Global transfer of carbon by rivers

by Michel Meybeck and Charles Vörösmarty

The global system of rivers is increasingly being recognized as a major component of the biogeochemistry of our planet, as demonstrated nearly 30 years ago in the pioneering work of Garrels and Mackenzie (1). Rivers indeed serve an important role in the terrestrial water cycle, regulating the mobilization and transport of constituents from the continental land mass to the world's coastal oceans. Riverine constituent fluxes arise from a complex suite of physical, biotic, and anthropogenic processes that are well-exemplified by the sources, transport, and fates of waterborne carbon. Although riverine C fluxes are a minor component of the global carbon circulation, they are very sensitive to regional and global change. Dissolved Inorganic Carbon (DIC), derived from silicate weathering and linked to tectonics, is also believed to be a major control of atmospheric CO_2 over geological time frames (2).

The basic nature of riverine carbon

Rivers carry multiple forms of carbon, including particulate organic (POC) and inorganic (PIC) carbon, dissolved organic (DOC) and inorganic carbon (DIC, generally in the form of HCO_3^-) and dissolved CO_2. Their origins are multiple (1, 3-9) (see Table 1). This transport has been particularly studied in the 1980s for many major world rivers within the SCOPE-Carbon Programme (10). For POC the major source is mechanical erosion of carbonated rocks (i.e. limestone and loess) and of carbonaceous sedimentary rocks (i.e. shales, loess) containing highly resistant kerogens. For DIC chemical weathering of carbonate rock is also important, providing about half; the other half comes from atmospheric and soil CO_2. POC and DOC arise from leaching and erosion of topsoil and peat, as well as direct atmospheric CO_2 exchange within water bodies, regulated by pH. Organic carbon in rivers also arises from autochthonous production of organic matter in aquatic systems (POC), sometimes associated with *in situ* calcite precipitation and, more recently, direct organic waste discharge of DOC and POC from agriculture, cities, and industries.

River carbon "ages" (9), measured as the elapsed time since the initial atmospheric CO_2 uptake (see Table 1), range from a few hours for the short-term regulation of dissolved CO_2 to some hundreds of millions of years for the weathering of ancient carbonate rocks. "Total Atmospheric Carbon" (TAC), of special interest for the global change research community, has been defined as the sum of dissolved CO_2, DOC, the part of DIC originating from soil CO_2, autochthonous POC and PIC, soil POC, and organic pollution (9). River TAC is thus of relatively recent age, 10^0 to 10^3 years. At the global scale riverine TAC represents only a few percent of the net primary productivity of the continents (4). The regional pattern of this fraction is not yet known – in poorly drained river basins it is probably much higher. The concentration of total riverine carbon (TC) ranges from less than 5 mg L^{-1} for some sub-Sahelian rivers devoid of carbonated rocks (e.g. Gambia) up to 800 mg L^{-1} for the Huang He basin in China, which erodes the carbonated loess (age 50,000 yr). For basins like the Gambia, TAC/TC = 100%; for the Huang He, where mechanical erosion is maximum, this ratio is only 5% including the rarely found autochtonous PIC. TAC export rates typically vary over one order of magnitude while sediment transport rates vary over 2 to 3 orders of magni-

Table 1. Riverine carbon transfer and global change

	Sources	Age (y)	Flux #	Sensitivity to global change					
				A	B	C	D	E	F
PIC	Geologic	10^4-10^8	170	●					●
DIC	Geologic	10^4-10^8	140		●	●			●
	Atmospheric	0-10^2	245		●	●			●
DOC	Soils	10^0-10^3	200			●			●
	Pollution	10^{-2}-10^{-1}	(15)?					●	
CO_2	Atmospheric	0	(20 to 80)		●	●	●		
POC	Soil	10^0-10^3	(100)	●					●
	Algal	10^{-2}	(<10)				●		●
	Pollution	10^{-2}-10^0	(15)					●	
	Geologic	10^4-10^8	(80)	●					●

(#) present global flux to oceans mostly based on (8) and (9), 10^{12}gCy^{-1}
A = Land erosion; B = chemical weathering; C = Global warming and UV changes; D = eutrophication; E = organic pollution, F = basin management

tude (8-9).

There are several natural controls on C concentrations and fluxes in rivers, including parent rock lithology, soil type, climate, river flow velocity, river runoff, aquatic primary production and bacterial respiration (5) (11), UVB exposure (12), and river pH (5). Nonetheless, it has been found that river runoff acts as the prime controlling factor for carbon export, on which several of the current generation of global models have been based (13-17).

The changing nature of riverine carbon flux

There are numerous physical, geologic, biotic, and anthropogenic forces that have shaped the status of riverborne C over geologic and historical times. Since the Last Glacial Maximum the spatial organization of the continental land mass and its connection to the world's oceans has changed greatly. These changes are reflected in several geomorphometric indices, including the ratio of exorheic: endorheic land mass (flowing to oceans vs. internal drainage), rheic: arheic area (flowing vs. non-flowing), the extent of continental shelf exposed to weathering, ice cover, and land cover (13). In addition, the availability of continental runoff, which is sensitive to climate change, regulates the horizontal transport of water and hence C to the various ocean and internal receiving waters (18). Permafrost melting and leaching of post-glacial peat deposits are also major sources of DOC in Arctic rivers, highly sensitive to climate variations.

Anthropogenic change may be an especially important factor in the future, although gradual increases in atmospheric CO_2 might not themselves be critical in chemical weathering which is more related to soil pCO_2. Accelerated permafrost melting and change of UVB irradiance, which enhances DOC bacterial degradation after photolysis (12), will be key players in the future of global river C as well. In addition, land-use and land-cover changes, such as wetland filling and the decrease of organic soil carbon content through industrial fertilization of agricultural land, will be important. Land erosion will accelerate particulate carbon transfer but most of it may not ultimately reach the ocean due to storage on slopes, in floodplains, lakes and reservoirs. Lake and reservoir eutrophication may also store particulate carbon for 10^2 to 10^4 years (19-22). Direct waste emissions of organic material into rivers represents a large potential C source since the sewage treatment rate does not yet match overall population growth. However, this organic matter is mostly labile and most of it is degraded within some weeks or even days, as shown on the Seine River downstream of Paris (11). River eutrophication, now widely developed in low-turbidity, nutrient-saturated rivers, may add up to 6 mg L^{-1} of algal POC, highly labile, which can create near-anoxic conditions when reaching turbid coastal waters like the estuaries of Western Europe. A global data base for large reservoirs has already demonstrated a "runoff aging" up to 2 years for some basins (23), which allows for more in-basin aquatic processing of riverine carbon, as well as an enhanced sediment storage, estimated now to be at least 25% of global river flux (24).

Future carbon transfers through river basins will be accelerated with respect to both sources and sinks. However, the final global trend is not yet known and the evolution of regional problems will probably show counteracting tendencies, making for an interesting and challenging global change question. A careful accounting of the key controls is now being pursued by several teams using process studies and modeling (11) as well as global GIS and multiple regression analysis where lithology, relief and runoff are key factors (13-17). A set of working scenarios for future river response to all global changes has already been proposed by R. Stallard (21), taking into account various land-use practices. New global data bases have been established or are planned within IGBP through PAGES, BAHC, and LOICZ (25) to estimate riverine carbon and allied biogeochemical constituent fluxes.

Using these IGBP activities as a focal point, several key issues relating to riverborne C could be considered. Estimates of present-day fluxes of total DOC, total POC and DIC are now converging, although the breakdown of these in various sources is still not well known (see an attempt in Table 1) nor mapped at the global scale. A hotly-debated question concerns the quantity of recycled fossil POC originating from sedimentary rocks. It has been proposed that it could constitute up to 55% of total POC flux (8, 9), and, from ^{14}C analysis, it was estimated to be 70% in one highly eroded sedimentary basin (26). One important goal of forthcoming riverine carbon studies could be the reconstruction of the spatial distribution of river fluxes at various periods from the last glacial maximum to the present and into the future. Direct human impacts from organic waste inputs and eutrophication on DOC, POC and dissolved CO_2 fluxes are not well known at the global scale. Although these fluxes are probably minor compared to the other TAC components (see Table 1), their impact on local oxygen balance in rivers, lakes and estuaries is enormous. A study of these fluxes is thus a legitimate part of the larger global change question, encompassing not only global biogeochemistry, but also human and ecosystem health. Current IGBP activities targeted at river case studies, process modelling, and drainage basin typologies will yield a geographically-specific picture of riverine C response to climate and anthropogenic change at the global scale and form a a critical linkage within emerging Earth Systems Models (25, 27-30).

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