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Fluvial organic carbon losses from a Bornean blackwater river

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Abstract

The transport of carbon from terrestrial ecosystems such as peatlands into rivers and out to the oceans plays an important role in the carbon cycle because it provides a link between the terrestrial and marine carbon cycles. Concentrations of dissolved organic carbon (DOC) and particulate organic carbon (POC) were analysed from the source to the mouth of the River Sebangau in Central Kalimantan, Indonesia during the dry and wet seasons in 2008/2009 and an annual total organic carbon (TOC) flux estimated. DOC concentrations were higher and POC concentrations lower in the wet season compared to the dry season. As seen in other tropical blackwater rivers, DOC concentration is consistently around 10 times greater than POC concentration. We estimate the annual TOC flux discharged to the Java Sea to be 0.46 Tg year^{-1} comprising of 93% (0.43 Tg) DOC and 7% (0.03 Tg) POC. This equates to a fluvial TOC loss flux per unit area over the entire Sebangau catchment of 88 g C m^{-2} yr^{-1}. When extrapolating this TOC loss flux to the peat covered area of Indonesia (206 950 km^2), we estimate a TOC loss of 18.2 Tg C yr^{-1} or ~10% of current estimates of the global annual riverine DOC discharge into the ocean.

1 Introduction

The transport of carbon from terrestrial ecosystems such as peatlands into rivers and out to the oceans plays an important role in the carbon cycle because it provides a link between the terrestrial and marine carbon cycles (Meybeck, 1993). It is not yet known how much of the fluvial organic carbon that is lost from peatlands is converted into carbon dioxide and/or methane and lost to the atmosphere (i.e. processes that would further link the terrestrial and marine carbon cycles with the atmosphere) nor do we fully understand the quantity of carbon that remains climatically neutral through benthic deposition and storage as riverine and estuarine sediments. In terms of a global riverine flux of carbon, it is estimated that 1000 teragrams (Tg) (1 Tg = 10^9 kg) of carbon is discharged into the world's oceans each year (Ludwig et al., 1996). Of this carbon, approximately 60% is comprised of inorganic carbon and 40% is organic carbon (Meybeck 1993; Probst et al., 1994). For most rivers a greater proportion of carbon is lost to the oceans in inorganic forms (Meybeck 1982), however, it is believed that in tropical peat-swamp forest catchments, fluvial carbon fluxes to the oceans are dominated by organic forms. Two commonly accepted estimates put the annual figure of organic carbon discharged to oceans as somewhere between 330 and 370 Tg (Degens et al., 1991; Meybeck 1993).

Riverine "total organic carbon" (TOC) is made up of two components; dissolved organic carbon (DOC) and particulate organic carbon (POC). The distinction between these two components is generally made on the basis of whether or not material passes through a 0.45 µm filter; i.e. DOC will pass through as filtrate and POC will be retained by a filter of this pore size (Thurman, 1985). Additional subdivisions can be made within these two components as they are made up of a continuous spectrum of different sized molecules. Fulvic and humic acids comprise about 50–75% of DOC and colloidal organic matter is the other main constituent comprising around 20% (Hope et al., 1994). Humic acids are responsible for the dark colour of blackwater rivers. POC consists mainly of plant litter and soil organic matter and can also be subdivided according to size; coarse (> 1 mm), fine (1 mm–53 µm), and very fine (53 µm–0.45 µm) (Naiman et al., 1987).

Globally, POC fluxes comprise approximately 10% of TOC fluxes, although for individual rivers the POC/DOC ratio is subject to large variation being dependent upon a number of variables such as catchment ecosystem type, river size and velocity. In most wetland ecosystems nearly 100% of TOC is exported as DOC (Hope et al., 1994). According to various modelling estimates (Ludwig et al., 1996; Harrison et al., 2005), the global river-to-ocean DOC flux is currently thought to be around 170–250 Tg C yr^{-1}. Indonesian rivers account for approximately 11% (4.26×10^{12} m^3 yr^{-1}) of global freshwater discharge into the oceans (Syvitski et al., 2005) and are considered to be large contributors of DOC. This is primarily due to high precipitation rates and large surface

areas that are covered in peatlands (206 950 km^2) (Page et al., 2010), which are known to be an important source of riverine DOC (Hope et al., 1997; Aitkenhead and McDowell 2000). In a recent study, Baum et al. (2007) used data collected from the River Siak, a blackwater river in Sumatra to estimate a mean DOC flux of 0.32 Tg C yr^{-1} for the Siak catchment alone. This estimate was then extrapolated to the entire land area of Indonesia (~1.9×10^6 km^2), taking into account the percentage peat area cover, and the total fluvial DOC discharge was estimated to be 21 Tg yr^{-1}. According to Baum et al.'s extrapolated estimate and the current global modelling estimates (170–250 Tg yr^{-1}), Indonesian rivers account for approximately 10% of the global riverine DOC discharge into the ocean.

The value of this extrapolated estimate is, however, reduced by the limited availability of fluvial carbon data for other rivers in the region. Here we seek to remedy this deficiency by reporting data from an additional Indonesian blackwater river, the River Sebangau, in Central Kalimantan. Our study aims to quantify organic carbon dynamics in this river from the source (150 km inland) to the mouth where it discharges into the Java Sea.

2 Methods

2.1 Study site

The Sebangau River catchment lies in the southern part of Central Kalimantan, Indonesia. Central Kalimantan lies within the inter-tropical convergence zone (ITCZ) and experiences a tropical-monsoonal climate. The temperature remains relatively constant throughout the year (25–27 °C) and annual rainfall averages 2700 mm yr^{-1} (Page et al., 2004). Thirty years of rainfall records from Central Kalimantan indicate that there is approximately 9 months of wet season and 3 months of dry season each year (with dry months defined as periods of moisture deficit, i.e. when evapotranspiration exceeds rainfall) (Hooijer et al., 2008). The Sebangau catchment lies between the

River Katingan to the west and the River Kahayan to the east and has a total land area of approximately 5200 km^2 (Fig. 1). Kya, the source of the River Sebangau is approximately 20 km west of Palangka Raya, the provincial capital of Central Kalimantan. Almost the entire catchment is composed of peatland resulting in a high concentration of humic substances in the water, giving the River Sebangau water it's characteristically reddish-brown colour and a background pH of 3.5–4.0 (Haraguchi, 2007). To the west of the northern stretches of the Sebangau River lies the Sebangau National Park which contains some of the last remaining relatively undisturbed Peat Swamp Forest (PSF) in Kalimantan (Page et al., 1999). These forests have been subject to selective, commercial logging prior to 1996 and subsequently small-scale illegal logging activities but they retain a closed canopy and remain relatively unaffected by human activity when compared with adjacent areas to the east of the River Sebangau. The area of land to the west of the southern stretches of the Sebangau is a transmigration settlement area which experienced deforestation and land-use change in the 1970s through to the 1990s. The catchment area to the east of the entire stretch of the Sebangau River is referred to as "Block C" of the Ex-Mega Rice Project (EMRP). The EMRP was a one million hectare peat reclamation project which began in 1995 with the aim of establishing new rice fields to meet the country's demand for self-sufficiency in rice production. Converting these peatlands into land suitable for agriculture involved clearing the land of natural forest and creating approximately 6000 km of drainage canals in order to artificially control the water table levels (Radjagukguk, 1992). This land drainage has subsequently led to fires during the dry season which burn remaining forest stands as well as the upper layers of peat (Page et al., 2002). A combination of peatland drainage and the resulting fires has caused the irreversible shrinkage and subsidence of the peat dome in Block C and a much changed and degraded ecosystem (Wösten and Ritzema 2007; Ballhorn et al., 2009; Page et al., 2009).

There are seven channels that drain the western side of the catchment into the River Sebangau (Fig. 1). In order from source to mouth, these channels are called the Bakung, Rasau, Mangkoh, Bangah, Paduran I, Paduran II and Sampang. There

are also seven channels that drain the eastern side of the catchment into the River Sebangau and these are, in order from source to mouth, the Kalampangan, Garong, Tlalau, Buntol, Pankoh, Sampang and Lumpur. The maximum tidal range at the mouth of the River Sebangau is ~3 m (The United Kingdom Hydrographic Office, 2008). This is a relatively small range, however, due to the low-lying nature of the Sebangau catchment this has the potential to affect the river system over large distances inland.

2.2 Sample collection

Sampling was carried out on two separate occasions; the dry season in September 2008 (high-tide) and the subsequent wet season in March 2009 (low-tide). River water samples were collected from the main channel of the Sebangau at 3 km intervals from the mouth to the source, 150 km inland (a total of 50 samples). Baum et al. (2007) report horizontal and vertical DOC variability in a blackwater river in Sumatra to be ± 5% and ± 3% respectively, due to well mixed water. Accordingly, all samples were collected from the centre of the River Sebangau at a depth of 50 cm. Five replicate samples were collected from within each of the fourteen channels that drain into the River Sebangau (Fig. 1). The cross-sectional area and five replicate flow rate measurements were also taken and used to calculate the discharge rates for each of the fourteen channels.

Samples were collected in pre-rinsed 60 ml Nalgene bottles and the position of each sample point was recorded using a GPS (Garmin, eTrex Venture). Water temperature, pH and electrical conductivity (EC) were recorded immediately after collection using portable pH (Hanna HI9024D) and EC (Hanna HI8633) meters.

2.3 Sample preparation and analysis

To derive POC concentration, a known volume of river water was filtered using 0.45 µm cellulose acetate membrane filters (Whatman) under partial vacuum (hand-held vacuum pump, Mityvac, Nalgene). The residue and filter were retained and oven dried

(2 h at 80 °C) to quantify particulate matter which is assumed to be equal to particulate organic matter (POM) (given the dominance of peat soil in the catchment). POM was then converted to a POC value by assuming organic matter to be 50% carbon (Hope et al., 1994). Samples of filtrate were acidified to pH 2.0 using a solution of dilute sulphuric acid (20%). The samples were then stored at 2–5 °C and analysed after the samples were returned to the Open University. DOC was determined using a Total Organic Carboniser (Shimadzu, TOC-V_{CPN}). DOC/POC concentrations were then combined with discharge rates to calculate the TOC flux from each of the channels. The same method was used to establish the total DOC/POC flux into the Java Sea.

3 Results

3.1 DOC

DOC comprises 88% and 94% of TOC in the dry and wet seasons, respectively. DOC concentrations within the River Sebangau fluctuate from source to mouth (Fig. 3). In both seasons, as expected, the DOC concentration is lower at the river mouth than at the source (Fig. 3). DOC concentration remains relatively constant for the first 100 km from the source but then decreases as the water enters the last 50 km of the river before discharging into the Java Sea. In the wet season, concentrations averaged 51.8 mg l^{-1} for the first 100 km of the river and 44.1 mg l^{-1} during the dry season over the same stretch. Concentrations of DOC tended to decrease beyond this point to 28.2 mg l^{-1} and 35.3 mg l^{-1} in the last 50 km of the river in the dry and wet seasons, respectively.

Differences between the two sampling runs are partly attributable to differences in tidal conditions; dry season sampling was undertaken at high tide, and some influence of sea-water (defined as electrical conductivity (EC) > 200 µS cm^{-1}) was observed in samples collected below 126 km from the source. Dry season samples above and below this point were therefore analysed separately. In the wet season, sampling was undertaken at low tide, and all samples had conductivity < 110 µS cm^{-1}, implying that

all samples contained freshwater. All wet season samples were therefore analysed together. Figures 2a, c show that from 0–126 km from the source, the river follows a similar transition in both seasons; from stable (high DOC, low EC) peat-derived water (0–90 km) through to a more peat/mineral-derived mix of water with a higher EC and lower DOC concentration further downstream. In the dry season, below 126 km from the source, the river water becomes progressively mixed with seawater, raising the EC and lowering DOC concentrations. The EC/DOC relationship 126–150 km from source (Fig. 2b) is not linear, and therefore cannot be explained by conservative mixing. The non-linear relationship observed (polynomial 2nd order; $r^2 = 0.99$) within a stretch of the river without major tributary inputs, suggests that some form of DOC removal is also taking place. Percent estuarine DOC removal at high tide (dry season) was estimated by extrapolating linear regressions between DOC and EC for samples collected at the lower end of the estuary, following the method of Spencer et al. (2007). This method permits an estimate of the DOC concentration of a freshwater end-member, assuming conservative mixing, with the difference between this estimate and the observed DOC concentration of the last freshwater sample (EC< 200 µS) providing an indication of the amount of DOC removal that has occurred within the estuary. Linear regression lines were derived using the last three samples at the seaward end of the estuary (150–144 km) and for the last four samples (150–141 km). These suggested a removal of DOC in the Sebangau estuary of 27% and 12% respectively. It therefore appears that significant DOC processing is occurring in the estuary, reducing the flux into the ocean. This implies that the C flux measured from the river mouth, at least during the dry season high-tide sampling, is a conservative estimate when compared to the actual C loss from the peat itself.

3.2 POC

POC comprises 12% and 6% of TOC in the dry and wet seasons, respectively. Figure 4 shows that despite varying concentrations and high spatial variability, POC follows a similar trend in both the dry and wet seasons; a decrease in concentration from source

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to mouth. Across both seasons, average POC concentrations 0–25 km from the source are ~4 times higher than POC concentrations 125–150 km from the source. This difference is most pronounced in the wet season when the average POC concentration is 6.7 times greater 0–25 km from the source (4.76 mg l^{-1}) than at 125–150 km from the source (0.71 mg l^{-1}).

The large within-river variability seen across both seasons can be attributed to the influence of the fourteen channels that discharge into the River Sebangau. The positioning of these discharge points is represented in Fig. 3 by vertical lines, and the "inputs" denote the POC concentration of the channel prior to discharge into the River Sebangau. For example, in the dry season, River Paduran I (channel 9) is discharging water with a high POC concentration (6.7 mg l^{-1}) relative to the River Sebangau. The effect of this POC input is seen in the next sample point immediately downstream. The influence of these inputs on the River Sebangau is also dependent upon the actual discharge rate. For example, in the wet season, a high POC concentration (relative to the River Sebangau) of 4.3 mg l^{-1} from the Pankoh channel (channel 10) has no influence on POC concentrations in the River Sebangau. This is because the discharge rate of this canal is so low that the overall POC flux is too small (Table 1) to have any effect on the concentration of the sample taken immediately downstream in the river.

3.3 Dry season vs. wet season

Most tropical regions only have two seasons; a wet season and a dry season with less rainfall, with the temperature staying relatively constant throughout the two seasons. This monsoonal climate is highly favourable for plant growth and results in large quantities of organic material being washed into rivers year round. As a result, DOC concentrations should be relatively constant throughout the year, without evidence of the summer/autumnal peak that is commonly reported in temperate regions owing to maximum ecosystem productivity or autumn leaf fall (Wetzel and Manny, 1977; Naiman and Sibert, 1978; Skiba and Cresser, 1991). Our results show, however, that the mean DOC concentration in the wet season (46 mg l^{-1}) is higher than in the dry season

(39 mg l^{-1}). Conversely, average POC concentrations are higher in the dry season (5.2 mg l^{-1}) compared to the wet season (2.7 mg l^{-1}). In temperate ecosystems the main control on POC concentrations is reported to be storm events (Gurtz et al., 1980; Naiman, 1982) and large quantities of POC can be exported over relatively short periods of time. For example, Crisp and Robson (1979) found that 80% of the annual particulate organic matter exported from a small Pennine stream occurred in less than 3% of the total year. Compared to highland temperate regions, however, such isolated, one-off storm events are uncommon in a peatland catchment with a tropical monsoonal climate. Due to the hydrological buffering effect of peatlands, run-off is a slow process and therefore rapid changes in riverine discharge are uncommon. Lower water tables during the dry season result in a larger area of peat drying out compared to the wet season. This drying of peat and the resulting increased rate of aerobic decomposition leads to increased amounts of POC being released during the dry season.

3.4 TOC export to the Java Sea

In order to estimate the TOC flux from the River Sebangau into the Java Sea, the mean DOC and POC concentrations of five samples collected across the width of the mouth of the river were multiplied by the mean flow rates measured at those sampling points. In the dry season, the DOC and POC fluxes are 0.00067 Tg day^{-1} and 0.00015 Tg day^{-1}, respectively. In the wet season the DOC flux is double at 0.00134 Tg day^{-1} but the POC flux is less than half at 0.00006 Tg day^{-1}. In order to convert these seasonal data into annual fluxes, Central Kalimantan average seasonal climate patterns were used which consist of three months (90 days) dry season and nine months (275 days) wet season (Hooijer et al., 2008). Using the 3:9 ("dry month: wet month") ratio, the TOC flux is estimated to be 0.46 Tg C $year^{-1}$, with 93% (0.43 Tg) comprising DOC and 7% (0.03 Tg) comprising POC. If there are any inorganic particulates present, the POC fraction may be a slight overestimate (see POC methods), however as this is a small portion of the TOC, it would not alter the overall flux considerably.

In 2004, Baum et al. (2007) conducted a similar study on the River Siak which drains part of the province of Riau in Sumatra, Indonesia. They estimated the DOC flux into the ocean to be 0.3 ± 0.03 Tg year^{-1}. This figure places the River Siak at number 17 on the ranking list of DOC exports of major global rivers (Ludwig et al., 1996). Baum et al. (2007) did not determine POC flux and therefore the TOC flux cannot be estimated. They also used dry and wet season data with an even balance between the two to work out mean monthly DOC fluxes due to slightly different climate patterns in Sumatra (the meridional migration of the Intertropical Convergence Zone). In Sumatra there is generally 6 months of dry season and 6 months of wet season (6:6 "dry month: wet month" ratio as opposed to 3:9 in Kalimantan). Using the respective climate ratios, the data imply that the River Sebangau discharges approximately ∼50% more DOC to the ocean per annum than the River Siak.

4 Discussion

In our catchment scale study of fluvial organic carbon dynamics along the course of an Indonesian blackwater river, the observed trends can be explained through a combination of tributary inputs and in-stream processes. These are discussed in turn for DOC and POC and then inter-seasonal differences are considered. Flux estimates for the Sebangau basin are applied to the whole of the peat covered area of Indonesia to derive a regional estimate of the fluvial organic carbon flux.

4.1 DOC

In this fluvial carbon size fraction, the changes between 0–126 km from the source can be explained by simple mixing, with tributaries of different composition entering the river. For example, it is clear from Fig. 3 that in the wet season, tributary number 11 (Paduran II) is low in DOC and the discharge large enough in size to reduce the main channel DOC concentration post tributary discharge. An alternative, or additional,

explanation for changes in DOC concentration is the result of in-stream processes such as microbial respiration and oxidation which results in DOC removal and appears to be a significant biotic mechanism in blackwater rivers (Meyer 1986). Several studies have shown that in-stream production of DOC (for example from POC degradation) is small in comparison to that which is derived from terrestrial sources (e.g. Worrall et al., 2007). In the dry season, below 126 km from the source, the most likely DOC removal mechanism is via flocculation to become POC or adsorption to existing POC or mineral particles, resulting from decreased DOC solubility with increasing salinity (Battin et al., 2008). Studies of DOC transport through estuaries in temperate regions have shown varied evidence of conservative and non-conservative mixing in different systems (e.g. Spencer et al., 2007). Similarly, the only previous study of an Indonesian blackwater river (Baum et al., 2007) reported a linear relationship ($r^2 = 0.97$) between salinity and DOC concentration in the Siak estuary, suggesting conservative mixing during the period of observation.

4.2 POC

The movement of POC through river systems is very different to that of DOC. POC is subject to gravitational settling, hydrodynamic lift and drag forces which result in transport occurring as a series of discrete movements (Battin et al., 2008). This accounts for the larger in-stream variability and fluctuation of POC concentration down the river. The most likely cause for the overall decrease in POC concentration from source to mouth is gravitational settling onto the benthic layer of the river bed. River flow rates determine the proportion of the POC that is carried as suspended sediment within the water column and how much settles onto the river bed. When flow rates drop below a threshold value (variable depending on the river system), particulates accumulate on the river bed, while at flow rates above the critical value particulates are re-suspended and transported downstream (Wainwright et al., 1992). The source of the River Sebangau is 150 km inland, yet only 12 m a.s.l. Averaged over the entire course of the river, there is, therefore, only a 1 m change in elevation for every 12.5 km of river length.

Such a low gradient leads to low water velocities throughout the river. The velocity at the source is considerably higher than at the mouth in both seasons, varying from $0.49\,\mathrm{m\,s^{-1}}$ to $0.57\,\mathrm{m\,s^{-1}}$ at the source and dropping to $0.12\,\mathrm{m\,s^{-1}}$ and $0.15\,\mathrm{m\,s^{-1}}$ at the river mouth during the dry and wet seasons respectively. It is likely, therefore, that higher flow rates in the upper reaches of the river suspend more particulates which result in higher recorded POC concentrations. Similarly, lower flow rates towards the mouth of the river result in more benthic accumulation of POC and less POC in the water column. It may therefore be the case that there is no regular overall loss of POC from the river system, but instead a relocation of the suspended POC in the more turbulent upper reaches of the river to the river bed through deposition due to slower flowing water in the lower reaches of the river. If this is the case, then it is likely that there is episodic re-suspension of organic sediment during high flows which transport a pulse of POC into the ocean. This repositioning is possible, given the extensive interchange that occurs between the suspended and deposited POC fractions along the course of a river (Minshall et al., 1983).

Another explanation for decreasing POC concentrations along the course of the river is that there is a loss in total POC as a result of in-stream biological processes. Although very little research on invertebrate communities in PSF ecosystems has been conducted (Wells and Yule, 2008) and in particular, no biotic assessment of the River Sebangau has ever been carried out, it is known that blackwater rivers in Kalimantan contain a large number of fungal and bacterial communities, the former best suited to degrading particulates and the latter to consuming smaller molecules released during fungal metabolism (MacKinnon 1996; Dudgeon, 2000). It is therefore possible that some form of biological POC degradation occurs, as is reported from temperate streams (Monaghan et al., 2001).

4.3 Dry season vs. wet season

The effect that an increased flow rate (frequently due to increased rainfall) has on DOC concentration is still unclear and can differ according to ecosystem type. In peatlands,

which are typically permanently waterlogged, throughflow at both high and low water levels is through an organic layer which has been shown to result in a negative relationship between stream flow and DOC concentration due to the dilution effect (Clark et al., 2007; Schiff et al., 1998). The relationship in this study shows the opposite and may be attributed to the 'flushing effect' whereby water with a high DOC concentration (due to long residence time in the soil/peat layer throughout the dry season) is washed into the rivers by the rising water level during the onset of the wet season (Pearce et al., 1986; Hornberger et al., 1994). A strong positive correlation between DOC concentration and discharge was also reported from the Congo basin which comprises evergreen forest, savannah and swamp forest (Coynel et al., 2005). The "flushing" process is enhanced when the previously dry or stagnant upper limits of the river bed/bank are inundated with large amounts of water as discharge rates increase (Casey and Farr, 1982).

Our data suggest that the River Sebangau is a major contributor of organic carbon to the ocean. DOC concentrations in the River Sebangau are amongst the highest ever recorded, exceeding most others reported for other tropical rivers as well as all of the "world rivers" mentioned by Ludwig et al. (1996). The high DOC concentrations can be attributed to the large expanse of peatlands within the Sebangau catchment, thus supporting the general assumption that soil carbon is a major source of DOC in river waters (Hope et al., 1997; Aitkenhead and McDowell 2000). Soil carbon is also thought to be the main source of riverine POC (Hedges et al., 1986). POC concentrations are generally only a tenth of the DOC concentrations largely because of the low topography in the Sebangau catchment which results in slower runoff and a likely depositional environment throughout the river's course. Differences in DOC and POC concentrations occur between dry and wet seasons, but the most pronounced interseasonal differences are between DOC and POC fluxes because these take into account discharge which is strongly correlated with precipitation. TOC flux from the river to the ocean was nearly twice as large during the wet season, despite there being considerably higher POC concentrations in the dry season.

We estimate the TOC flux from the River Sebangau to the Java Sea to be 0.46 Tg year^{-1}, comprised of 93% (0.43 Tg) DOC and 7% (0.03 Tg) POC. This equates to a fluvial TOC flux per unit area over the whole catchment (5200 km^2) of 88 g C m^{-2} yr^{-1}, a figure which far exceeds those reported for northern peatlands (10-30 g C m^{-2} yr^{-1}; Billett et al., 2004; Koehler et al., 2009). The entire land area of Indonesia is ~1.9×10^6 km^2 of which over 10% (206 950 km^2) is covered by peat soils (Page et al., 2010). On extrapolating the Sebangau catchment TOC flux to the total peat covered area of Indonesia we estimate a TOC loss of 18.2 Tg C yr^{-1}. This result approximates that of the Baum et al. (2007) estimate based on the River Siak and therefore provides some validation to the conclusion that Indonesian rivers account for approximately 10% of the global annual riverine DOC discharge into the ocean.

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Table 1. DOC, POC and TOC concentrations (± s.e.) and fluxes (s.e.<1%) from the confluences of 14 channels that discharge into the River Sebangau, during the dry and the wet season in 2008/09. The row titled River Sebangau represents concentrations and fluxes from the River Sebangau to the Java Sea.

Number on graph	Channel	Distance from river source (km)	DOC conc (mg/l)		DOC flux (kg×10^3/day)		POC Conc (mg/l)		POC flux (kg×10^3/day)		TOC Conc (mg/l)		TOC flux (kg×10^3/day)	
			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1	Kalampangan	13.8	50.3 ± 0.3	55.3 ± 0.2	0.1	5.3	4.0 ± 0.2	1.8 ± 0.1	0.1	0.2	54.4 ± 0.5	57.1 ± 0.3	1.0	5.4
2	Bakung	19.5	54.5 ± 0.2	53.8 ± 0.3	12.6	25.6	4.9 ± 0.1	0.7 ± 0.1	1.1	0.3	59.4 ± 0.3	54.5 ± 0.3	13.8	25.9
3	Rasau	31.0	52.0 ± 0.1	52.3 ± 0.2	19.8	40.8	7.6 ± 0.2	4.2 ± 0.4	2.9	3.3	59.6 ± 0.3	56.4 ± 0.6	22.7	44.1
4	Mangkoh	46.5	dna	51.5 ± 0.2	dna	35.2	dna	2.5 ± 0.5	dna	1.7	dna	54.0 ± 0.7	dna	36.9
5	Garong	52.8	37.3 ± 0.3	51.2 ± 0.1	2.4	23.9	4.7 ± 0.3	0.7 ± 0.1	0.3	0.3	41.9 ± 0.6	51.9 ± 0.2	2.7	24.2
6	Tlalau	58.1	46.0 ± 0.3	52.3 ± 0.4	0.8	16.9	3.7 ± 0.2	4.3 ± 0.2	0.1	1.4	49.6 ± 0.5	56.6 ± 0.6	0.8	18.3
7	Bangah	64.6	48.2 ± 0.3	52.1 ± 0.1	26.3	72.5	3.3 ± 0.4	4.5 ± 0.3	1.8	6.3	51.4 ± 0.7	56.7 ± 0.4	28.0	78.8
8	Buntol	86.0	45.0 ± 0.5	50.6 ± 0.2	11.1	49.5	2.4 ± 0.2	2.9 ± 0.2	0.6	2.8	47.4 ± 0.7	53.4 ± 0.4	11.7	52.4
9	Paduran I	96.3	40.4 ± 0.8	33.0 ± 0.3	207.2	669.9	6.7 ± 0.2	1.2 ± 0.1	34.2	23.7	47.0 ± 1.0	34.2 ± 0.4	241.4	693.6
10	Pankoh	102.2	32.5 ± 0.4	40.1 ± 0.4	24.8	36.8	7.1 ± 0.2	4.3 ± 0.1	5.4	3.9	39.6 ± 0.6	44.4 ± 0.5	30.2	40.7
11	Paduran II	106.5	dna	6.8 ± 0.1	dna	24.0	dna	3.0 ± 0.2	dna	10.4	dna	9.8 ± 0.3	dna	34.4
12	Sampang	124.0	32.3 ± 0.3	45.9 ± 0.3	147.5	234.4	5.7 ± 0.2	0.1 ± 0.1	26.0	0.7	38.0 ± 0.5	46.0 ± 0.4	173.5	235.1
13	Sampang	124.8	31.3 ± 0.2	36.4 ± 0.4	67.6	93.6	6.6 ± 0.1	4.5 ± 0.2	14.3	11.5	37.9 ± 0.3	40.8 ± 0.6	81.9	105.1
14	Lumpur	148.9	15.8 ± 0.1	33.4 ± 0.1	59.4	111.4	4.1 ± 0.3	1.0 ± 0.3	15.4	3.4	19.9 ± 0.4	34.4 ± 0.4	74.8	114.8
	River Sebangau	150.0	17.3 ± 0.4	33.6 ± 0.1	667.9	1337.2	3.8 ± 0.8	1.5 ± 0.1	146.4	61.1	21.1 ± 1.2	35.1 ± 0.2	814.3	1398.3
	Total mean		40.5	43.9	48.4	102.8	5.1	2.5	8.5	5.0	45.5	46.4	56.9	107.8

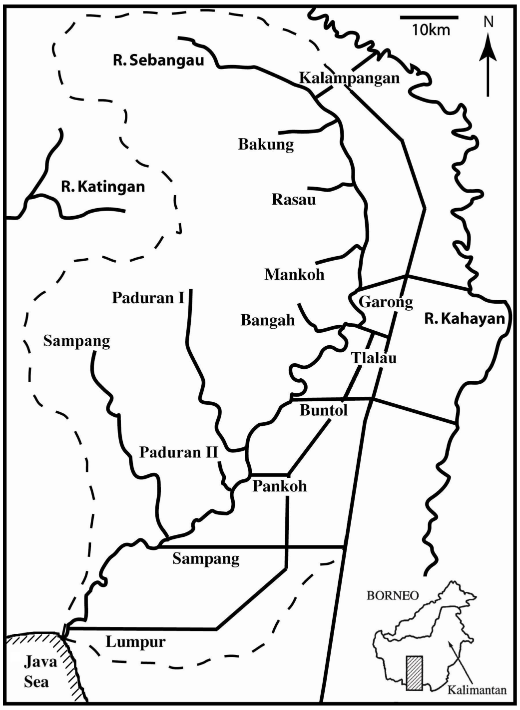

Fig. 1. Map of the Sebangau basin in Central Kalimantan, Borneo (inset). The Sebangau watershed (dashed line) is positioned between the Katingan River to the west and the Kahayan River to the east. The Sebangau River (centre) runs from North to South draining into the Java Sea. The 14 other named channels all drain the Sebangau catchment into the Sebangau River.

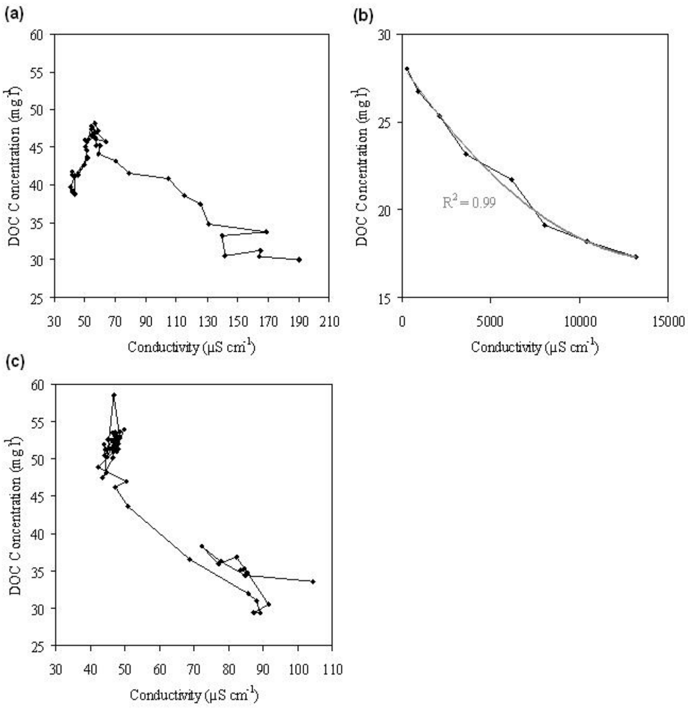

Fig. 2. Electrical conductivity (EC; as a proxy for salinity) vs. DOC concentration plots for samples from the River Sebangau in the dry season **(a)** 0–126 km from source and **(b)** 126–150 km from source (polynomial 2nd order relationship; $r^2 = 0.99$) and the wet season **(c)** 0–150 km from source. Note different y axis scale in Fig. 2b.

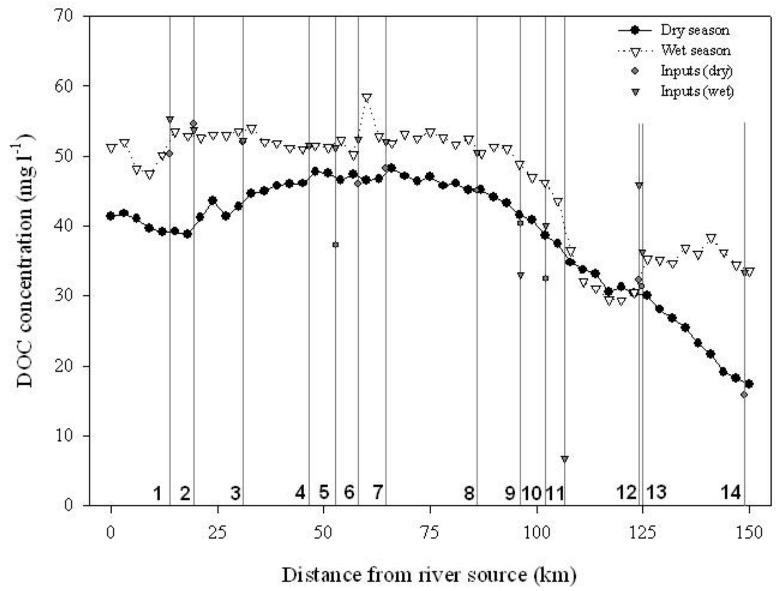

Fig. 3. DOC concentration along the course of the River Sebangau during the dry and wet seasons. Vertical lines represent the confluences of fourteen channels that discharge into the River Sebangau. Each confluence has an identification number above the x-axis (see Table 1). Single point data represent DOC concentrations in each channel prior to discharge into the River Sebangau.

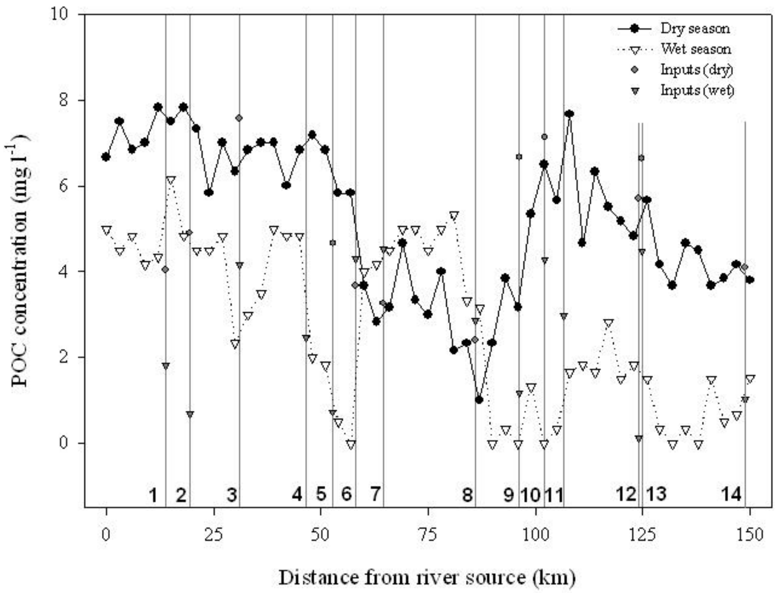

Fig. 4. POC concentration along the course of the River Sebangau during the dry and wet seasons. Vertical lines represent the confluences of fourteen channels that discharge into the River Sebangau. Each confluence has an identification number above the x-axis (see Table 1). Single point data represent POC concentrations in each channel prior to discharge into the River Sebangau.

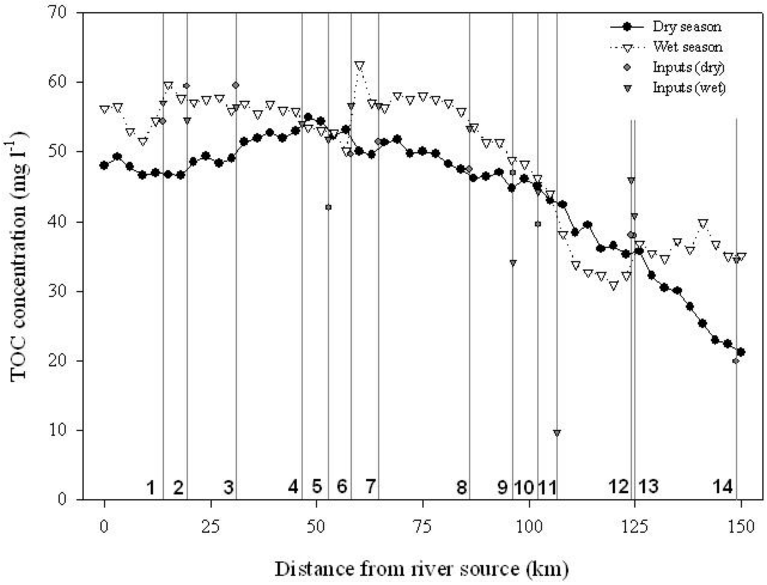

Fig. 5. TOC concentration along the course of the River Sebangau during the dry and wet seasons. Vertical lines represent the confluences of fourteen channels that discharge into the River Sebangau. Each confluence has an identification number above the x-axis (see Table 1). Single point data represent TOC concentrations in each channel prior to discharge into the River Sebangau.