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The organic carbon dynamics of a small catchment in the humid tropics

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Abstract The general purpose of this study is to understand the dynamics of organic carbon in a humid tropical environment by investigating the transfer of dissolved and particulate organic carbon (DOC, POC), and total mineral dissolved solids (TDS) and total suspended solids (TSS), in the different functional pools of the Nsimi catchment at Zoetele in south Cameroon (Central Africa). The carbon stock reaches 59 000 t km^{-2} in the soil cover (mean thickness about 30 m), and demonstrates marked enrichment in the upper 2 m of the profile. The DOC content in the wet atmospheric deposits is negligible, but recycling by throughfall is significant (5.45 t km^{-2} $year^{-1}$). DOC is very abundant in the coloured ("tea water") drainage waters that have flowed through the wet depressions (concentrations near 16 mg l^{-1} and fluxes between 5 and 8 t km^{-2} $year^{-1}$) and is of the same magnitude as the TDS. The organic matter plays a key role in the dissolution and transport of cations and trace elements, as well as in compensating for the anionic deficit observed in these waters. The POC fluxes (0.6–1.4 t km^{-2} $year^{-1}$) represent about 20% of the TSS. Based on the total carbon outputs documented by the study, the turnover time of this element in the soils can be estimated to be about 950 years in the upper part of the soil cover.

Key words atmospheric deposition; Cameroon; Central Africa; humid tropics; hydrobiogeochemistry; organic carbon; soil cover; stream water; weathering rate

INTRODUCTION

The key role of organic and inorganic carbon in maintaining the equilibrium of the environment is widely accepted. Although carbon concentration and flux data are available for many rivers, such as the Niger (Martins & Probst, 1991; Boeglin & Probst, 1996), the Congo (Probst *et al*., 1994; Seyler *et al*., 1995) and the Amazon (Richey *et al*., 1990), the carbon content and stock of the soil cover and the effects of organic matter on soil/ water interactions are still poorly understood in the humid tropics (Boeglin *et al*., 2005). The purpose of the work reported here was to analyse carbon concentrations and fluxes in their various forms in the different water reservoirs, in relation to the weathering rate and carbon content of the soils, in the Mengong catchment at Nsimi, southern Cameroon, in order to understand the dynamics of this element in a humid tropical environment. This forested granitic watershed is considered to be representative of the humid tropical domain and has been monitored since 2003 by the French Ministry of Research as an ORE/BVET (Observatoire de Recherche en Environnement/Bassins Versants Experimentaux Tropicaux).

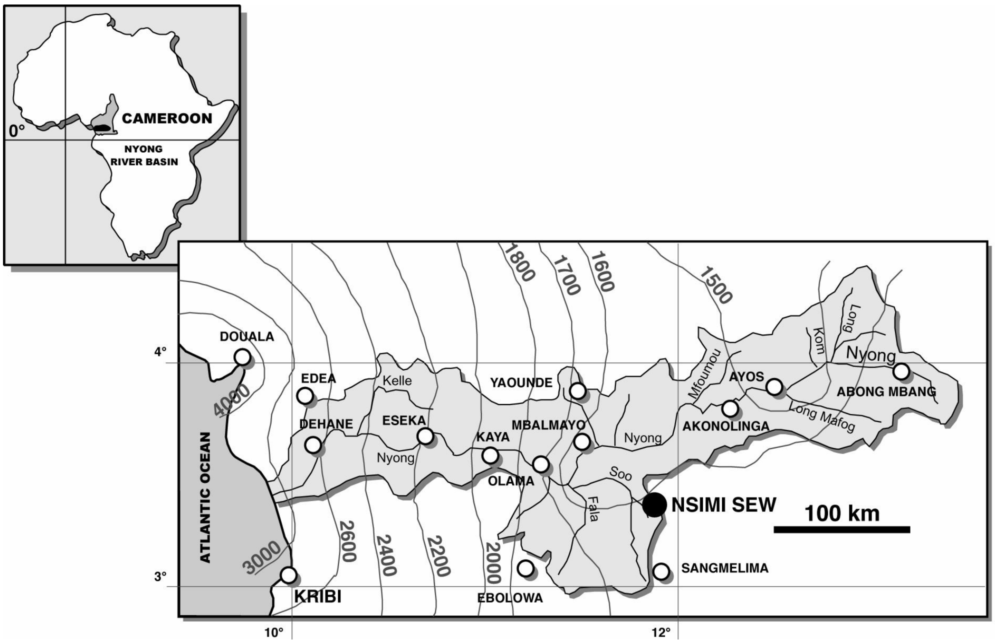

Fig. 1 Location of the Nsimi catchment in the Nyong River basin (south Cameroon).

STUDY AREA

The Mengong experimental catchment (area about 1 km^2) is located close to Nsimi village, near Zoetele in southern Cameroon (3°10′N, 11°50′E), 120 km south-southeast from Yaoundé city and some 200 km from the Atlantic Ocean. It forms part of the Nyong River basin, which is located entirely within the tropical rainforest, between latitudes 2°48′N and 4°32′N (Fig. 1). The geomorphology of the Mengong catchment is representative of the erosion surface of the South Cameroon Plateau, which mainly comprises a succession of convex rounded hills separated by flat swamps of variable extent. Two convex hills about 700 m high surround a large swampy zone, representing 20% of the whole catchment area. The Mengong stream, fed by several springs located within the upper part of the basin, flows towards the So'o stream, the most important left hand tributary of the Nyong River. The swamp is entirely preserved and covered by raphia palm trees and other hydrophilic vegetation. The soil cover is developed on an intensively faulted granitic basement (charnockite), of Liberian age (2800 million years). The soil cover on the hills reaches a thickness of 40 m on the hilltops. In the flat swamp, a hydromorphic soil cover about 1–2 m thick has developed either directly on the parent granodiorite (very rarely) or on oxidized saprolitic horizons (Nyeck *et al*., 1993). Southern Cameroon has a Guinean type climate, with four seasons. The wet seasons (March–May and September–November) are separated by a short dry season, whereas the well-defined long dry season extends from December to February. The annual rainfall is between 1500 and 2000 mm (based on the period 1994–2003). The temperature averages about 25°C and is characterized by an annual amplitude of 2–3°C. The potential evapotranspiration is 1250 mm year^{-1}. For the water year 1998/99, rainfall (*P*) and runoff (*R*) were respectively 1822 and 387 mm for the Mengong catchment and 1667 and 283 mm for the Nyong basin at Olama. These values correspond to runoff ratios (*R*/*P*) of 21 and 17%, respectively.

METHODOLOGY

The soils within the Nsimi catchment were sampled using pits on the hills and slopes and in holes or by drilling in the swampy depression. Their organic carbon content was analysed by colour change titration, using an ammonium-iron (II) sulphate solution after digestion with a hot potassium dichromate solution (Anne's method, Rouiller *et al.*, in Bonneau & Souchier, 1994). This analysis was undertaken at the Hydrological Research Centre in Yaoundé, Cameroon (Abata, 2003).

All the water samples (atmospheric deposition, surface and groundwater) analysed were collected during the 1994/95–1998/99 period. Sampling was undertaken regularly at the source and the outlet, with a weekly or bimonthly frequency. The atmospheric inputs considered in this study include: (a) wet deposition sampled in the open using an automatic collector functioning only during the rain events; (b) bulk deposition sampled in the open; and (c) throughfall deposition sampled with PVC funnels pre-rinsed with distilled, de-ionized water. In the case of the slope and depression waters, sampling was more random and was undertaken using piezometers or pits. After measurement of some physico-chemical parameters (temperature, pH, electrical conductivity) and filtration in the field, the subsamples intended for carbon analyses were filtered (0.7 μm micro glassfibre membrane) prior to DOC and POC determination. DOC was analysed at the Laboratoire de Mécanismes et Transferts en Géologie (Toulouse) and POC analysis was undertaken at the Centre de Recherche sur les Environnements Sédimentaires et Océaniques of Bordeaux I University (Viers *et al.*, 1997; Oliva *et al.*, 1999; Braun *et al.*, 2002).

RESULTS

Carbon in soils

The soil carbon content exhibited a very heterogeneous distribution in the different soil profiles. High concentrations were only found in the upper metres of the soils overlying the hills and slopes, whilst high concentrations were found in hydromorphic soils (up to 6% in the sandy-clayey horizon) in the swampy depression (Abata, 2003; Boeglin *et al.*, 2005). Carbon concentrations were very low (<2%) in all the deep horizons. These results are in close agreement with the analyses performed by Humbel *et al.* (1977) in different ferrallitic soils of Cameroon. The total organic carbon stock was estimated to be about 35 000 tons in the 17×10^6 m^3 of soil within the Mengong catchment.

DOC in water samples (rainwater, groundwater and surface water)

Atmospheric deposition, the wet deposition (WD) and bulk deposition (BD) samples were acidic ($4.5 < pH < 5.9$) and showed a low mineral content (Ndam-Ngoupayou *et al.*, 2002). Their DOC content was below the detection limit (0.1 mg l^{-1}) in the WD samples and present in only small amounts in the BD samples (0.2 to 1 mg l^{-1}). The throughfall deposits (TD) were characterized by significantly higher concentrations than the WD and BD samples (Table 1). Their DOC content varied from 0.7 to 11.5 mg l^{-1}, with a

DOC volume-weighted mean (VWM) concentration of 2.8 mg l^{-1}. These values are similar to those reported by Thurman (1985) for canopy drip and there are good correl ations between DOC and each of the following elements: SiO_2, K^+, Cl^-, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, demonstrating the influence of biological cycling within the forest on the cycling of these elements.

Groundwater and surface water

Based on their colour and DOC content, the catchment water samples can be divided into two groups (Ndam-Ngoupayou, 1997; Viers *et al*., 1997; Oliva *et al*., 1999):

(a) Hillslope groundwater and spring water represented by clear water with a low TDS and DOC content (<2 mg l^{-1}) (Table 1). These waters are acidic (4 < pH < 6).

(b) Water from the Mengong stream and groundwater from the surficial swamp characterized by a "tea colour" due to the high DOC content (10 < DOC < 30 mg l^{-1}). These waters are acidic and have a higher inorganic ion content. The surficial water chemistry is similar to that of the Rio Negro and the organic-rich northern tributaries of the Congo (Dupré *et al*., 1996).

Table 1 Chemical composition of the dissolved/particulate load for the Mengong experimental catchment (Nsimi) and the Nyong River stations from upstream to downstream.

Pools and sampling	pH	TDS		DOC		POC		TSS	
	C	*C*	*F*	*C*	*F*	*C*	*F*	*C*	*F*
Mengong experimental catchment in Nsimi									
Atmospheric deposits									
Wet deposition (WD)	4.96	1.52	2.8	<0.3	-	<DL	–	<DL	–
Bulk deposition (BD)	4.72	1.9	3.5	0.61	1.31	<DL	–	<DL	–
Throughfall deposition (TD)	5.15	7.0	10.5	3.62	5.45	nd	–	nd	–
Clear waters									
Main spring at Nsimi	4.91	8.5	nd	0.7	nd	<DL	–	<1	–
Hillside groundwater (1 m deep)	4.68	8.7	nd	0.7	nd	nd	–	nd	–
Hillside groundwater (15 m deep)	5.08	9.3	nd	1.1	nd	nd	–	nd	–
Hillside/swamp boundary (1 m)	4.70	9.7	nd	1.2	nd	nd	–	<1	–
Hillside /swamp boundary (2 m)	5.38	9.6	nd	0.7	nd	nd	–	<1	–
Coloured waters									
Swamp (1 m)	5.60	26.2	nd	15.7	nd	nd	–	nd	–
Swamp (2 m)	5.80	35.5	nd	2.2	nd	nd	–	<1	–
Mengong brook (outlet)	5.54	16.5	5.9	15.1	5.7	2.2	0.68	8.1	2.8
Nyong River stations from upstream to downstream (coloured waters)									
Awout at Messam	4.98	20.2	6.97	23	9.3	4.06	1.2	14.1	4.11
So'o at pont So'o	5.47	22.9	7.15	15.2	6.32	4.95	1.67	20.6	6.97
Nyong at Mbalmayo	5.70	24.7	4.98	15.7	4.67	2.38	0.59	13.3	3.32
Nyong at Olama	5.75	22.4	5.59	15.4	4.85	2.01	0.63	14.3	4.49

TDS: total inorganic dissolved solids; TSS: total suspended solids; DOC: dissolved organic carbon; POC: particulate organic carbon; *C*: mean annual concentration in mg l^{-1}; *F*: annual specific flux in t km^{-2} $year^{-1}$.
nd: not determined; <DL: below detection limit.

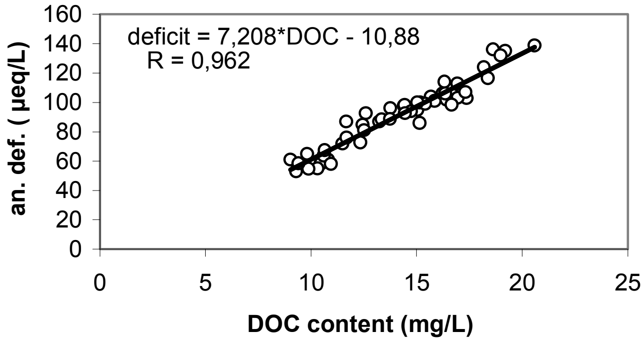

Fig. 2 Correlation between the anionic deficit and the DOC content of the Mengong river waters during the water year 1998/99.

For the water year 1998/99, the mean annual DOC concentration was 0.30 mg l^{-1} in the spring and 14.4 mg l^{-1} in the stream at the outlet. The mean annual DOC river fluxes are between 4.7 and 9.3 t km^{-2} $year^{-1}$ (Table 1).

The organic-rich coloured waters exhibit a very high ionic imbalance (δ) between the cationic sum (S_c) and the anionic sum (S_a), due to an important anionic deficit. The mean annual deficit averages 54–90%, according to the sampling station. This imbalance is mainly due to organic anions, which are not taken into account in the alkalinity measurements. Consequently, as seen in Fig. 2, there is a very good correlation between ionic deficit δ (in µeq l^{-1}) and DOC content (in mg l^{-1}) for the Mengong River waters. The slope of the regression lines obtained for the different stations vary between 4.3 and 9.0 µeq mg^{-1} C; the correlation coefficients r calculated for all catchments are higher than 0.90.

Total suspended solids (TSS) and particulate organic carbon (POC)

Studies undertaken on the drainage waters of the Mengong catchment and the Nyong River have shown that the suspended sediment is enriched in organic matter, the mineral fraction being mainly composed of kaolinite, quartz and goethite, with amorphous silica present in diatom frustules or in phytoliths (Olivie-Lauquet *et al.*, 2000). The POC content represents on average 25% of the TSS content, with rather low variation compared to water discharge fluctuations. This percentage is very close to that (25.4%) obtained for the mean annual POC [-] calculated by Ndam-Ngoupayou (1997) for the water year 1995/96 on the Mengong River. This percentage is higher than those obtained in the same way for the Nyong at Mbalmayo (17.3%) and the Olama (13.8%), showing that the suspended material becomes less and less enriched in organic carbon, going from upstream to downstream, because at the same time, the TSS concentration increases due to the mechanical erosion of more inorganic materials. This pattern is comparable to those observed for most world rivers (Martins & Probst, 1991; Ludwig *et al.*, 1996). Using these data, the POC specific fluxes can be estimated to be between 0.55 and 0.75 t km^{-2} $year^{-1}$ for the different stations within the Nyong River basin.

DISCUSSION

The major role of coloured waters

Two main types of water have been distinguished in the Mengong catchment based on colour and DOC content: the clear waters and the coloured waters. For the latter, the colour, which remains after filtration and is not related to suspended matter, has been attributed to a high content of dissolved organic matter (Ndam-Ngoupayou, 1997). The clear waters in the Mengong catchment come not only from springs, but also from perched water tables on the hills and slopes and from the deep water table in the depression. On the other hand, coloured waters, which are primarily associated with the river waters, are also found in the surficial groundwater within the depression. The major role of dissolved organic matter in chemical weathering in this catchment has been demonstrated by Viers *et al.* (1997) and Oliva *et al.* (1999), but also by Idir *et al.* (1999) in the Strengbach catchment in the Vosges Mountains (France). The organic acids, which are abundant in the swampy depression waters, are responsible for enhanced dissolution of soil minerals and for the transport, in a complexed form, of insoluble metallic elements.

The important contribution of DOC fluxes

In term of specific fluxes in the river, it can be seen from Table 1 that the DOC fluxes are comparable to those of inorganic TDS (within which the dissolved silica flux represents 40–56% according to the station), whereas the DOC fluxes are between one and two times higher than the TSS fluxes. Considering that POC averages 20% of TSS, the mean annual flux of total organic carbon (DOC + POC) represents 38–50% of the total inorganic and organic load (TDS + DOC + TSS) transported by the rivers at the different sampling stations. These percentages correspond to (DOC + POC) specific fluxes of between 5.2 and 10.5 t km^{-2} $year^{-1}$. Our results are comparable with those reported by Sigha-Nkamdjou *et al.* (1995) for other forested south-Cameroonian catchments (Ntem, Kadéi, Boumba, Dja, Ngoko), where the calculated fluxes are between 3.3 and 5.3 t km^{-2} $year^{-1}$ for DOC, and between 0.6 and 1.2 t km^{-2} $year^{-1}$ for POC. For savannah Cameroonian basins (Sanaga, Mbam), Ndam-Ngoupayou (1997) obtained lower values for DOC (~1.5 t km^{-2} $year^{-1}$), undoubtedly due to lower vegetation biomass, although the POC fluxes appear rather high (1 t km^{-2} $year^{-1}$ for the Sanaga, 4.2 t km^{-2} $year^{-1}$ for the Mbam), reflecting the relatively high TSS fluxes (18 and 98 t km^{-2} $year^{-1}$ respectively). A comparison between the DOC fluxes from the Niger basin: 0.593 t km^{-2} $year^{-1}$ at Lokodja (Martins & Probst, 1991) and 0.455 t km^{-2} $year^{-1}$ at Bamako (Boeglin & Probst, 1996) on the one hand, and from the Congo basin: 2.9 or 3.1 t km^{-2} $year^{-1}$ (Seyler *et al.*, 1995) on the other hand, provides a clear illustration of the influence of vegetation type on organic carbon solubilization. As an indication, Ludwig *et al.* (1996) proposed a mean DOC flux of 1.043 t km^{-2} $year^{-1}$ in the dry tropical zone, and of 3.818 t km^{-2} $year^{-1}$ in the humid tropical zone.

The chemical composition of the DOC and its transport capacity for trace elements

The strong correlation between the anionic deficit and the DOC content associated with all the sampling stations in the Nyong basin clearly demonstrates that the presence of organic anions compensates for the lack of negative mineral charges, as previously shown by Munson & Guerini (1993). The specific charge of the organic matter (in µeq mg^{-1} DOC), given by the slope of the regression line, varies between the stations: 7.2 for the Mengong at Nsimi, 9.0 for the Awout at Messam, 5.2 for the So'o at Pont So'o, 4.8 for the upper Nyong at Mbalmayo, and 4.3 for Nyong at Olama. The decrease in the specific charge from upstream to downstream (with a particularly high value for the Awout stream) could reflect a progressive structural modification of the organic compounds in the river waters. The travel time associated with the river reach between Nsimi and Olama (~100 km) is about 3–6 days. This means that the capacity of the dissolved organic matter to complex the cations, particularly the heavy metals, decreases from upstream to downstream, increasing the transport of heavy metals by the suspended material.

CONCLUSION

The analyses of the different forms of organic carbon in the soils and in the waters, undertaken for the Nsimi catchment, provide important information on the transfer dynamics and mass balance for a tropical humid environment, viz.:

1. The upper horizons of the soil cover and the corresponding drainage waters exhibit high concentrations of organic carbon. Considering that the soil cover provides a specific carbon stock of 59 000 t km^{-2}, about 26% of this amount is concentrated in the upper 2 m of the soil profiles (mean thickness = 30 m). In the coloured river and swamp waters, DOC fluxes are between 4.5 and 9 t km^{-2} $year^{-1}$ (which is comparable to inorganic TDS fluxes), whereas POC fluxes (representing about 20% of TSS) are between 0.5 and 1.3 t km^{-2} $year^{-1}$. On the contrary, clear spring waters or groundwaters are characterized by very low DOC contents.
2. The turnover time for the carbon (organic + inorganic) in the Mengong catchment is estimated to be about 9000 years, if one takes into account the whole carbon stock of the soil cover. However, considering that only the carbon contained in the hydromorphic soil horizons of the swampy zone is involved in the exchange and recycling processes, the residence time decreases to 950 years.
3. The strong anionic deficit (54–90%) associated with all drainage waters is strongly correlated with the DOC content. The specific charge of the dissolved organic matter has been estimated to be in the range 4.3–9.0 µeq mg^{-1} C. This value decreases progressively from upstream to downstream within the Nyong River basin, probably indicating a progressive structural modification of the organic dissolved species during transfer, producing a decreasing capacity for trace element complexing and transport.
4. Values of specific carbon flux obtained from the Nsimi catchment are similar to those for the different stations of the Nyong network. From upstream to downstream, the DOC specific fluxes are comparable. On the contrary, the POC specific fluxes are variable from one station to another, depending on the TSS flux.

However, the POC/TSS ratio is slightly variable around 20%. These results can be attributed to comparable carbon dynamics at the scale of the Nyong river basin, independent of the surface area of the different sub-catchments.

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