.

2. Material and methods

2.1. Study site and sampling

The Petit Saut dam was constructed on the Sinnamary River in French Guiana 100 km upstream its mouth to the Atlantic Ocean (Fig. 1). The Sinnamary River has an average discharge of 235 $m^3 s^{-1}$ with important seasonal and interannual variability. The

reservoir started to be filled in January 1994 and covers 80 km of the Sinnamary River course. At its maximal level of 35 m (first reached in July 1995), 360 km^2 of uncleared tropical forest were flooded (Fig. 1). Average residence time of waters is ~5 months. Downstream of the dam, the Sinnamary River has an average depth of 4 m and is influenced by the tide with an amplitude of 0.5 m. Salt intrusion starts however only at the river mouth, salinity at the limit of the coast being around 3–5. The lower reach of the estuary is influenced by Amazonian highly turbid waters coming from the Eastern shelf (Aller, 1998).

The Petit Saut reservoir's water body is highly stratified with an oxic epilimnion and an anoxic hypolimnion, separated by a quasi permanent oxicline located around 5–7 m depths (Galy-Lacaux et al., 1999). The hypolimnion is rich in methane (300 $\mu mol\,l^{-1}$) and in Fe^{2+} (80 $\mu mol\,l^{-1}$) (Richard, 1996). When passing through the turbines, waters originating mainly from the hypolimnion get reoxidized at an aerating weir which was specially designed to avoid hypoxia problems in the Sinnamary tidal river downstream. Owing to the intense oxidation of Fe(II) to Fe(III) downstream of the turbines, red/brown flocs are observed floating in the water and, also, rocks are brown colored in this area.

The terrestrial OM flooded at Petit Saut was composed of soils, litters, trunks as well as leaves that have fallen into the water few months after flooding. The reservoir epilimnion was rapidly colonized by phytoplankton, mainly composed of Chlorophyceae (Vaquer et al., 1997). Methanotrophic bacteria are found in the oxic epilimnion and phototrophic green bacteria (Chlorobiaceae) just below the oxycline (Dumestre et al., 2001). In addition, tree trunks and branches left in place got colonized by green biofilms (epiphyton), about one centimeter thick. Brown biofilms also more than 1 cm thick develop on rocks (epilithon) just downstream of the dam in the shallow Sinnamary river.

Samples were collected during the dry season in December 2003 at 7 Stations located upstream and downstream of the dam (Fig. 1). Station 1 is located on the Sinnamary River, just at the entrance of the reservoir. It receives POM carried by the river and is characterized by intense local sedimentation owing to the sudden drop in current

BGD
2, 1159–1196, 2005

velocities. Station 2 and 4 are located in the reservoir, in open waters on the previous Sinnamary river bed, with water depth of approximately 30 m, the maximum depth observed in the artificial lake during this period. Station 3 is located on a flooded forest site in the reservoir, with shallow water. Station 5 is located immediately downstream of the dam and the aerating weir. Station 6 is an intermediate tidal, freshwater station. Finally, Station 7 is located at the mouth of the Sinnamary River, with a salinity of 3, when sampling.

Water samples were taken at Stations 1, 4, 5, 6 and 7 at the surface and in a complete water column vertical profile (depths 3, 6, 7, 10, 15 and 25 m) at Station 4 with a peristaltic pump. Using an oxygen probe, the oxicline was located at 6 m depth. Waters were filtered on precombusted glass-fiber filters (porosity of 0.7 μm). Surface sediments were collected in two ways. Upstream the dam (Station 1) and at the mouth of Sinnamary estuary (Station 7), where waters are shallow, a perch was used to collect surface sediment. At deep stations in the reservoir, the presence of trunks and branches at the bottom precludes the use of box cores. Consequently, at Stations 2 and 4 (25 and 30 m depth), surface sediment was collected with a peristaltic pump; this material comprises sedimentary material settled on the bottom or on the trunks and branches. Finally, a 20 cm-long sediment core was collected in the littoral zone of the reservoir under 50-cm of water at Station 3. While also the latter sediment is always submerged (sampling was performed when the lake was at its minimum level), the sedimentation is probably very different in the littoral zone than at the center of the reservoir. Biofilms were also collected on two sites: one epiphytic green biofilm on a tree branch in the lake at 20 cm depth (Station 4) and one epilithic brown biofilm on the rocks just downstream of the dam (Station 5) at 10 cm depth. Sediment traps were collected and had been deployed during 48 days at −7, −20 and −30 (at the bottom) m at Station 4. No poison was used in sediment traps because the same material was used for incubation purpose. The OM was undergoing degradation during the collection period and results must be interpreted in consequence. Finally, litter and soil were sampled in the tropical forest nearby the dam.

BGD

2, 1159–1196, 2005

Water samples were filtered on pre-weighted and pre-combusted GF/F filters (porosity 0.7 μm). The sediment core was cut in 2 cm slides. Filters and sediments used for pigment analyses, were frozen at −20°C immediately after sampling, then transported within one week back to France and finally stored in an ultracold freezer at −80°C two months before analysis. For Organic Carbon (OC), isotopic composition and C/N ratio analyses, filters and sediments were immediately dried at 60°C and stored at ambient temperature until analysis.

2.2. Analyses

2.2.1. Organic Carbon, δ^{13}C and C/N ratio analyses

Dry filters were first weighted to determine Suspended Particulate Matter (SPM) concentrations and dried sediments were grinded and homogenized. Then samples were acidified with HCl(2N) to remove carbonates and dried at 50°C overnight before analysis. A Carbon LECO CS-125 analyzer was used based on direct combustion in an induction furnace and infrared absorption determination of the CO_2 produced. Analysis was done on duplicate. Small pieces of filters (1 cm^2) and few quantities of sediments (∼1 g), were used for δ^{13}C analysis. Measurements were done by coupling a 2500 CARLO-ERBA CN Elemental Analyzer and a Mass Spectrometer of type Micromass Isoprime (Isotope Ratio Mass Spectrometer) following an acidification procedure for sediments (Nieuwenhuize et al., 1994). Carbon isotope ratio is expressed in the delta notation (δ^{13}C) relative to Pee Dee Belemnite. Calibration of the mass spectrometer was done with two standards at 10 and 35 per mil. Analysis was done on triplicates. C/N ratio on filters and sediments were measured by a CN Elemental Analyzer (Flash Elemental) following Nieuwenhuize et al. (1994) method, based on catalytical combustion (1020°C) of OM with oxygen and dosage of each gas formed by combustion (CO_2 and N_2) with an infrared cellule or catharometer. Analysis was done on duplicates.

2.2.2. Pigments analyses

Pigments were extracted with acetone and analyzed by reverse phase HPLC according previously described methods (Buffan-Dubau et al., 2001; Lemaire et al., 2002). In summary, acetone was added to samples which were sonicated and left one hour at −4°C in the dark. The samples were spin down in a centrifuge at 3900 g and the supernatants were collected. A second acetone extraction was performed as described and the two extracts were pooled. The combined extracts were filtered (0.22 μm) after addition of diazomethane (N_2CH_3) to convert pigments with carboxylic groups into their corresponding methylesters. Subsequently, the extracts were totally evaporated using a speed-vacuum and stored in the dark at −80°C until analysis. Immediately before the HPLC analyses, the dried extracts were dissolved in solvent A (50% methanol, 45% acetonitrile, 5% of 0.05 M ammonium acetate in water at pH=7.2) and a 50 or 100 μl aliquot was injected on a Thermofinnigan HPLC chain using a Lichrospher column 100RP18 (250×4 mm, 5 μm), a binary gradient from solvent A to B (solvent B=80% ethylacetate, 19% methanol, 1% acetonitrile) and photometric detection using a TSP UV6000 diode array spectrophotometer. The spectrophotometer was programmed to obtain the on-line spectra from 320 to 800 nm and chromatograms were collected at 440 nm for the quantification of carotenoid pigments, and at 664 nm for the quantification of chlorophylls and phaeopigments.

Pigments were identified by comparing their retention times and absorption spectra with those of authentic standards (International Agency for ^{14}C determination), using pigment response factors (F) obtained by calibration:

Hence injected weight W(μg)=area/F

Pigment concentrations (μg/L) in the original sample were thus equivalent to:

$$[\text{Pigment}]=(W\times V_{\text{dissolution}})/(V_{\text{filtered}}\times V_{\text{injection}})$$

The response factor for bacteriochlorophyll c (BChl *c*, online absorption maxima λ=432 nm and λ=661 nm) was determined using an axenic culture of *Prosthecochloris aestuarii* strain CE 2404 as a standard (Massé et al., 2004). No authentic standards

were available for bacteriochlorophyll *d* (BChl *d*, online absorption maxima λ=428 nm and λ=652 nm) . However, the sample at 7 m depth (Station 4) was completely dominated by BChl *d*. The concentration of BChl *d* in this extract was determined by spectrophotometry in acetone extracts using an extinction coefficient of ε=98 L g^{-1} cm^{-1} (Stanier and Smith, 1960). HPLC analysis of this sample showed that BChl *d* consisted as different allomers which were separated between 9 and 26 min. The major component eluting at around 10 min, which by analogy with their BChl *c* counterparts from *Prosthecochloris eastuarii* (Massé et al., 2004) could be identified as farnesyl esterified bacteriochlorophyll d allomers (BChl d_f). All areas corresponding to the different BChl *d* allomers were summed and compared to the total weight injected , which allowed us to determine the following response factors F=8.63 10^6 at 440 nm and F=4.45 10^6 at 664 nm.

Both BChl *c* and BChl *d* distributions were dominated by farnesyl esterified allomers, with minor quantities of secondary homologs eluting between 14 and 26 min, corresponding to allomers esterified with other alcohols. For quantification, we summed all the allomers and calculated a sum of BChl *c* and BChl *d* (i.e. $\sum$BChl *c*+BChl *d*) for the different samples.

One of the farnesyl esterified bacteriochlorophyll d allomers (BChl d_f) coeluted with lutein at Rt=10 min. Nonetheless, in most cases it was possible to quantify lutein by the following procedure. Firstly, since lutein does not absorb in the red, we determined the quantity of the BChl d_f allomer corresponding to this peak by using its area at 664 nm. Secondly, the partial contribution of the BChl d_f allomer was calculated at 440 nm and substracted from the measured value to obtain the 440 nm area attributed to lutein.

3. Results

3.1. Particulate Organic Matter in water samples

Upstream the reservoir in the Sinnamary river (Station 1), SPM value was low (5 mg/L, Fig. 3 and Table 1), with POC (% SPM), δ^{13}C and C/N ratio respectively around 10%, −29 per mil and 14. All pigments were below detection limit in SPM at this Station. In the reservoir at Station 4 SPM values in the 30 m water column were still low (<5 mg/L) but POC contents were much higher than upstream, between 20 and 40%. C/N ratio were around 10 at Station 4 at all depths except at the surface were a value of 21 was measured. δ^{13}C values were lighter at Station 4 (average −31 per mil) than in the Sinnamary upstream. In the lake at Station 4, pigments could be detected from the water surface to a depth of 10 m, with a maximum of 180 μg L^{-1} of total pigments at 7 m-depth. Chlorophyll *a* (Chl *a*) predominated at −3 m whereas Bchl *d* at −6 m and below (Table 1). Immediately downstream of the dam at Station 5, the POM characteristics were similar to the ones found in the reservoir water column. SPM values were low (2.5 mg L-1), with a high POC content (38%), a C/N ratio of 11.8. However, the δ^{13}C value was significantly lighter (−33 per mil) at Station 5 than in the reservoir upstream (water column average: −31 per mil). The pigment concentration was 19 μg L^{-1} with a 80% contribution of $\sum$BChl *c*+BChl *d* and a 20% contribution of Chl *a*. Downstream the Sinnamary River and estuary (Stations 5 to 7), SPM progressively increased and POC contents decreased to reach 200 mg L^{-1} and 1.1%, respectively at the estuarine mouth (Station 7). Conversely, the C/N ratios decreased and the δ^{13}C value increased to reach respectively 7.9 and −27 per mil at Station 7. In this section of the Sinnamary River and estuary, total pigments decreased downstream from 19 μg L^{-1} at Station 5 to 1 μg L^{-1} at Station 7. In addition, $\sum$BChl *c*+BChl *d* gradually disappeared and fucoxanthine appeared in the estuary.

The vertical profiles obtained in the reservoir water body at Station 4 are shown in Fig. 4, together with the position of the oxicline at 6 m and the results of surface sediments. SPM showed a maximum at −7 m (5.5 mg L^{-1}) just below the oxicline and

BGD
2, 1159–1196, 2005

a decreasing trend with depth. POC decreased from 40% at −3 m to 22% at −20 m, and increased again to 35% at −25 m. POC in surface sediments was more than 5 times lower than in the above water column. The C/N ratio was very high at −3 m (21) and decreased to a rather constant value around 11 at depths below −6 m. By contrast, the C/N ratio in surface sediments was about 15. The δ^{13}C values were relatively light in the oxic epilimnion and then increased to −30 per mil at −25 m. The δ^{13}C in surface sediments was lighter (−31 per mil) than in water column suspensions. Pigments in the three first meters were dominated by Chl *a* at −3 m (80% of total pigments) followed by Chlorophyll *b* (Chl *b*), violaxanthin and lutein (Table 1). The maximum Chl *a* was located at −6 m, but at this depth Chl *a* accounted for only 10% of the total pigments. BChl *d* and BChl *c* were predominant at −6 m to −15 m but it was below detection limit at −3 m. At −7 m, the BChl *d* concentration reached 200 μg L^{-1} and represented more than 99% of the total pigment with few amounts of lutein (Table 1). However, even if the presence of lutein was obvious at 7 m-depth, its concentration could not be adequately quantified because of coelution with BChl *d*.

3.2. Organic Matter in sediment traps

In sediment traps, POC contents were much lower (average 11%) than in the water column (Table 1). POC was maximum at the intermediate 20 m depth (13%), whereas at 7 m and 30 m, values were 10.7 and 8.5%, respectively. By contrast to the water column suspensions, C/N ratio in the sediment traps increased with depth from 11 at 7 m to 14 at 30 m, and δ^{13}C decreased from −28 per mil at −3 m to −29.7 per mil at 30 m (Table 1). Pigment concentrations also decreased with depth from 500 to 250 μg g^{-1} of sediment. Pigment diversity was much higher in the material collected in the sediment traps than in the material collected at individual depths in the water column. Among the pigments also observed in the water column, Chl *a*, $\sum$BChl *c*+BChl *d* , and lutein represented respectively 29%, 17% and 10% of the total pigments, on average for the three traps. In addition, Pheo *a* and β-caroten were also abundant in the traps (respectively 26% and 14% of total pigments on average). Pheo *a* was most abundant in

the bottom trap, whereas β-caroten was most abundant in the 7 m-depth trap and was associated with small quantities of violaxanthin (Table 1). Finally, Chl *b* was present only in the trap at 7 m and some traces of scytonemin, which could not be quantified, were found in the three traps.

3.3. Organic Matter in sediments and biofilms

The contents of surface sediments collected along the Sinnamary River upstream and downstream of the dam, at the Petit Saut reservoir bottom and in the first 2 cm of the near-bank sediment core are presented in Fig. 5. The compositions of the two biofilms collected upstream and downstream of the dam are also shown. The OC content in the surface sediments at the upstream river station was close to 5% with a C/N ratio of 20 and a δ^{13}C value of −30 per mil. By contrast to the SPM sampled in the water, several pigments could be detected in the surface sediments at Station 1: 5 μg g^{-1} of Chl a, 6 μg g^{-1} of Pheo *a* and few amonts of Chl *b*, lutein, violaxanthin, fucoxanthin, β-carotene and Pheo *b*. Surface sediments collected at high water depths in the center of the reservoir (Stations 2 and 4), had similar characteristics with a OC content around 9%, a C/N ratio of 15 and a δ^{13}C value of −31 per mil. At Station 4, surface sediment contained very few amounts of pigments, composed in majority of cantaxanthin and zeaxanthin. At the near bank station with shallow depth (Station 3), the surface sediment had very different characteristics from those at the center of the reservoir (Fig. 5); OC content was 13%, the C/N ratio was 31 and δ^{13}C was −29 per mil. Total pigment content was high, at 16.4 μg g^{-1}. Finally, in the estuary (Station 7), surface sediment had the same low OC content as the SPM (1%), whereas its C/N ratio (10) and δ^{13}C value (−26 per mil) were slightly higher than in SPM. Pigments were below detection limit in this estuarine sediment.

The two biofilms sampled upstream on trucks in the lake and downstream on rocks in the Sinnamary river, had very different POC and δ^{13}C values (Fig. 5, Table 1). The green epiphytic biofilm sampled on the trunks of the lake, had a OC of 40% and a δ^{13}C of −21 per mil, whereas the brown lithophytic biofilm just downstream of the

BGD
2, 1159–1196, 2005

dam, contained only 5.9% OC with a very light $\delta^{13}C$ (−36 per mil). By contrast, the C/N ratios of the two biofilms were similar at 16–17. The epiphytic biofilm contained 40 $\mu g\,g^{-1}$ of pigments and Chl *a* was dominant (96% of total pigments) followed by β-carotene, lutein (Table 1), with few amounts of scytonemin and cantaxanthin. The lithophytic biofilm downstream of the dam was richer in pigments with 100 $\mu g\,g^{-1}$; Chl *a* accounted for 74% of total pigments, followed by fucoxanthin (18%), ∑BChl *c*+BChl *d* (5% $\mu g\,g^{-1}$), and traces of Chl *b*, lutein, and β-carotene.

The vertical profiles obtained in the sediment core collected at the littoral station (Station 3) are shown in Fig. 6. Results obtained in the litter and soil samples are also reported for comparison. OC and C/N ratio decreased quickly in the 8 first centimeters of the core, respectively from 14% to 1% and from 31 to 17 and remained constant below. At the core surface, OC was slightly lower than OC of litter and soil, whereas C/N values were the same as in the litter. In the 2–8 cm interval of the core, the C/N ratio was the same as in the soil. The $\delta^{13}C$ values decreased from −29 to −30.5 per mil in the first 4 cm and then increased progressively to −25,7 per mil at 20 cm depth. The $\delta^{13}C$ of litter (−28.7 per mil) and soil (−29 per mil) were similar to those in the first centimeters of the core. Pigments were present only in the first 8 cm and varied between 8 and 16 $\mu g\,g^{-1}$ (Fig. 6). The contribution of Chl *a* to total pigment was 50% in surface sediment and decreased with depth. The degradation products Pheo *a* and Pheo *b* were the predominant pigments at 5 cm where they represented 70% of the total pigment. Finally, carotenoïds (fucoxanthin, lutein, Violaxanthin and β-carotene) were also present at concentrations below <1.5 $\mu g\,g^{-1}$ until 5 cm depth.

4. Discussion

The combination of the three kind of tracers used in this study allows to describe the majors patterns of OM origin, transfers and degradation in the Petit-Saut reservoir. In this discussion section, we characterize the origin and transformation of OM in the different components of the system using $\delta^{13}C$ versus C/N diagrams and referring

to pigment data in order to complement the argumentation. We first compare the OM carried by the river upstream the reservoir with the one found in the water column of the lake. Then, we investigate the sedimentation patterns in the lake and the composition of the sediment/soil core sampled on the bank. Finally, we discuss the transfers and transformations of OM through the turbine of the dam and in the Sinnamary river and estuary downstream.

4.1. OM origins in the Sinnamary upstream and in the lake

At the upstream Sinnamary river station, δ^{13}C was −29 per mil and −30 per mil, respectively in SPM and in surface sediments. These values were similar to those of the soil and litter samples (Table 1), suggesting a terrestrial origin of POM. The lighter value in the sediment might be due either to decomposition processes occurring in the sediment (Lehmann et al., 2002) or to a temporal change in the δ^{13}C of POM carried by the river (Tan, 1987) that would be integrated in the sediment at the entrance of the reservoir. C/N ratio were high at this upstream station (respectively 14 and 20 in SPM and sediment), which confirms the major contribution of terrestrial OM (Elser et al., 2000). In addition, no pigment was detected in the SPM and the surface sediment had a POC/Chl *a* ratio >10 000, which also shows a major contribution of terrestrial OM. The Chl *a*, Chl *b*, lutein, *β*-carotene and violaxanthin found in surface sediment of Station 1 (Table 1) thus originate from higher plants (Bianchi et al., 1993a, b) in the primary forest. This material undergoes intense degradation in the sediment as revealed by high Pheo *a* and Pheo *b* concentrations. Finally, the presence of few amounts of fucoxanthin at the surface of this sediment, also reveals a small contribution of diatoms, most probably benthic in this shallow waters.

At the center of the lake of the Petit Saut reservoir (Station 4), POM in the water column had a distinct δ^{13}C and C/N signature from the upstream river station, with lower C/N ratio (except at 3 m depth, see below) and lighter δ^{13}C (Fig. 7). These low C/N ratio associate with low POC/ΣChl ratios (down to 8 at −7 m just below the oxicline, Table 1) reveal the large predominance of lacustrine phytoplankton in the POM pool (Elser et

BGD
2, 1159–1196, 2005

al., 2000). This phytoplanktonic material has a δ^{13}C between −32.5 and −31 per mil. The δ^{13}C signature of phytoplankton may vary over a wide range in freshwaters. In tropical waters, values reported so far in phytoplankton-dominated waters varied from −23 per mil in Lake Tanganyika (O'Reilly et al., 2002) to −37 per mil in Oronico River floodplains (Hamilton and Lewis, 1992). Such differences might be due to changes in the δ^{13}C of the DIC used by phytoplankton and to the contribution of chemoautotrophic and/or methanotrophic bacteria that result to more ^{13}C-depleted values. In the water column of the Petit Saut reservoir, the δ^{13}C of POM is also influenced by the presence of different types of bacteria, as discussed below.

The distribution of pigments with depth at Station 4 in the water column of the reservoir (Fig. 4) is in accordance with studies conducted earlier in Petit-Saut (Vaquer et al., 1997; Dumestre et al., 1999; 2001). At 3 m-depth, the presence of Chl *a*, Chl *b*, Lutein and Violaxanthin (Table 1) reveal the predominance of Chlorophyceae (Jeffrey et al., 1997), a finding confirmed by the microscopic observations reported by Vaquer et al. (1997). In addition, the Chl *b*/Lutein ratio was 2.8 close to the one of Chlorophyceae and very different from higher plants (Chl *b*/Lutein∼1, Bianchi and Findlay, 1990). The presence of Chlorobiaceae below the oxicline was confirmed by the high concentrations of bacteriochlorophylls *c* and *d*. The BChl *c* and BChl *d* compounds eluting around 10 min (see Fig. 3), which correspond to farnesyl esterified allomers, were most abundant. In addition secondary allomers, which eluted between 14 and 26 min and which are allomers estergified with other alcohols (Borrego et al., 1994; Massé et al., 2004) were present in minor quantities. It was remarkable that the sample at 7 m depth was completely dominated by BChl *d*, while the sample at 6 m depth presented a mixture of BChl *c* and BChl *d* allomers. The presence of the bacteriochlorophylls of Chlorobiaceae has also been observed by Vaquer et al. (1997) and Dumestre et al. (1999).

Chlorobiaceae were present in high densities at 6 m depth and achieved maximum biomass and their pigments fully dominated the pigment distributions at 7 m depth just below the oxicline in Petit-Saut reservoir. At 7 m depth the COP/ ($\sum$ BChl *c*+BChl

BGD
2, 1159–1196, 2005

d) ratio was 8 and the C/N ratio between 10–12. Surprisingly, the δ^{13}C values at 6 to 7 m depth (around −31 per mil) appeared not to reflect the contribution of the isotopically heavier Chlorobiaceae (Sirevåg et al., 1977). This can be explained by the presence of aerobic methanotrophic bacteria at these depths and above (Dumestre et al., 2001). With a highly ^{13}C-depleted biomass (δ^{13}C=−80 to −100 per mil), only a small contribution of methanotrophic bacteria to the total POM is needed in order to counterbalance the contribution of the ^{13}C isotopically heavier Chlorobiaceae. It is worth to note however, that small methanotrophic bacteria occurring as free living in the water may have not been retained on the 0.7 μm filters. Nevertheless, the vertical δ^{13}C-POM profile in the reservoir water column (Fig. 4) can be interpreted as the relative contribution of methanotrophic bacteria and of Chlorobiaceae to the >0.7 μm POM. At the oxicline and in the oxic epilimnion δ^{13}C is as negative as −32.5 per mil at 3 m-depth, present at and below the oxicline were δ^{13}C get heavier.

As discussed above, POM in the reservoir waters at Station 4 is mainly autochthonous, composed of phytoplankton and bacteria. However, at 3 m-depth, an unexpected high C/N ratio of 21 was found. In the Tucupido and Bonocó reservoirs in Venezuela, Bellanger et al. (2004) found similar high C/N ratio in the first meters of the water column. These authors did not conclude whether this was due to the occurrence of unusual phytoplankton with high C/N ratio or to a high contribution of land vascular plant debris. In the case of the Petit Saut reservoir, several indications support the first hypothesis. From microscopic observations, Vaquer et al. (1997) have described the phytoplankton at Petit Saut as picophytoplankton composed of Chlorophyceae and surrounded by mucus. This mucus is presumably exudation products of the phytoplanktonic cells that forms aggregates retained on 0.7 μm filters. The material collected on the filters at 3 m-depth was white with a creamy texture. In the marine environment, the coagulation and aggregation of phytoplanktonic exudates has been shown to produce transparent exopolymeric particules (TEP) (Mari et al., 2001). In the ocean TEP usually appear when the phytoplankton becomes nitrogen limited, which is also the case in the epilimnion of the Petit-Saut reservoir (Collos et al., 2001). TEP have a C/N ratio

BGD
2, 1159–1196, 2005

much higher than the Redfield ratio, on average around 21 in Northwestern Mediterranean Sea (Mari et al., 2001; Passow, 2002). In the Petit Saut reservoir at 3 m depth, nitrogen-depleted aggregates similar to TEP could contribute in a major part of POM. At this depth, POC/Chl *a* ratio was 260, which is higher than the classical phytoplankton POC/Chl *a* ratios of 30–50. This is probably due to a contribution of aggregates to the POC but not to chlorophyll content.

4.2. Sedimentation in the lake and POM origin in the lake sediment

The OM collected in the sediment traps at the three different depths had a C/N ratio which increased with depth and a δ^{13}C values which decreased with depth (Table 1). The surface sediment collected at the same station was also consistent with this trend (Fig. 8). In Lake Lugano, Lehmann et al. (2002) made the same observation, which can be attributed to the degradation of a single OM source during its fall in the water column. In our study, degradation also occurred during collection, in the sediment traps that were not poisoned. From Fig. 8 it appears that the major source that falls in the water column has a C/N ratio around 11, i.e. similar to the lacustrine POM found in the water column. This sedimentary material also contains high concentrations of Chl *a*, Chl *b*, Lutein and $\sum$BChl *c*+BChl *d*, and has a low POC/ΣChl ratio (Table 1) which also shows a large contribution of the two major phototrophic planktonic populations found in the water column (Chlorophyceae and Chlorobiaceae). The presence of degradation pigments and, in particular, the high concentrations of Pheo *a* confirm the occurrence of intense degradation processes during the fall in the water column and in the traps themselves. The δ^{13}C value of the sedimentary source is however much heavier (about −28 per mil) than the ones found in the water column (Fig. 8), which suggests either a preferential sedimentation of Chlorobiacea and Chlorophyceae against methanotrophic bacteria or a preferential mineralization of the methanotrophs. Pigment concentrations suggest however an additional source of sedimentary POM than phytoplankton and bacterioplankton. Traces of scytonemin were found in all traps as well as in the epiphytic biofilm but not in the water column of the reservoir. Scytone-

min is a UV-absorbing compound that is produced by cyanobacteria to protect against radiation (Sinha et al., 1998). Its presence at all depths in the sediment traps shows a contribution of the epiphytic biofilm to the sedimentary POM in the reservoir. The C/N ratio of this biofilm is however higher than the ones of the sedimentary POM, which suggests this source is relatively minor compared to the planktonic source. Finally, the presence of high concentrations of β-carotene in the sediment traps is difficult to explain. In the water column, β-carotene was always below detection limit (Table 1) and in the epiphytic biofilm its concentration was 26 times lower than Chl *a*. By contrast, in the sediment traps, β-carotene was nearly as much abundant as Chl *a* at 7 m and only 5 times lower at 20 m and 30 m. Such high β-carotene/Chl *a* ratio could be due to a slower degradation of β-carotene compared to Chl *a*, as shown on geological time scales in lake sediments (Zullig, 1989).

The surface sediment sampled at the littoral station had very different δ^{13}C and C/N signature than the surface sediment sampled at Stations 2 and 4, with higher C/N ratios and heavier δ^{13}C (Fig. 9). By contrast to the center of the reservoir, where the organic material settled at the bottom has a lacustrine origin, the sediment at the littoral station is mainly composed of terrestrial OM. Along the vertical profile sampled, the first 2 cm matched well the litter δ^{13}C and C/N signature; the 2–6 cm depths has the soil signature as well as the signature of the surface sediment from Station 1 where terrestrial material dominates (Fig. 9). This terrestrial origin is also confirmed by pigment data with high OC/ΣChl ratios (>10 000) the presence of violaxanthin, Chl *b* and lutein and a Chl *b*/Lut ratio <1 as in submerged plants (Bianchi and Findlay, 1990) in the first 6 cm of the core (Fig. 6). Deeper in the core, the ferralitic soil was found with OC<1%, a constant C/N ratio at ~16, an absence of pigment and a net increase in δ^{13}C (Fig. 6). Such increase in δ^{13}C with depth is typical of what is found in soils as the result of complex biological and chemical mechanisms occurring at long time scales (Garten et al., 2000; Powers and Schlesinger, 2002). It thus appears that the sediment core sampled here is composed of the soil flooded when the reservoir was impounded 10 years before. This is consistent with finding of Abril et al. (2005) who showed that, 10 years

BGD
2, 1159–1196, 2005

after impounding, only 22% of the flooded carbon has escaped to the atmosphere as CO_2 and CH_4. In addition, some deposition of leaves at the littoral station probably also occurred after the flooding, followed by very slow degradation at the reservoir bottom, as indicated by the high concentrations of pheophytin *a* and *b* at 6 cm depth (Fig. 6). Finally, the presence of fucoxanthin in the first 4 cm of the core (Fig. 6) also reveals the development of benthic diatoms in this shallow area, as the case at Station 1.

To summarize, four different origins of OM can be distinguished at the reservoir bottom: (1) the soil flooded 10 years before, clearly identified by the $\delta^{13}C$ and C/N composition of the core sampled in the littoral zone at Station 3, but most probably also present in the deeper zone of the reservoir where sediment core could not be sampled; (2) some leaves debris which can either have fallen to the ground and be converted to litter before flooding and/or have fallen to the reservoir bottom after flooding; this material is undergoing slow degradation as revealed by the high pheophytin *a* and *b* concentrations; (3) the lacustrine OM (phyto- and bacterio-plankton and epiphytic biofilm) that settles in the deep zone of the reservoir (Stations 2 and 4); This material has a clearly different $\delta^{13}C$ and C/N composition (Fig. 9) which matches well with the degraded material found in the sediment traps (Fig. 8); (4) benthic diatoms developing at the surface sediments of shallow waters at Stations 1 and 3. As is typical for tropical aquatic environments, the relatively stable (low turbulence) oligotrophic epilimnetic water column is characterized by an assemblage of small Chlorophyceae and is not favorable for the development of pelagic diatom communities (Reynolds, 1997).

4.3. Origin and fate of POM downstream of the dam

At Station 5 immediately downstream of the dam, the $\delta^{13}C$ in POM was significantly lighter than in the water column of the reservoir (Fig. 10). The epilithic biofilm had an even more negative $\delta^{13}C$ of −36.3 per mil. This depletion in ^{13}C can be attributed to an increasing contribution of methanotrophic bacteria to the total biomass. Indeed, when passing on the aerating weir, waters coming from the reservoir's hypolimnion get re-oxygenated and loose a fraction of their methane content but not all of it. In the river

downstream of the dam, relatively high concentrations of oxygen (100–200 μmol l^{-1}) and methane (50–100 μmol l^{-1}) coexist and waters are the site of intense methane oxidation. This oxidation occurs until 40 km downstream, where methane concentration get lower than 1 μmol l^{-1} (Abril et al., 2005). Residence time of waters in this river section is about two days, which can explain why the suspended POM is less ^{13}C-depleted than the biofilm OM: Methanotrophic bacteria can develop a larger biomass as fixed within the biofilm, staying that way longer in the methane-rich area than when suspended in the water. The low POC content of the epilithic biofilm at Station 5 could be explained by its red/brown color which suggests a high contribution of Fe(III) oxides and presumably also Iron-oxidizing bacteria. Finally, like in the surface sediments of shallow areas of the reservoir, benthic diatoms are also present in the epilithic biofilm at Station 5, as revealed by the high concentrations of fucoxanthin (Fig. 5).

The presence of BChl *d*, BChl *c* and lutein in the water at Stations 5 and 6 (Fig. 3) and in the epilithic biofilm at Station 5 (Fig. 5) results from a transfer of POM from the reservoir through the turbines. Indeed, the oxic conditions in the tidal river preclude in situ development of the strictly anaerobic Chlorobiaceae. In addition, the presence of lutein but the absence of Chl *b* reveal a contribution of OM derived from the Chlorophyceae produced in the reservoir epilimnion that has been partially degraded. Indeed, in sediments, Chl *b* is degraded much faster than lutein (Bianchi et al., 1993b), which can explain the absence of Chl *b* in the water at Stations 5 and 6. Downstream the river from Station 5 to Station 7, $\sum$BChl *c*+BChl *d* and lutein decrease in the water and fucoxanthin increase (Fig. 3). This shows that the lacustine POM (Chlorobiacea and Chlorophyceae) is decomposed, being progressively replaced by diatoms, the phytoplanktonic group generally dominant in estuaries and coastal waters (Bianchi et al., 1993a, b; Lemaire et al., 2002). This pattern of degradation of POM from the reservoir together with mixing with estuarine/marine POM is confirmed by the δ^{13}C and C/N signature (Fig. 10): δ^{13}C increases and C/N decreases downstream the Sinnamary estuary to reach the composition of Amazonian POM carried by the mobile mud belt (δ^{13}C$\sim$–25 per mil and C/N ~7–8)(Keil et al., 1997; Mayer et al., 1998). At this

BGD
2, 1159–1196, 2005

estuarine Station at the mouth of the Sinnamary, the suspended matter and surface sediments have the same low OC content (1.1%) and the same $\delta^{13}C$ and C/N signature showing that the Amazonian/marine mixture found in the mobile mud belt (Aller, 1998) has become predominant in both waters and sediments.

4.4. Quantitative aspects

Although the dataset presented here is by far not sufficient to accurately quantify the transfers of each individual source of POM in the Petit Saut reservoir and Sinnamary estuary, the orders of magnitude of some POM fluxes can still be compare with the other terms of the carbon cycle quantified in other works. First, the POC flux derived from the sediment traps data was very similar at the three depths and equal to $1.2\pm0.2\,mmol\,m^{-2}\,d^{-1}$ (average and standard deviation of the three traps) or $5.2\pm0.9\,tC\,d^{-1}$ (integrated over the reservoir surface area). As discussed earlier, this material is mainly of planktonic origin. Three years after impounding, in 1997, using ^{14}C short incubations, Vaquer et al. (1997) have estimated a gross primary production (GPP) in the Petit Saut reservoir epilimnion of $90\pm27\,mmol\,m^{-2}\,d^{-1}$, which is 17 times higher than the POM sedimentation we have recorded in December 2003. Although GPP has probably decreased since that period owing to lower nutrients concentrations, it appears that a very minor fraction of GPP reaches the reservoir bottom. This confirms the intense recycling and mineralization of the POM produced in the reservoir, as revealed by the high concentrations of pheopigments in the traps and at the reservoir bottom (Table 1).

In December 2003, the flux of POC passing through the turbines, calculated from the water discharge of $180\,m^3\,s^{-1}$ and the POC concentration at Station 5, was $18\,tC\,d^{-1}$. This shows that about 4 times more POC is transported laterally through the dam, than settled in the reservoir. As discussed before, this material has a lacustrine origin and is almost totally decomposed by heterotrophic activity in the Sinnamary estuary. The CO_2 emissions to the atmosphere measured during the same period in December 2003 in the Sinnamary estuary was $\sim100\,tC\,d^{-1}$, among which 25% was excess CO_2

originating from the reservoir (Abril et al., 2005). The transfer and further mineralization of the lacustrine POM downstream of the dam contributes to an additional CO_2 source of only 18%.

5. Conclusion

This study allowed a first description of the POM origins and transfers in a tropical reservoir and its river downstream, which are complex systems and poorly documented in general. The different biogeochemical tracers used allowed us to trace the origin of the different POM pools in the reservoir and the river downstream, where we differentiated sources comprising, (i) terrestrial OM carried by the Sinnamary River, (ii) soil and litter flooded during impounding, (iii) phytoplankton from the epilimnion of the reservoir, (iv) phototrophic and methanotrophic planktonic bacteria developing at the redoxcline in the reservoir and (v) different epilithic and epiphytic biofilms. In addition, this supplied information on transfers, mixing and recycling processes occurring in the water and sediments of the reservoir and in the estuary downstream, although these fluxes require improved quantification. The aquatic POM was characterized by an extreme diversity according to water depth, light and redox conditions, fixed or free living biomass. Future studies should focus on the metabolism of the different phototrophic microorganisms and their role in the cycles of redox species in the reservoir. In addition, our observations highlight the importance of Transparent Exopolymeric Particules (TEP), which merit further studies including improved quantification and addressing their biogeochemical and ecological role in the system. Finally, we realize that our first estimates of POC vertical and lateral fluxes need to be re-evaluated on a seasonal scale, taking into account the pronounced difference between dry and wet periods. Nevertheless, the POM fluxes appear however to be small, when compared to dissolved and gaseous carbon fluxes.

Acknowledgements. This work was funded by Electricité de France and by the French National research programs PNCA and ECCO-PNBC. We thank S. Richard and all the Hydreco Staff at

Petit Saut for sampling facilities. This work was possible owing to the analytical facilities available at the EPOC institute. We are grateful to P. Martinez, X. Crosta, H. Etcheber and C. Glé for their numerous advices. R. Delmas (Laboratoire d'Aérologie, Toulouse) and A. Grégoire (EDF) were the initiators of this research on the C cycle at Petit Saut. F. Guérin benefited to a PhD grant from EDF.

References

Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., and Matvienko, B.: Carbon dioxide and methane emissions and the carbon budget of a 10-years old tropical reservoir (Petit Saut, French Guiana), Global Biogeochem. Cycles, in press, 2005.

Aller, R.: Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors, Mar. Chem., 61, 143–155, 1998.

Bellanger, B., Huon, S., Steinmann, P., Chabaux, F., Velasquez, F., Valles, V., Arn, K., Clauer, N., and Mariotti, A.: Oxic-anoxic conditions in the water column of a tropical freshwater reservoir (Pena-Larga dam, NW Venezuela), Applied Geochem., 19, 1295–1314, 2004.

Bianchi, T. S. and Findlay, S.: Plant pigments as tracers of emergent and submergent macrophytes from the Hudson River, Can. J. Fish. Aqu. Sci., 492–494, 1990.

Bianchi, T. S., Findlay, S., and Dawson, R.: Organic matter sources in the water column and sediments of the Hudson River Estuary: the use of plant pigments as tracers, Est., Coast. Shelf Sci., 36, 359–376, 1993a.

Bianchi, T. S., Dibb, J. E., and Findlay, S.: Early diagenesis of plants in the Hudson River sediments, Est., Coast. Shelf Sci., 36, 517–527, 1993b.

Blair, N.: The $\delta^{13}C$ of Biogenic methane in marine sediments: the influence of C_{org} deposition rate, Chem. Geol., 139–150, 1998.

Borrego, C. M. and Garcia-Gil, J.: Separation of bacteriochlorophyll homologues from green photosynthetic sulfur bacteria by reversed-phase HPLC, Photosynth. Res., 41, 157–163, 1994.

Boschker, H. T. S. and Middelburg, J. J.: Stable isotopes and biomarkers in microbial ecology, FEMS Microbiol. Ecol., 40, 85–95, 2002.

Buchanan, B. B. and Arnold, D. I.: A reverse KREBS cycle in photosynthesis: consensus at last, Photosynth. Res., 24, 47–53, 1990.
Buffan-Dubau, E., Pringault, O., and De Wit, R.: Artificial cold-adapted mats cultured from Antarctic lake samples. 1. Formation and structure, Aqu. Microbial Ecol., 26, 115–125, 2001.
Collos, Y., Vaquer, A., Johnston, A. M., Pons, V., Bibent, B., and Richard, S.: Carbon fixation, ammonium uptake and regeneration in an equatorial lake: biological versus physical control, J. Plankton Res., 23, 263–270, 2001.
Dumestre, J.-F., Vaquer, A., Gosse, P., Richard, S., and Labroue, L.: Bacterial ecology of a young equatorial hydrohelectric reservoir (Petit-Saut, French Guiana), Hydrobiol., 400, 75–83, 1999.
Dumestre, J.-F., Casamayor, E. O., Massana, R., and Pedros-Alio, C.: Changes in bacterial and archeal assemblages in an equatorial river induced by the water eutrophication of Petit-Saut dam reservoir, Aqu. Microbial Ecol., 26, 209–221, 2001.
Elser, J. J., Fagan, W. F., Denno, R. F., Dobberfuhl, D. R., Folarin, A., Huberty, A., Interlandi, S., Kilham, S. S., McCauley, E., Schulz, K. L., Siemann, E. H., and Sterner, R. W.: Nutritional constraints in terrestrial and freshwater food webs, Nature, 408, 578–580, 2000.
Galy-Lacaux, C., Delmas, R., Kouadio, G., Richard, S., and Gosse, P.: Long-Term greenhouse gas emissions from hydroelectric reservoirs in tropical forest regions, Global Biogeochem. Cycles, 13, 503–517, 1999.
Garten, C. T., Cooper, L. W., Post III, W. M., and Hanson, P. J.: Climate controls on forest soil C isotope ratios in the southern Appalachian mountains, Ecology, 81, 1108–1119, 2000.
Hamilton, S. K. and Lewis Jr., W. M.: Stable carbon and nitrogen isotopes in algae and detritus from the Orinoco River floodplain, Venezuela, Geochim. Cosmochim Acta, 56, 4237–4246, 1992.
Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A.: Climate Change 2001: the scientific basis, Cambridge University Press, New York, 2001.
Hunsucker, S. W., Tissue, B. A., Potts, M., and Helm, R. F.: Screening Protocol for the UltraViolet-Photoprotective Pigment Scytonemin, Analytical Biochemistry, 288, 227–230, 2001.
Jeffrey, S. W., Mantoura, R. F. C., and Wright, S. W.: Phytoplankton pigments in oceanography, UNESCO Publishing, 1997.

Keil, R. G., Mayer, L. M., Quay, P. D., Richey, J. E., and Hedges, J. I.: Loss of organic matter from riverine particles in deltas, Geochim. Cosmochim. Acta, 61, 1507–1511, 1997

Lee, S. and Furhman, J. D.: Relationships between biovolume and biomass of naturally derived marine bacterioplankton, Applied Env. Microbiol., 1298–1303, 1987.

Lehmann, M. F., Bernasconi, S. M., Barbieri, A., and McKenzie, J. A.: Preservation of organic matter and alteration of its carbon and nitrogen isotope composition during simulated and in situ early sedimentary diagenesis, Geochim. Cosmochim. Acta, 66, 3573–3584, 2002.

Lemaire, E., Abril, G., De Wit, R., and Etcheber, H.: Distribution of phytoplankton pigments in nine European estuaries and implications for an estuarine typology, Biogeochem., 59, 5–23, 2002.

Lonchouarn, P., Lucotte, M., and Farella, N.: Historical and geographical variations of sources and transport of terrigenous organic matter within a large-scale coastal environment, Org. Geochem., 30, 675–699, 1999.

Mari, X., Beauvais, S., Lemee, R., and Pedrotti, M. L.: Non-Redfield C:N ratio of transparent exoplymeric particules in the Northwestern Mediterranean Sea, Limnol. Oceanogr., 46, 1831–1836, 2001.

Massé, A., Airs, R. L., Keely, B. J., and De Wit, R.: The impact of different intensities of green light on the bacteriochlorophyll homologue composition of the chlorobiaceae *Prosthecochloris aestuarii* and *Chlorobium phaeobacteroides*, Microbiology, 150, 2555–2564, 2004.

Mayer, L. M., Keil, R. G., Macko, S. A., Joye, S. B., Ruttenberg, K. C., and Aller, R. C.: Importance of suspended particulates in riverine delivery of bioavailable nitrogen to coastal zones, Global Biogeochemical Cycles, 12, 573–579, 1998.

Mook, W. G. and Tan, F. C.: Stable carbon isotopes in rivers and estuaries, SCOPE 42, 245–264, 1991.

Nieuwenhuize, J., Maas, Y. E. M., and Middelburg, J. J.: Rapid analysis of organic carbon and nitrogen in particulate materials, Mar. Chem. 45, 217–224, 1994.

Onstad, G. O., Canfield, D. E., Quay, P. D., and Hedges, J. I.: Sources of particulate organic matter in rivers from the continental USA: lignin phenol and stable carbon isotope compositions, Geochim. Cosmochim. Acta, 64, 3539–3546, 2000.

O'Reilly, C. M., Hecky, R. E., Cohen, A. S., and Plisnier, P.-D.: Interpreting stable isotopes in food webs: recognizing the role of time averaging at different trophic levels, Limnol. Oceanogr., 47, 306–309, 2002.

Reynolds, C. S.: Vegetation processus in the pelagic: a model for ecosystem theory, Excellence

in Ecology, 9, Ecology Institute, Oldendorf/Luhe, 1997.
Passow, U.: Transparent Exopolymeric Particules (TEP) in aquatic environments, Prog. Oceanogr., 55, 287–333, 2002.
Powers, J. S. and Schlesinger W. H.: Geographic and vertical patterns of stable carbon isotopes in tropical rain forest soils of Costa Rica, Geoderma 109, 141–160, 2002.
Richard, S.: La mise en eau du barrage de Petit-Saut (Guyane française). Hydrochimie du fleuve Sinnamary avant la mise en eau, de la retenue pendant la mise en eau, du fleuve en aval, PhD Thesis, University Aix-Marseille I, 277 p., 1996.
Schouten, S., Rupstra, W. I. C., Kok, M., Hopmans, E. C., Summons, R. E., Volkman, J. K., and Sinninghe Damste, J. S.: Molecular organic tracers of biogeochemical processes in a saline meromictic Lake (Ace Lake), Geochim. Cosmochim. Acta, 56, 1629–1640, 2001.
Sinha, R. P., Klish, M., Gröniger, A., and Häder, D.-P.: Ultraviolet-absorbing/screening substances in cyanobacteria, phytoplankton and macroalgae, J. Photochem. Photobiol. B: Biol., 47, 83–94, 1998.
Sirevag, R., Buchanan, B. B., Berry, J. A., and Troughton, J. H.: Mechanisms of CO_2 fixation in bacterial photosynthesis studied by the carbon isotope fractionation technique, Arch Microbiol., 112, 35–38, 1977.
Stanier, R. Y. and Smith, J. H. C.: The chlorophylls of green bacteria, Biochim. Biopgys. Acta, 41, 478–484, 1960.
St Louis, V. L., Kelly, C. A., Duchemin, E., Rudd, J. W. M., and Rosenberg, D. M.: Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate, BioScience, 50, 766–775, 2000.
Tan, F. C.: Discharge and carbon isotope composition of particulate organic carbon from the St Lawrence River, Canada, in: Transport of carbon and minerals in major world rivers, edited by: Degens, E. T., Kempe, S., and Weibin, G., Mitt. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd., 64, 301–310. 1987.
Vaquer, A., Pons, V., Lautier, J. Distribution Spatio-Temporelle du Phytoplancton dans le Réservoir de Petit-Saut (Guyane Française), Hydroécologie Appliquée, 9, 169–193, 1997.
Zullig, H.: Role of carotenoids in lake sediments for reconstructing trophic history during the late Quaternary, J. Paleolimnol, 2, 23–40, 1989.

Table 1. Synthesis of the data obtained in all samples. "bdl" means below the detection limit, "<0.1" indicates that the pigment was present at very low concentrations and "nm" means not measured. * indicates that lutein and BChl *d* co-eluted in the samples and lutein concentrations were corrected from the BChl *c* and BChl *d* concentration as detailed in the text. At Station 4 in the SPM at −7 m, lutein could not be quantified because BChl *d* concentration was too important and prevented measurements. In addition, 3 μg/g of Zeaxanthin was found in the surface sediments at Station 4 and traces of schytonemin was found in the biofilm at Station 4 and in the sediment traps at all depths.

samples/depth	SPM	OC	$\delta^{13}C$	C/N	Total Pigment	OC/ Tot pig.	Chl *a*	Pheo *a*	Chl *b*	Pheo *b*	Lutein	Fucoxanthin	β-carotene	Violaxanthin	ΣBChl c & d
SPM	mg/L	per cent	per mil		μg.L-1	g.g-1	μg.L-1		μg.L-1		ng.L-1	ng.L-1		ng.L-1	μg.L-1
St. 1/Surf	5.6	10.3	−28.9	13.7	bdl	–	bdl	bdl	nd	bdl	bdl	bdl	bdl	bdl	bdl
St.4/−3m	4.2	39.9	−32.5	21.1	6.9	242	6.4	bdl	0.9	bdl	330.9	bdl	bdl	218.6	bdl
St.4/−6m	4.0	28.5	−31.7	10.1	72.6	16	9.7	bdl	bdl	bdl	59.1*	bdl	bdl	bdl	62.8
St.4/−7m	5.4	27.0	−30.8	11.5	189.2	8	0.9	bdl	bdl	bdl	bdl*	bdl	bdl	bdl	188.3
St.4/−10m	3.9	23.0	−30.4	10.9	20.5	44	bdl	bdl	bdl	bdl	39.4*	bdl	bdl	bdl	20.4
St.4/−15m	2.9	21.9	−30.1	10.8	<0.1	–	bdl	bdl	bdl	bdl	<0.1*	bdl	bdl	bdl	<0.1
St.4/−25m	2.5	34.7	−30.0	10.1	<0.1	–	bdl	bdl	bdl	bdl	<0.1*	bdl	bdl	bdl	<0.1
St.5/Surf	3.0	38.3	−33.2	11.8	18.6	62	2.5	bdl	bdl	bdl	<0.1*	bdl	bdl	bdl	16.2
St.6/Surf	19.3	8.7	−31.6	11.9	5.3	317	3.3	bdl	bdl	bdl	41.4*	279.1	bdl	bdl	1.7
St.7/Surf	202.8	1.1	−26.9	7.9	1.0	2190	0.8	bdl	bdl	bdl	bdl	195.4	bdl	bdl	<0.1
Sediment Traps					μg.g-1		μg.g-1	μg.g-1	μg.g-1	μg.g-1	μg.g-1	μg.g-1	μg.g-1	μg.g-1	μg.g-1
St.4/−7m		10.7	−28.0	11.2	504.6	21	179.5	36.5	17.0	<0.1	21.4*	bdl	133.2	5.5	111.52
St.4/−20m		13.1	−28.8	12.4	416.6	55	119.4	180	bdl	bdl	72*	bdl	22.4	bdl	22.73
St.4/−30m		8.5	−29.7	14.0	254.0	55	44.8	100	bdl	bdl	28.2*	bdl	10.8	bdl	70.16
Sediments															
St.1/Surf		5.1	−29.8	20.0	12.7	405	4.7	5.7	<0.1	1.0	0.6	0.6	0.1	bdl	bdl
St.2/Surf		10.3	−30.8	14.9	nm	–	nm	nm	nm	nm	nm	nm	nm	nm	nm
St.3/0−2cm		12.8	−29.1	30.9	16.4	781	8.4	3.5	0.1	1.4	0.8	1.4	0.5	0.3	bdl
St.3/2−4cm		14.4	−30.4	20.3	8.4	1708	2.0	3.3	<0.1	1.2	0.6	1.1	0.2	<0.1	bdl
St.3/4−6cm		6.3	−30.1	19.1	15.1	417	3.3	6.5	0.2	4.8	0.3	bdl	bdl	<0.1	bdl
St.3/6−8cm		1.5	−28.3	16.9	0.3	5001	bdl	<0.1	bdl	<0.1	bdl	bdl	bdl	bdl	bdl
St.3/8−10cm		1.4	−27.3	16.4	<0.1	43916	bdl	<0.1	bdl	<0.1	bdl	bdl	bdl	bdl	bdl
St.3/10−12cm		1.1	−26.6	15.7	<0.1	75633	bdl	<0.1	bdl	<0.1	bdl	bdl	bdl	bdl	bdl
St.3/14−16cm		1.2	−27.0	14.9	bdl	–	bdl	<0.1	bdl	<0.1	bdl	bdl	bdl	bdl	bdl
St.3/18−20cm		1.0	−25.7	16.1	bdl	–	bdl	<0.1	bdl	<0.1	bdl	bdl	bdl	bdl	bdl
St.4/Surf		8.1	−31.0	14.9	3.1	–	bdl	bdl	bdl	bdl	<0.1	<0.1	bdl	bdl	bdl
St.7		1.1	−25.9	9.5	<0.1	–	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Soil		17.0	−28.6	19.0	nm	–	nm	nm	nm	nm	nm	nm	nm	nm	nm
Litter		20.5	−29.0	27.3	nm	–	nm	nm	nm	nm	nm	nm	nm	nm	nm
Biofilms															
St.4/Surf		42.9	−27.4	16.0	37.9	1129	36.4	bdl	bdl	bdl	0.1	bdl	1.4	bdl	bdl
St.5/Surf		5.9	−36.3	17.2	100.1	59	74.3	bdl	0.4	bdl	0.9	18.3	0.9	bdl	5.3

BGD
2, 1159–1196, 2005

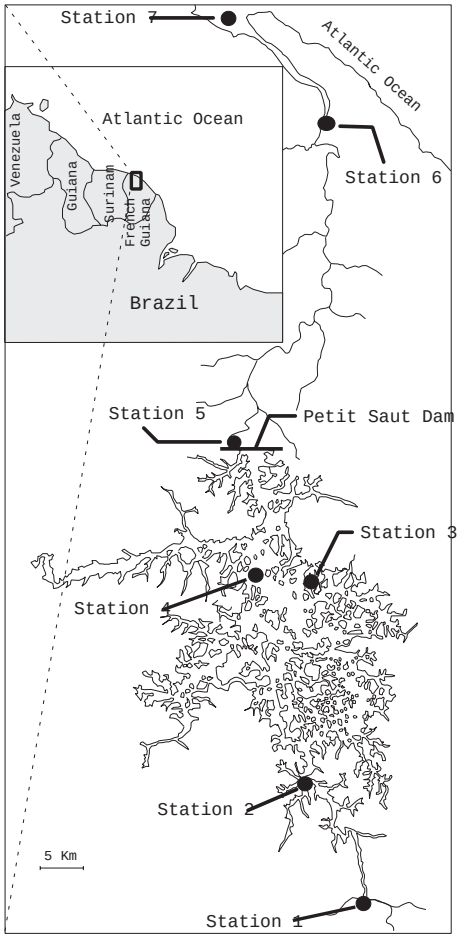

Fig. 1. Map of the study site showing the location of the sampling stations along the Petit-Saut reservoir and on the Sinnamary tidal river and estuary.

BGD

2, 1159–1196, 2005

Sources and transfers of POM in a tropical reservoir

A. de Junet et al.

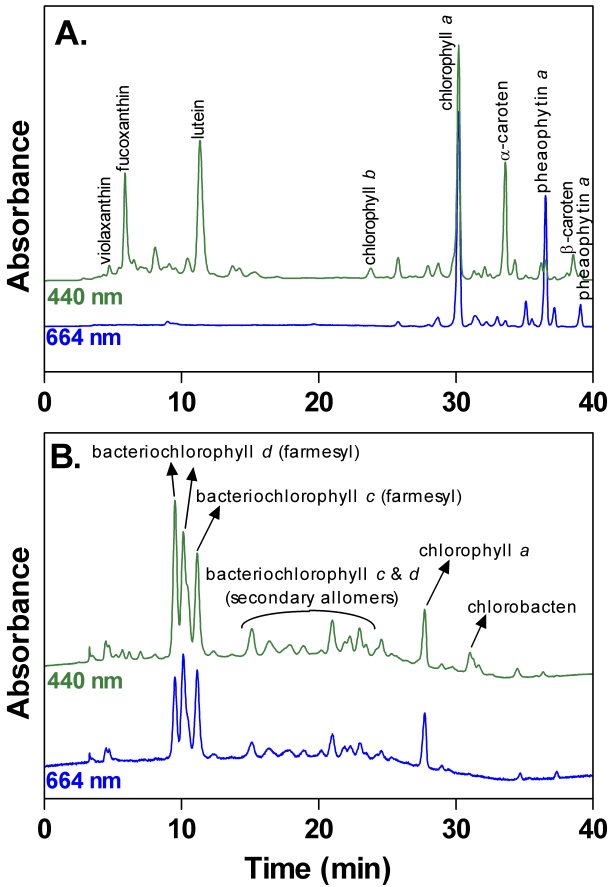

Fig. 2. Typical chromatograms at 440 and 664 nm showing most of the pigments quantified in the Petit Saut samples. **(A)** surface sediment at Station 1; **(B)** suspended matter at −6 m depth at Station 4.

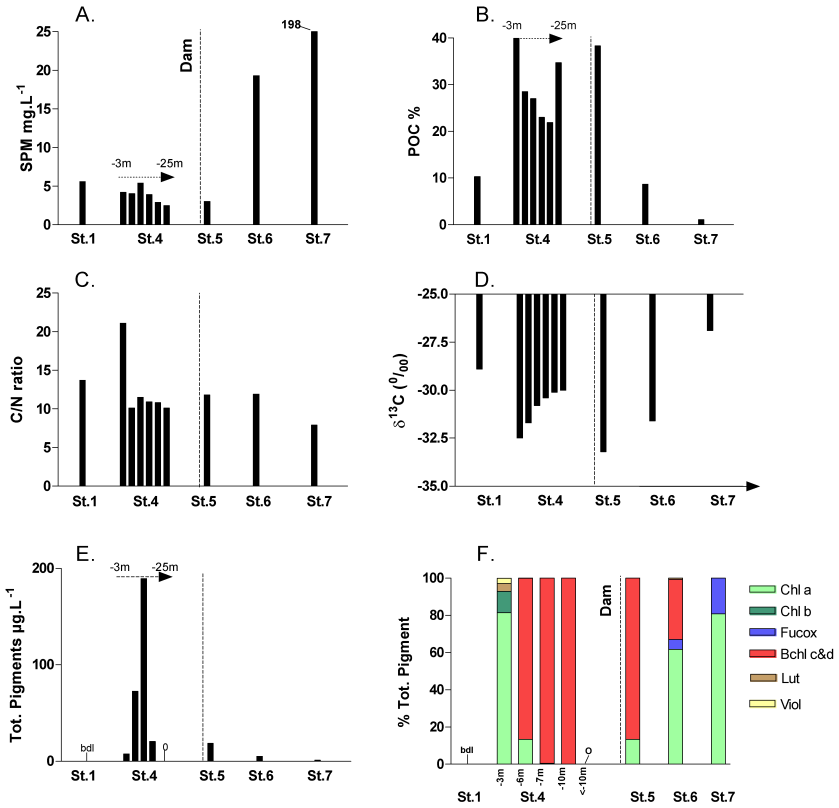

Fig. 3. Longitudinal distribution in particulate organic matter sampled in the Petit Saut system, upstream and downstream of the dam. **(A)** SPM concentration, **(B)** percentage of POC, **(C)** C/N ratio, **(D)** δ^{13}C of POC, **(E)** total pigments, and **(F)** relative contribution (percents) of each pigment to the total pigments content. When noted "0", no pigment where present, when noted "bdl", the presence of some pigments could be observed with the HPLC protocol but they were below the detection limit and could not be quantified.

BGD
2, 1159–1196, 2005

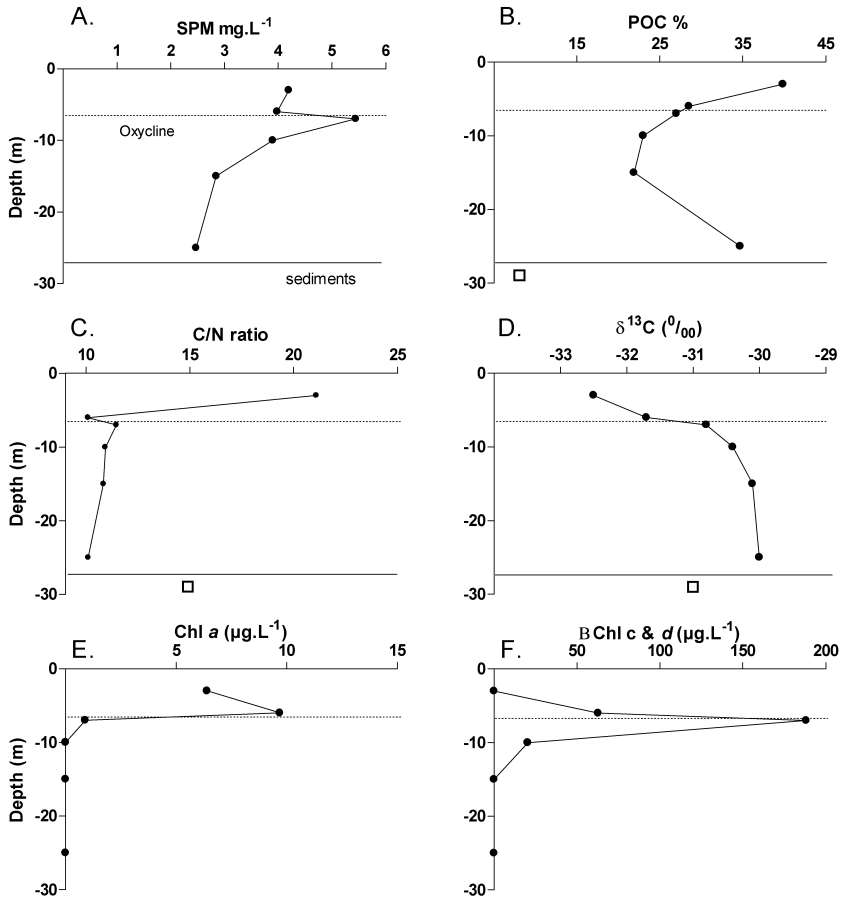

Fig. 4. Vertical profile in particulate organic matter at Station 4. **(A)** SPM concentration, **(B)** percentage of POC, **(C)** C/N ratio, **(D)** δ^{13}C of POC, **(E)** Chl *a*, and **(F)** ∑BChl *c*+BChl *d*. For POC, C/N and δ^{13}C, values in surface sediments settled at Station 4 are also shown for comparison (squares).

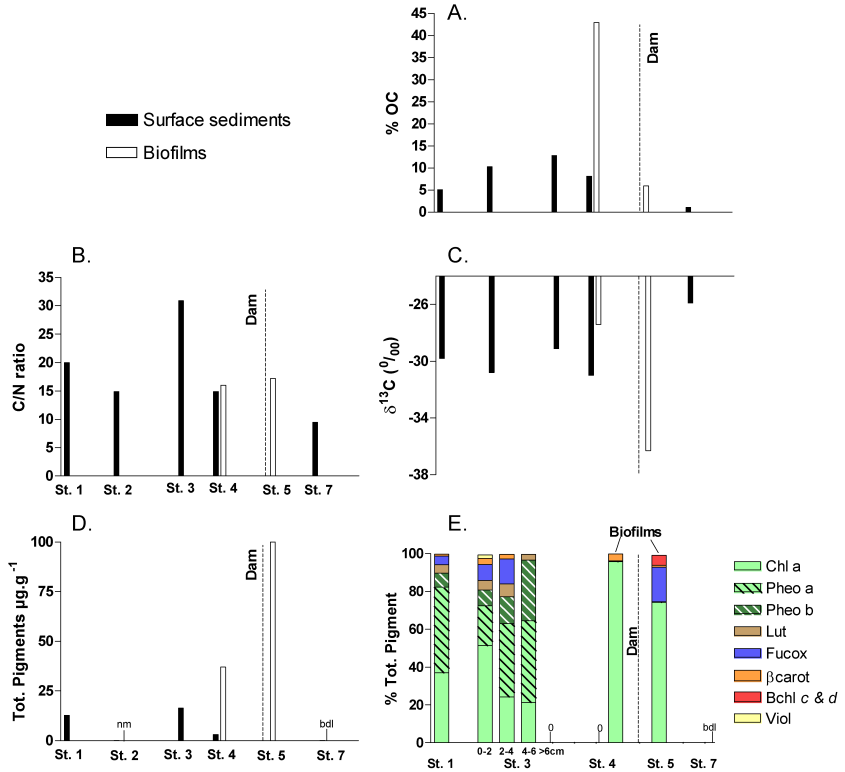

Fig. 5. Longitudinal distribution in surface sediments (black) and biofilms (white) sampled in the Petit Saut system, upstream and downstream of the dam. **(A)** percentage of POC, **(B)** C/N ratio, **(C)** δ^{13}C of POC, **(D)** total pigments, and **(E)** relative contribution (percents) of each pigment to the total pigments content. In panel E, the relative contributions of pigments is also shown at different depths in the core sampled at Station 3 (shallow littoral station). When noted "0", no pigment where present; when noted "bdl", the presence of some pigments could be observed with the HPLC protocol but areas were below the detection limit and concentrations could not be quantified; when noted "nm" no pigment measurement were performed.

BGD
2, 1159–1196, 2005

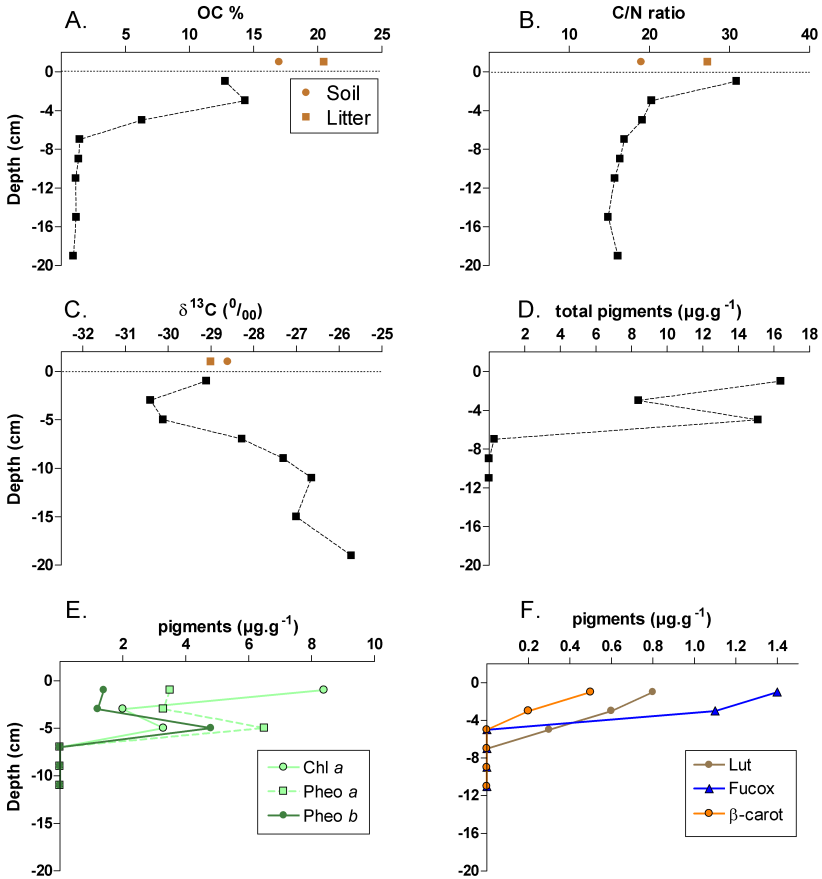

Fig. 6. Vertical profile in the sediment core collected at the shallow littoral Station 3. **(A)** percentage of OC, **(B)** C/N ratio, **(C)** δ^{13}C of OC, **(D)** total pigments, **(E)** Chl *a* and phaeopigments, and **(F)** carotenoids.

BGD
2, 1159–1196, 2005

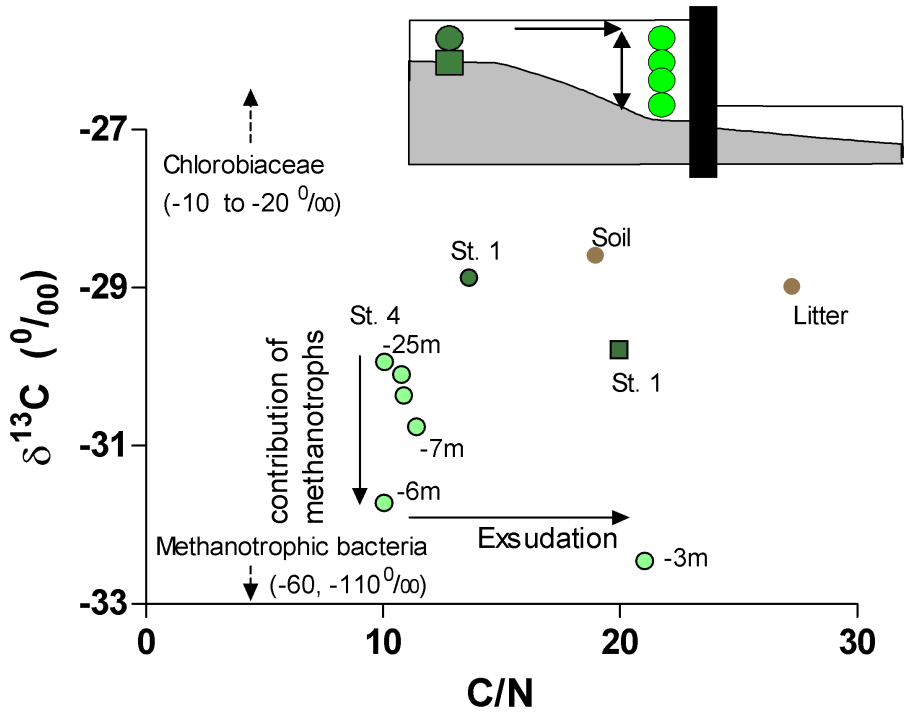

Fig. 7. δ^{13}C-C/N diagram of SPM (circle) and surface sediments (squares) in the river upstream at Station 1 (dark green) and in water column of the reservoir at Station 4 (light green) from −3 m to −25 m depths. The soil and litter sampled in the surrounding forest are shown for comparison (brown).

BGD
2, 1159–1196, 2005

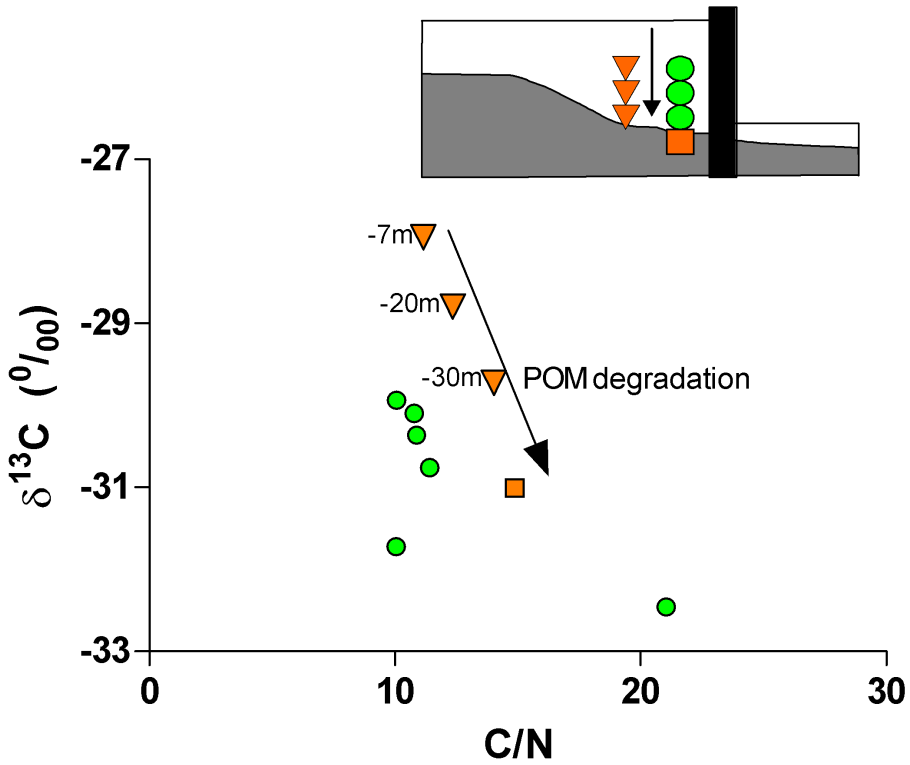

Fig. 8. δ^{13}C-C/N diagram of material collected in the sediment traps at −7 m, −20 m and −30 m depths (orange triangles) compared to the SPM in the water column of the reservoir from −3 m to −25 m depths (green circles). Data from Station 4.

BGD
2, 1159–1196, 2005

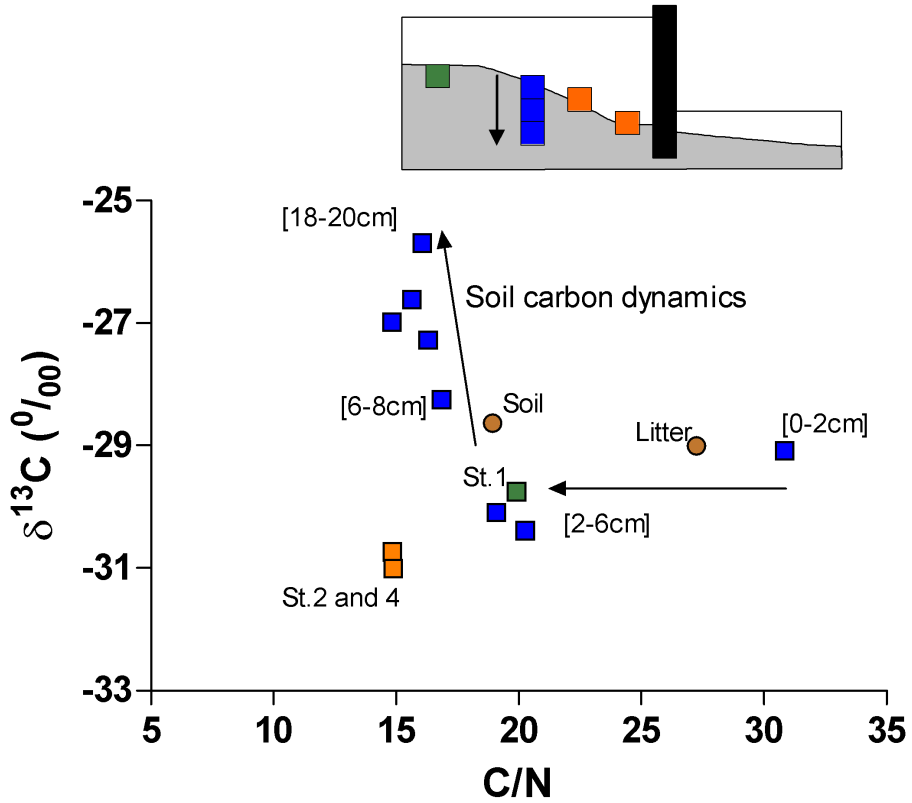

Fig. 9. δ^{13}C-C/N diagram of the sediment core sampled at the littoral shallow Station 3 in the Petit-Saut reservoir (blue squares) compared to the surface sediment collected in the river upstream at Station 1 (green square) and in the deep zone of the reservoir at Stations 2 and 4 (orange squares). The soil and litter sampled in the surrounding forest are also shown (brown circles).

BGD
2, 1159–1196, 2005

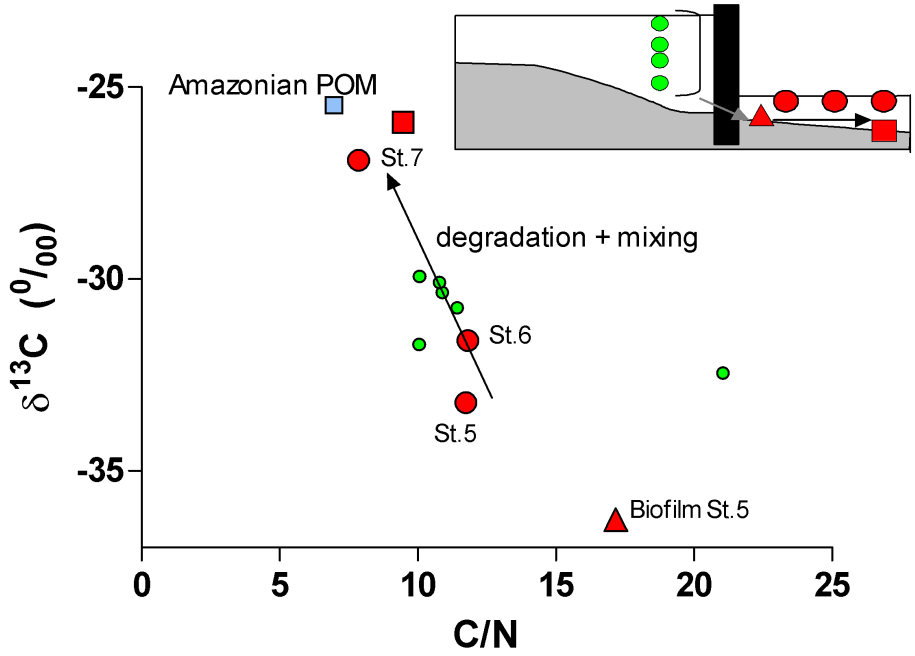

Fig. 10. δ^{13}C-C/N diagram of SPM (red circles), biofilm (red triangle) and sediment in the Sinnamary tidal river and estuary downstream of the dam, compared to SPM in the reservoir (green circles) and Amazonian SPM carried by the mobile mud belt (Blue square, from Keil et al., 1997; Mayer et al., 1998).

BGD
2, 1159–1196, 2005