Concentrations, loads and yields of organic carbon from two tropical peat swamp forest streams in Riau Province, Sumatra, Indonesia

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SUMMARY

Tropical peat swamp forest (PSF) stores large quantities of carbon. To estimate how much organic C is released from this type of landscape we determined organic carbon (C) concentrations, loads and yields in two contrasting watercourses draining from PSF in Riau Province, Sumatra (Indonesia). Meranti Ditch (MD) is an artificial watercourse whose small catchment (estimated area 4.8 km^2) is in semi-intact condition, whereas Turip River (TR) has a large natural catchment (estimated area 458 km^2) covered with fairly intact PSF where > 75 % of the original canopy trees remain. The organic C load (Gg C yr^{-1}) of each watercourse was calculated by combining TOC concentration with water discharge rate to give organic C yield (g C m^{-2} yr^{-1}). Dissolved organic carbon (DOC) was the dominant (95.0–99.8 %) component of total organic carbon (TOC) in the water. TOC concentration was 85–94 mg C L^{-1} in MD and 50–58 mg C L^{-1} in TR. The high concentration in MD was not surprising because this catchment had been disturbed by repeated phases of logging and a dense network of ditches was excavated ten years ago. The TOC loads were 0.23 Gg C yr^{-1} in MD and 14.0 Gg C yr^{-1} in TR. TOC yields (i.e. TOC fluxes through the fluvial system) were 41.6–55.5 g C m^{-2} yr^{-1} in MD and 26.2–34.9 g C m^{-2} yr^{-1} in TR.

KEY WORDS: carbon leaching, DOC, fluvial carbon, TOC, tropical peatland

INTRODUCTION

Approximately 11 % (4.41 × 10^5 km^2) of the global area of peatland lies within the tropics. Of this, 56 % (approximately 2.48 × 10^5 km^2) is located in south-east Asia, mostly in Indonesia and Malaysia (Page *et al.* 2011). The 88.6 GT of carbon (C) stored in tropical peat accounts for 11–14 % of the global peat C store, and south-east Asia's peat deposits are estimated to contain 77 % (68.5 Gt) of this. The largest accumulations of tropical peat C are in Indonesia (57.4 Gt C, i.e. 65 % of the total C in tropical peat) and Malaysia (9.1 Gt, 10 %) (Page *et al*. 2011). Jaenicke *et al.* (2008) also estimate that 55 ± 10 Gt of C is stored in Indonesian peatland. Tropical pet swamp forest (PSF) is formed when organic matter accumulates as a peat layer. It has important roles in regulating water movement, the hydrological cycle (Dommain *et al.* 2010), C storage (Limpens *et al.* 2008) and the regional and global C cycles. When affected by human activities, the organic C pool in peatlands can potentially release large amounts of C into the environment as gaseous emissions and waterborne (fluvial) losses (IPCC 2000).

Organic C is released from peatlands in substantial amounts (Page *et al*. 1999, Tachibana *et al*. 2006, Alkhatib *et al*. 2007, Baum *et al*. 2007, Rixen *et al*. 2008, Lähteenoja & Page 2011, Moore *et al.* 2011, Wright *et al*. 2011, Moore *et al*. 2013) and waterborne C may constitute a substantial part of the peatland C balance, as reported for boreal peatland (Roulet *et al*. 2007, Nilsson *et al*. 2008). Carbon is released into watercourses in both organic and inorganic forms (Meybeck 1993) and partly as free (gaseous) CO_2 and CH_4 (Dawson *et al*. 2004). Organic forms include dissolved organic C (DOC) and particulate organic C (POC). It is well known that the water in tropical peatland rivers has very high DOC concentrations (Alkhatib *et al*. 2007, Miyamoto *et al*. 2009) and lower POC concentrations (Yoshioka *et al*. 2002).

Despite increasing interest in C release *via* PSF river systems, few studies have been conducted. Baum *et al*. (2007) used data collected from the Siak River in Sumatra to calculate that *ca*. 0.3 Tg C yr^{-1} of DOC was released to Bengkalis Strait, whilst Moore *et al*. (2011) estimated from their own measurements in the Sebangau River in Central Kalimantan that 0.46 Tg C yr^{-1} of (total) organic C (TOC) was released to the Java Sea. These are valuable results, obtained by hard work in the field. However, to improve accuracy and to clarify how discharge variability influences the organic C load in PSF watercourses, it is necessary to have continuous measurements of water discharge. This is because both rainfall events and discharge responses affect the rate of flow in streams and rivers. Periodic measurements of stream discharge combined with continuous recording of stream water level (stage) can provide accurate continuous flow rate data if the rating curve (i.e. a graph of discharge *versus* stage) is available (Bedient *et al*. 2008).

The purpose of this study was to quantify the C loads of watercourses draining from PSF in Riau Province, Sumatra (Indonesia) by combining continuous flow data with measurements of organic C concentration in the water; and thus to estimate catchment yields of organic C. We also compare results obtained using continuous measurements of organic C load with those that would be indicated by periodic measurements.

METHODS

Study area

The study area is located on peatland in the south-west portion of Kampar Peninsular, in Pelelawan District of Riau Province, Sumatra, Indonesia. It is approximately 20 km across (Figure 1) and lies approximately 130 km east-south-east of Pekanbaru, the capital city of Riau Province. Altitudes were derived from the Shuttle Radar Topographic Mission - Digital Surface Model (SRTM-DSM), and by levelling survey on the ground. The landscape within the study area slopes upwards from the tidal Kampar River to a raised peat plain approximately 9 m above sea level. The underlying geology is dominated by unripened marine clays and alluvium. Mean annual rainfall is 3,300 mm with a brief dry spell in February and a distinct dry season in June–August, with mean daily temperature 27.2 °C and daily evapotranspiration 3.9 mm (20-year records from Pekanbaru Airport).

The vegetation of the study area consists of tropical peat swamp forest (PSF) whose structure and composition varies with altitude, the tall diverse mixed forest at sea level beside the Kampar River grading into short pole forest with few tree species at 6 m altitude, then into stunted dwarf forest on the peat plain at 8–9 m a.s.l. The present-day condition of the forest also grades in this direction, from almost absent beside the Kampar River, to degraded, and

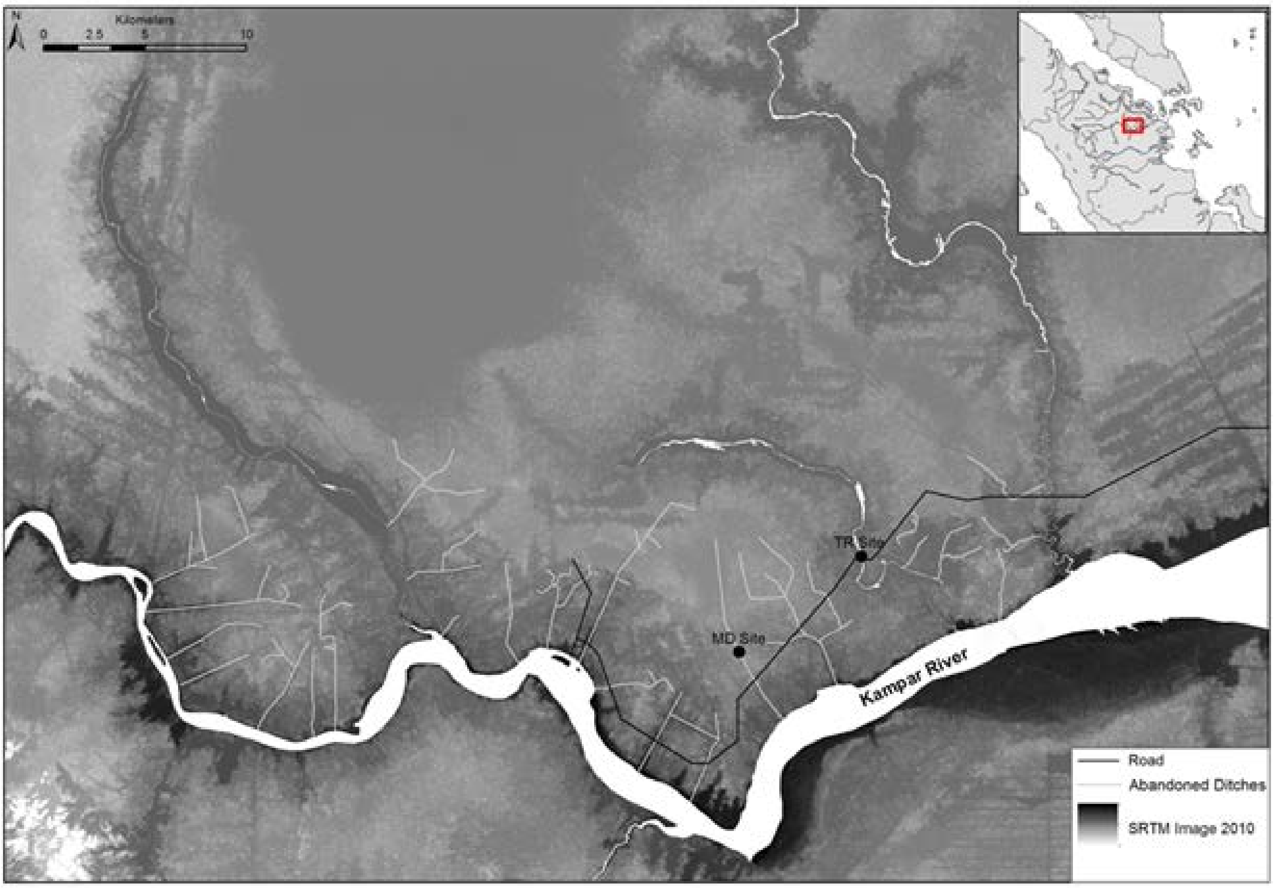

Figure 1. Satellite image (details) showing the locations of the Meranti Ditch (MD) and Turip River (TR) gauging stations in the Kampar River system, Riau Province, Sumatra, Indonesia.

then to relatively intact above 5–6 m a.s.l. The common tree species of the original forest include *Palaqium* sp., *Payena* spp., *Euginia* sp., *Antidesma bunius*, *Alseodaphne panduriformis*, *Helicia excelsa*, *Shorea* sp., *Shorea platycarpa* Heim., *Gonystylus* spp. and *Ilex cymosa*. Other vegetation includes an understorey of shrubs and young trees.

The lower half of the study area was selectively logged under licence from 1985 to 2005, using a light railway to carry timber to the Kampar River. Selective logging typically left 50 % or more of the large trees standing, creating ‘semi-intact to intact’ forest cover in the terminology of Bathgate & Rachmady (2012). From 2001 to 2010 about half of the previously logged area was subject to further unregulated (‘illegal’) logging. Excavators were used to create ditches, spaced a few kilometres apart, in order to float the logs to the nearest point on the Kampar River. Although subsequently disused, these logging ditches continued to drain the peatland (Figure 1). In addition, some accessible riparian areas along the Kampar River were cleared for unregulated agriculture by burning. The result was a patchwork of intact forest, degraded forest where fewer than 50 % of original large trees remained, and scrubland (Bathgate & Rachmady 2012).

In 2010 Riau Andalan Pulp and Paper (RAPP) developed part of the study area as a fibre plantation concession. Land use zones were arranged according to altitude, with a community livelihood plantation beside the Kampar River, *Acacia* plantation at 3–5 m a.s.l., and above that a zone of regenerating natural forest to form a buffer for the conserved zone. Within the conserved zone, the abandoned logging ditches were surveyed for subsidence and the depressions (‘sunken valleys’) they had created were closed with permanent weirs in order to restrict drainage and rewet the peat. The conserved forest is monitored for ongoing peat subsidence, trends in PSF biomass recovery, and wildlife (Bathgate & Rachmady 2012).

The study streams and their catchments

Two watercourses were selected for hydrological measurements. One is a small artificial stream named Meranti Ditch (MD) and the other is Turip River (TR) (Figure 1). The catchments of MD and TR are formed entirely from recent peat deposits (Brady 1997), and high concentrations of humic acids in stream runoff are indicated by the dark orange-black colour of the water. Sampling of peat profiles with a Russian pattern corer (Belokoptyov & Beresnevich 1955, Jowsey 1965) showed that the peat layer at the MD and TR sampling stations was 6 m and 7 m thick, respectively.

MD was excavated in 2001 for logging purposes. It is 2 m wide and 2 m deep, with a mean gradient of 0.0004 (derived from SRTM-DSM data). Topographic levelling in 2010 showed a subsided valley up to 1 m deep centred on the ditch (Bathgate & Rachmady 2012). The small MD catchment lies on a peat dome with semi-intact PSF and terminates in the buffer zone of regenerating forest between conserved PSF and *Acacia* plantation. In 2010 a series of six weirs was installed on MD to restrict water discharge, maintain high water table in the ditch and adjacent peatland during dry spells, and thus to promote conservation of both the peat soil and the forest. The ditch contains water even during periods of lowest rainfall, and adjacent land is shallowly flooded at times of peak rainfall. Since 2010, peat has continued to subside at mean rates of 1 cm p.a. in the upper MD catchment and 2 cm p.a. in the buffer zone (RAPP, unpublished data).

TR is a natural river (without artificial regulation) with a larger catchment than MD, extending from its origin on the peat plain to the TR sampling site just upstream of the road (Figure 1). The flatness of the peat plain means that the catchment boundary cannot be precisely delineated from SRTM-DSM data. The river has a mean gradient of 0.0002. The TR catchment is almost entirely covered by PSF whose condition is estimated from Landsat 8 satellite images and high-resolution aerial photography to be 75 % intact and 25 % degraded. A small area of plantation located upslope of the road is drained by a managed ditch that discharges into the TR downstream from the study catchment.

Hydrological measurements

Stream water level (SWL) was measured near the downstream ends of both catchments, at 0° 15' 0.1" N, 102° 34' 29.6" E for MD and 0° 17' 26.3" N, 102° 37' 50.4" E for TR. SWL at each location was measured ‘continuously’ (at intervals of 30 minutes) using an absolute pressure type water level data logger (Onset Hobo U20-001), which was installed inside a perforated PVC pipe set in the stream. Barometric pressure was also measured at both sites to enable conversion of the raw water pressure data into actual water levels. The measurements at MD were conducted from 24 May 2012 to 12 December 2013, and at TR from 25 May 2012 until the logger was stolen (after data download on 08 February 2013). The data indicated that there was no tidal effect on SWL at either of these locations.

Groundwater depth (GWD) was measured in both catchments over the same time periods, using water level data loggers of the same type, installed in dipwells made from 5 cm internal diameter perforated PVC pipe that penetrated 2 m into the mineral substratum (and were thus anchored securely). For accessibility reasons, the two GWD measurement sites were located only ~ 300–400 m from the stream, at 0° 15' 12.5" N, 102° 34' 34.0" E for MD and 0° 17' 37.8" N, 102° 37' 58.7" E for TR.

Flow rates were measured at the locations on MD and TR where the SWL data were collected (which had stable stream cross-sections), using an electromagnetic velocity meter (DENTAN TK–105x). Flow data were gathered 12 times at each site between June 2012 and March 2013. Measurements were made at almost weekly intervals during June and July 2012 (7 in MD, 8 in TR), then once a month from November 2012 to March 2013 (5 in MD, 4 in TR). Streamflow was not measured during August, September and October in 2012. Each measurement was performed by dividing the cross-section of the stream into more than ten subsections, then measuring flow velocity at a single point in each subsection. This point was located at the lateral centre of the subsection, at a height above the stream bed calculated as 40 % of the average of the water depths at the two ends of the subsection. Each flow velocity measurement was repeated more than three times and averaged, then multiplied by the area of the subsection to derive its flow rate ($m^3 s^{-1}$). Total flow (discharge) rate (Q) was calculated by summing the subsection values across the full width of the stream.

For each stream, the 12 flow measurements were used to create a discharge rating curve expressing the relationship between Q and SWL. The discharge rating curve was then used to convert the continuous SWL data to continuous flow rate data for the whole period of measurement. For the calculation of annual discharge, the missing SWL data for TR (08 February to 12 December 2013) were reconstructed by estimating SWL values from the moving average of the previous three days' GWD data when the water table was below ground level, and taking SWL = GWD when the GWD data indicated that the ground surface was flooded.

Rainfall was recorded by a 0.5 mm tipping bucket raingauge (Ota Keiki Seisakusho Co., Ltd., OW-34-BP) equipped with a data logger (Onset Hobo UA-003-64) sited in an open area near the MD stream measurement site (0° 15' 0.2" N, 102° 34' 30.8" E). A similar raingauge installed near the TR stream gauging site malfunctioned, so the MD rainfall data were used to represent both sites.

Catchment areas

It is not easy to define catchment areas on the almost-flat PSF landscape, and estimates of catchment areas in PSF are scarce. Siderius (2004) and Baum *et al*. (2007) estimated their catchment areas from SRTM DEM data using ArcGIS.

In this study, the catchment areas of the MD and TR stream gauging sites were estimated using two approaches. The first was a water balance approach in which runoff depth (q) was calculated by subtracting an assumed evapotranspiration (ET) value from rainfall (P), then the catchment area (A) was determined by dividing total discharge by the runoff depth (q). ET was determined using data from the studies conducted by Kumagai *et al*. (2005) and Hirano *et al*. (2014) in tropical peatland on Borneo, and by Baum *et al*. (2007) on Sumatra. This approach ignored any contribution of groundwater inflow or outflow to storage changes in the catchment water stores during the study period. The second approach involved using the Spatial Analyst extension of ArcGIS to analyse SRTM-DSM data obtained from the USGS EarthExplorer website (http://earthexplorer.usgs.gov/), enhanced with data from the RAPP topographic survey, and identification on high resolution images of ditches and other reference features within the study area. Where the catchment boundaries could not be defined from topographic data they were estimated by assuming that they lay midway between watercourses, including the abandoned logging ditches.

Water sampling and analytical procedures

Streamwater samples were collected in 250 ml plastic bottles from ~ 30 cm depth below the water surface, without filtering, at the same times and locations as the flow rate measurements were made. Electrical conductivity (EC) (Horiba Twin Cond EC meter) and pH (Horiba Twin pH meter) were measured directly at the sites each time water samples were collected. There was no water sampling between the end of July and early November in 2012. This was a period of low rainfall and low flow rate, which would have only a small effect the on load and yield results.

Rainwater was sampled six times at MD and seven times at TR (from 28 May to 27 July 2012 for both sites). It was collected in 250 ml plastic bottles, each equipped with a funnel and nylon net cover (mesh size 0.1 mm) to exclude insects, whose rim was set 150 cm above ground level. These rainfall collectors were located in open areas well away from any vegetation canopy effect, and the bottles were changed at each site visit.

Streamwater and rainwater samples were stored at approximately 5 °C in the dark until analysis. TOC and DOC concentrations were measured in the laboratory using a TOC analyser (Shimadzu TOC-VcpH). TOC concentrations were determined on unfiltered water samples. DOC is defined as C that can pass through a 0.45 µm filter, and POC is the C that is retained by a filter of this pore size (Thurman 1985). Thus, to measure their DOC concentrations, the water samples were passed through 0.45 µm glass fibre filters before analysis. The POC concentration for each sample was determined as the difference between its TOC and DOC concentrations, i.e. POC was not specifically measured.

Due to the remote location of the study area, the water samples were transported over a long distance and stored for some time before analysis in the laboratory. Thus, there was potential for changes in their chemistry, including organic C content, during transportation and storage. To assess any POC decomposition during storage, on one occasion at four sites we collected duplicate water samples from which we removed particulate organic C (POC) at the sampling site, immediately after collection, using a syringe with a glass fibre filter (0.45 µm pore size). These water samples were transported to the laboratory in 20 ml vials, which were stored with the corresponding 250 ml samples for 35–38 days before analysis and comparison of DOC concentrations. This comparison was performed on streamwater and groundwater samples from MD, TR, an *Acacia* plantation approximately 6 km from TR at Meranti (Riau Province, Sumatra) and Taruna Canal, 20 km from Palangka Raya in Central Kalimantan (Borneo). We found that both unfiltered and filtered samples of the same water returned the same C concentrations (linear regression $R^2 = 0.99$), i.e. that POC had not been transformed into DOC during storage of any of these samples.

Calculation of carbon loads and yields

The carbon data were adjusted for the organic C concentration reduction effect that occurs during storage by applying a DOC loss rate factor of 0.039 % day^{-1} (Peacock *et al.* 2015). The maximum storage time for our water samples was 138 days.

TOC and DOC loads were derived by multiplying instantaneous concentrations of TOC or DOC by the flow rate at the time of sampling. Then, for both MD and TR, the relationship between organic C load ($L_{(TOC)}$ or $L_{(DOC)}$) and flow rate (Q) (the L-Q formula) was determined by linear regression (in Microsoft Excel), as follows:

For MD: $$L_{(TOC)} = 92.22Q - 0.29 \quad [1]$$

$$L_{(DOC)} = 89.83Q - 0.26 \quad [2]$$

For TR: $$L_{(TOC)} = 53.71Q - 7.38 \quad [3]$$

$$L_{(DOC)} = 52.91Q - 4.51 \quad [4]$$

The R^2 values for all of these equations exceeded 0.99. To determine ‘continuous’ organic C loads throughout the observation period, the L-Q formulae were applied to the flow rate (Q) data. Total quantities of TOC and DOC ($\sum L_{(TOC)}$, $\sum L_{(DOC)}$) discharged during a period of 365 days (01 June 2012 to 31 May 2013) at MD and TR were then derived by summing the 30-minute values of $L_{(DOC)}$ and $L_{(TOC)}$ over this period. The total quantity of POC discharged over the same period ($\sum L_{(POC)}$) was obtained by subtracting $\sum L_{(DOC)}$ from $\sum L_{(TOC)}$. Organic C yields were obtained by dividing the organic C discharge totals by the appropriate catchment area (A).

For comparative purposes, we also calculated long-term C loads (DOC and TOC) using periodic data. In this case the trapezoidal method (Atkinson 1989) was used to estimate annual load from the instantaneous DOC and TOC loads calculated above.

RESULTS

Rainfall, SWL and GWD

Monthly rainfall at MD and Pekanbaru Airport (127 km west-north-west of MD) during the study period is shown in Figure 2. The difference in rainfall between rainy and dry seasons was clear. There was also a significant difference in total annual rainfall between these two locations for the year June 2012 to May 2013, when 1,831 mm was recorded at MD and 2,685 mm at Pekanbaru Airport.

Figure 3 shows the progress of SWL and GWD at both sites. The water level in streams and peat rose rapidly after each rainfall event then gradually receded due to drainage and evapotranspiration. At MD, SWL rose immediately in response to rainfall whereas the response at TR was delayed. This is attributed to differences in characteristics of the two catchments. Stream and peat water levels were high during the rainy season (September to December) and low throughout the (longer) dry season (January to August).

SWL and GWD data for both sites are shown in Figure 3. The patterns of SWL and GWD fluctuation were closely similar in the two catchments, suggesting that there was no significant deep groundwater contribution to streamflow. During the monitoring period, the water table at MD was always below the ground surface, even in the rainy season. Thus, the highest position of the water table relative to the ground surface (which displayed a type of hummock-hollow microtopography) was consistent with water discharge occurring by shallow subsurface flow. In contrast, the groundwater level at

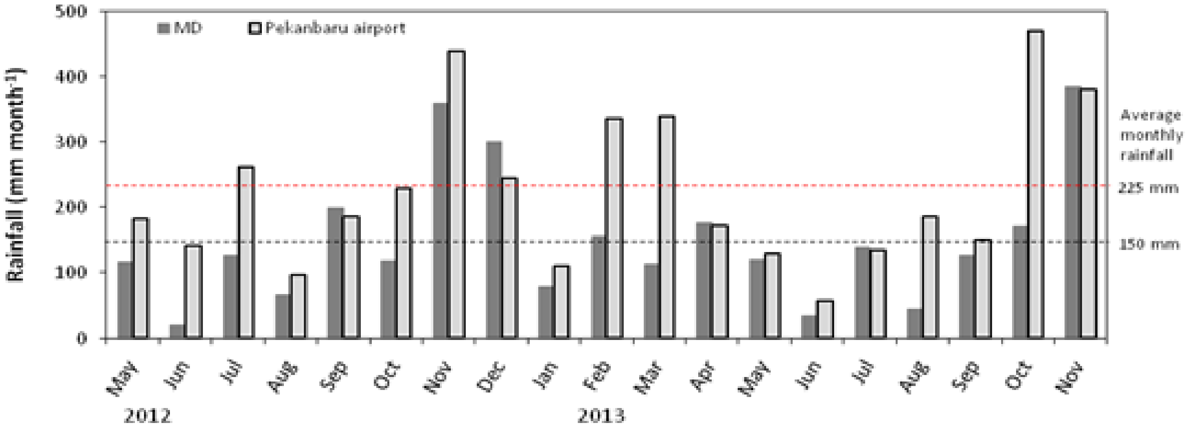

Figure 2. Monthly rainfall at the Meranti Ditch (MD) study site and Pekanbaru Airport, May 2012 to November 2013.

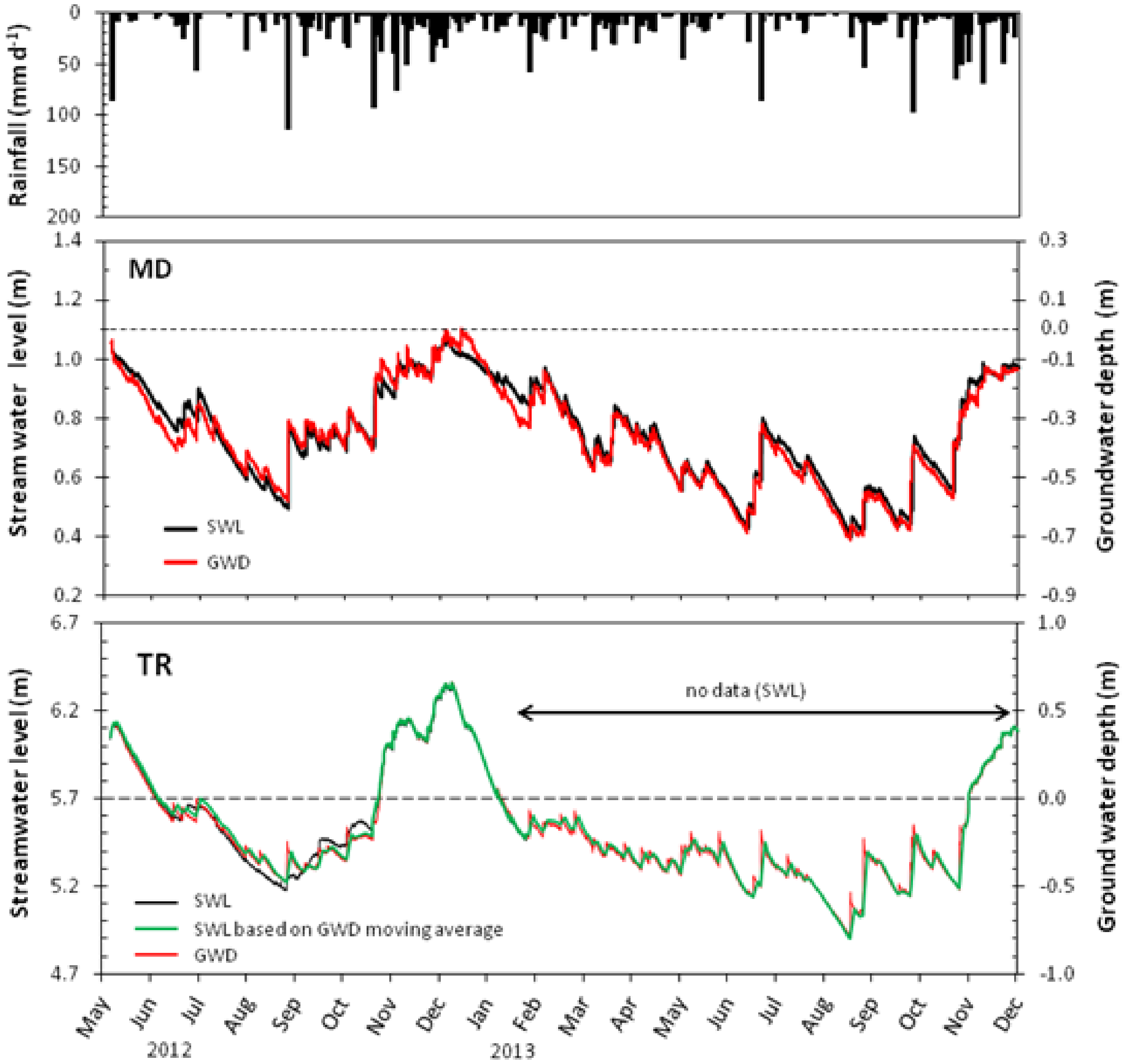

Figure 3. Rainfall (top pane), stream water level (SWL) and groundwater depth (GWD) (middle pane) measured at Meranti Ditch (MD); and SWL and GWD measured at Turip River (TR) together with SWL estimated from moving averages of GWD for that location (bottom pane).

TR became much higher than the ground surface at certain times of year (from the start of the record until June 2012, November 2012 to January 2013, and after November 2013). During these periods of high water table, the ranges and patterns of fluctuations in SWL and GWD were very similar and responses to rainfall events were not apparent (Figure 3). This indicates that the stream flooded during the rainy season, inundating the adjacent peatland. The fluctuations of stream and groundwater levels during the dry season had a different character. Then, although the general trends in GWD and SWL fluctuations were quite similar, the response of GWD to each rainfall event was much sharper and more immediate than the response in SWL, which was slight at most. It appeared that GWD in the peatland responded directly to rainfall, discharge and evapotranspiration but the maximum drawdown of the water table was controlled by the water level in the stream.

Stream discharge

From the relationships between Q (discharge, $m^3\ s^{-1}$) and h (SWL, m) for MD and TR, the following discharge rating equations were obtained:

For MD: $$Q = 0.21\, h^{6.09} \qquad [5]$$

$$0.72 < h < 0.96 \qquad (R^2 = 0.86)$$

For TR: $$Q = 13.9\, h - 69.8 \qquad [6]$$

$$5.3 < h < 5.9 \qquad (R^2 = 0.63)$$

The continuous discharge records generated by applying these rating equations to continuously recorded SWL are shown in Figure 4.

Table 1 shows the discharge characteristics for both sites. In MD, the average discharge was $0.10\ m^3\ s^{-1}$ while in TR it was $9.27\ m^3\ s^{-1}$. The coefficient of streamflow regime (maximum discharge / minimum discharge) for the 259-day period considered was 107 in MD and 8 in TR, indicating that the difference in discharge between dry and rainy seasons is not high in TR. The larger discharge and more stable flow regime of TR is presumably a consequence of its larger catchment.

Catchment areas

For the estimation of catchment areas using the water balance approach, water loss by evapotranspiration was assumed to be 60 %, 65 %, and 70 % of the total rainfall recorded at MD. The resulting estimates were 4.2–5.6 km^2 for MD and 401–535 km^2 for TR (Table 2). Spatial analysis of SRTM-DSM data yielded catchment area estimates of 3.6 km^2 for MD and 420 km^2 for TR (Table 2). To test the accuracy of the SRTM-DSM results, the water balance was back-calculated. This calculation indicated that the

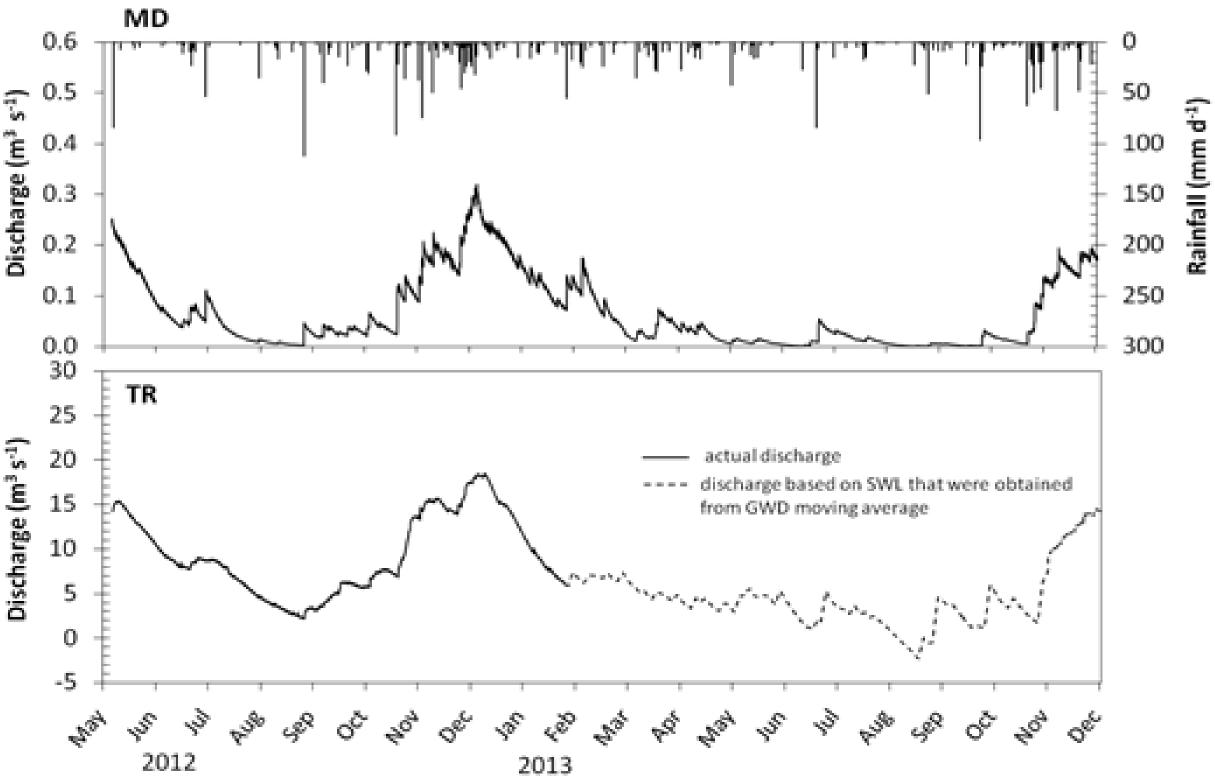

Figure 4. Discharge from Meranti Ditch (MD) and Turip River (TR).

Table 1. Discharge characteristics of Meranti Ditch (MD) and Turip River (TR), calculated for the period 25 May 2012 to 08 February 2013 (259 days). (Q_{max} / Q_{min}) is the coefficient of streamflow regime.

Site	Q_{max} (m^3 s^{-1})	Q_{ave} (m^3 s^{-1})	Q_{min} (m^3 s^{-1})	Q_{max} / Q_{min}
MD	0.32	0.10	0.003	107
TR	18.55	9.27	2.20	8

Table 2. Derivation of catchment area estimates, from the water balance for the period 25 May 2012 to 08 February 2013 (259 days). *P* = total observed rainfall at MD, *ET* = evapotranspiration, *q* = runoff depth, discharge = total observed stream discharge. Catchment area estimates derived by spatial analysis of SRTM-DSM data are shown for comparison.

Site	*P* (mm)	*ET* (estimated) (%)	*ET* (estimated) (mm)	*q* (mm)	discharge (m^3)	catchment area (km^2) from water balance	catchment area (km^2) using SRTM-DSM
	i	ii	iii = (i*ii)/100	iv = i - iii	v	vi = (v/iv*10^3)/10^6	
MD	1,291	60	775	516	2.17E+06	4.2	3.6
		65	839	452		4.8	
		70	904	387		5.6	
TR	1,291	60	775	516	2.07E+08	401	420.0
		65	839	452		458	
		70	904	387		535	

fraction of total rainfall lost through ET was 53 % in MD and 62 % in TR. Essentially, both methods were approximate, and there was no significant difference between the estimates obtained using the two approaches. For the calculations of carbon yields and loads presented here we adopted catchment area values generated using the water balance approach.

TOC, DOC, and POC concentrations

The concentrations of DOC in rainwater and TOC, DOC, POC in streamwater are shown in Figure 5. TOC concentrations ranged from 85 to 94 mg C L^{-1} at MD and from 50 to 58 mg C L^{-1} at TR. For both streams, most of the TOC was in the form of DOC with a range of 82–90 mg C L^{-1} for MD and 49–57 mg C L^{-1} for TR. Only a small portion of TOC was in the form of POC (0.2–5 %, or around 0.2–4.5 mg C L^{-1}). TOC concentration was higher at MD than at TR.

As shown in Figure 6, the TOC and DOC concentrations in streamwater were fairly stable (SD = 2.07 mg C L^{-1} for MD and 2.05 mg C L^{-1} for TR). Linear regression calculations in Microsoft Excel indicated that they were not affected by discharge rate (R^2 = 0.05–0.20, ρ = 0.15–0.51) and were not related to groundwater depth despite some groundwater depth fluctuations (R^2 = 0.003–0.05, ρ = 0.42–0.86). Streamwater pH ranged from 3.4 to 4.1 at both sites (*SD* = 0.2 and 0.1) and did not affect the TOC and DOC concentrations (R^2 = 0.007–0.08, ρ = 0.44–0.81). The relationship between TOC and DOC concentrations and streamwater EC was not significant for either site (R^2 = 0.003–0.10, ρ = 0.38–0.89).

Carbon loads and yields

Applying the catchment area estimates shown in Table 2, the TOC yield values were 41.6–55.5 g C m^{-2} yr^{-1} for MD and 26.2–34.9 g C m^{-2} yr^{-1} for TR (Table 3). The POC yields were very small, amounting to only 0.6–1.3 % of the TOC yields. The organic C yield (TOC, DOC and POC) was higher for MD than for TR. This is a reflection of the higher organic C concentration in MD.

The TOC load released from PSF to MD was calculated as 0.23 Gg C yr^{-1}, whereas the TOC load for TR was estimated at 14.0 Gg C yr^{-1} (Table 3). This value is based on a year of continuous hydrological observations (01 June 2012 to 31 May 2013) as

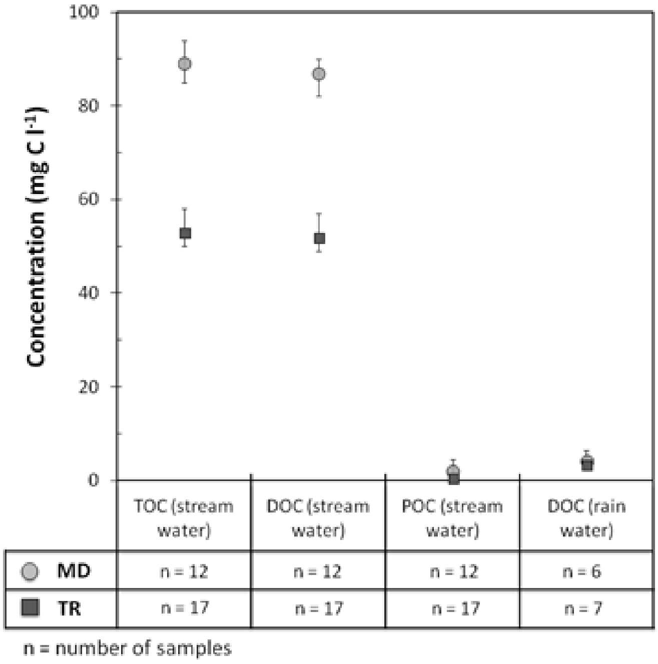

Figure 5. Organic carbon concentrations in Meranti Ditch (MD), Turip River (TR) and rainwater. Error bars indicate the maximum and minimum values observed.

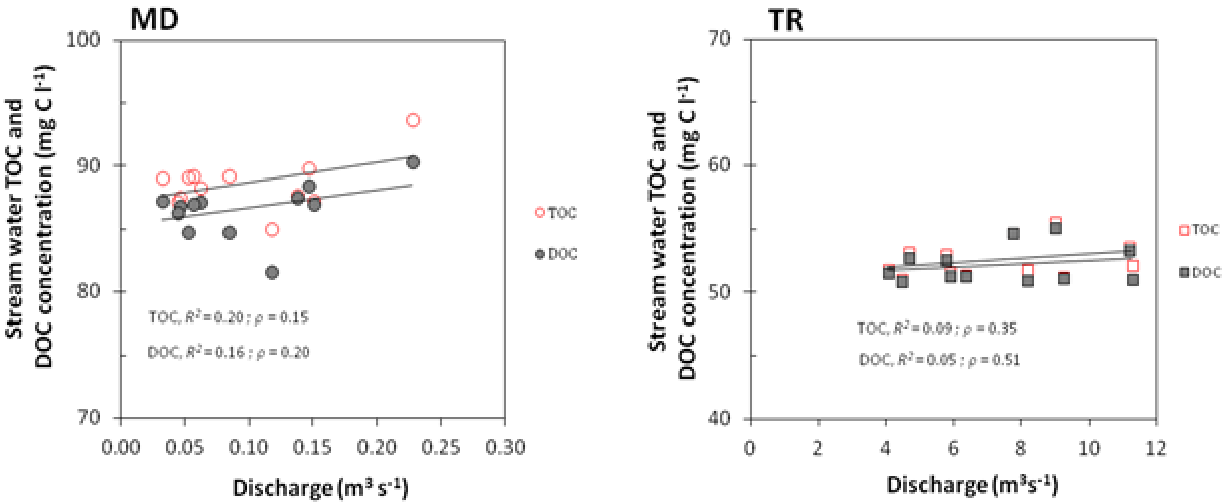

Figure 6. Relationships between TOC and DOC concentrations and stream discharge, in Meranti Ditch (MD) and Turip River (TR).

shown in Figure 4. Table 3 shows that there are also significant differences between the organic C loads estimated using continuous and periodic data. TOC loads estimated using periodic data were 27 % higher than those estimated from continuous load for MD, and 8.8 % lower for TR. This was due to discharge variability during the monitoring period that could not be taken into account by the calculation using periodic data.

DISCUSSION AND CONCLUSIONS

There were significant differences in the estimates of organic C load that we obtained using continuous and periodic data. However, regardless of the calculation method, it was clear that almost all of the TOC contained in PSF streamwater was in the form of DOC, with only 0.2–5.0 % occurring as POC. The TOC load transported from the PSF catchment to the

Table 3. Annual organic carbon (TOC, DOC and POC) yields and loads of Meranti Ditch (MD) and Turip River (TR) calculated using continuous and periodic stream stage data for the period 01 June 2012 to 31 May 2013. Yield = load / catchment area; * = upper estimate, ** = lower estimate (based on the lowest and highest estimates of catchment area obtained using the water balance method, see Table 2). For loads calculated from periodic data, values in parentheses indicate the results as percentages of the corresponding loads calculated using continuous data.

site	property	data type	TOC	DOC	POC
MD	yield (Gg C m^{-2} yr^{-1})	continuous *	55.5	54.8	0.7
		continuous **	41.6	41.1	0.5
	load (Gg C yr^{-1})	continuous	0.233	0.230	0.003
		periodic	0.296 (127 %)	0.287 (125 %)	0.009 (200 %)
TR	yield (Gg C m^{-2} yr^{-1})	continuous *	34.9	34.7	0.2
		continuous **	26.2	26.0	0.2
	load (Gg C yr^{-1})	continuous	14.0	13.9	0.1
		periodic	12.8 (91.2 %)	12.7 (91.5 %)	0.1 (58 %)

stream during the study period was estimated at 0.23 Gg C yr^{-1} for MD and 14.0 Gg C yr^{-1} for TR. Seasonal monitoring at these two sites showed that TOC and DOC concentrations in the stream were fairly stable and were not affected by the flow rate. The streamwater was acidic with pH in the range 3.4–4.1 and an EC of 73–151 µs cm^{-1}, but the concentrations of TOC and DOC were not affected by variation in either these factors or discharge (flow rate). There was also no relationship between fluctuations of groundwater depth in the catchment and the concentrations of TOC and DOC in the stream. This invariability of C concentrations in PSF water could be attributed to the intact condition of the PSF and its consequently high organic C content, which enables it to provide a nearly constant supply of organic C to drainage water regardless of the rate at which water is moving through the system.

Stream TOC concentrations in MD (85–94 mg C L^{-1}) were higher than in TR (50–58 mg C L^{-1}). The high concentrations in MD are not surprising, as this catchment has been much disturbed by repeated rounds of logging which also involved the excavation of a dense network of ditches approximately ten years ago, with associated changes in peatland gradient and topography (subsidence). Under these conditions it seems likely that surface and subsurface water flow will readily flush peat C into streams. By comparison, TR has a large catchment of which 75 % is covered by intact PSF, including a large peat plain headwater that has never been logged and, therefore, contributes less organic C to streamwater.

The average DOC concentrations in rainwater were 3.3 ± 1.6 mg C L^{-1} at MD and 4.1 ± 1.5 mg C L^{-1} at TR, and higher than in rainwater originating from other non-urban sites (Table 4). The DOC concentrations in our rainwater samples may have been influenced by haze from widespread burning of PSF in the drier months when most of the rainwater samples were collected (May–July 2012).

Table 5 gives DOC concentrations in streamwater from several locations and regions with a variety of catchment types, from this and previously published studies. The DOC concentration we recorded at MD was high compared to other sites. Several other PSF locations also had high DOC concentrations.

Table 6 summarises DOC yields reported for different catchment types and regions, from this and previous studies. It is clear that PSF has a high DOC yield compared to other catchment types in boreal and temperate regions. However, Baum *et al*. (2007) reported that oil palm and rubber estates in lowland catchments had lower DOC yields than PSF. It should be noted that the fraction of disturbed peat area in those catchments ranged from 3.9 to 53.4 %.

In our study, TOC yields ranged from 41.6 to 55.5 g C m^{-2} yr^{-1} in the small (4.8 km^2) MD catchment and from 26.2 to 34.9 g C m^{-2} yr^{-1} in the larger (458 km^2) TR catchment. This result matches the findings of Dawson *et al*. (2004), who report that smaller catchments in C-rich landscapes typically have higher C yields or fluxes than similar but larger

Table 4. DOC concentrations ((DOC), mg C L^{-1}) in the rainwater of areas with different land uses/locations.

Type	Location	(DOC)	Reference
tropical PSF (MD)	Sumatra, Indonesia	3.30	this study
tropical PSF (TR)	Sumatra, Indonesia	4.10	this study
forest	Thailand	1.7	Möller *et al*. (2005)
	Taiwan	4.7	Liu & Sheu (2003)
Amazon Basin	Amazonia (Brazil)	0.82	Andraea *et al*. (1990)
	Amazonia (Brazil)	1.91	Williams *et al*. (1997)
rural	Hubbard Brook, New Hampshire, USA	1.09	Likens *et al*. (1983)
	New York, USA	1.92	Likens *et al*. (1983)
	The Netherlands	1.93	Nguyen *et al*. (1990)
urban	Tokyo	1.44	Sempéré & Kawamura (1994)
		7.44	
	northern China	2.4–3.9	Yuepeng *et al*. (2010)
	Seoul, Korea	1.13	Yan & Kim (2012)
coastal	Puerto Rico	0.62	McDowell *et al*. (1990)
	Costa Rica	0.70	Eklund *et al*. (1997)
	Wilmington, North Carolina, USA	1.37	Willey *et al*. (2000)
	New Zealand	0.70	Kieber *et al*. (2002)
marine	Enewetak Atoll, Pacific Ocean, USA	1.18	Zafiriou *et al*. (1985)
		0.26	
	West Pacific, USA	1.50	Sempéré & Kawamura (1996)
	south New Zealand	0.29	Willey *et al*. (2000)

Table 5. DOC concentrations ((DOC), mg C L^{-1}) in streamwater within different regions/catchment types.

		Location	Catchment type	(DOC)	Reference
Indonesia	Riau Province	MD (Meranti Ditch)	tropical PSF	82–90	this study
		TR (Turip River)	tropical PSF	49–57	this study
		Dumai River	tropical PSF and lowland forest	60.6	Alkhatib *et al*. (2007)
	central Sumatra	Tapung Kanan River	oil palm and rubber estates, lowland forest and shrubs (53.4 % peatland by area)	20.4–21.7	Baum *et al*. (2007)
		Tapung Kiri River	oil palm and rubber estates, lowland forest and shrubs (3.9 % peatland by area)	6.9–7.4	Baum *et al*. (2007)
		Mandau River	oil palm and rubber estates, lowland forest and shrubs (48.1 % peatland by area)	35.0–36.7	Baum *et al*. (2007)
	Central Kalimantan Province	Sebangau Forest	natural tropical PSF	62.0–64.1	Moore *et al*. (2013)
		Tumbang Nusa	disturbed tropical PSF	54.7–62.4	Moore *et al*. (2013)
		Kalampangan	disturbed tropical PSF	39.1–47.9	Moore *et al*. (2013)
		Taruna Main Canal	disturbed tropical PSF	32.4	Yupi & Inoue (unpublished data)
Malaysia	Peninsular Malaysia	channel draining oil palm plantation on peatland	oil palm on peatland (abandoned)	6	Moore *et al*. (2013)
			oil palm on peatland (active)	13	Moore *et al*. (2013)
Japan	Hokkaido	stream in Sarobetsu Mire	natural boreal peatland	20	Takechi (2013)
Canada	Northern Manitoba	Sapochi River East and West Basin Stream	spruce, jack pine, palsa, fen and bog	15–30	Moore (2003)

Table 6. DOC yields (g C m^{-2} yr^{-1}) from different catchment types in different regions.

Site	Catchment Type	DOC yield	Reference
Hubbard Brook, New Hampshire, USA	temperate deciduous forest	2	McDowell & Likens (1988)
Luquillo Mountains, Puerto Rico	tropical evergreen forest	3.25	McDowell (1998)
Troutbeck catchment, Moorhouse, UK	upland peat	4–7.4	Worall *et al.* (2006)
Maimai, Westland, New Zealand	temperate evergreen forest	6.8	Moore (1989)
Ochil Hills, Scotland	upland peat	8	Grieve (1984)
Mer Bleue bog, Ontario, Cananda	bog	8.3	Fraser *et al.* (2001)
Upper Hafren, Wales	upland peat	8.4	Dawson *et al.* (2002)
Sapochi River East and West Basin Stream, Manitoba, Canada	spruce, jack pine, palsa, fen and bog	10–30	Moore (2003)
Loch Ard, Burn 11, Scotland	temperate evergreen forest	15	Grieve (1994)
Loch Ard, Burn 10, Scotland	temperate evergreen forest	16	Grieve (1994)
Brocky Burn, Scotland	upland peat	16.9	Dawson *et al.* (2002)
Larry River, Westland, New Zealand	wetland (moss/fern/scrub vegetation)	65.1	Moore & Jackson (1989)
Tapung Kanan River, central Sumatra, Indonesia	oil palm and rubber estates, lowland forest and shrubs (53.4 % peatland)	4.9–41.1	Baum *et al.* (2007)
Tapung Kiri River, central Sumatra, Indonesia	oil palm and rubber estates, lowland forest and shrubs (3.9 % peatland)	1.7–14.8	Baum *et al.* (2007)
Mandau River, central Sumatra, Indonesia	oil palm and rubber estates, lowland forest and shrubs (48.1 % peatland)	9.1–70.4	Baum *et al.* (2007)
Sebangau River, Central Kalimantan Indonesia	natural tropical PSF	83	Moore *et al.* (2011)
three channels in Sebangau forest , Central Kalimantan, Indonesia	natural tropical PSF	61.3	Moore *et al.* (2011)
two channels in Tubangnusa, Central Kalimantan, Indonesia	disturbed tropical PSF, moderately drained	95.7	Moore *et al.* (2011)
three channels in Kalampangan, Central Kalimantan, Indonesia	disturbed tropical PSF, severely drained	81.5	Moore *et al.* (2011)
Meranti Ditch, Riau Province, Sumatra, Indonesia	tropical PSF	39.3–52.4	this study
Turip River, Riau Province, Sumatra, Indonesia	tropical PSF	26.0–34.7	this study

catchments. The quantities of organic C discharged by the MD and TR streams, *per* unit area of PSF, were only 2.7–5.4 % of current estimates of the total amount of C released to the atmosphere from PSF, e.g. 974.0–1,035.3 g C m^{-2} yr^{-1} (Hirano *et al*. 2009). Our report of relatively small amounts of C being released through streamwater is relevant to improving estimates of the PSF C budget, as well as to our understanding of how C is transferred between PSF and the hydrosphere.

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