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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 fluviatile organic carbon discharge- and burial rates. According to these results, approximately 430×10^{12} 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 43×10^{12} 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 (55×10^{12} gC year^{-1}). Adding both estimates gives approximately 100×10^{12} 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 400×10^{12} 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

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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 320×10^{12} 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 334.5×10^{12} gC year^{-1} (Degens et al. 1991) to 368×10^{12} gC year^{-1} (Meybeck 1993) and 380×10^{12} 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 (31×10^{12} gC year^{-1}; Richey et al. 1991), Congo (12.95×10^{12} gC year^{-1}; Martins and Probst 1991) and the high number of small rivers draining Oceania (90×10^{12} gC year^{-1}; Nittrouer 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 (Nittrouer 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 Korolev 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 fluviatile 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.

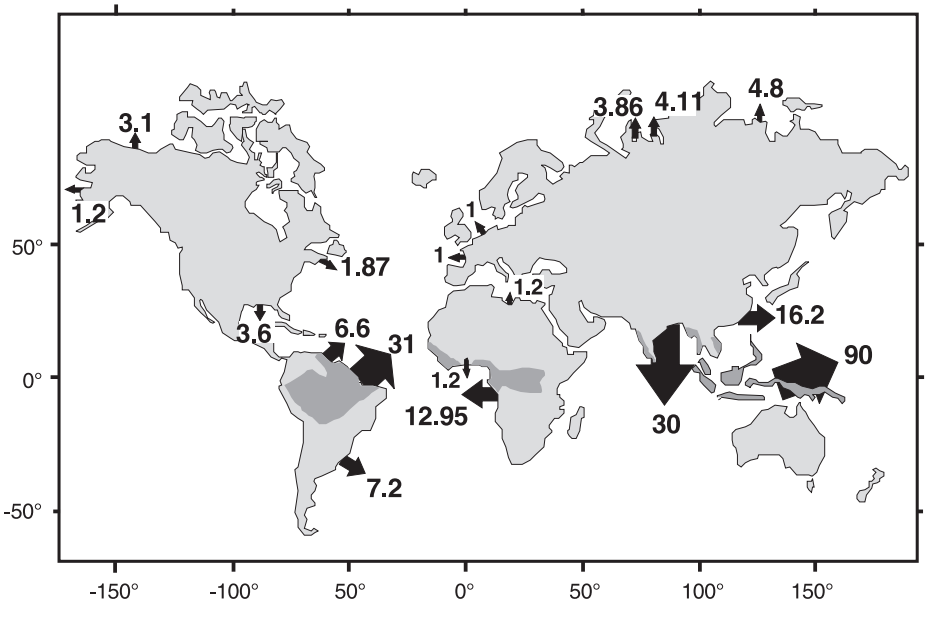

Fig. 1 Annual discharge of total organic carbon of major world rivers to the oceans (organic carbon fluxes are in 10^{12} gC year^{-1}; wet tropics are underlain in *dark grey*). Data are from: Telang et al. (1991; Mackenzie, Yukon, St. Lawrence, Mississippi); Depetris and Paolini (1991; Orinoco, Parana); Richey et al. (1991; Amazon); Martins and Probst (1991; Zaire, Niger); Degens et al. (1991; Nile); Kempe et al. (1991; Rhine + Elbe, Seine + Loire + Gironde); Telang et al. (1991; Ob, Yenisei, Lena); Gan-Wei-Bin et al. (1983; Yangtze); Subramanian and Ittekkot (1991; Ganges + Brahmaputra + Indus); Bird et al. (1995; Oceania)

Re-estimating the terrestrial OC input to the ocean by rivers

An overview on past estimates for the global annual quantity of terrestrial OC runoff from land to the oceans calculated in the past 30 years is given in Table 1. Obviously, these fluxes vary by nearly two orders of magnitude from 30 to 1000×10^{12} gC year^{-1}. Ignoring the highest and lowest estimates, averaged fluxes of worldwide input of terrestrial OC to the ocean is $357 \pm 155 \times 10^{12}$ gC year^{-1}, which is close to the latest estimates of Degens et al. (1991), Meybeck (1993) and Ludwig et al. (1996; Table 1).

The methods used to establish global riverine OC flux estimates are not uniform and unfortunately some authors give no rationale, which makes it difficult to evaluate their flux estimates. The other methods used are described briefly:

1. Garrels and MacKenzie (1971; cited in Handa 1977) and Duce and Duursma (1977) multiplied an average riverine OC concentration of 10 gC m^{-3} with an estimated global riverine runoff.
2. Richey et al. (1980) extrapolated data from the Amazon on the assumption that DOC averages 4 gC m^{-3} and that POC is 5% of total suspended matter (TSS) in tropical rivers and 2% of TSS in non-tropical rivers.
3. Meybeck (1981, 1988) extrapolated data based on a typology of OC concentration according to climate, vegetation and hydrology. The amount of water discharge found in the sample of collected data must be divided among these classes of rivers defined in the typology, which is then extrapolated inside each class.
4. Kempe (1979, 1985), Michaelis et al. (1986) and Degens et al. (1991) extrapolated data based on the collected sample for each continent. Total continental discharges are compared with total discharge of the collected data, which are considered representative. A global flux estimate is derived by simply summing up extrapolated fluxes of each continent.
5. Schlesinger and Melack (1981) compiled seven major rivers and five medium-sized rivers by plotting their OC load as a function of their mean annual discharge (with logarithmic scale). To predict the total worldwide river transport of OC the equation of the logarithmic regression is used to calculate the OC load for the 50 largest rivers. The resulting carbon load is extrapolated to worldwide discharge via the world's annual runoff.
6. Schlesinger and Melack's (1981) second estimate is based on the denudation rate of terrestrial watersheds with respect to OC.
7. Mantoura and Woodward's (1983) calculation is based on assuming the world terrestrial primary production to be approximately 100 times the TOC export rate (Meybeck 1981), a relationship which was checked in the Severn watershed only.
8. Ludwig et al. (1996) established an empirical relationship between the observed OC fluxes and the climatic, biological and geomorphological patterns characterising the river basins.

Table 1 Estimates of the global riverine organic carbon input to the oceans. Note that the calculated fluxes are estimates only, but they do serve to establish possible ranges. *TOC* total organic carbon

Reference	TOC (10^{12} gC year^{-1})
Gibbs (1967; c.f. Handa 1977)	300
Williams (1971; c.f. Schlesinger and Melack 1981)	30
Garrels and MacKenzie (1971; c.f. Handa 1977)	320
Reiners (1973; c.f. Schlesinger and Melack 1981)	200–1000
Garrels et al. (1975; c.f. Schlesinger and Melack 1981)	200
Duce and Duursma (1977)	100–150
Stewart et al. (1978; c.f. Schlesinger and Melack 1981)	520
Kempe (1979)	190
Richey et al. (1980)	1000
Meybeck (1981)	383
Schlesinger and Melack (1981)	370–410
Mantoura and Woodward (1983)	780
Kempe (1985)	280
Michaelis et al. (1986)	530
Meybeck (1988)	302
Degens et al. (1991)	334.5
Spitzy and Ittekkot (1991)	500
Meybeck (1993)	370
Ludwig et al. (1996)	378

Although the knowledge about the sources, transport and behaviour of OC in rivers has improved during the past 30 years, there are still some uncertainties. Especially the Asian rivers, which alone account for 40% of the total annual sediment discharge from land to sea, are only insufficiently documented. Early investigations of Milliman and Meade (1983) assumed a sediment yield of 1000 t km^{-2} year^{-1} for the high-standing islands of Oceania, whereas new data from New Guinea, the Philippines, Java, New Zealand, and Taiwan now suggest an average sediment yield of 3000 t km^{-2} year^{-1} (Milliman and Syvitski 1992). According to these new data Oceania annually discharges 9000×10^{12} g year^{-1} of sediments, compared with global fluxes of $20{,}000 \times 10^{12}$ g year^{-1} (Milliman and Syvitski 1992). Based on these estimates Bird et al. (1995) calculated that the rivers of Oceania supply 90×10^{12} gC year^{-1} to the world oceans. These values are higher then all the published data for North America, South America and Africa combined (Bird et al. 1995). Unfortunately, none of the rivers draining Oceania has formerly been taken into account for a worldwide riverine OC flux compilation. Also the Himalayan rivers, i.e. Ganges, Brahmaputra and Indus, which contribute nearly one third of the global sediment load transported to the world oceans (Milliman

and Meade 1983), are still a point of uncertainty. According to Subramanian and Ittekkot (1991) the combined discharge-weighted estimate of terrestrial OC for the Ganges, Brahmaputra and Indus is 30×10^{12} gC year^{-1}. If the calculations are non-discharge weighted, which means that it is not taken into account that approximately 90% of the sediment transport occurs within 3–4 months, the annual transport of OC in these rivers would double to 69×10^{12} gC year^{-1}. In addition, the OC load of the Amazon, which is one of the most investigated rivers in the world, is still in discussion, whereas the latest calculations give a total annual export of OC of 31×10^{12} g year^{-1} (Richey et al. 1991). Thus, the Amazon is the largest single supplier of terrestrial OC to the oceans.

Apart from the sometimes poor data density in previous estimates, it must be kept in mind that rivers should be sampled at all river stages for at least one hydrological year (Schlesinger and Melack 1981). Furthermore, the separation of dissolved and particulate organic matter differs between the studies and is sometimes only vaguely outlined. Lastly, data which include coarse particulate OC, such as trees, leafs or roots, are only sparse.

Aware of these uncertainties, a new estimate for the terrestrial OC discharged by rivers will be added, in order to take into account new flux data. These estimates are based mainly on data for the most part found in Degens et al. (1991) and Kempe (1985). In addition, the set of data contains data for Oceania (New Guinea, the Philippines, Java, New Zealand, and Taiwan; Bird et al. 1995) and the combined flux estimates for the Ganges, Brahmaputra and Indus from Subramanian and Ittekkot (1991).

Our estimate of the total OC discharge of rivers (Table 2) is obtained by assuming the OC and water discharge data representative of a major part of each continent drained. By comparing water discharge estimates of each continent based on computed mean runoff depths of individual river basins (Baumgartner and Reichel 1975) with the total discharge of the collected data of each continent a simple extrapolation can be made. This is the same method used by Kempe (1979, 1985), Michaelis et al. (1986) and Degens et al. (1991). Note that according to the definition of Baumgartner and Reichel (1975) the islands of Oceania belong partly to Asia and partly to Australia. Dissenting from this definition, Oceania is separated as one "continent" to use the riverine OC flux estimate of Bird et al. (1995). According to Milliman et al. (1995) the water discharge from the islands of Oceania is 3900 km^3 year^{-1}. Australia and Antarctica are neglected, and the discharge from Asia is reduced to take into account that Oceania is separated.

In summary, 51.6% or 19,907 km^3 year^{-1} of the annual continental freshwater and 236×10^{12} gC year^{-1} of the riverine OC runoff is represented in Table 2. Taking the values of each continent as representative the total annual OC flux of each continent is calculated and added up. This results in an estimated flux of 434×10^{12} gC year^{-1} for the global OC discharge of rivers. Table 2 also emphasises that the database in North America, Africa, Europe and, especially, Asia, which alone accounts for one third of the global annual discharge, is most incomplete. These are uncertainties in data availability and must be considered critically with respect to the riverine OC flux estimate. However, this estimate of the OC transported to the oceans by rivers falls well within the range of published data (Table 1) but is – due to new flux data – as expected higher than the latest estimates of Degens et al. (1991), Meybeck (1993) and Ludwig et al. (1996; see Table 1).

How much riverine OC is stored in marine sediments?

To unravel the importance of riverine transport of terrestrial OC into the ocean, it is not only important to consider the amount discharged, but also how much is finally buried in marine sediments. In addition, it must be discerned how the relation of the riverine terrestrial OC flux and burial rate are in comparison with the primary production and burial rates of marine OC. Therefore, the amount of riverine OC is estimated by extrapolating data from the Amazon area, which is then compared with the marine OC accumulation.

Table 2 Estimate of the total continental TOC discharge to the oceans by rivers

	Continental runoff[a] (km^3 year^{-1})	Water discharge published		TOC discharge published (10^{12} gC year^{-1})	Estimated riverine TOC discharge (10^{12} gC year^{-1})
		(km^3 year^{-1})	(%)		
South America	11,100	7,652	68.9	47	68.2
North America	5,900	1,626	27.6	12	43.5
Africa	3,400	1,503	44.2	15	33.9
Asia	11,600	4,238	36.5	64	175.2
Oceania	3,900	3,900	100	90	90.0
Europe	2,800	989	35.3	8	22.6
World	38,600[a]	19,907	51.6	236	434

[a] After Baumgartner and Reichel 1975 without Australia and Antarctica

According to Berner (1982) both marine and terrestrial global OC deposition amounts to 126×10^{12} gC year^{-1}. This total OC burial was subdivided by Berner (1982) in 104×10^{12} gC year^{-1} for "terrestrial OC" accumulating in deltaic-shelf sediments and 22×10^{12} gC year^{-1} for marine OC, the latter accumulating under high-productivity areas (10×10^{12} gC year^{-1}), in shallow-water carbonate-rich sediments (6×10^{12} gC year^{-1}), in pelagic sediments (5×10^{12} gC year^{-1}) and in anoxic basins (1×10^{12} gC year^{-1}). The "terrestrial" OC buried in modern deltaic-shelf sediments is calculated by multiplying the global rate of sediment discharge from rivers with an average sedimentary OC content of deltaic sediments, which were assumed to collect the entire input of clastic material discharged by rivers. Nevertheless, shelf areas are known to be productive – not least of all due to river discharge of nutrients – and therefore do contain marine-derived OC (see discussion below). Berner's (1982) estimate is recalculated by Hedges and Keil (1995) assuming that 33% of the riverine load is deposited outside of deltas, with twice the average OC content of deltaic sediments. Again only the total OC content is interpreted. This estimate amounts in a burial of 70×10^{12} gC year^{-1} in deltaic and 68×10^{12} gC year^{-1} in shelf sediments. Because both estimates are based on total OC contents but speak about terrestrial OC, it seems obvious that the terrestrial portion of the sedimentary OC in shelf-deltaic and slope deposits is overestimated.

In order to give an idea of the quantity of sedimentary terrestrial organic matter burial adjacent to rivers, results from the largest single source of terrestrial OC, the Amazon river, are extrapolated. The Amazon annually discharges 31×10^{12} g of terrestrial OC into the western equatorial Atlantic (Richey et al. 1991). Based on an average sediment surface OC content of 0.66% and averaged accumulation rates, approximately 4.5×10^{12} gC year^{-1} is accumulating in Amazon shelf sediments of which according to stable OC isotopes 3.1×10^{12} gC year^{-1} is from terrestrial sources (Showers and Angle 1986). Following these results only approximately 10% of the OC discharged is finally buried in the sediments of the Amazon continental shelf in modern times. Assuming that these OC burial rates are representative the modern global deposition of riverine OC is in the range of 43×10^{12} gC year^{-1}. This is only approximately half the amount estimated by Berner (1982) and one third of the Hedges and Keil (1995) estimate. So, what about the difference between these calculations?

Antoine et al. (1996) used Coastal Zone Colour Scanner images to calculate the global marine primary production to be 36.5×10^{15} gC year^{-1}. This is nearly 1000 times the amount calculated for the storage of river carbon, but only a very small amount is finally buried in the sediment. Wollast (1991) calculated a primary production of approximately 6.9×10^{15} g of marine OC in the coastal oceans per year of which 0.8% (Berger et al. 1989) or 55.2×10^{12} gC year^{-1} is finally buried (Table 3). Adding these amounts to the terrestrial flux estimate of 43×10^{12} gC year^{-1} a total OC burial rate of the order of 100×10^{12} gC year^{-1} is calculated. This is nearly exactly the amount calculated by Berner (1982) for deltaic-shelf environments by extrapolating total OC data.

Going one step further in order to calculate the global burial of OC in the ocean, estimates on OC burial for the open ocean, coastal ocean, the burial of terrestrial OC from river input and the aeolian supply are added up (Table 3). This amounts to approximately 140×10^{12} g of total OC buried in marine sediments every year, which is close to the global estimate of Berner (1982), and to mean total burial rates of 82 to 157×10^{12} gC year^{-1} for whole-ocean sediments calculated by Wollast (1991).

Although the previously mentioned fluxes are rough estimates only, it is obvious that the amount of terrestrial OC annually buried off rivers is comparable to the burial of marine OC. Furthermore, following the fact that the estimated global burial of 140×10^{12} gC year^{-1} fits well within previous estimates of Berner (1989), Hedges and Keil (1995) and Wollast (1991), it is suggested that the 10% burial of fluvial OC under modern conditions is a good approximation because same amounts of total OC burial in shelf deposits are estimated as in Berner (1982), when adding marine to terrestrial OC burial fluxes. Interestingly, new data for

Table 3 Estimated amount of OC burial in marine sediments

Organic carbon source	Global Flux (10^{12} gC year^{-1})	Burial (%)	Burial (10^{12} gC year^{-1})
Global marine primary production	36,500[a]		
Coastal ocean	6,900[b]	0.8[e]	55.2
Open ocean	29,600	0.03[e]	8.8
River input	434[c]	10[c]	43.4[c]
Aeolian input	320[d]	10	32
Total			139.4

[a] Antoine et al. (1996)
[b] Wollast (1991)
[c] This paper
[d] Romankevich (1984)
[e] Berger et al. (1989)

Table 4 Comparison between modern and Last Glacial terrestrial OC discharge-, accumulation- and burial rates for the Amazon area. Note that these are rough estimates only and do not take into account human activities

	Modern	Last Glacial
OC discharge (10^{12} gC year^{-1})	31[a]	?27–31?[c]
Terrigeneous OC accumulation (10^{12} gC year^{-1})	3.1[b]	3.7[d]
Burial rate (%)	10	12–14[c]
Depocentre	Continental shelf	Deep sea fan

[a] Richey et al. (1991)
[b] Showers and Angle (1986)
[c] Assuming that the global riverine OC input was reduced by approximately 10%, whereas particulate OC remains almost unchanged, Ludwig and Probst (1999)
[d] Schlünz et al. (1999)

glacial burial rates of terrestrial OC from the Amazon fan (Schlünz et al. 1999) suggest that no significant difference exists between modern terrestrial OC burial and those for the Last Glacial Maximum (LGM). Ludwig and Probst (1999) have calculated that during the LGM the riverine OC input into the oceans was at least 10% lower than it is presently. This is due mostly to the reduction in the fluxes of dissolved OC, whereas the fluxes of particulate OC remained almost unchanged (Ludwig and Probst 1999). Following these results one might propose that due to the Last Glacial sea-level fall only the depocentres for terrestrial OC has changed (Table 4). In contrast, Milliman and Syvitski (1992) note that it has to be kept in mind that human influences which might have increased the sediment discharge by a factor of 2 or more since the Last Glacial.

But regarding the present situation: Where is the rest of approximately 400×10^{12} gC year^{-1} not recognised in marine sediments? Are our global budgets totally wrong or is there a way the ocean gets rid of terrestrial OC while preserving marine organic matter? According to Ittekkot (1988) at least 65% of the POC load of rivers is refractory because it has been subject to several microbial attacks in soils (Oades 1988) and aquifers (Nelson et al. 1993). Approximately 46% of the global riverine OC load is in particulate form (Meybeck 1981; Meybeck 1993; Ludwig et al. 1996). Thus, approximately 130×10^{12} gC year^{-1} of the total riverine OC flux should be refractory and accumulate in marine sediments. This contradicts the aforementioned results where it is shown that only approximately 40×10^{12} gC year^{-1} are buried. Although there are uncertainties, it seems evident that most of the terrestrial OC that enters the marine environment is rapidly oxidised, although the mechanisms are largely unknown. Some possible mechanisms are listed and discussed briefly:

1. The results of Showers and Angle (1986) from the Amazon continental shelf are not representative for the global storage of terrestrial OC. Nevertheless, according to the foregoing discussion the burial rate of 10% seems to be a good approximation.
2. A part, especially of the DOC, should escape in estuaries (Mantoura and Woodward 1983; Eisma and Cadée 1991) when salinity increases. Sholkovitz (1976), for example, demonstrated that between 3 and 11% of the riverine-dissolved organic matter is rapidly flocculated when mixed with seawater. However, studies of the dynamics of terrestrial organic matter along continental margins have not demonstrated pronounced removal on the annual and shorter time scales of estuarine mixing or offshore advection (Hedges et al. 1997).
3. Riverine POC is thought to be rapidly and extensively mineralised in seawater or marine-surface sediments (Eisma and Cadée 1991; Hedges and Keil 1995). On the other hand, riverine POC has been subjected to severe microbial attacks in soils (Oades 1988) and aquifers (Nelson et al. 1993), which results in 65% of the particulate OC being refractory. This refractory fraction should resist extensive degradation in estuaries and at sea.
4. The terrestrial OC exported to the oceans could be deposited not only adjacent to the river mouths but also dispersed throughout the whole ocean by currents and accumulate in pelagic sediments. For example, carbon isotopes (Druffel et al. 1986) and lipid biomarker methods (Zafiriou et al. 1985; Prahl and Muelhausen 1989) indicate the presence of appreciable amounts of terrigenous OC in the water column and pelagic sediments. However, isotopic and chemical evidence suggest that the bulk of organic matter in seawater is marine derived (Thurman 1985), so that apparently most of the land-derived OC entering the sea is oxidised (Emerson and Hedges 1988). On the other hand, results from Goni et al. (1997) demonstrate that the offshore lignins in the Gulf of Mexico derive from erosion of extensive grassland (C_4) soils of the Mississippi River drainage basin, and that the nearshore lignins originate largely from C_3 plant detritus from coastal forests and swamps. These results suggest that the terrestrial fraction of the OC can be significantly underestimated in pelagic sediments by not recognising the contribution of C_4 plants to the stable OC isotope composition.

Conclusion

The new estimates for the input of riverine OC to the ocean, the amount buried in continental shelf sediments, as well as the global sedimentary organic carbon deposition estimate fall within previous estimates. In addition, they take into account new data from Oceania not previously involved in global flux estimates and detail the amount of terrestrial organic carbon buried

in continental shelf sediments. On a global scale OC in continental shelf sediments is, according to our estimates, composed of nearly the same amounts of marine (55.2×10^{12} gC year^{-1}) and terrestrial (43.4×10^{12} gC year^{-1}) organic carbon. Adding up both estimates gives nearly exactly the amount calculated by Berner (1982) for deltaic shelf sediments (104×10^{12} gC year^{-1}). Therefore, it is believed that the 10% burial of terrestrial OC discharged by rivers under modern conditions is a good approximation for global estimates. However, to calculate global ocean carbon budgets more accurately and to estimate the importance of the burial of OC as a major driving force for climatic changes, we do need more detailed quantifications of OC fluxes in the different parts of the world's oceans. Special emphasis should be put on continental margin environments where the highest amounts of OC accumulate.

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