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The carbon flux of global rivers: A re-evaluation of amount and spatial patterns

Mingxu Li[a], Changhui Peng[a,b,*], Meng Wang[a], Wei Xue[a], Kerou Zhang[a], Kefeng Wang[a], Guohua Shi[a], Qiuan Zhu[a,**]

[a] Center for Ecological Forecasting and Global Change, College of Forestry, Northwest A & F University, Yangling 712100, China
[b] Institute of Environment Sciences, Department of Biology Sciences, University of Quebec at Montreal, Case Postale 8888, Succursale Centre-Ville, Montreal Quebec H3C 3P8, Canada

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ABSTRACT

Global rivers connect three large carbon reservoirs in the world: soil, atmosphere, and ocean. The amount and spatial pattern of riverine carbon flux are essential for the global carbon budget but are still not well understood. Therefore, three linear regression models for riverine DOC (dissolved organic carbon), POC (particulate organic carbon), and DIC (dissolved inorganic carbon) fluxes were established with related generating and transfer factors based on an updated global database. The three models then were applied to simulate the spatial distribution of riverine DOC, POC, and DIC fluxes and to estimate the total global riverine carbon flux. The major conclusions of this study are as follows: the correlation analysis showed that riverine DOC flux is significantly related to discharge (r^2 = 0.93, n = 109) and soil organic carbon amount (r^2 = 0.60), POC flux increases with discharge (r^2 = 0.55, n = 98) and amount of soil erosion (r^2 = 0.48), and DIC flux is strongly linked to CO_2 consumption by rock weathering (r^2 = 0.66, n = 111) and discharge (r^2 = 0.63). In addition, Asia exports more DOC and POC than other continents and North America exports more DIC. The Atlantic Ocean accepts the major portion of riverine DOC, POC, and DIC fluxes of all the oceans. The highest riverine DOC flux occurs in the 0–30°S zone, and the highest riverine POC and DIC fluxes appear in the 30–60°N zone. Furthermore, re-estimation revealed that global rivers export approximately 1.06 Pg C to oceans every year, including 0.24 Pg DOC, 0.24 Pg POC, 0.41 Pg DIC, and 0.17 Pg PIC.

1. Introduction

Global exorheic rivers continuously transport carbon matter from terrestrial ecosystems and the atmosphere to oceanic carbon reservoirs, playing a critical role in the global carbon cycle and causing a wide range of biogeochemical and ecological consequences for river and coastal sea environments (Meybeck and Vörösmarty, 1999; Schlünz and Schneider, 2000; Raymond et al., 2013). According to solubility and biodegradation, riverine carbon can be classified into four forms: dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC), and particulate inorganic carbon (PIC). The source and composition of the four forms of riverine carbon are disparate, resulting in different responses to global change and human activities (Ludwig et al., 1996b). During the past few decades, there have been many attempts to explore the source as well as the spatial and temporal variations of different riverine carbon fluxes under increasing global climate change and intensifying anthropogenic perturbation conditions (Meybeck, 1982; Ludwig et al., 1996a; Huang et al., 2012; Zhang et al., 2013; Regnier et al., 2013).

In general, large-scale studies of riverine carbon flux arose with the project named 'Transport of Carbon and Minerals in Major World Rivers,' which was sponsored by SCOPE/UNEP (Scientific Committee on Problems of the Environment/United Nations Environment Programme) in the early 1980s (Ludwig et al., 1996a). One important conclusion of this global survey showed that approximately 1 Pg C is transported from the land to the ocean by world rivers every year, of which 40% is organic, including 0.22 Pg DOC and 0.18 Pg POC, and 60% is inorganic, including 0.43 Pg DIC and 0.17 Pg PIC (Probst et al., 1994). In subsequent studies, researchers gradually adopted empirical equations or simple models to estimate the riverine carbon flux using the factors that control river carbon fluxes from several rivers. Ludwig et al. (1996a) proposed empirical equations between riverine carbon fluxes (F_{DOC}, F_{POC}) and the climatic, biologic, and geomorphologic factors from 29 and 19 world river basins, respectively (Lueding et al.,

* Corresponding author at: Center for Ecological Forecasting and Global Change, College of Forestry, Northwest A & F University, Yangling, 712100, China.
** Corresponding author at: Center for Ecological Forecasting and Global Change, College of Forestry, Northwest A & F University, Yangling, 712100, China.
E-mail addresses: peng.changhui@uqam.ca (C. Peng), zhuqa@nwsuaf.edu.cn (Q. Zhu).

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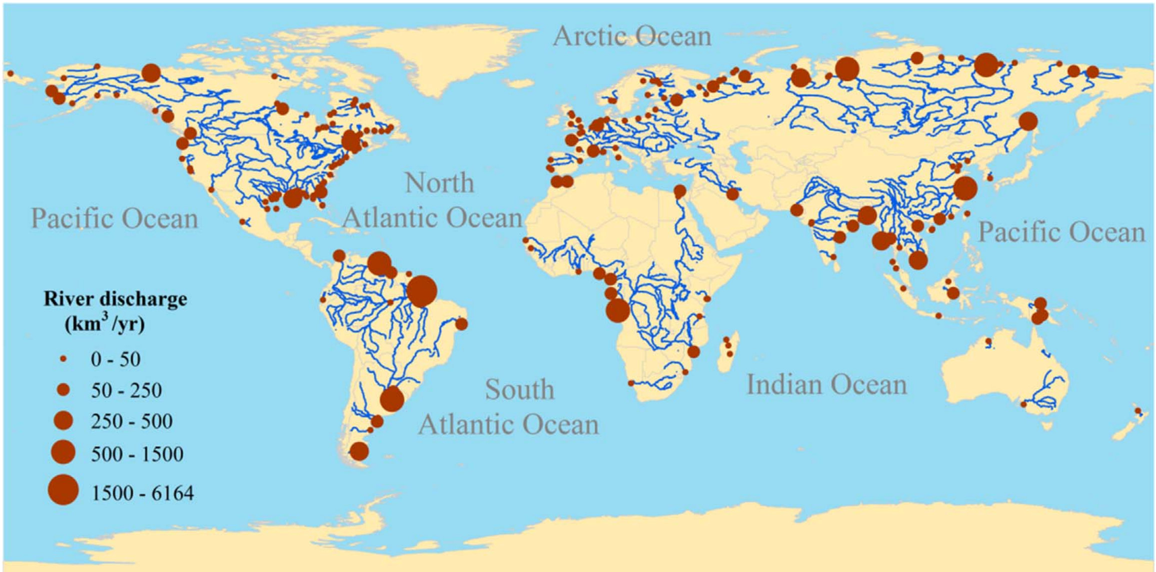

Fig. 1. Location and river discharge of study sites based on an updated global river database integrated with the GEMS-GLORI database and 115 published papers up to 2015.

1996). In addition, the authors noted that the main factors that determined the F_{DOC} were drainage intensity, basin slope, and the amount of soil carbon and the main factors that determined the F_{POC} were annual TSS (total suspended sediment) flux and the percentage of POC in TSAitkenhead and McDowell (2000) also estimated that the global river DOC flux was 0.36 Pg/yr with a significant correlation (r^2 = 0.99) between DOC fluxes and a soil C:N ratio from 164 world rivers grouped into 15 biome types.

Subsequently, several models have been created to estimate riverine carbon fluxes at different scales and regions. For example, Harrison et al. (2005) and Beusen et al. (2005) proposed the NEWS-DOC model as a function of annual runoff, wetland area, and consumptive water use and the NEWS-PNU model with concentration and flux of TSS, respectively, to predict global DOC and POC exports. Furthermore, on a watershed scale or larger, some models have been tested and applied to simulate riverine carbon flux, such as the DLEM (Dynamic Land Ecosystem Model) (Tian et al., 2015), RothC (Rothamsted organic carbon turnover model) (Skjemstad et al., 2004), and INCA-C models (the Integrated Catchments Model for Carbon) (Futter et al., 2007). These models attempt to explain the generation mechanism of riverine carbon and to demonstrate the temporal and spatial variation of this carbon. However, the detailed parameters and complex processes of these models may temporarily cause some difficulties when applying these models to a larger scale or global rivers.

Beyond these methods, field surveys would be the most accurate way to estimate the riverine carbon fluxes on a regional scale, but field surveys may not be the best option for most researchers because they require huge payouts of manpower and materials every year on a global scale. Most of the previous studies regarding the empirical equation between fluvial carbon flux and environmental factors generally referred to Ludwig et al. (1996a) method. This method involves the construction of multivariate models to estimate riverine DOC and POC fluxes based on a database that only included some large rivers (n = 29 for DOC; n = 19 for POC). Furthermore, in this method, relevant data regarding riverine TSS flux are not easy to acquire for all world rivers. There are ways to simulate TSS flux, such as the WBM/WTM model (Water Balance and Transport Model of the University of New Hampshire) (Milliman and Syvitski, 1992; Syvitski et al., 2003). In addition, Huang et al. (2012) used TSS flux simulated by the WBM/WTM model to predict POC and PIC fluxes in tropical rivers; however, there was a negative result in part due to the low simulated TSS values compared with the measured values. Estimations of global riverine inorganic carbon are relatively rare and conflicting (Degens et al., 1991; Ludwig et al., 1996b). Moreover, because of climate change and anthropogenic disturbances, riverine carbon flux has greatly changed in recent years (Raymond et al., 2008; Cai, 2011; Hu et al., 2015). Therefore, a simplified and effective way to re-estimate recent riverine carbon flux of rivers worldwide needs to be proposed. In this study, we did not consider PIC flux as less data information in previous studies. And PIC flux is generally not taken into account in the global carbon budget because PIC is gradually trapped in lowlands, floodplains, lakes, estuaries and on the continental shelf before reaching the coast (Ciais et al., 2006; Cauwet and Mackenzie, 1993; Probst et al., 1994).

To address these limitations, we created a new database for global riverine carbon flux based on the GEMS-GLORI dadabase (GEMS/WATER Global Register of River Inputs database) (Meybeck and Ragu, 2012) and updated data from 115 papers published up to 2015. The objectives of this study are as follows: (1) to analyze the critical factors for riverine carbon flux and establish empirical models for riverine DOC, POC, and DIC; (2) to explore the spatial distribution pattern of riverine DOC, POC, and DIC fluxes; and (3) to re-estimate the amount of global riverine carbon fluxes from the land to the ocean.

2. Materials and methods

2.1. Database of global river carbon flux and other ancillary data

The updated global riverine carbon database includes 263 global rivers from throughout all of the continents except for Antarctica and Greenland (Fig. 1). During data collection, we used the following three criteria: (1) we adopted only those sampling sites that were close to estuaries in the main streams for each river and recorded the location information of the sampling site during data collection; (2) we adopted the most recent carbon flux if it revealed obvious changes compared with previous studies, i.e., the POC flux of the Yellow River (Hu et al., 2015), or calculated the average if the change of the carbon flux from different years was not obvious; (3) all endorheic rivers and lakes were not included in our database despite their larger discharge and basin area among the global rivers, e.g., Volga, Ural, Lake Chad, and other water bodies.

Meteorological data (monthly precipitation and air temperature, 1981–2013) were derived from the CRU dataset (Climate Research Unit, TS 3.24, 0.5° × 0.5°) (Harris et al., 2014). Topography data (slope length and slope grade) were calculated using ETOPO5 dataset (5-min