Carbon Dioxide Emission from Streams and Rivers as an Integrative Part of Terrestrial Respiration

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Abstract

Streams and rivers emit significant CO_2 to the atmosphere and are ecologically heterotrophic receiving carbon inputs from the terrestrial ecosystem. Despite close coupling between two ecosystems, CO_2 emission from streams and rivers has never been integrated or compared to other terrestrial carbon fluxes. Here a framework integrating stream and river CO_2 emission to terrestrial carbon fluxes was proposed for a better perspective of the role of streams and rivers in global carbon cycle. Using terrestrial net primary product (NPP) as the base for comparison, it is found that streams and rivers emitted more carbon than expected from their areal extent on the landscape. This elevated role of streams and rivers in releasing terrestrial carbon to the atmosphere is believed to result from a disproportional transfer of terrestrial carbon (both organic and gaseous) to the inland waters. Correlations between riverine carbon emissions and areal extent of the flowing waters suggest a hydrology-driven mediation of terrestrial carbon release by streams and rivers.

Keywords: Carbon dioxide; River; Global carbon cycle; Inland waters; Terrestrial respiration

Short Communication

Streams and rivers participate in the global biogeochemical cycle of carbon not only by laterally transferring carbon from the terrestrial landscape to inland waters but also transforming and releasing large quantities of carbon as CO_2 to the atmosphere [1-7]. Oversaturated CO_2 in inland waters is either internally produced from aquatic organic carbon degradation or externally flushed from catchment soils [7-9]. From an aquatic ecology point of view, inland waters are net heterotrophic because they mostly release significantly more CO_2 as a respiration product than they assimilate CO_2 through *in situ* aquatic primary production [10,11]. As both river organic carbon and excess CO_2 are dominantly from the terrestrial landscape, heterotrophy in aquatic ecosystems must not be viewed individually as an independent process but collectively as part of a larger biogeochemical cycle. From the point of view of a coupled biogeochemical cycle, net heterotrophy and excess CO_2 emission from inland waters represent a part of the terrestrial respiration that is no more distinguishable from the rest of terrestrial carbon fluxes (e.g., heterotrophic soil respiration) [5-12]. However, while a few studies propose to link the aquatic CO_2 emission to terrestrial carbon fluxes [11,13,14], no systematic comparison has been made between the magnitude of aquatic CO_2 emission and terrestrial carbon fluxes from the perspective of a combined biogeochemical cycle of carbon on land and in inland waters.

Herein I propose a framework that integrates CO_2 emission from streams and rivers to carbon fluxes of the terrestrial ecosystem. Essentially, magnitudes of CO_2 emission from regional rivers were compared with net primary production (NPP) of their coupled terrestrial ecosystem (i.e., ratio of carbon emission from rivers to regional NPP, Table 1). Importance of carbon emission from the rivers with respect to the terrestrial carbon fluxes was further assessed using an elevation ratio (ER) defined as the ratio of riverine carbon emission to regional NPP, divided by the ratio of the areal extent of the river network to total land area of the study region/catchment (see footnote of Table 1). CO_2 emission estimates from rivers were made by independent authors by scaling up multi-location emission rates to the whole study region/catchment and compiled here for analysis. The assumption is that from the perspective of an integrated terrestrial and aquatic carbon cycle, terrestrial NPP

represents the maximum amount of ecosystem products that are available for heterotrophic respiration in both terrestrial ecosystem and linked aquatic ecosystems [15,16].

The elevation ratio (ER) calculations show that the reviewed river networks, covering eight orders of magnitude in land area, exhibited higher carbon emission to terrestrial NPP ratios than indicated by the areal extent of their fluvial channels on land (i.e., ER > 1; Table 1). Elevation ratios also varied greatly at different spatial scales and climate zones. For example, small catchments (with catchment areas ranging from <1 to 160km^2) had ERs ranging from 1.5 to 7.8 [17-21] and the highest value of 16 was found in a 1.3km^2 peat land catchment in Scotland [17].

The highest values are likely associated with substantial lateral convey of soil CO_2 from the terrestrial ecosystem to the stream networks [18-21]. Large river networks (areas > 7.5×10^4km^2) in temperate regions generally had higher ERs than rivers in tropical regions: 2-5 versus ~1 [1,7,12,22-24] (Table 1). This 2-to-5fold difference suggests temperate rivers released higher portions of terrestrial NPP to the atmosphere than tropical rivers as to tropical ecosystems despite lower areal extents of the temperate rivers (Table 1). This is thought to be related to significantly lower terrestrial NPP in temperate than in tropical ecosystems [25-27]; carbon emission rates were however comparable between temperate and tropical rivers (Table 1).

Table 1: A synthesis of CO_2 emission from river networks and its relationship with regional terrestrial NPP.

Stream \ River	Region / Catchment Area* (km^2)	Stream Order	Region / Catchment Terrestrial NPP◊ (Tg yr^{-1})	Mean Water Surface CO_2 Emission Rate*(g Cm^{-2}yr^{-1})	Ratio of River Surface Area to Region / Catchment Area* (%)	Ratio of Carbon Emission from Rivers to Regional Terrestrial NPP (%)	Elevation Ratio∆
Streams							
West Fork of Walker Branch, Tennessee	0.38	1	1.9×10^{-4}	1104	0.26	0.4	1.5
Rocky Burn Stream near Aberdeen, Scotland	1.3	1	6.5×10^{-4}	8428	0.17	2.8	16
Streams near Juruena in Mato Grosso, Brazil	6	1-2	4.8×10^{-3}	2271	1.8	4.97	2.8
Streams at Tanguro Ranch, Mato Grosso, Brazil	13.2	1	1.1×10^{-2}	5994	0.007	0.055	7.8
Streams in Paragominas, Pará, Brazil	32.5-161	-	26.6	–	0.15	0.25-0.5	1.7-3.3
Tropical River Networks							
Ji-Paraná River at Rondônia, Brazil	75400	3-6	61	2233	0.45	0.47	1
Mekong River	7.95×10^5	-	639	852	1	1.1	1.1
Amazon River	1.8×10^6	?-12	3180	830	14.3	14.9	1
Temperate River Networks							
Yellow River, China	7.5×10^5	1-6	372	1065	0.4	0.72	1.8
Sweden streams and rivers	4.5×10^5	1-5	171	473-3032	0.1	0.5	5
Conterminous US streams and rivers	7.8×10^6	1-10	3.860×10^3	882-4008	0.52	2.5	4.8
Global Estimates							
Global○	1.33×10^8	–	5.35×10^4	890-2880	0.47	1.0–3.4	2.1-7.2

*Data of catchment area, water surface area, and carbon emission rate were obtained from ref. 1, 6, 7, 12, 17-24. ◊NPP for conterminous US is obtained from supplementary ref. 25, and its area-averaged value (495g m^{-2} yr^{-1}) is used for calculating regional NPP in temperate basins (the Yellow River basin, the Scotland and Tennessee stream); NPP for the Amazon basin is obtained from ref. 26 (by proportioning relevant NPP to the studied area in ref. 1), and its area-averaged value (804g m^{-2} yr^{-1}) is used for calculating NPP of rivers in the same region (the Brazilian streams and rivers) and the tropical Mekong River; NPP for Sweden (380g m^{-2} yr^{-1}) is obtained from ref. 27 (area-averaged NPP was used in order that different land uses are equally represented). ∆ = Ratio of river water surface to catchment area / Ratio of C emission from rivers to regional NPP. ○Antarctic is excluded from the Earth land surface area; global terrestrial NPP is obtained from supplementary ref. 26; global C emission (0.56-1.8Pg yr^{-1}) from streams and rivers are obtained from ref. 2, 3, 6; area of global streams and rivers are obtained from ref. 6.

This analysis suggests CO_2 emission from streams and rivers comprises a variable part of terrestrial carbon fluxes, representing <1–16% of terrestrial NPP depending on different spatial scales and climates. Considering higher carbon emission from streams and rivers than expected from their areal extent on the landscape (i.e., ER > 1), it is suggested that carbon emission from rivers represents an elevated portion of terrestrial carbon release to the atmosphere in comparison to other terrestrial carbon fluxes. Globally, about 0.47% of the Earth surface occupied by fluvial channels released carbon in quantities representing 1.0-3.4% of the global terrestrial NPP (Table 1). Despite a still large uncertainty in current estimates of the CO_2 emission fluxes from global streams and rivers (0.56-1.8Pg C yr^{-1}) [2,3,6], available data clearly highlight streams and rivers as hotspot of carbon emission from the terrestrial landscape. Neglecting CO_2 emission from streams and rivers in land-atmosphere carbon exchanges (for instance, the Intergovernmental Panel on Climate Change 2007 (IPCC 2007) report omitted carbon released from global inland waters; the new IPCC 2013 report has however included this carbon flux), therefore, misses a small but disproportionally active player in the global carbon cycle.

Elevated carbon emission from streams and rivers is thought to be related to disproportional transfer of terrestrial carbon to these inland waters during hydrological processes (Figure 1). First, CO_2 produced by heterotrophic degradation of organic carbon in soils and plant root respiration accumulates to high concentrations in soils due to limited gas diffusivity and ventilation [18,20]. Soil CO_2 is however easily mobilized and incorporated into local streams and rivers, sustaining high carbon emissions especially from streams and small rivers which are of high connectivity to the terrestrial ecosystem and make up a significant portion of the river network [6-8]. Second, there is a differential effect for soil organic carbon whereby lighter and organic-rich soils are preferentially mobilized, leached and transported to streams and rivers during hydrological processes, resulting in a relative enrichment of land-sourced labile organic carbon in rivers [28]. Degradation of river organic carbon is further facilitated by favourable aquatic conditions (e.g. rich microbial biodiversity) that allow for efficient mineralization river organic carbon during transport [8,10]. Finally, high turbulence in streams and rivers allows for quick evasion of the gas to the atmosphere in comparison with soils that are relatively less frequently disturbed [7,21,29] (Figure 2).

Figure 1: CO_2 emission from streams and rivers as an integrative part of terrestrial respiration. The disproportional role of streams and rivers in emitting terrestrial carbon to the atmosphere is strengthened by (a) high input of soil CO_2 to streams and small rivers, (b) differential transport of organic rich soils to streams and rivers and (c) high turbulence in streams and rivers that facilitates quick evasion of the gas to the atmosphere.

In a sense, excess CO_2 emission from streams and rivers represents a part of the terrestrial carbon that is released under mediation of the flowing surface waters of the Earth and is further deduced to vary spatially with the spatial extent of these waters. In this case, a strong positive relationship was found between the areal extent of river networks and rate of riverine carbon emission normalized to catchment area or the ratio of riverine carbon emission to terrestrial NPP (R_2 = 0.85 and 0.75, respectively) (Figure 2), suggesting hydrology as the primary driver of the carbon emission from streams and rivers [7,30].
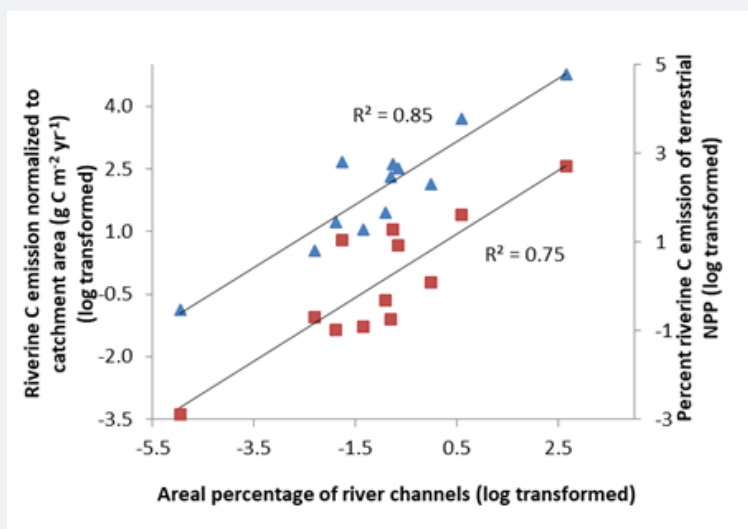
Figure 2: Positive correlations between areal extent of river networks and riverine carbon emission rate normalized to catchment area (▲) and percentage riverine carbon emission of annual terrestrial NPP (■). Riverine carbon emission rate normalized to catchment area was calculated as the total amount of CO_2 emission from rivers (g C yr^{-1}) divided by catchment area (m^2). Percentage riverine carbon emission of annual terrestrial NPP was calculated as the total amount of CO_2 emission from rivers (g C yr^{-1}) divided by catchment terrestrial NPP (g C yr^{-1}). All data were natural log transformed.

To summarize, a framework that links CO_2 emission from streams and rivers to terrestrial carbon fluxes was proposed for a better understanding of the role of streams and rivers in global carbon cycle. Emission of CO_2 from riverine channels represents an elevated portion of terrestrial carbon that is released to the atmosphere by streams and rivers; however, mechanisms that dictate the elevated role of streams and rivers in terrestrial carbon cycle are still uncertain. New comparative studies of ecological functions of terrestrial soils and inland waters would help resolve this problem.

Acknowledgement

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