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Fluvial carbon fluxes in tropical rivers

Ting-Hsuan Huang, Yu-Han Fu, Pei-Yi Pan and Chen-Tung Arthur Chen

The export of fluvial carbon from land to the ocean is an important connection between two of the largest carbon reservoirs in the world. Previous investigations have estimated that river water annually provides 0.80–1.33 Pg of carbon to the world's oceans. This investigation combines a review of published data from 80 tropical (30°N–30°S) rivers, with supplementary, unpublished data concerning 95 additional rivers, mostly from South and Southeast Asia. These rivers deliver approximately 0.53 Pg carbon to the estuaries annually. Of this, 0.21 Pg C is dissolved inorganic carbon (DIC), 0.14 Pg C is dissolved organic carbon (DOC), 0.05 Pg C is particulate inorganic carbon (PIC), and 0.13 Pg C is particulate organic carbon (POC). Rivers in the equatorial region between 3°N and 6°S register high DOC values but low DIC values; the difference is primarily associated with type of soil. Rivers in mainland Asia have the highest specific export rates in terms of DIC, DOC and POC.

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Current Opinion in Environmental Sustainability 2012, **4**:162–169

This review comes from a themed issue on
Carbon and nitrogen cycles
Edited by Chen-Tung Arthur Chen and Dennis Peter Swaney

Received 14 October 2011; Accepted 20 February 2012
Available online 10th March 2012

DOI 10.1016/j.cosust.2012.02.004

Introduction

In the global carbon cycle, rivers have a critical role in connecting terrestrial, oceanic and atmospheric carbon reservoirs. River water transports atmospheric and terrestrial carbon to the ocean. Of the portion that originates from the atmosphere, organic carbon is formed by the photosynthesis reaction; the fraction of atmospheric carbon, that is, dissolved inorganic carbon (DIC) comes from soil CO_2, fixed from the atmosphere by the weathering of rocks and air-water exchange. Of the terrestrial portion, DIC and particulate inorganic carbon (PIC) are associated with the weathering of rock. Total global riverine carbon flux is 0.80–1.33 Pg C/y [1••,2,3•,4••,5–9,10••].

Two approaches are available for estimating global fluvial carbon fluxes. One uses carbon data for large rivers in various regions. For instance, Meybeck [11] estimated global DIC and PIC fluxes (0.38 Pg C/y and 0.17 Pg C/y) based on data for 60 large rivers or groups of rivers that together are responsible for 63% of global river discharge, and considered runoff and average watershed temperature to obtain information regarding the other 37%. Ludwig *et al.* [12] utilized a database of mean annual dissolved organic carbon (DOC) and particulate organic carbon (POC) fluxes of 29 and 19 rivers, respectively, and other ecological factors to calculate DOC and POC fluxes (0.21 and 0.17 Pg C/y, respectively). The main determinants of DOC fluxes are the drainage intensity, basin slope and amount of organic soil carbon. The main factors that govern POC fluxes are the total mass of suspended matter (TSM) and sediment load.

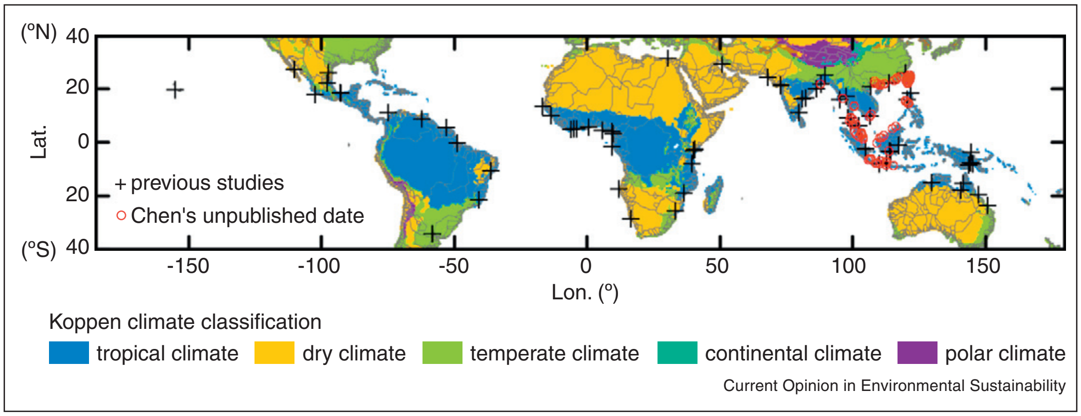
The other approach considers the mass balance. For example, Mackenzie *et al.* [2] evaluated fluvial inorganic and organic carbon fluxes (0.72 and 0.61 Pg C/y) using a conceptual model. Notably, published results consider only the total quantity of inorganic or organic carbon (in the case of Mackenzie *et al.* [2]) or only some of the four carbon components (in the case of Meybeck [11] and Ludwig *et al.* [12]). Importantly, the latest IPCC [9] report considered only DIC and DOC fluxes.

Prior investigations [1••,4••] have classified riverine data concerning various climates to predict regional carbon fluxes. Of these climates, the humid tropical climate is associated with the highest carbon yield. The tropical region (30°N–30°S) includes 42.7% by area of the world's land, but contributes a disproportionate 66.2% of global freshwater outflow, 73.2% of sediment load and over 61% of terrestrial net primary production [13,14•]. Therefore, tropical rivers are critical to total global fluvial carbon flux. Unfortunately, prior studies for global fluvial carbon fluxes are incomplete because only a few large tropical rivers are considered, and available PIC data are even more limited. Related investigations have generally not included carbon fluxes in tropical Asia and in small rivers. This study reviews published data for 80 tropical (30°N–30°S) rivers, most of which are large. These data are supplemented by unpublished information concerning 95 rivers, most of which are small, in Southeast and South Asia.

Data

This investigation compiles carbon parameters concerning 175 rivers between 30°N and 30°S. Data for 80 of

Figure 1



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Location of study sites. Symbols in red are sites for which unpublished data of CTA Chen are used.

these rivers are taken from the literature while the data for the other 95 are unpublished data of CTA Chen, one of the coauthors, and concern rivers in both South and Southeast Asia (Figure 1). The discharge data are obtained from the Global Runoff Data Center (GRDC) and are co-registered by the Simulated Topological Network (0.5°latitude × 0.5°longitude; STN-30). These data describe the global system of around 6200 drainage basins [15,16]. The sediment fluxes are calculated using the water balance and transport model of the University of New Hampshire (WBM/WTM; [14•]). These discharge data concern 219, 392, 603 and 144 rivers in tropical Africa, the Americas, Asia and Oceania, respectively.

Reported global discharges (37,400–42,000 km^3/y; [12,14•,17,18]) are consistent with the GRDC data (38,540 km^3/y). The global sediment load determined using WBM/WTM (12,610 Mt/y), however, is somewhat lower than previous estimates (13,505–20,000 Mt/y; [12,13,19,20]). This fact may result in some differences between the findings of this investigation and those of earlier studies. Furthermore, human activities have reduced the sediment load [21], and this effect is ignored herein in this study. The data on soil organic carbon density and river slope were released by the Global Soil Data Task Group [22] and the Global Drainage Basin Database [23], respectively.

Method

A tropical river is defined herein as one for which more than 60% of its river basin is within the range of latitudes from 30°N to 30°S. For instance, the Mississippi River is not included because 99% of the river basin is located north of 30°N. On the other hand, the Paraná Rivers are included, because 92% of their basins are north of 30°S, despite the fact that the estuary is situated close to 35°S. The DIC database covers 63.5% of the total water discharge of all tropical rivers, while the DOC database covers 54.9% of the total water discharge. The PIC and POC databases cover rivers that carry 11.4% and 49.7%, respectively, of the sediment load of tropical rivers.

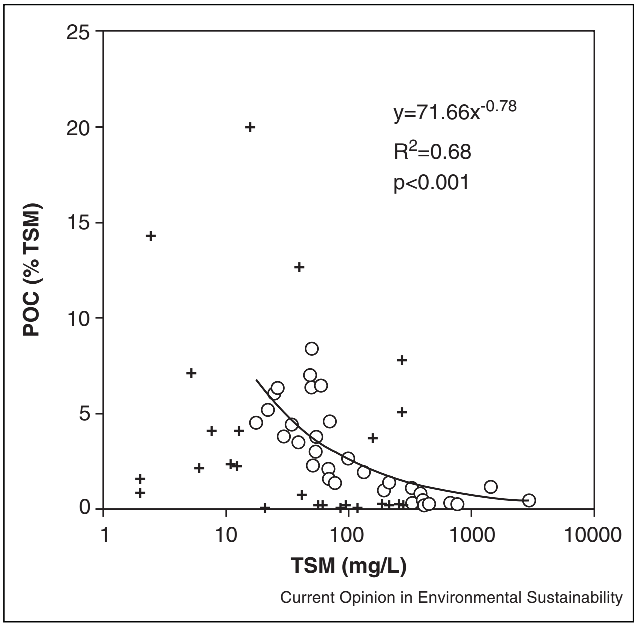
To estimate the carbon fluxes of rivers for which no data are available, four approaches are utilized to obtain data for the various carbon components. The first is based on the Köppen climate classification and known DIC and DOC concentrations in adjacent regions. The Köppen climate classification separates climates into five main groups — tropical, dry, temperate, continental and polar (Figure 1). For each river basin, the percentages of the total area of the basin that is associated with these five main groups are calculated, and unknown carbon concentrations are estimated using the known contributions of different climate groups.

The second approach uses a linear model to estimate the DOC flux [12]:

$$\begin{aligned}\text{DOC flux}\ (10^{12}\,\text{gC/y}) &= 0.004 \times \text{discharge}\ (10^{9}\ \text{m}^{3}/\text{y}) \\ &\quad + 0.004 \times \text{soil organic carbon density} \\ &\quad (\text{kgC/m}^{2}\ \text{to depth of}\ 1\,\text{m}) - 0.095 \\ &\quad \times \text{slope} + 0.276 \quad n = 57,\ r^{2} = 0.97,\ p < 0.001 \qquad (1)\end{aligned}$$

However, this model seems to overestimate DOC fluxes in some streams. Therefore, unreasonable data (calculated DOC concentrations higher than 2500 μM) are replaced with results obtained using the first approach. The third method is utilized to estimate the POC percentage, by correlating the POC percentage in TSM with

Figure 2



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POC percentage in TSM versus TSM concentration. Calculations are made using only data in that are represented by circles.

the TSM concentration (Figure 2):

$$\mathrm{POC}\% = 71.66 \times \mathrm{TSM}(10^{12}\ \mathrm{g/y})^{-0.78} \quad n = 32,$$
$$r^2 = 0.68, \quad p < 0.001 \qquad (2)$$

The fourth approach uses the known PIC percentage in nearby regions to estimate the weighted mean PIC in the region of interest (weighted mean PIC in a continent = (river sediment load × PIC%)/(river sediment load) (3)). Notably, all of the above determine fluxes to the estuaries in which the biogeochemistry is complex (Chen *et al.* [24] and Cai *et al.* [25], for example). The amount of carbon that actually enters the oceans is not examined here.

Inorganic carbon

Inorganic carbon is the largest component of the fluvial carbon that is delivered to the ocean. Riverine inorganic carbon is formed mostly by the weathering of carbonate and silicate minerals as follows:

$$\text{Carbonates}: \mathrm{CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-} \qquad (4)$$

$$\text{Silicates}: \mathrm{CaSiO_3 + 2CO_2 + 3H_2O \leftrightarrow 2HCO_3^- + Ca^{2+} + H_4SiO_4} \qquad (5)$$

Inorganic carbon comprises PIC and DIC, and their concentrations are causally related. PIC may be precipitated when river water becomes oversaturated with $CaCO_3$, reducing the DIC concentration. Conversely, PIC may also dissolve into the DIC.

DIC consists of three species, which are the bicarbonate ion (HCO_3^-), the carbonate ion (CO_3^{2-}) and aqueous carbon (CO_{2aq}, or carbonic acid, H_2CO_3). The relative proportions of these three species relate to the pH of the water; HCO_3^- is the predominate species in river water. Carbonate minerals provide half of the HCO_3^-; the other half comes from the atmosphere and soil CO_2 [26••]. All HCO_3^- that is associated with silicate weathering is derived from the atmosphere and soil CO_2 [8]. The global riverine HCO_3^- flux has been estimated to be 0.33–0.44 Pg/y [1••,4••,26••,27–29].

In this investigation, DIC, HCO_3^- and alkalinity (a widely used inorganic carbon parameter) are assumed to be identical. Most published data are presented as concentration of HCO_3^- or alkalinity.

The mean discharge-weighted DIC concentrations vary by a factor of four among the tropical regions of various continents. They are 395, 434, 1064 and 1781 μM in tropical Africa, the Americas, Asia and Oceania, respectively (Table 1). Lithology is responsible for most of the variation. The percentage of carbonate rock, which has the highest weathering rate, is highest in Asia and lowest in South America [30•]. Tropical rivers provide 48–64% (0.21 Pg C/y) of the total global DIC flux, which is less than the proportion of global water discharge for which they are responsible (66.2%). The specific DIC yield (flux/area) varies by a factor of 15; the values are 0.63, 3.33, 9.79 and 3.38 gC/m^2/y in tropical Africa, the Americas, Asia and Oceania, respectively (Table 1). The DIC flux in Asia is the highest among the four regions, mainly because the percentage of carbonate rock is highest there. The discharge in Asia is the second highest and the ratio of freshwater discharge to land area is the highest (Table 1). With respect to latitudinal variations, DIC concentrations are generally low in equatorial rivers between 3°N and 6°S, but seem to increase with latitude (0°–30°N: Africa DIC = 210.13 + 25.35 × latitude (6), $r^2 = 0.58$, $p = 0.006$; the Americas DIC = 231.24 + 127.1 × latitude (7), $r^2 = 0.79$ $p < 0.001$; Asia DIC = 382.07 + 80.48 × latitude (8), $r^2 = 0.28$, $p < 0.001$; 30°S–0°: Africa, $p = 0.82$; the Americas, $p = 0.74$, Asia DIC = −401.6 + 376.19 × latitude (9), $r^2 = 0.53$, $p < 0.001$; Oceania DIC = 1118.8 + 42.42 × latitude (10), $r^2 = 0.22$, $p = 0.19$). This result is in line with the small topical areas of carbonate outcrops (Figure 3a). Usually, PIC participates in the transfer of carbonate and silicate rocks from highland to lowland.

The global PIC flux is estimated to be 0.17 Pg C/y based on an assumed PIC/TSM percentage of 1% [3•,31]. Available PIC data for tropical rivers are extremely limited, with no data available from the tropical Americas,

Table 1

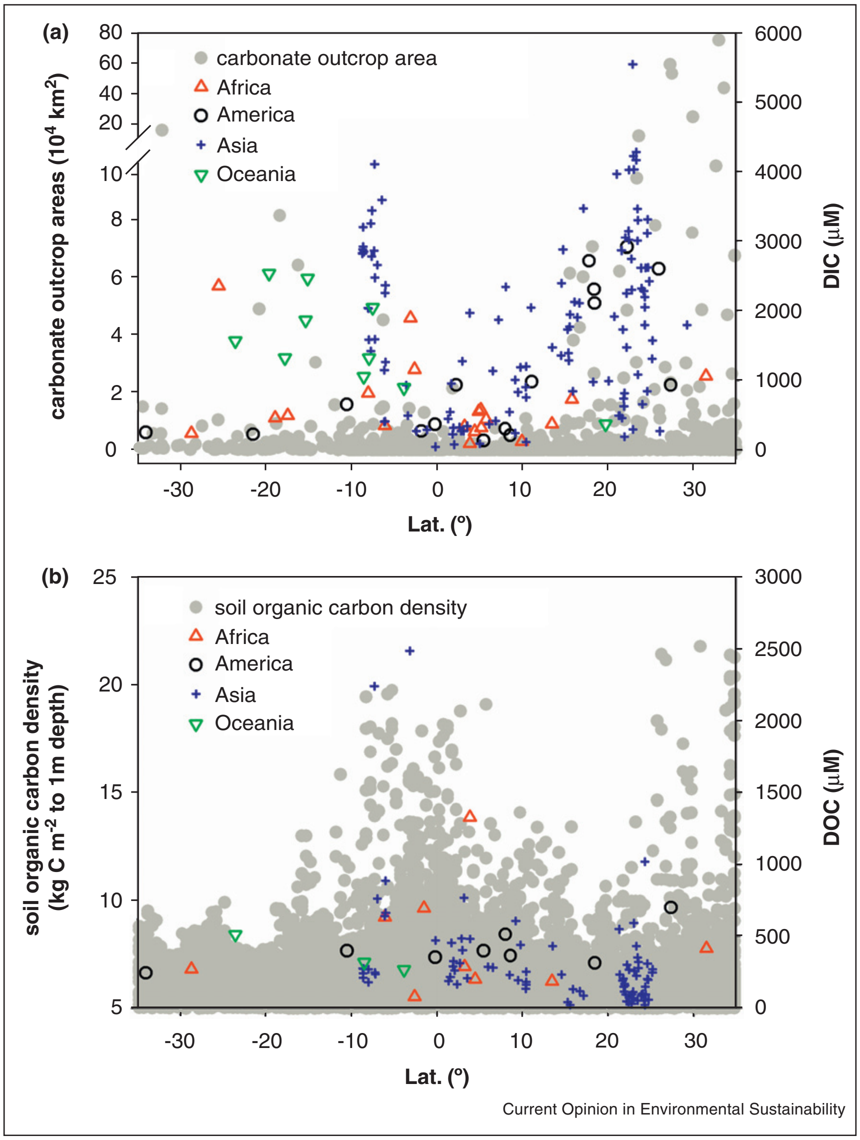
Basic information and mean concentrations of carbonate species and fluxes for tropical rivers of the four continents.

Continent (30°N–30°S)	Area[a] (km^2)	Discharge[a] (km^3/y)	Sediment[b] (tons/y)	Mean DIC (μM)	Mean DOC (μM)	Mean (%) PIC/TSM	Mean (%) POC/TSM	DIC flux (gC/y)	DOC flux (gC/y)	PIC flux (gC/y)	POC flux (gC/y)
Africa	28,100,202	3786	7.40×10^8	390	616	1.00	1.27	1.77×10^{13}	2.80×10^{13}	7.40×10^{12}	9.41×10^{12}
Americas	18,425,492	11,799	2.82×10^9	434	411	1.00	1.92	6.14×10^{13}	5.82×10^{13}	2.82×10^{13}	5.43×10^{13}
Asia	11,342,854	8694	4.91×10^9	1064	431	0.31	1.23	1.11×10^{14}	4.50×10^{13}	1.53×10^{13}	6.03×10^{13}
Oceania	5,915,568	934	4.85×10^8	1781	399	0.05	1.44	2.00×10^{13}	4.48×10^{12}	2.49×10^{11}	6.98×10^{12}
Total tropical area	6.38×10^7	25,213	8.96×10^9	695	448	0.57	1.46	2.10×10^{14}	1.36×10^{14}	5.12×10^{13}	1.31×10^{14}
Global	1.50×10^8	37,400[c] 38,170[d]	1.70×10^{10c} 1.81×10^{10d}	858[c] 714[d]	479[c] 450[d]	1.00[c] –	1.21[c] 1.04[d]	3.85×10^{14c} 3.27×10^{14d}	2.15×10^{14c} 2.06×10^{14d}	1.70×10^{14c}	2.05×10^{14c} 1.88×10^{14d}
Tropical/global (%)	42.7	67.4[c] 66.1[d]	52.7[c] 49.5[d]					54.6[c] 64.3[d]	63.1[c] 65.8[d]	30.1[c]	63.9[c] 69.8[d]

Continent (30°N–30°S)	DIC yield (gC/m^2/y)	DOC yield (gC/m^2/y)	PIC yield (gC/m^2/y)	POC yield (gC/m^2/y)	Total C yield (gC/m^2/y)
Africa	0.63	1.00	0.26	0.33	2.22
Americas	3.33	3.16	1.53	2.95	10.97
Asia	9.79	3.97	1.35	5.32	20.43
Oceania	3.38	0.76	0.04	1.18	5.35
Total tropical area	3.29	2.13	0.80	2.05	8.28
Global	2.58[c] 2.19[d]	1.44[c] 1.38[d]	1.14[c] –	1.37[c] 1.25[d]	6.52[c] 4.82[d]

References:
African rivers: [33,40,49–56].
American rivers: [33,56–67].
Asian rivers: [33,42,43••,44,56,68–75]; (Chen, unpublished).
Oceania rivers: [32,33,76–78].
[a] GRDC.
[b] WBM/WTM.
[c] Ref. [8].
[d] Ref. [1••].

Figure 3



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Latitudinal distribution of **(a)** DIC and carbonate outcrop areas (data from http://web.env.auckland.ac.nz/our_research/karst/) and **(b)** DOC concentrations and soil organic carbon density.

and with only one datum available each for Africa and Oceania. This fact has led to large inaccuracies in estimated PIC data [32,33]. The weighted mean PIC/TSM percentages are 1, 1, 0.31 and 0.05 in tropical Africa, the Americas (a conjecture based on the work of Meybeck [31]), Asia and Oceania, respectively (Table 1). The PIC fluxes are 7.40×10^{12}, 2.82×10^{13}, 1.53×10^{13} and 2.49×10^{11} g C/y in tropical Africa, the Americas, Asia and Oceania, respectively (Table 1). The ratio of tropical to global PIC flux (30.1%) is less than that of tropical to global surface area (42.7%), mainly because the PIC content of suspended matter is lower than has been previously conjectured. Moreover, the estimated sediment load of WBM/WTM adopted herein is only 63–93% of previously published values.

Organic carbon

Most fluvial organic material comes from soil, algae, the tissue of plants on land, pollution, geological features and groundwater [8,24,34]. The transport of organic material by rivers to the ocean is important to coastal heterotrophic organisms, even though riverine organic carbon represents only a small fraction (0.9%) of net global terrestrial primary production [35]. The global riverine organic material flux has been estimated to be 0.33–0.43 Pg C/y [3•,12,36–39].

The mean discharge-weighted DOC concentrations are 616, 411, 431, 399 μM in tropical Africa, the Americas, Asia and Oceania, respectively (Table 1). Equatorial rivers between 3°N and 6°S have higher DOC concentrations than those at other latitudes, and the pattern of DOC distribution is similar to the distribution of soil organic carbon density in the tropical region (Figure 3b). The high DOC concentrations of Africa, such as in the Nyong River, result mostly from plants and kaolinite, which are rich in old organic matter, in the river basin (1333 μM; [40,41]). In tropical Asia, and particularly in Indonesia, the unusually high DOC concentration (2200 μM) is characteristic of reported black-water rivers, and is caused by their basins mostly covered by peat [42,43••,44,45]. The DOC fluxes are 2.80×10^{13}, 5.82×10^{13}, 4.50×10^{13} and 4.48×10^{12} gC/y in tropical Africa, the Americas, Asia and Oceania, respectively, for a total DOC flux of 0.136 Pg C/y (Table 1). For comparison, Dai *et al.* ([46], this issue) obtained a value of 0.128 Pg C/y using a smaller database.

The global riverine particulate organic material flux is estimated to be 0.17–0.20 Pg C/y [8,12]. Owing to a lack of data, the summary of the POC concentrations in, and fluxes from, tropical rivers are subject to a larger error than for DIC. In this investigation, the POC percentage in suspended particles non-linearly decreases as TSM concentration increases, indicating that riverine POC is diluted with high concentrations of mineral matter that enters rivers through various erosion processes [12]. TSM concentration is estimated: herein as annual sediment flux divided by the discharge. This approach may underestimate tropical POC fluxes, however, because riverine POC flux increases exponentially in small mountainous rivers following a typhoon, which is a high-intensity, low-frequency event [47]. Additionally, the enhancement of soil erosion by agricultural processes has increased POC input [48]. The weighted-average POC percentages of TSM are 1.27, 1.92, 1.23 and 1.44 in tropical Africa, the Americas, Asia and Oceania, respectively (Table 1).

Conclusions

This investigation estimated fluvial carbon fluxes of tropical rivers from carbonate data for 175 rivers. Tropical rivers provide 0.53 Pg C/y of riverine carbon to the oceans, of which 39.8% is DIC, 25.7% is DOC, 9.7% is PIC, and 24.8% is POC. The largest DIC flux within the tropical region is found in Asia, because the DIC concentration is highest there and the discharge is second highest. The Americas have the highest DOC flux in the tropical area, owing to the sheer volume of discharge. The highest PIC flux in tropical regions is also found in the Americas because they have the highest PIC/TSM ratio and the second highest sediment load. Asia has the highest specific carbon yields in the tropical region, because of the high ratios of discharge to surface area, and sediment load to surface area. Anthropogenic activities, however, such as reducing sediment load and increasing the amount of detrital organic matter in rivers, may continue to change the fluvial carbon fluxes of tropical rivers.

Acknowledgements

We thank two unknown reviewers for their constructive comments. This research was partially supported by the National Science Council of Taiwan (NSC 98-2621-M-110-001-MY3, 99-2611-M-110-002-MY3) and the ‘Aim for the Top University Plan’.

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