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Transport of terrestrial organic carbon to the oceans by rivers: re-estimating flux- and burial rates

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Abstract This study re-estimates one important component in the global carbon cycle: the modern global fluvial terrestrial organic carbon discharge- and burial rates. According to these results, approximately $430 \times 10^{12} \text{ g}$ of terrestrial organic carbon are transported to the ocean in modern times. This amount is higher than the latest estimates but takes into account new data from Oceania not previously considered in global flux studies. However, only the minor amount of 10% or approximately $43 \times 10^{12} \text{ gC year}^{-1}$ is most likely buried in marine sediments. This amount is similar to the burial of marine organic carbon in the coastal ocean ($55 \times 10^{12} \text{ gC year}^{-1}$). Adding both estimates gives approximately $100 \times 10^{12} \text{ gC year}^{-1}$, which is the value calculated by Berner (1982) for “terrestrial” deltaic-shelf sediments. However, the results in this study suggest that on a global scale the organic carbon content in coastal ocean sediments is not solely of terrestrial origin but a mixture of nearly equal amounts of marine and terrestrial organic carbon. The major part of the terrestrial organic carbon that enters the ocean by rivers (approximately $400 \times 10^{12} \text{ gC year}^{-1}$) seems to be either (a) remineralised in the ocean, whereas the mechanism by which the terrestrial organic carbon is oxidised in the ocean are unknown; or (b) is dispersed throughout the oceans and accumulates in pelagic sediments.

Key words Carbon cycle · Terrestrial organic carbon · Fluvial organic carbon discharge · Organic carbon burial rate · Organic carbon budget

Introduction

Models which attempt to balance the biogeochemical carbon cycle on a global scale (Woodwell et al. 1978; Broecker et al. 1979; Tans et al. 1990; IPCC 1992; IPCC 1995; Sarmiento and Sundquist 1992; Langenfelds et al. 1997; Bender et al. 1997; Rayner et al. 1997) do have problems when anthropogenic combustions of fossil fuels and deforestation are included. The main problem is to recognise all the different pathways in the terrestrial and marine subcycles, as well as uncertainties in the amount of the various carbon fluxes. Therefore, for the understanding of the global carbon cycle it is important to quantify and balance the various carbon fluxes.

This paper focuses on one important component in the global carbon cycle: the transport of terrestrial organic carbon (OC) from land to the ocean by rivers and its burial in marine sediments.

Generally, terrestrial OC is supplied to the world oceans by rivers, by wind and in high latitudes by icebergs or sea ice. There is little data available which enables a realistic estimation of average total flux rates of terrestrial OC by glaciomarine deposition in high-latitude oceans (Wagner and Dupont 1999). Also the aeolian supply of terrestrial OC to the sea is difficult to quantify because variable wind systems and wind speeds give a very complex terrestrial OC distribution pattern. According to Romankevich (1984) the total global aeolian flux of terrestrial OC to the ocean may be as large as $320 \times 10^{12} \text{ gC year}^{-1}$, and may be important at open ocean sites where the aeolian input appears to be comparable to the flux of marine-derived organic matter to surface sediments (Zafiriou et al. 1985). The transport of total OC from land to the ocean by rivers is much better studied. Latest estimates of the quantity of OC runoff from land via rivers vary from $334.5 \times 10^{12} \text{ gC year}^{-1}$ (Degens et al. 1991) to $368 \times 10^{12} \text{ gC year}^{-1}$ (Meybeck 1993) and $380 \times 10^{12} \text{ gC year}^{-1}$ (Ludwig et al. 1996).
The total annual OC discharge of major world rivers is shown in Fig. 1. Obviously the largest quantities of OC are transported by wet tropical rivers, such as, for example, the Amazon ($31 \times 10^{12}$ gC year$^{-1}$; Richey et al. 1991), Congo ($12.95 \times 10^{12}$ gC year$^{-1}$; Martins and Probst 1991) and the high number of small rivers draining Oceania ($90 \times 10^{12}$ gC year$^{-1}$; Nittouer et al. 1995). Changing oceanic processes which operate adjacent to river mouths control whether the organic material is trapped, bypassed or transformed on the continental margins (Nittouer et al. 1995).

During the Holocene sea-level high stand most of the sediments discharged by the world rivers are deposited almost entirely on the continental shelves (Berner 1982; Berner 1989; Hedges 1992). This is the result of the postglacial rise in sea level which has been much too fast to allow sediment deposition to keep pace. Consequently, the OC that enters the marine environment via rivers affects mainly the coastal zone with only little bypassed to the deep sea. However, some of the world rivers discharge their terrestrial OC load beyond the continental shelf (a) in turbidity currents down submarine canyons (Congo, Ganges, Brahmaputra), (b) over a narrow shelf (i.e. the small rivers draining New Guinea) or (c) in high latitudes by sea ice (i.e. Lena, Ob). These transport mechanisms mimic processes more common in times of sea-level lowstands.

Transport of OC in rivers is divided into two fractions: dissolved and particulate OC. The dissolved load is derived largely from rainfall and soil processes, including leaching of plant litter and chemical weathering. The particulate load, dominated by the products of mechanical weathering, represents erosion and sediment transport from the surface of the soil. Globally, 35% of the riverine particulate OC belongs to the labile fraction and may become oxidised in the marine environment, whereas the rest appears to be highly degraded, with the bulk entering the tropical and subtropical ocean (Fig. 1; Ittekkot 1988). Land-derived OC that flows to the oceans in rivers includes not only recently biosynthesised plant debris and dissolved humic substances accompanied by older soil humus, but also recycled fossil OC eroded from sedimentary rocks (Hedges et al. 1986). From the nature of the mineral fraction the organic matter is very often associated with clay (Konta 1985). Both, the high degradation and the close association to clay minerals, render the organic matter less susceptible to further degradation, which for this reason has at least partly the chance to accumulate in marine sediments (Ittekkot 1988). Despite the huge amount of reduced terrestrial OC transported to the oceans, its relative resistance to microbial degradation and the knowledge of several terrestrial biomarkers which can be investigated, there is only little evidence for terrestrial OC to be a major component of organic mixtures in sea-water and marine sediments (Hedges and Keil 1995). However, most of the terrestrial OC load of rivers draining into the Arctic Ocean (i.e. Lena) is accumulated in near-coastal zones but is also transported further offshore by different processes such as sea ice, ocean currents and turbidity currents (Stein and Koroel 1994; Schubert and Stein 1996, 1997; Fahl and Stein 1997). One of the major problems associated with the calculation of the actual flux of riverine carbon to the ocean is the uncertainty concerning the amount of organic carbon decomposed in estuarine and coastal environments (Ittekkot and Laane 1991).

To more properly address the question of the fate of terrestrial OC in the marine environment, a re-estimate of modern fluvial terrestrial OC discharge and burial rates is performed on a global scale. This should enable a better estimation of the portion of terrestrial OC which survives degradation until fixed in marine sediments and how much this amount is in relation to the burial of marine OC.