

**Sediment and
organic carbon
dynamics in the Tana
River**

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Distribution and origin of suspended sediments and organic carbon pools in the Tana River Basin, Kenya

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We studied patterns in organic carbon pools and their origin in the Tana River Basin (Kenya), in February 2008 (dry season), September–November 2009 (wet season), and June–July 2010 (end of wet season), and covering the full continuum from headwater streams to lowland mainstream sites. A consistent downstream increase in total suspended matter (TSM, 0.6 to 7058 mg l⁻¹) and particulate organic carbon (POC, 0.23 to 119.8 mg l⁻¹) was observed during all three sampling campaigns, particularly pronounced below 1000 m above sea level, indicating that most particulate matter exported towards the coastal zone originated from the mid and low altitude zones rather than from headwater regions. This indicates that the cascade of hydroelectrical reservoirs act as an extremely efficient particle trap. The decrease in ⁷Be/²¹⁰Pb_{xs} ratios of TSM downstream (range: 0.43 to 1.93) during the wet season indicated that the increasing sediment load in the lower Tana was largely due to recent surface erosion. During lower flow conditions, however, the gradual longitudinal increase in TSM coincided with more variable ⁷Be/²¹⁰Pb_{xs} ratios (0 to 4.5), suggesting that bank erosion and/or remobilisation of older sediments are the sources of the increasing TSM concentrations downstream. With the exception of reservoir waters, POC was predominantly of terrestrial origin as indicated by generally high POC/Chl-*a* ratios (up to ~ 41 000). Stable isotope signatures of POC ($\delta^{13}\text{C}_{\text{POC}}$) ranged between -32 and -20 ‰ and increased downstream, reflecting an increasing contribution of C4-derived carbon in combination with an expected shift in $\delta^{13}\text{C}$ for C3 vegetation towards the more semi-arid lowlands. Sediments from the main reservoir (Masinga) showed $\delta^{13}\text{C}$ values higher (-19.5 to -15.7 ‰) than found in any of the riverine samples, indicating selective retention of particles associated with C4 fraction. Dissolved organic carbon (DOC) concentrations were highest during the end of wet season (2.1 to 6.9 mg l⁻¹), with a stable isotope signatures generally between -28 and -22 ‰. A consistent downstream decrease in % organic carbon (%OC) was observed for both soils, riverine sediments, and suspended matter; likely due to better preservation of the organic fraction

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in colder high altitude regions, with loss of carbon during downstream spiraling. Both $\delta^{13}\text{C}$ values for soil and sediment did not exhibit clear altitudinal patterns, but values reflect the full spectrum from C3-dominated to C4-dominated sites. Very low ratios of organic carbon to mineral surface area (OC:SA) were found in reservoir sediments and suspended matter in the lower Tana River, indicating that these are stable OC pools which have undergone extensive degradation.

1 Introduction

Rivers play an important role in the global carbon (C) cycle, and process $\sim 2.7 \text{ Pg C}$ annually of which $\sim 0.9 \text{ Pg C yr}^{-1}$ is estimated to reach oceans (Cole et al., 2007; Aufdenkampe et al., 2011). Rivers do not merely transport C from the terrestrial biome to the oceanic environment, but also bury and process organic matter, and generally acting as a source of CO_2 to the atmosphere (Cole and Caraco, 2001; Mayorga et al., 2005; Cole et al., 2007). Although the riverine C flux may be small compared to the gross global fluxes between ocean-atmosphere (90 Pg C yr^{-1}) and terrestrial-atmosphere (120 Pg C yr^{-1}) interfaces (Schlünz and Schneider, 2000; Prentice et al., 2001; Houghton, 2004; Sabine et al., 2004), the fluvial C flux transport is of the same order as the respective net ecosystem production (2.2 Pg C yr^{-1}) (Cole and Caraco, 2001; Cole et al., 2007; Battin et al., 2008; Aufdenkampe et al., 2011).

Riverine systems transport C mainly in form of dissolved organic C (DOC), particulate organic C (POC) and dissolved inorganic C (DIC). Globally, rivers discharge into the world's ocean approximately 0.5 Pg C yr^{-1} as DIC and about 0.4 Pg C yr^{-1} as organic C with about one-half each as POC and DOC (Meybeck, 1993; Probst et al., 1994; Ludwig et al., 1996; Schlünz and Schneider, 2000). Fluvial C fluxes (i.e., C yields) may differ strongly among individual rivers due to the naturally large variation in variables such as catchment slopes, vegetation, geology, climate and size (Hope et al., 1994). The global sediment yield of rivers is estimated at $160\text{--}180 \text{ t km}^{-2} \text{ yr}^{-1}$.

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in pre-dammed conditions (Vörösmarty et al., 2003). However, most current C flux estimates do not account for human impact such as retention of material in reservoirs, hence, actual sediment load and POC transport to the oceans may be lower because of increased damming of rivers (Vörösmarty et al., 2003). Further, recent estimates of CO₂ outgassing from streams and rivers suggests land-derived organic matter may be oxidized in a matter of days or weeks on its transit along fluvial ecosystems (Battin et al., 2008).

Riverine POC is mainly derived from soils, litterfall and autochthonous production while DOC arises from degradation of organic matter in the soil, leaching of plant litter and, to a lesser degree, from the contribution of autochthonous biological processes occurring in the stream (Meybeck, 1993; Ludwig et al., 1996; Finlay and Kendall, 2007). Globally, riverine DOC fluxes are dependent on drainage intensity, basin slope and to a larger extent, the amount of C stored in soils, while POC on the other hand is a function of TSM fluxes which principally depend on drainage intensity, rainfall intensity and basin slope (Ludwig et al., 1996). The global riverine POC fluxes have been estimated based on modeled global sediment fluxes and %POC versus TSM relationships (Meybeck, 1982, 1993; Ittekkot, 1988; Ludwig et al., 1996; Mayorga et al., 2010). In the majority of rivers, the POC content of TSM ranges between 1 and 20 %, but it can exceptionally reach 0.5 % for highly turbid rivers, or values greater than 20 % for lowland rivers draining swamps.

The origin of riverine organic C is commonly categorized as either allochthonous-derived from terrestrial organic matter or autochthonous-derived from in-situ biological production (Hope et al., 1994; Finlay and Kendall, 2007). According to the river continuum concept (Vannote et al., 1980), the relative contribution of different sources to total OC varies with stream size, where allochthonous C is expected to be important in first order streams giving way to autochthonous production downstream as the stream size increases. As turbidity increases in large or disturbed rivers, light limits autotrophic production again; and hence allochthonous forms of C are expected to dominate energy flow (Vannote et al., 1980). Since the seminal work of Vannote et al. (1980), other

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about -28 and -13 ‰, respectively (Still and Powell, 2010; Kohn, 2010). Freshwater autotrophs such as phytoplankton can have a wide range of $\delta^{13}\text{C}$ signatures (-42 to -19 ‰ according to Finlay and Kendall, 2007) depending e.g., on the $\delta^{13}\text{C}$ values of DIC.

Thus, stable isotopes have frequently been used, in combination with other proxies such as elemental ratios (POC : PN) and/or POC : chlorophyll-*a* ratios, to constrain the relative contribution of different organic matter sources (autochthonous vs. allochthonous), and to understand C fluxes and the fate of terrigenous C in river systems (Kendall et al., 2001; Finlay and Kendall, 2007). Radionuclides, particularly ^7Be , ^{210}Pb and ^{137}Cs have been applied as tracers to identify source regions of sediments, quantify residence and settling times of particles within a given riverine basin, as well as understanding aspects of fluvial sediment erosion, transport, deposition and resuspension (Matisoff et al., 2005). Both ^7Be ($t_{1/2} = 53.3$ d) and ^{210}Pb ($t_{1/2} = 22.3$ yr) are washed from the atmosphere and delivered to the earth surface through both wet and dry fallout and both sorb strongly to particles, hence, they qualify as tracers of sediment origin (Bonniwell et al., 1999; Matisoff et al., 2002; Saari et al., 2010). The ratio of $^7\text{Be}/^{210}\text{Pb}_{\text{xs}}$ in suspended sediments reflects the age of sediment (i.e. the time since the sediment received both ^7Be and $^{210}\text{Pb}_{\text{xs}}$ from atmospheric deposition) and can be used to quantify the proportion of resuspended bottom material in the water column (Olsen et al., 1986). Thus, a decrease in the $^7\text{Be}/^{210}\text{Pb}_{\text{xs}}$ ratio reflects an increase in the time since the sediment was “tagged” with atmospherically derived ^7Be and $^{210}\text{Pb}_{\text{xs}}$, since ^7Be has a much shorter half-life than ^{210}Pb . Alternatively, a decrease in this ratio may reflect dilution of ^7Be -rich sediment with ^7Be -deficient old sediment (Matisoff et al., 2005).

The present study focuses on the distribution and origin of organic C pools in the Tana River, Kenya as regulated by reservoirs and along a longitudinal gradient. It is based on three basin-wide surveys covering different seasons (dry season-February 2008, wet season-September-November 2009, and end of wet season-June-July 2010). These data provide one of the most complete studies quantifying and

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characterising riverine organic C at the scale of an entire tropical river catchment, and will provide the background for the interpretation of complementary data on greenhouse gas fluxes, nutrient and inorganic C dynamics which will be discussed elsewhere.

2 Materials and methods

2.1 Study area

The Tana River is the longest river in Kenya (~ 1300 km), with a total catchment area of ~ 130 000 km² (Fig. 1) (Kitheka et al., 2005). The basin experiences a bimodal hydrological cycle, with long rains between March and May, and short rains between October and December. The river system can be separated into two main parts, here referred to as the “Tana headwaters” and the “lower main Tana”. The Tana headwaters encompass a set of small mountainous streams that form the perennial source of the Tana River, and which originate from the Aberdares Range in the central highlands of Kenya, the highlands around Mount Kenya, and the Nyambene Hills in Eastern Kenya. The lower main Tana encompasses the section downstream of the Nyambene Hills, where the river continues for about ~ 800 km through semi-arid plains. Along this stretch, tributaries only discharge in short pulses during the wet season. As a result, the lower main Tana forms a single transport channel during the dry season, delivering material to the Indian Ocean (Maingi and Marsh, 2002). Along the lower main Tana, extensive floodplains are found between the towns of Garissa and Garsen (Fig. 1). Yet, flooding is irregular in recent decades, as the river flow is regulated by five hydro-electric dams upstream (Maingi and Marsh, 2002). The associated reservoirs have a combined surface area of 150 km², and a substantial amount of sediment is trapped behind these dams (Dunne and Ongweny, 1976; Schneider and Brown, 1998). The mean annual river discharge is 156 m³ s⁻¹ as measured at Garissa gauging station (Fig. 2).

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2.2 Sampling and analytical techniques

Water, sediment and soil sampling was carried out during four campaigns in February 2008 (dry season), September–November 2009 (wet season), and June–July 2010 (end of wet season), and October/November 2011 (wet season). Samples were taken throughout the river basin (Fig. 1 – Supplement Table 1), and sampling sites included a subset of small streams in the headwater regions, an approximately equidistant set of locations along the main lower Tana, and two of the five hydro-electric reservoirs (Masinga and Kamburu). The first field survey in February 2008 only covered a subset of these field sites. The associated water column data have already been presented in Bouillon et al. (2009) and only the data on soils and riverine sediments are further detailed here. In both the 2009 and 2010 campaigns, an extensive basin-wide survey was carried out. During the follow-up fieldtrip in October/November 2011, depth profiles of river bank soils were collected at several sites along the lower Tana River.

Samples for total suspended matter were taken by filtration of a known volume of surface water on 47 mm GF/F filters (nominal porosity = 0.7 μm), which were pre-weighed and pre-combusted (overnight at 450 °C), and which were dried and re-weighed after filtration. Samples for POC, particulate nitrogen (PN), and $\delta^{13}\text{C}_{\text{POC}}$ were obtained in a similar way by filtering a known volume of surface water on pre-combusted 25 mm GF/F filters (0.7 μm) and drying. In the laboratory, these filters were exposed to HCl fumes for 4 h to remove inorganic C, and the residue was re-dried and packed in Ag cups.

Top soil samples (surface 0–5 cm layer) were collected at all sampling sites (except the Masinga and Kamburu reservoirs), slightly upstream from the water sampling location and ~ 10 m from the river bank. Along the main Tana River, riverbed sediments were sampled with a Van Veen grab, while in the shallow headwater streams, sediment was directly collected into sample tubes. An unusually dry period preceded the fieldwork in September–October 2009 and led to historically low water levels in the Masinga reservoir. This enabled easy access to the reservoir bottom. Three short

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sediment cores (up to 30 cm) were taken at the lowest sites accessible, and within the zone where clear, thick sediment deposits were present. In the same campaign, the Van Veen grab was used to retrieve surface sediment from the Kamburu reservoir. All soil and sediment samples were stored in liquid N₂ during transport, and upon return to the laboratory, they were preserved at -20 °C until further analysis. In the laboratory, sediment and soil samples were ground and homogenized using a mortar and pestle. A weighed subsample was transferred into a Ag cup to which a 10 % HCl solution was added to remove all carbonates. The samples were then dried at 60 °C for 24 h, and if necessary, the procedure was repeated.

POC, PN, and $\delta^{13}\text{C}_{\text{POC}}$ from filters, soil and sediment samples were determined on a Thermo elemental analyzer–isotope ratio mass spectrometer (EA-IRMS) system (various configurations, either Flash1112, FlashHT with Delta+XL or DeltaV Advantage), using the thermal conductivity detector (TCD) signal of the elemental analyzer (EA) to quantify POC and PN, and by monitoring 44, 45, and 46 *m/z* signal on the isotope-ratio mass spectrometer (IRMS). Quantification and calibration of $\delta^{13}\text{C}$ data was performed with IAEA-C6 and acetanilide which was internally calibrated vs. international standards. Reproducibility of $\delta^{13}\text{C}_{\text{POC}}$ measurements was typically better than $\pm 0.2\%$.

Samples for dissolved organic C (DOC) and $\delta^{13}\text{C}_{\text{DOC}}$ were obtained by pre-filtering surface water through pre-combusted GF/F filters (0.7 μm), with further filtration through 0.2 μm syringe filters, and were preserved with H₃PO₄ in glass vials with teflon-coated screw caps. DOC and $\delta^{13}\text{C}_{\text{DOC}}$ were measured with either a customized Thermo HiperTOC coupled to a Delta+XL IRMS (Bouillon et al., 2006), or by manual injection in a Thermo IsoLink HPLC-IRMS (similar to the method described in Albéric, 2011). Samples for pigment analysis were obtained by filtering a known volume of surface water on pre-combusted 47 mm GF/F filters, which were immediately packed in cryotubes and stored in liquid N₂. Upon return to the laboratory, these were stored at -20 °C until further analysis. Pigments were extracted in 10 ml acetone : water mixture (90 : 10), and a subsample was separated by HPLC on a C18 reverse phase column

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(Bouillon et al., 2009). Calibration was performed with working standards prepared from commercially available pure compounds.

Surface area (SA) measurements were made on 200–600 mg freeze-dried and homogenized samples of soils, sediments and TSM, using multi-point Brunauer–Emmett-Teller adsorption isotherms (Brunauer et al., 1938). Measurements were made using a 25 Quantachrome NOVA 3000 SA analyzer, and verified with BCR-173 (Institute for Reference Materials and Measurements).

Samples for radionuclide analysis were obtained by filtering a known volume of surface water on 102 mm polycarbonate membrane filters. The activities of ^7Be , ^{210}Pb and ^{226}Ra were determined on the dried suspended matter using a low background-high efficiency well type γ -counter placed in a lead shield and protected from cosmic ray using an anti-cosmic shielding made of plastic scintillators (Schmidt et al., 2009). Standards used for calibration of the γ -detector were IAEA standards (RGU-1; RGTh-1; IAEA-314). ^7Be values were corrected for radioactive decay that occurred between sample collection and counting. Excess ^{210}Pb ($^{210}\text{Pb}_{\text{xs}}$) was calculated by subtracting the activity supported by parent isotope ^{226}Ra from the total activity measured in particles.

3 Results

3.1 Total suspended matter and particulate organic carbon

The full dataset is available as Supplement Tables 1–6. The Total Suspended Matter (TSM) concentrations recorded during the dry season in 2008 (0.6 to 483 mg l^{-1}) showed a similar range as during the end-of-wet-season conditions in 2010 (1 to 471 mg l^{-1}), while the range during the wet-season was one order of magnitude larger (2 to 7058 mg l^{-1}), with the highest values obtained in the lower main Tana. Paired t -tests confirm that TSM values were similar during dry season and end of wet season datasets ($p > 0.05$), but significantly higher during the wet season campaign.

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A downstream increase in TSM was observed during all three sampling campaigns (Fig. 3a). In the dry-season campaign of 2008, there is consistent increase in TSM in the lower main Tana, and this pattern is basically replicated in 2010. In the wet season campaign of 2009, TSM concentrations are an order of magnitude higher, and show no trend along the river axis. In the headwater regions, TSM shows strong variability between streams in all campaigns.

TSM for Aberdares tributaries were similar during the three campaigns ($p > 0.05$) and ranged from 0.6 to 224 mg l⁻¹. One tributary (Muringato) recorded notably high values during the three sampling surveys (68.8 to 157.5 mg l⁻¹). Similarly, Mt. Kenya tributaries generally recorded similar TSM (~ 36.5 mg l⁻¹) during the three campaigns ($p > 0.05$), but for three tributaries (Mathioya, Mutonga and Maara), which showed exceptionally high values (1460 to 5904 mg l⁻¹) during wet-season campaign. Tributaries in the Nyambene Hills also gave similar TSM values during the three campaigns ($p > 0.05$) though during the wet season campaign, one tributary (Thanandu) recorded an exceptionally high value (3688 mg l⁻¹).

Concentrations of POC ranged from 0.3 to 5.8 mg l⁻¹, 0.23 to 119.8 mg l⁻¹ and 0.4 to 12.6 mg l⁻¹ during dry season, wet season and end of wet-season, respectively (Supplement Table 1). POC shows a similar pattern with altitude as TSM, i.e., a consistent downstream increase during all sampling campaigns (paired t -test, $p < 0.01$). Paired t -tests show that POC significantly differed between seasons ($p < 0.05$). POC concentrations for different headwater tributaries were similar during the three campaigns (paired t -test, $p > 0.05$) with a few exceptions (e.g. Muringato, Mathioya, Mutonga and Maara) which recorded high values during the wet season campaign (32.2 to 85.5 mg l⁻¹). The POC values along lower main Tana were different during the three campaigns (one-way ANOVA, $p < 0.01$).

The organic C content (%OC) of the suspended matter ranged from 1.1 to 49.8%, 0.9 to 32.1 % and 1.2 to 37.9 % for dry season, wet season and end of wet season campaigns, respectively (Supplement Table 1), and the organic C content decreased downstream (Fig. 3b). TSM and %OC showed an inverse relationship during the three

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seasons ($p < 0.01$). POC/PN ratios were significantly lower during the wet season (9.6 ± 2.5) as compared to end of wet season (12.1 ± 4.3) and dry-season (10.5 ± 2.6) datasets.

The $\delta^{13}\text{C}_{\text{POC}}$ values ranged from -26.5 to -21.2% , -31.8 to -19.9% , and -27.1 to -21.4% with means of $-23.8 \pm 1.6\%$, $-24.7 \pm 2.8\%$ and $-24.3 \pm 1.6\%$ during dry season, wet season and end of wet-season campaigns, respectively (Supplement Table 1). The values for different seasons were not significantly different (paired t -test, $p > 0.05$). Generally, the $\delta^{13}\text{C}_{\text{POC}}$ values increased downstream during all the three sampling campaigns ($p < 0.01$) (Fig. 4a). Overall, the $\delta^{13}\text{C}_{\text{POC}}$ values during the three seasons were not significantly different for the three headwaters and so were the values for the lower main Tana (paired t -test, $p > 0.05$). However, values for most sites above 2950 m in Aberdares and Mt. Kenya headwaters were more ^{13}C -enriched. Overall, Mt. Kenya tributaries were the most depleted ($-26.3 \pm 2.0\%$), Aberdares and Nyambene Hill intermediate (-24.6 ± 1.0 and $-24.0 \pm 1.8\%$, respectively) and Tana River mainstream the most enriched ($-22.5 \pm 1.0\%$).

3.2 Dissolved organic carbon and $\delta^{13}\text{C}_{\text{DOC}}$

DOC concentrations ranged from 0.3 to 2.5 mg l^{-1} , 0.2 to 6.4 mg l^{-1} and 2.1 to 6.9 mg l^{-1} for dry season, wet season and end of wet season campaigns, respectively (Supplement Table 1; Fig. 5a) and showed significant seasonal differences (paired t -test, $p < 0.01$) the lowest values generally occurring in the dry season. Overall, DOC values for Aberdares, Mt. Kenya tributaries and Tana River mainstream showed seasonal differences ($p < 0.01$) but values for Nyambene Hills tributaries were similar during the three seasons ($p > 0.05$).

The $\delta^{13}\text{C}_{\text{DOC}}$ values ranged from -27.7 to -21.8% , -26.9 to -21.4% and -26.9% to -20.9% , with means of $-23.8 \pm 1.1\%$, $-24.4 \pm 1.3\%$ and $-24.0 \pm 1.1\%$ for dry season, wet season and end of wet season campaigns, respectively (Supplement Table 1). The values were similar during all the three campaigns (paired t -test, $p > 0.05$). The

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mean values were $-24.2 \pm 1.0\text{‰}$, $-24.6 \pm 1.3\text{‰}$, $-24.2 \pm 1.7\text{‰}$ and $-23.7 \pm 0.9\text{‰}$ for Aberdares, Mt. Kenya, Nyambene Hills and Tana mainstream, respectively. The $\delta^{13}\text{C}_{\text{DOC}}$ values for Aberdares and Mt. Kenya tributaries above 2950 m were divergent and more ^{13}C -enriched during all the three campaigns (Fig. 5b). $\delta^{13}\text{C}_{\text{DOC}}$ and $\delta^{13}\text{C}_{\text{POC}}$ were significantly correlated only during the wet season (Pearson correlation, $r^2 = 0.55$; $p < 0.01$; Fig. 6a). The ratio of dissolved to particulate organic C (DOC : POC) ranged from 0.02 to 16.4 for the entire dataset over the three campaigns. The means were 0.95 ± 0.59 , 1.52 ± 2.50 and 2.26 ± 2.01 for dry season, wet season and end of wet season campaigns, respectively. DOC : POC ratios show a decreasing trend with TSM, and hence generally decreased downstream during all the three seasons (Pearson correlation, $p < 0.01$; Fig. 7a).

3.3 Soil and sediment carbon pools

Data on organic C content of soils and riverine sediments were combined for the three sampling campaigns. The soil organic C ranged between 0.03 to 20.2 %, (Supplement Table 2), with a mean basin-wide value of 3.5 ± 3.9 . Similarly, the organic C content of riverine sediment (%OC) ranged from 0.01 to 5.7 % with a basin-wide mean of 1.3 ± 2.6 (Supplement Table 2). Both the soil and sediment C content decreased consistently downstream (Pearson correlation, $p < 0.01$; Fig. 3b). Soil and sediment values were significantly different (paired t -test, $p > 0.05$). The $\delta^{13}\text{C}$ values of the soil organic C pool show a weak positive correlation with altitude (Pearson correlation, $r^2 = 0.23$; $p < 0.05$), ranging overall between -28.5 and -13.2‰ (Supplement Table 2). The $\delta^{13}\text{C}$ data of the riverine sediment showed a slightly smaller range (between -27.8 and -16.2‰ – Supplement Table 2) and did not show a systematic pattern with altitude (Pearson correlation, $p > 0.05$).

Overall, %OC from river bank soil depth profiles ranged between 0.05 to 1.7 % whereas $\delta^{13}\text{C}$ values ranged between -26.1 and -11.9‰ (Supplement Table 5). The %OC decreased with depth while $\delta^{13}\text{C}$ values generally increased with depth at Tana

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Primate and Garsen sites (Pearson correlation, $p < 0.05$) but no systematic patterns could be discerned at the Garissa and Hola sites (Pearson correlation, $p > 0.05$).

Sediment %OC on cores from Masinga Reservoir ranged from 1.1 to 1.9% (Supplement Table 3) and although concentrations differed between the cores, they generally decreased with depth (Fig. 9a); while that of surface sediments in Kamburu Reservoir was 1.84%. The $\delta^{13}\text{C}$ values from Masinga cores ranged between -19.6 and -15.7% (Supplement Table 3), and increased consistently with depth (Fig. 9b) whereas the single sample from Kamburu reservoir surface sediments was -20.7% .

3.4 Specific surface areas

Specific SA ranged between 2.4 to $98.2\text{m}^2\text{g}^{-1}$, 0.9 to $105\text{m}^2\text{g}^{-1}$ and 39.9 to $82.3\text{m}^2\text{g}^{-1}$ for soil, riverine sediment and suspended matter, respectively (Supplement Table 4). The SA for soils and riverine sediments decreased consistently downstream while those of suspended matter increased downstream (Pearson correlation, $p < 0.01$; Fig. 8a). Sediment %OC and SA were positively correlated (Pearson correlation, $p < 0.01$; Fig. 8b) but soil and suspended matter were not correlated ($p > 0.05$). The SA values from the Masinga and Kamburu reservoir sediments were notably high, and ranged between 59.8 to $93.8\text{m}^2\text{g}^{-1}$ (Supplement Tables 3 and 4). The OC:SA ratios ranged between 0.1 to 14.6mg OC m^{-2} , 0.1 to 7.1mg OC m^{-2} and 0.2 to 0.5mg OC m^{-2} for soil, sediment and suspended matter, respectively (Supplement Table 4). Generally, soil OC:SA ratios were significantly higher than riverine sediments ($p < 0.01$). However, OC:SA ratios did not show a systematic pattern with altitude. The OC:SA ratios from Masinga and Kamburu dams sediment cores ranged between 0.16 to 0.25mg OC m^{-2} (Supplement Table 3). However, neither SA nor the OC:SA ratio exhibited a systematic pattern with core depth.

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3.5 Activities of radionuclides

The particulate activity ratios of ${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ (${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ AR) ranged between 0.4 and 1.9 during wet season and increased consistently downstream (Pearson correlation, $p < 0.05$; $R^2 = 0.76$). During the end-of-wet-season campaign, values were higher (range between 1.0 to 4.5) and there was no systematic pattern downstream (Fig. 10a). However, the ratios were generally low in lower Tana sites, for example Hola and Sankuri sites compared to Ura river site in the middle of the Tana catchment. Generally, ${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ ratios were highest during end of wet season compared to wet season. The ${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ AR can be used to calculate the age of the sediments or the fraction of new sediments (Matisoff et al., 2005):

$$\text{Age} = \frac{1}{(\lambda_{7\text{Be}} - \lambda_{210\text{Pb}})} \ln(\text{AR}_0/\text{AR}) \quad (1)$$

$$\% \text{ new sediment} = (\text{AR}/\text{AR}_0) \times 100 \quad (2)$$

where $\lambda_{7\text{Be}}$ and $\lambda_{210\text{Pb}}$ are the decay constants of ${}^7\text{Be}$ (0.013 d^{-1}) and ${}^{210}\text{Pb}$ ($8.509 \times 10^{-5} \text{ d}^{-1}$). AR and AR_0 are the ${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ AR of suspended particles and of the atmospheric fallout, respectively. The age of particulate suspended matter (SPM) (Fig. 10b) decreased consistently downstream ($p > 0.05$; $R^2 = 0.86$ and 0.82 , respectively) during wet season but no systematic pattern could be discerned during end of wet season (Pearson correlation, $p < 0.05$). The sample collected at Sankuri during the end-of-wet season sampling recorded the highest age ($\sim 480 \text{ yr}$; or estimated contribution of new sediments of $< 1 \%$).

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4 Discussion

4.1 Sediment dynamics along the Tana River flow-path

The average river discharge measured at Garissa station during the wet season campaign (208.5 m³ s⁻¹; October and November 2009) was 1.7 and 1.4 times higher than during the dry season (122.9 m³ s⁻¹; February 2008) and end-of-wet-season campaign (145.2 m³ s⁻¹; June and July 2010), respectively. As expected (Dunne and Ongweny, 1976; Kitheka et al., 2005), TSM concentrations were highest during high-flow conditions of the wet season, in particular for the lower main Tana River. TSM profiles during all seasons studied show that, with few exceptions, high-altitude streams have relatively low TSM concentrations. Considering that the Tana River sustains several reservoirs along its channel, a substantial amount of sediment is trapped, with Masinga and Kam-buru dam alone estimated to retain ~ 6.0 and 3.0 million t yr⁻¹, respectively (Dunne and Ongweny, 1976; Schneider and Brown, 1998 and references therein). Despite the presence of these reservoirs, high TSM values were recorded beyond the reservoirs in the lower main Tana. The TSM profile is much more variable during the wet season, with several minima and maxima along the lower river course (see Fig. 3, note the log scale on the Y-axis). Sediment inputs could be expected from the ephemeral streams (lagas) during flash floods. Monthly sampling conducted by Kitheka et al. (2005) for two years between 2000 to 2003 recorded TSM concentrations in the range of 530 to 1930 mg l⁻¹ at Garsen (see Fig. 1 for location). The maximum of this range is much lower than the value we recorded during our wet season campaign at the same site (5098 mg l⁻¹). Compared to many other African river systems (e.g., Martins, 1983; Lesack et al., 1984; Seyler et al., 1995; Bird et al., 1998; Coynel et al., 2005; 1.7 to 135 mg l⁻¹), the TSM concentrations encountered in the lower main Tana during the wet season were exceptionally high.

In the dry and post-wet season, TSM concentration data are lower than in the wet season, but still high compared to the headwaters, even right after the dams. Moreover, there is a very conspicuous strong increase in TSM in the lower main Tana (Fig. 3a),

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where the river flows through semi-arid plains for ~ 800 km, and has no tributaries in the dry season. Based on data from the dry season sampling in 2008, Bouillon et al. (2009) suggested that this downstream increase in TSM during low flow conditions could be explained by resuspension of internally stored riverbed sediments. However, such a resuspension mechanism implies that the river bed must act as a sink of TSM during other period, i.e., during the wet season. Given the high current speeds and high TSM values recorded during our wet season campaign, it is unlikely that the river beds accumulates sediment during this period. Instead, the downstream increase in TSM below the reservoirs most likely shows that the lower Tana River is in a non-equilibrium state with respect to sediment transport. Past studies have documented similar impacts of upstream damming to downstream river networks (Scodanibbio and Mañez, 2005), such as river channel incision, associated river bank erosion and downstream sedimentation (Rosgen, 1997). In the case of the Tana river, Maingi and Marsh (2002) reported that following the construction of Masinga dam, river meandering rates have decreased and the river channel of the lower Tana has deepened. Our observations of strongly increasing TSM concentrations during different stages of the hydrograph thus suggest that much of the sediment generated in the lower section of the Tana River, at least during periods of lower discharge, is derived from the collapse of incised and unstable river banks.

The contribution of bank sediments in explaining the increasing TSM load along the lower Tana River appears to be consistent with organic C data from river bank sediments. The high TSM loads coincide with lower %POC values and higher $\delta^{13}\text{C}_{\text{POC}}$ signatures, and a comparison with bank sediment data illustrates that these could represent an end-member consistent with observations on the riverine POC (Fig. 11).

Variations in $^7\text{Be}/^{210}\text{Pb}_{\text{xs}}$ ratios form an important tool for tracing suspended particles along the river continuum (Matisoff et al., 2005; Saari et al., 2010). In the context of identifying the sources of sediments in the lower Tana River, these data allow us to make an analysis of the relative importance of surface erosion (material with high $^7\text{Be}/^{210}\text{Pb}_{\text{xs}}$ ratios) versus river bed resuspension or river bank collapse (material with

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species, which are dominant in the high altitude headwater catchments. The $\delta^{13}\text{C}_{\text{POC}}$ values increase downstream in contrast to patterns observed in the Amazon Basin (Cai et al., 1988; Aufdenkampe et al., 2001; Townsend-Small et al., 2005), although a similar pattern has been reported in a tropical river system in Cameroon (Bird et al., 1994b). Such a downstream increase in $\delta^{13}\text{C}_{\text{POC}}$ could result from a combination of two processes: (i) altitudinal differences in the $\delta^{13}\text{C}$ signature of C3 vegetation, and/or (ii) a shift towards a higher contribution of C4 vegetation at lower altitudes. Regarding the first mechanism, $\delta^{13}\text{C}$ values of C3 plants have been reported to increase with decreasing mean annual precipitation (MAP) (e.g., Kohn, 2010). The rainfall pattern in Tana River basin decreases from 2200 mm yr⁻¹ at high altitudes to 450 mm yr⁻¹ in lower and drier Tana catchment (Schneider and Brown, 1998). Employing these precipitation data together with the empirical relationship between altitude, precipitation and $\delta^{13}\text{C}$ of C3 vegetation established by Kohn (2010), the average C3 vegetation is expected to have average signatures of -28.7 and -26.5‰ for the highest and lowest altitudes, respectively, i.e. a shift of +2.2‰. This shift is much smaller than the observed shift of ~7‰ in our dataset, (Fig. 4a). This indicates that the downstream increase in $\delta^{13}\text{C}$ values is to a large extent due to increased contributions from C4 vegetation or C4-dominated soil organic matter. One notable exception to this elevational pattern is the much higher than expected C4 contribution at some of the high altitude sites (Aberdares, Mt. Kenya), where both the POC and DOC show distinctly higher $\delta^{13}\text{C}$ signatures (Figs. 4a and 5b). This observed C4 contribution is explained by the frequent occurrence of *Andropogon amethystinus*, a tussock-forming C4 grass species for which our $\delta^{13}\text{C}$ measurements range between -13.64 and -12.14‰, (Tieszen et al., 1979; Wooller et al., 2001).

The downstream increase in C4 vegetation as reflected in $\delta^{13}\text{C}_{\text{POC}}$ values is related to an increasing aridity and the associated vegetation gradient, where forested ecosystems at high altitudes gradually shift towards savannah dominated ecosystems along the lower main Tana. Based on a simple mixing model, and using end-member values for C4 and C3 vegetation of -12.1 and -27.6‰, respectively, the estimated C3

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contribution in the POC pool in the lower main Tana is surprisingly high (63%), despite the open savannah vegetation in the lower altitude Tana basin probably due to contribution from riverine forest. Past studies from other tropical rivers suggest minimal contribution of POC from algal sources in fluvial systems (Bird et al., 1994a,b). The $\delta^{13}\text{C}$ signatures for POC at Masinga (Bouillon et al., 2009) and Kamburu dams showed depleted $\delta^{13}\text{C}$ values, low POC/Chl-*a* ratios, high %POC and low POC/PN ratios, thus reflecting POC contributions from algal sources (Supplement Table 1; Fig. 4a,b). This effect was particularly more pronounced during dry season campaign (Bouillon et al., 2009). Yet, in our riverine samples, there is a negligible contribution of phytoplankton to the POC pool as confirmed by the absence of positive correlations between $\delta^{13}\text{C}$ signatures of POC and those of algae-specific phospholipid fatty acid markers (20:5 ω 3 and 18:3 ω 3), while these markers show an excellent correlation with $\delta^{13}\text{C}$ data of dissolved inorganic C (Van den Meersche and Tamooh, unpublished data).

The $\delta^{13}\text{C}$ values for Masinga dam sediment cores were surprisingly high (−19.5 to −17.3‰) and inconsistent with the values measured in tributaries feeding into the Masinga reservoir (Fig. 7b). These signatures similarly do not match the phytoplankton in the reservoir (grey symbols in Fig. 7b), suggesting that selective retention of particles associated with the C4 fraction or/and preferential mineralization of isotopically light POM could be responsible for these unexpected $\delta^{13}\text{C}$ signatures. This, however, conflicts with the hypothesis proposed by Wynn and Bird (2007) that C4 derived organic matter decomposes faster than C3-derived material. The reservoir cores show a decrease in organic C with depth, and an increase of $\delta^{13}\text{C}$ with depth, which could be interpreted as resulting from post-depositional mineralisation of OC. However, organic matter mineralization typically induces only a minimal shift in $\delta^{13}\text{C}$ signatures due to fractionation (e.g., Kunz et al., 2011), and hence, the increase of $\delta^{13}\text{C}$ with depth would suggest that C3 material preferentially mineralized over C4. One mechanism could be that C3 material is less protected on minerals of the reservoir sediment, which has very high SA values (Fig. 8a). A first-order estimate of post-depositional C losses can be obtained by comparing the %OC data between the upper and lower

layers of deepest sediment core. This way, we estimate a $\sim 30\%$ OC loss thus suggesting a relatively high burial efficiency of organic C ($\sim 70\%$) in the Masinga reservoir. The burial efficiency of OC in our study is significantly higher compared to $\sim 40\%$ reported in other temperate and tropical lakes (Sobek et al., 2009; Kunz et al., 2011), but it should be stressed that our estimate is derived from a limited number of data. Nevertheless, even this coarse estimate underscores the significant role reservoirs play as sinks in global C cycle (Cole et al., 2007; Battin et al., 2008; Tranvik et al., 2009). The surface area (SA) for suspended matter along lower main Tana ($60\text{--}80\text{ m}^2\text{ g}^{-1}$) were within the same range as those reported by Bouillon et al. (2009) but are much higher than those reported for coastal sediments, estuaries and rivers ($< 50\text{ m}^2\text{ g}^{-1}$) (Mayer, 1994; Keil et al., 1997; Aufdenkampe et al., 2007). Compared to the TSM, the riverine sediment showed a much larger range in SA, due to the sandy and muddy deposits in the river bed. As expected, (Mayer, 1994; Keil et al., 1997), riverine sediment %OC showed a positive correlation with SA (Fig. 8b), a strong indication of protective organic matter adsorption to mineral surface areas. For coarser, sandy sediments (low SA values), %OC were generally higher than expected for the “monolayer equivalent” (Mayer, 1994), whereas the opposite was true for more clay-rich riverine sediments (higher SA). This would be consistent with a significant fraction of non-bound particulate matter in coarser sediments, while most of the particulate C in fine-grained sediments is more strongly bound to clay minerals. In contrast, soil %OC did not show significant relationship with corresponding SA (Fig. 8b), and the majority of soil samples had %OC values above the monolayer equivalence lines, which is consistent with a contribution from non-bound plant-derived organic matter. The OC : SA ratios for riverine sediments were consistently lower than those of soils with similar SA values, suggesting that riverine OC particles have been subjected to extensive degradation losses. All reservoir sediments and suspended matter samples showed high SA values of $> 60\text{ m}^2\text{ g}^{-1}$, and organic C loadings were always below the monolayer equivalent zone. The observed range of OC : SA values in these suspended matter and reservoir sediment samples (0.14–0.53 and 0.16–0.25 mg OC m^{-2} , respectively) are markedly lower than the range

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previously observed in other large river systems such as the Amazon, Fly, Columbia, and Hung He (typically between 0.25 and 1; see Keil et al., 1997), and fall more in the range of values found in coastal or marine sediments (Aufdenkampe et al., 2007). These low OC : SA values thus suggest a very stable organic C pool which has undergone extensive degradation of the more labile fractions during erosional and riverine transport and retention cycles. The relationship between %POC and TSM followed an inverse relationship as reported for other world rivers (Meybeck, 1982). Two different hypotheses have been proposed to explain this relationship (Thurman, 1985, Ludwig et al., 1996). First, decreasing %POC in suspended matter with increasing TSM concentrations could reflect the variable contribution of the autochthonous C produced by riverine phytoplankton. Secondly, this pattern may reflect mixing between more organic-rich surface soil runoff and/or direct litter contributions, and deeper soil-derived sediments with reduced organic C loading. In our study, the high POC : Chl-*a* ratios (Fig. 4b) strongly favour the second hypothesis. Only for the reservoirs (Kamburu and Masinga) do our data suggest that the elevated %POC is explained by in-situ phytoplankton production. The elevated %POC recorded in headwater tributaries is majorly derived from allochthonous fresh plant materials, while low %POC values recorded in lower main Tana particularly during the wet season are due to dilution by soil mineral particles (from mechanical erosion associated with surface runoff during flash floods during the wet season and bank instability during dry season). During wet season sampling, high amount of terrigenous and lithological materials originating from soil and/or bank erosion, characterized by low organic C content is a dominant characteristic. The %POC relationship from our data fits well with an empirical model based on Ludwig et al. (1996) data in the lower TSM range (up to $\sim 1000 \text{ mg l}^{-1}$), but %OC values are markedly higher than global averages in the higher TSM range ($> 1000 \text{ mg l}^{-1}$). In addition, %POC was generally higher than soil %OC particularly in higher altitude sites due to additional contributions from the riparian vegetation in form of direct litter inputs rich in organic matter. Higher %POC are also likely due from contributions from eroded soil organic matter and top soil detritus.

DOC concentrations in the present study (0.2 to 6.9 mg l⁻¹) are relatively low compared to those reported for other African rivers (range 0.6 to 51.2; Martins, 1983; Seyler et al., 1995; Coynel et al., 2005; Brunet et al., 2009; Spencer et al., 2010) but consistent with average values for rivers crossing semi-arid climates as reported by Spitzky and Leenheer (1991). The altitudinal profiles show contrasting patterns during different seasons: for the dry season, concentrations were consistently low throughout the basin (Bouillon et al., 2009), increased gradually downstream during the wet season (Fig. 5a), or showed consistently higher values in the high-elevation sites (end of wet season, Fig. 5a) in Aberdare and Mt. Kenya headwaters which may be attributed to presence of peatlands and swamps. DOC in high mountain streams are typically much lower than those of other natural waters (Meybeck, 1982; Hedges et al., 2000). However, most of these studies were conducted at higher latitudes where organic-rich peat soils do not occur (Townsend-Small et al., 2005). The generally higher DOC concentrations during wet and end of wet season would be consistent with a terrestrial-derived origin of DOC, which is also most likely given the minimal contribution of phytoplankton to POC pool. DOC : POC ratios were relatively low and ranged from 0.02 in the lower reaches of Tana River main channel to 5.5 in the headwaters. The global average contribution of DOC to the total riverine OC pool is highly variable, ranging between 10 and 90 % (Meybeck, 1982) but recent estimates put global mean DOC contribution at 73 ± 21 %, and 61 ± 30 % for tropical systems (Alvarez-Cobelas et al., 2010). In the Tana basin, DOC typically dominated in the tributaries (59 ± 21 %) while POC dominated in the main Tana River (DOC contribution of 34 ± 23 %), which is typical for highly erosive and turbid systems and in line with the general trend of lower DOC : POC ratios with increasing TSM (Meybeck, 1982; Ittekkot and Laane, 1991; Middelburg and Herman, 2007; Ralison et al., 2008; Bouillon et al., 2009). The $\delta^{13}\text{C}_{\text{DOC}}$ values gradually increase downstream (Fig. 5b), but much less pronounced as what is observed for POC (Fig. 4a). As observed for $\delta^{13}\text{C}_{\text{POC}}$, $\delta^{13}\text{C}$ signatures of DOC in many of the headwater streams of the Aberdares and Mt. Kenya were not as low as expected and suggest an influence of the tussock-forming C4 grass species *Andropogon amethystinus*. The

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weak correlation between $\delta^{13}\text{C}_{\text{DOC}}$ and $\delta^{13}\text{C}_{\text{POC}}$ (Fig. 6a) suggests that the exchange of C between POC and DOC pools is limited.

4.3 Links between terrestrial and aquatic carbon pools

Soil %OC showed a marked altitudinal gradient, with high values in high altitude sites and consistently decrease to low values in sites along the lower Tana River. This altitudinal gradient in soil organic C is in accordance with previous and more large-scale datasets on soil organic C stocks in Kenya (Batjes, 1996, 2004), and is also observed in other large-scale studies such as in the Amazon Basin (e.g., Townsend-Small et al., 2005; Aufdenkampe et al., 2007). A similar gradient was observed in riverine sediment %OC (Fig. 3b). Such gradients are typically explained by the associated temperature gradient, which leads to less efficient soil organic matter degradation in colder, high-altitude regions (Couteaux et al., 2002; Finlay and Kendall, 2007). As expected (e.g., Townsend-Small et al., 2005), both soil and sediment TOC/TN ratios showed an altitudinal gradient, although more pronounced in sediments ($R^2 = 0.25$ and 0.37 , respectively). The stable isotope composition of soil organic matter in principle reflects the isotope signatures of the vegetation. Thus, soil organic matter $\delta^{13}\text{C}$ values of about -27‰ and -13‰ are expected in areas dominated by C3 and C4 plants, respectively (Finlay and Kendall, 2007; Kendall et al., 2001). Although $\delta^{13}\text{C}$ -soil values in the present study do not show systematic patterns with altitude/downstream, the values exhibited the full range of C3 to C4 signatures (-28.5 to -13.2‰) consistent with the variable vegetation patterns within the catchment. The distribution of C3 and C4 grasses in Kenya has been documented by Tieszen et al. (1979), and they found a clear altitudinal shift of a complete C4-dominance below 2000 m to a dominance of C3 grass species above 3000 m. A few notable exceptions, however, occur in this pattern, and particularly relevant here is the occurrence of the tussock-forming C4 grass *A. amethystinus* in the Aberdare range and on Mt. Kenya, even above 3000 m altitude. Similarly, as mentioned in an earlier section, local soils from Aberdares and Mt. Kenya

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sites show a clear C4 influence and so is POC and riverine sediments (see above). The $\delta^{13}\text{C}$ -sediment values (-27.8 to -16.2‰) show a more narrow range of values with less variability than surface soils considering sediments integrate soil inputs from larger areas and so are more mixed than spot samples in soils. This concurs with Bird et al. (1994b) findings from an African tropical system that $\delta^{13}\text{C}$ -sediment values are controlled and/or reflective of the dominant vegetation type present in the river catchment among other factors such as altitude. It should be stressed that estimates of C3 and C4 contributions using soil $\delta^{13}\text{C}$ data refer to C inputs from these 2 vegetation types, and do not necessarily reflect their relative standing biomass, due to potential differences in their relative productivity and degradability of litter. Gillson et al. (2004), for example, demonstrated that soil $\delta^{13}\text{C}$ data in Kenyan mixed C3-C4 savannas significantly underestimated local C3 plant biomass.

The relationship between $\delta^{13}\text{C}_{\text{soil}}$ values and $\delta^{13}\text{C}_{\text{DOC}}$ and $\delta^{13}\text{C}_{\text{POC}}$ values for tributaries (Fig. 6b) shows that DOC and POC in the aquatic system usually have a stronger C3 contribution than soils in the subcatchments (with the obvious caveat that our soil samples are not necessarily representative of the entire subcatchment). Organic matter in some of the tributaries also appears to be derived from direct litter inputs, given the higher %OC than observed in soils.

5 Conclusions

Generally, suspended sediment and POC delivery in Tana River was highest during high-flow conditions, with the majority of the suspended load being generated in the lower section of the Tana River. We propose that river bank erosion, coupled with sediment pulses from ephemeral streams form the main sources of these high TSM loads. Thus, the cascade of reservoirs on the Tana River at mid-altitude appear to be very efficient traps for suspended material from high-altitude regions, but also result in a disequilibrium in the lower course of the river, with increased sediment mobilisation downstream. The $\delta^{13}\text{C}$ values constrained from bulk C organic measurements

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show that C3 derived organic matter dominates the riverine DOC and POC pools, with important C4 contributions mainly in the high-altitude regions and in the lower Tana. The generally high POC:Chl-*a* ratios suggest there is a negligible contribution from in-stream phytoplankton production except in Kamburu and Masinga reservoirs. $\delta^{13}\text{C}$ values from sediments in Masinga and Kamburu reservoirs do not reflect phytoplankton production but rather selective retention of the C4 fraction of the organic matter.

Supplement material related to this article is available online at:
[http://www.biogeosciences-discuss.net/9/2523/2012/
bgd-9-2523-2012-supplement.pdf](http://www.biogeosciences-discuss.net/9/2523/2012/bgd-9-2523-2012-supplement.pdf).

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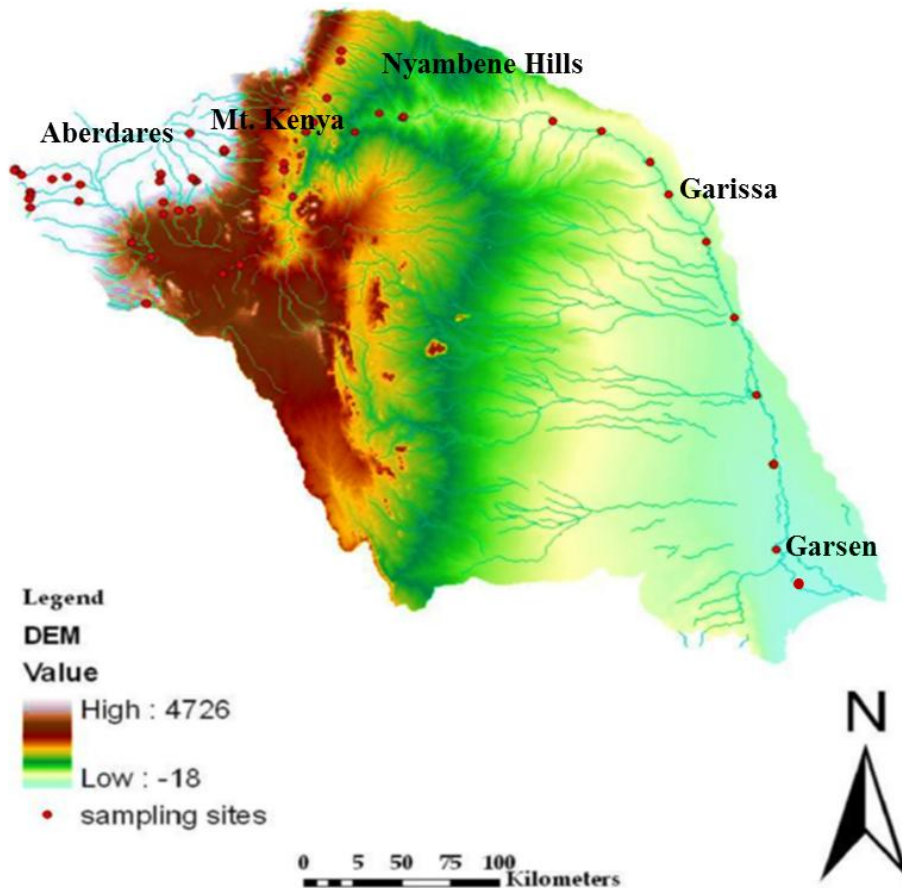


Fig. 1. Digital Elevation Model (DEM) of Tana River Basin, which consists of two main geographical units, the Tana headwaters and the main lower Tana. The 57 sampling sites are indicated by red dots.

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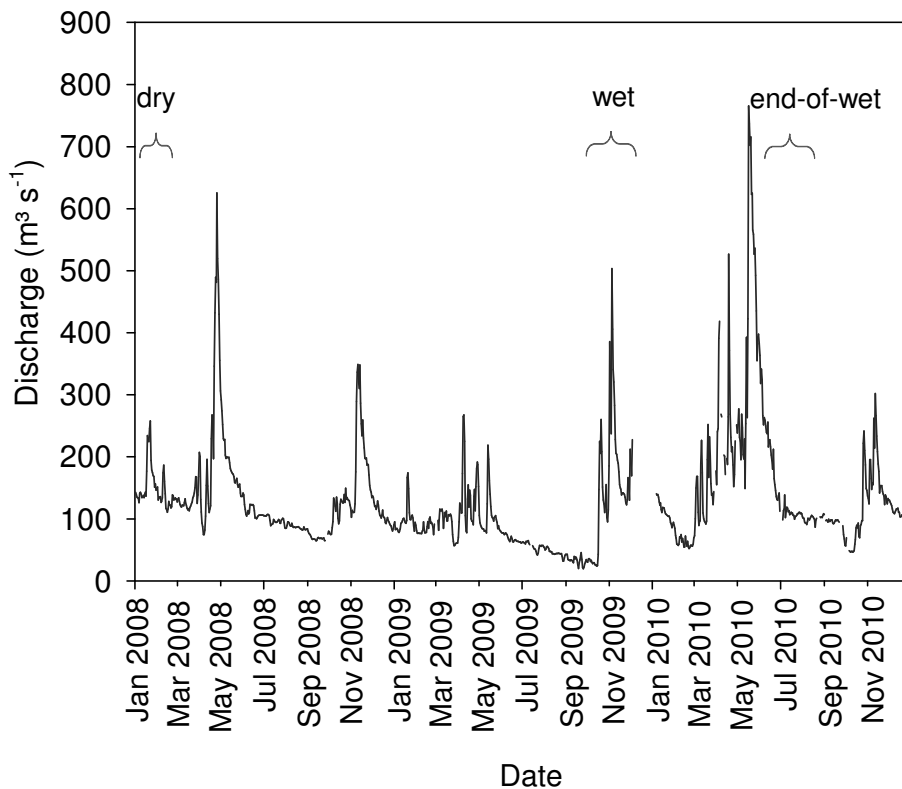


Fig. 2. Discharge measurements for the Tana River (2008–2010) as recorded at Garissa station. (Data source: Water Resource Management Authority.) Brace brackets indicate the duration of the three field investigations.

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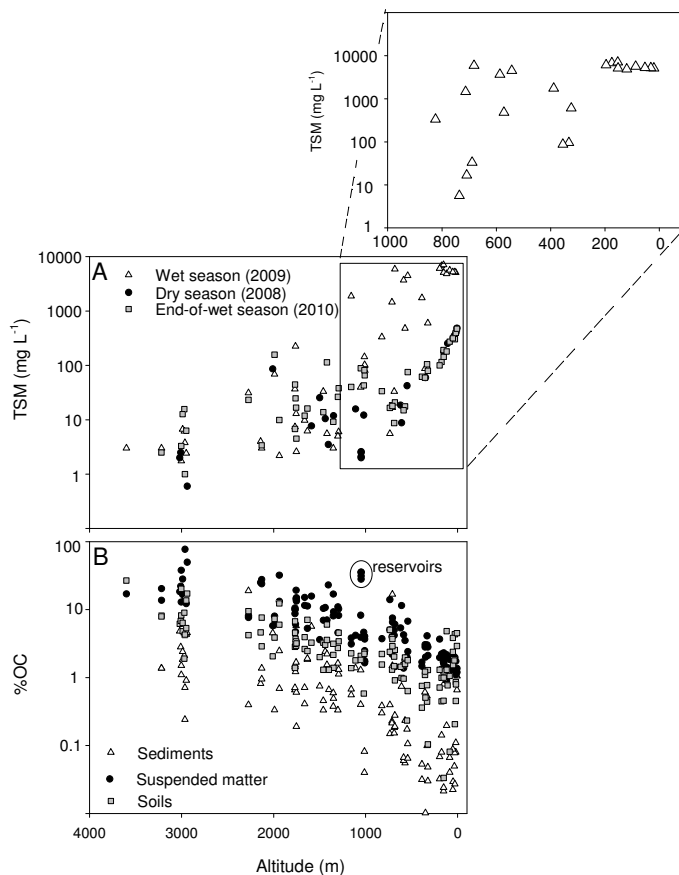


Fig. 3. Altitudinal profiles of **(A)** total suspended matter concentrations, and **(B)** %OC in suspended matter, soils and sediments along Tana River Basin during three sampling seasons. For panel **(B)**, data from the different sampling seasons were combined.

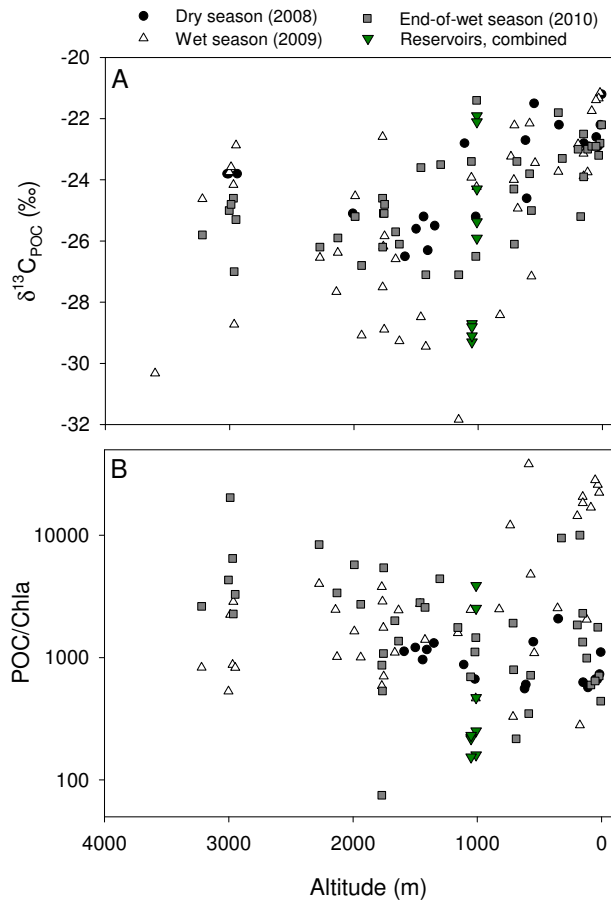


Fig. 4. Altitudinal profile of **(A)** $\delta^{13}C_{POC}$ and **(B)** POC/Chl-*a* ratios along Tana River Basin during three sampling seasons.

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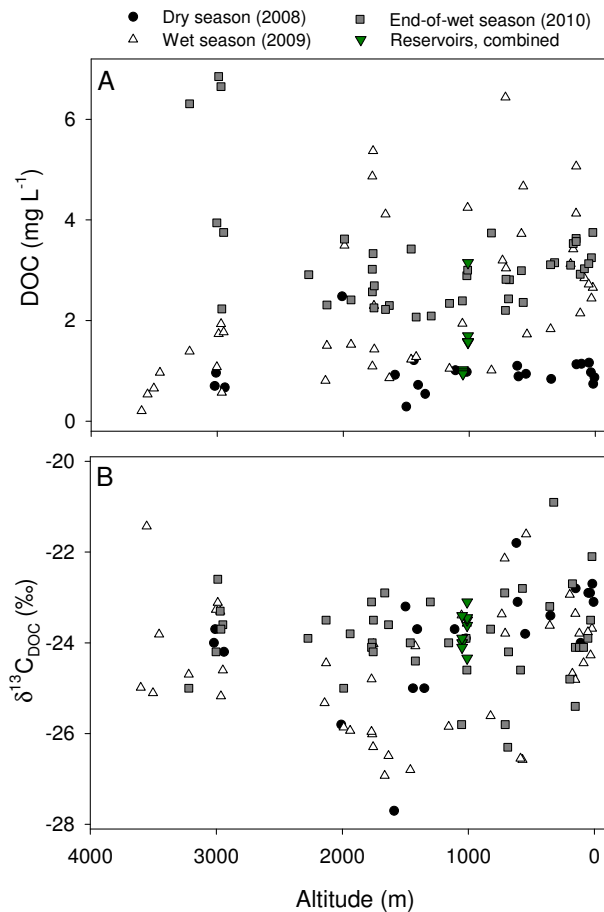


Fig. 5. Altitudinal profile of **(A)** DOC concentration, and **(B)** $\delta^{13}\text{C}_{\text{DOC}}$ along Tana River Basin during three sampling seasons.

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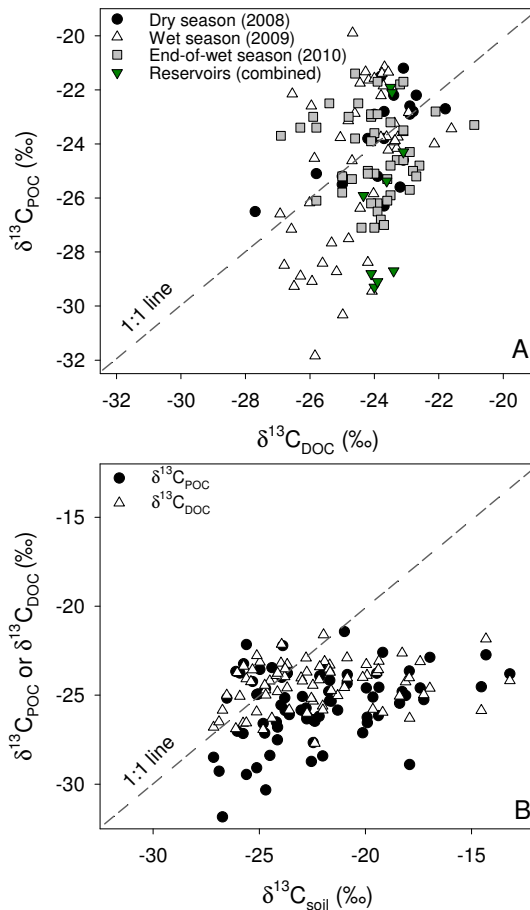


Fig. 6. Plots of **(A)** $\delta^{13}\text{C}_{\text{POC}}$ vs. $\delta^{13}\text{C}_{\text{DOC}}$ along Tana River Basin, **(B)** $\delta^{13}\text{C}_{\text{soil}}$ vs. $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{13}\text{C}_{\text{DOC}}$ for tributaries along Tana River Basin (i.e., mainstream data not included in panel **(B)**).

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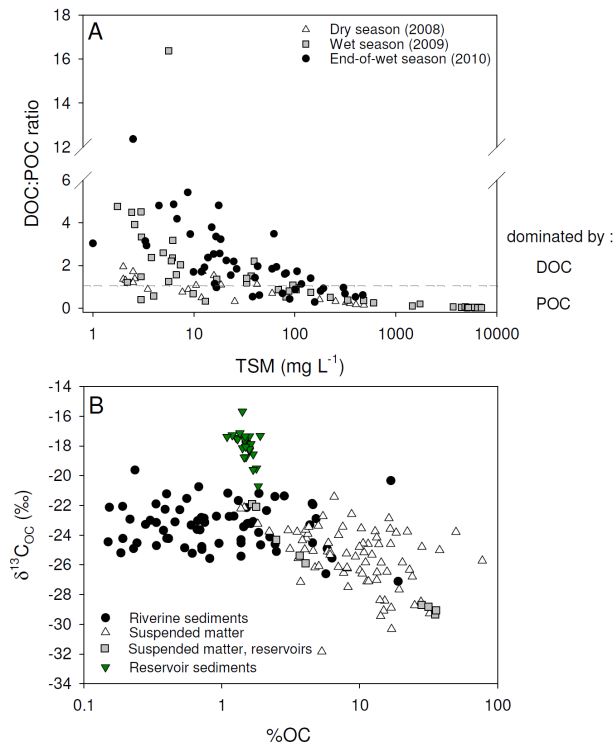


Fig. 7. Relation between **(A)** DOC : POC ratio vs. TSM along Tana River Basin, **(B)** %TOC vs. $\delta^{13}\text{C}_{\text{TOC}}$ for tributaries upstream of Masinga reservoir.

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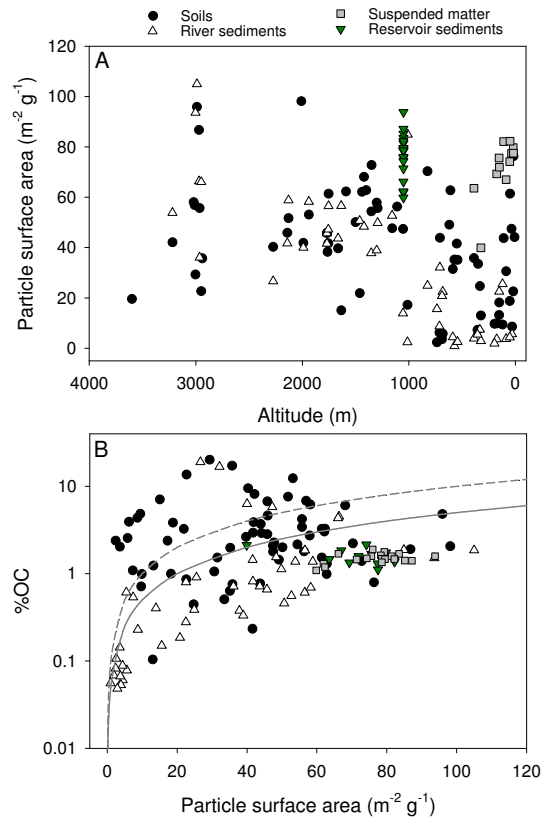


Fig. 8. Profile of (A) altitude vs. SA, (B) SA vs. %OC of soil, sediment and suspended matter along Tana River Basin during three sampling seasons. Dashed lines bound the monolayer equivalent lines; region of organic carbon to surface area ratios (OC : SA) of 0.5–1.0 mg OC m^{-2} SA.

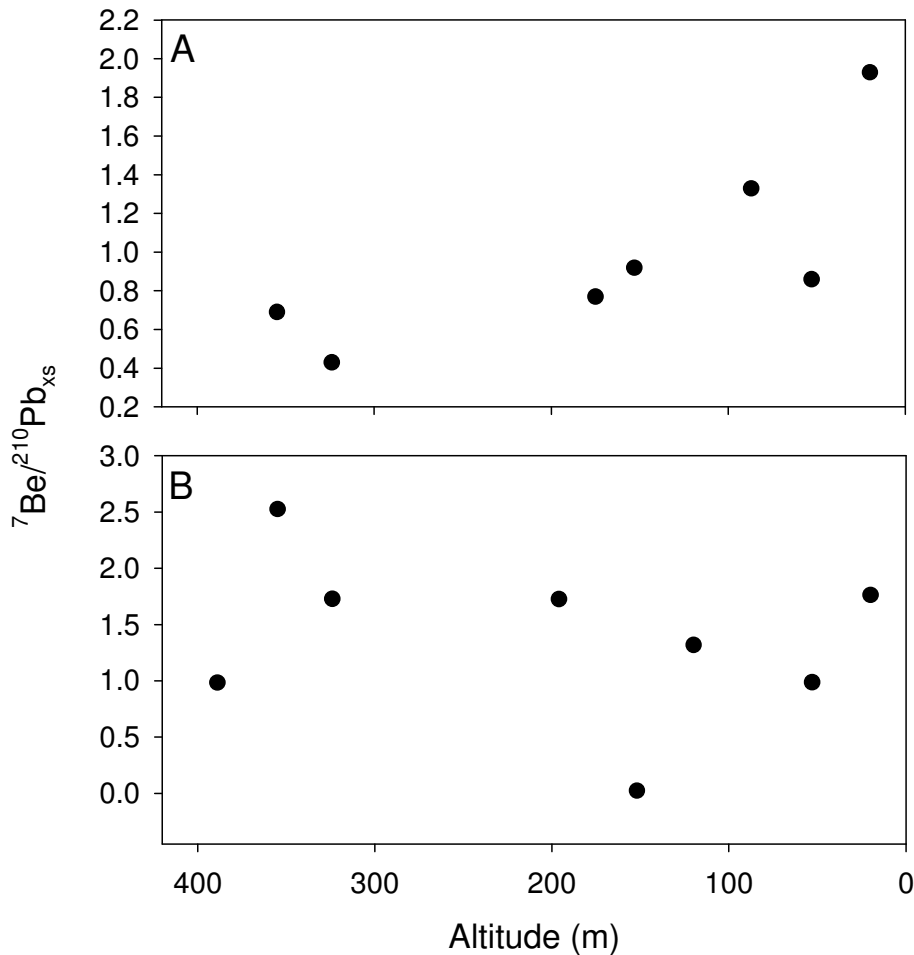


Fig. 10. Variations of ${}^7\text{Be}/{}^{210}\text{Pb}_{\text{xs}}$ ratios in suspended matter along the lower Tana River during **(A)** wet season, and **(B)**, end of wet season.

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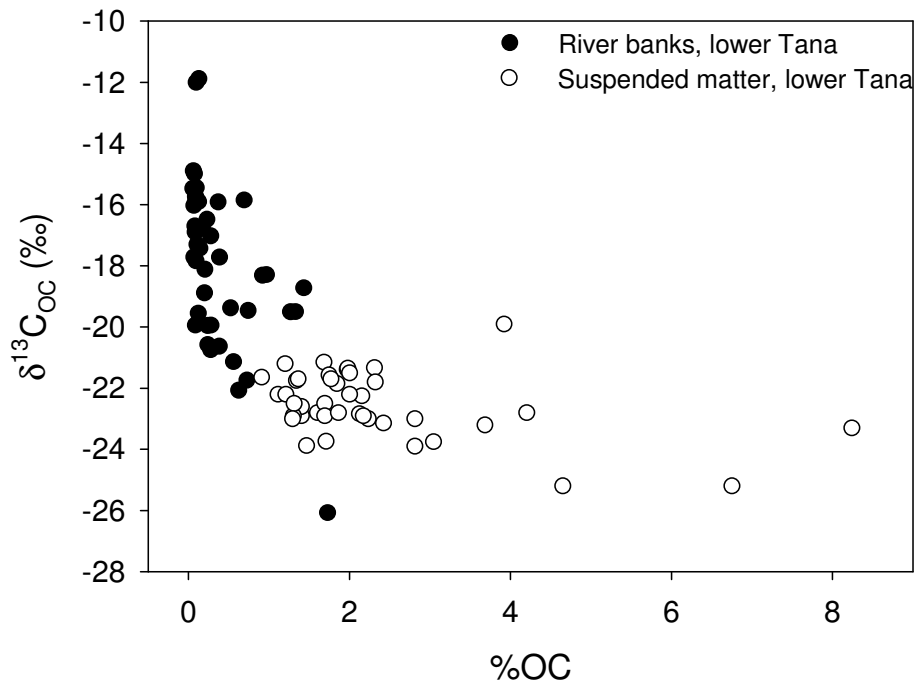


Fig. 11. Comparison of %OC and $\delta^{13}\text{C}$ signatures for bank sediments (black symbols) and riverine POC (grey symbols) from the lower Tana River.

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