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Transport of organic carbon in the world's rivers

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ABSTRACT

Total transport of organic carbon to the world's oceans in dissolved and particulate form in rivers is estimated as 0.37×10^{15} gC yr^{-1} by an inventory and extrapolation of data on loss of carbon per unit volume of river discharge from twelve intermediate and large rivers. An alternative estimate of 0.41×10^{15} gC yr^{-1} is derived from measurements of the fluvial loss of organic carbon per unit area of land in various ecosystem types. Rates of loss range from 1 gC m^{-2} yr^{-1} in grassland systems to 10 gC m^{-2} yr^{-1} in some forests. Organic carbon transport in rivers is a small flux in the global carbon cycle, but our present understanding is limited by inadequate sampling and few data from major world rivers.

1. Introduction

Despite several recent attempts to balance the biogeochemical cycle of carbon on a global scale (Woodwell et al., 1978; Broecker et al., 1979), the present models do not succeed when anthropogenic emissions from fossil fuels are included. Models of the terrestrial and marine components must be inadequate in recognizing all pathways of carbon movement and/or incorrect in assigning magnitudes to these fluxes. Currently the atmospheric carbon pool is increasing at about 2×10^{15} gC yr^{-1}, and the oceans are a net sink for a similar amount. Additionally, these models need to explain the fate of up to 1.0×10^{15} gC yr^{-1} in excess CO_2 that ought to be accumulating in the atmosphere from fossil fuel combustion. Oceanographers generally believe that the terrestrial biota acts as the sink (e.g., Broecker et al., 1979); others disagree and further suggest that the terrestrial biota and humus may even be a large additional source of CO_2 for the atmosphere (Bolin, 1977a; Woodwell et al., 1978).

It is the purpose of this paper to estimate one of the smaller, but poorly studied, transfers of carbon in the global cycle—the transport of dissolved and particulate organic carbon to the world's oceans by riverflow. Significant amounts of carbon transferred from terrestrial systems to the deep ocean or marine sediments would help balance models of the global carbon cycle. During the last decade, limnologists have carefully documented the transport and degradation of organic carbon in a few small streams and rivers, mainly in temperate regions. We rely heavily on these data to calculate an estimate of the annual transfer of organic carbon from terrestrial systems to the ocean. Furthermore, since the publication of the previous estimates of riverine organic carbon flux, measurements from several important rivers have been made or improved.

Organic carbon enters riverine ecosystems throughout their length from drainage and direct deposition from adjacent terrestrial ecosystems and from autochthonous carbon fixation. The biota of small streams is largely heterotrophic, dependent on utilizing carbon fixed in terrestrial ecosystems and provided in runoff. While the initial inputs are in both dissolved and particulate form, the coarse particulate organic matter is leached and degraded to finer particles and to dissolved organic carbon (DOC) during its transit downstream (Fisher, 1977). As the degradation of organic carbon continues, much of the remaining dissolved organic carbon is refractory compounds, particularly light-colored fulvic acids (Jackson, 1975; Handa, 1977; Reuter and Perdue, 1977). There are few studies which quantify the amount of

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organic carbon oxidized during stream transport. Moreover, autochthonous production of organic carbon appears increasingly important in higher order rivers, but its magnitude has only infrequently been studied (Wetzel, 1975b; Minshall, 1978). Cummins (1974) reviews these stream processes in more detail, and Vannote et al. (1980) present a general theory of stream processing of organic carbon. The importance of the dissolved organic carbon in freshwaters is stressed by Wetzel and Rich (1973; Wetzel, 1975a), who reported that in many lakes and streams the ratio of DOC to POC is often 10:1.

Concentrations of particulate carbon in small streams are generally positively related to streamflow, but the published data often show only weak correlations (e.g., Fisher and Likens, 1973). Some workers have also reported weak positive correlations between DOC concentrations and streamflow (Lewis and Tyburczy, 1974; Fisher and Likens, 1973; Larson, 1978; Lewis and Grant, 1979); others have found weak negative correlations (Fisher, 1977). More importantly there are strong hysteresis effects in organic transport. Concentrations of both DOC and POC are likely to be higher on the rising portion of stream hydrographs, during storms and spring runoff, and lower with declining streamflows (Baker et al., 1974; Bormann et al., 1974; Fisher and Likens, 1973; Brinson, 1976; Bilby and Likens, 1979). Thus, in north temperate regions it is essential that field researchers intensively sample spring snowmelt runoff, a period of losses of organic carbon that may exceed the total for the remainder of the year. In a temperate deciduous forest, Bormann et al. (1974) found that 78% of the total particulate matter removed in streamflow occurred during storms carrying only 9% of the annual flow. Furthermore, in arid regions of the world periods of intense rainfall are likely to result in large losses of organic carbon.

2. Data collection

Recent workers often partition the organic carbon in water into dissolved (DOC) and particulate (POC) components by filtration through a 0.45-μ pore filter. The separation of organic matter into these classes by filtration is more for analytical convenience than it is reflective of the true relations of the constituents in natural waters. Soluble compounds including soil humic substances, polysaccharides, polypeptides and some colloidal materials comprise the DOC. Living and dead micro-organisms and carbon in suspended sediments are isolated as fine particulate organic carbon (FPOC). Boling et al. (1975) and Cummins (1974) provide formal schemes for the further subdivision of these categories. However, Sharp (1973) has strongly criticized these separations, recommending instead the determination of total organic carbon (TOC).

Most literature values for DOC may be accurate only within a factor of 2 to 3, depending on which of several analytical methods were employed Mopper and Degens, 1979). Measurements by wet chemical and photo-oxidation methods are generally 5–10% lower than those determined by combustion techniques. Recent advances comparing and improving these techniques (e.g., Gershey et al., 1979) may make the analytical steps small sources of error in future studies and global compilations.

Only a few studies have considered measurements of coarse particulate organic carbon (CPOC), which is often defined as material greater than 1 mm diameter. In higher order rivers CPOC would include material as large as fallen trees, mats of floating aquatic weeds and eroded peat.

In this paper we have used only those studies which provided measurements of TOC, DOC, and FPOC as a function of annual streamflow or watershed area. Generally these measurements were made on surface samples taken at the river mouth. To the extent that concentrations vary with depth, these data may not fully reflect carbon transport and probably underestimate it (Curtis et al., 1979). We have also used data from studies reporting carbon transport in organic matter—i.e., TOM, DOM and FPOM. Unless an empirical value was given, we used 0.50 as a factor for converting these data to carbon. Initially we expected that some older data, which expressed transport of organic carbon in terms of Biological Oxygen Demand (BOD), might also be useful. However, these data are generally poorly correlated with measurements of total organic carbon in rivers (Maier and McConnell, 1974), and the organic carbon in most natural waters is below the detection limits of most BOD techniques. Similarly, attempts to calculate carbon transport from

concentrations of total dissolved and total suspended solids (TDS and TSS) were not fruitful. For example, Reeder et al. (1972) reported TOC, TDS and TSS for a large number of samples taken in the MacKenzie River. Correlations of TOC and TDS ($r = 0.22$) and TOC and TSS ($r = 0.10$) were very low. We also tried this approach using TOC and TDS data from 19 U.S. rivers measured during the NASQAN program (U.S. Geological Survey); the correlation coefficient was $r = 0.14$. Thus, at the risk of utilizing fewer studies, we have included only those data reported in the preferred form.

3. World estimates of organic carbon in riverflow

3.1. *Past estimates*

Past estimates of the total organic carbon flux in world rivers vary by nearly two orders of magnitude (Table 1). Many authors give no rationale for their value; others multiply an estimate of world runoff by an estimate of the average concentration of organic carbon in riverflow, usually 10 gC m^{-3}. The largest estimate (Richey et al., 1980) is an extrapolation based on data from the Amazon and the assumptions that DOC averages 4 gC m^{-3} and that POC is 5% and 2% of TSS in tropical and non-tropical rivers, respectively. There are no data from the large rivers of Southeastern Asia which contain large sediment loads (Holland, 1978).

Table 1. *Estimates of the total annual transfer of dissolved and particulate organic carbon to the world's oceans by freshwater riverflow. All values are in 10^{15} gC yr^{-1}*

Skopintsev (1971) (cf. Williams, 1975)	0.18
Williams (1971)	0.03
Garrels and MacKenzie (1971) (cf. Handa, 1977)	0.32
Reiners (1973)	0.2–1.0
Garrels et al. (1975)	0.20
Duce and Duursma (1977)	0.1–0.15
Stewart et al. (1978)	0.52
Kempe (1979)	0.19
Richey et al. (1980)	1.0
Present paper	
First approximation	0.37
Second approximation	0.41

3.2. *A first approximation*

Our first approximation of organic carbon transport in the world's rivers is based upon a compilation of major rivers flowing to the ocean for which the annual dissolved and particulate carbon flux has been measured. Of the 50 largest rivers (Todd, 1970),[1] reasonable data are available from only seven. In Fig. 1, we have plotted the total annual organic carbon load for these rivers (gC yr^{-1}) as a function of their mean annual discharge (m^3 yr^{-1}). Similar data from five medium-size rivers which drain directly into oceans are also included. With logarithmic axes, a linear regression with surprisingly high correlation ($R^2 = 0.987$) is apparent. The antilog of the slope of this line expresses the mean concentration, 10 g m^{-3} of total dissolved and particulate organic carbon in terrestrial runoff. This value is similar to previous estimates by several researchers (e.g., Garrels and MacKenzie, 1971).

Most of the rivers compiled in Fig. 1 drain temperate regions, but those draining boreal and tundra regions (e.g., the MacKenzie) and the tropical rain-forests (e.g., the Amazon) do not deviate from the relationship. Those rivers which do deviate from the general relation are often unusual. The comparatively small carbon flux in the St Lawrence may be related to the fact that it is the only major river included that passes through large lakes before reaching the ocean. It is likely that a substantial portion of its carbon load is oxidized or sedimented in the Great Lakes (cf. Pocklington and Leonard, 1979). Thus, we have not included the St Lawrence in the calculated regression (Fig. 1). The Satilla River in Georgia (U.S.A.) is a subtropical blackwater river (Beck et al., 1974); its carbon load is greater than predicted by the general relationship. In general, the data from smaller rivers might be expected to display greater deviations from the regression than those from larger rivers as the carbon loads of smaller rivers are more likely to be influenced by specific watershed characteristics and processes.

To predict the total world river transport of organic carbon from these data, we used the equation for the logarithmic regression (Fig. 1) to

[1] Todd (1970) lists the 49 largest rivers draining to the oceans. Throughout this paper we also include the Volga, draining into the Caspian Sea, since it would rank seventeenth in world flow on Todd's listing.

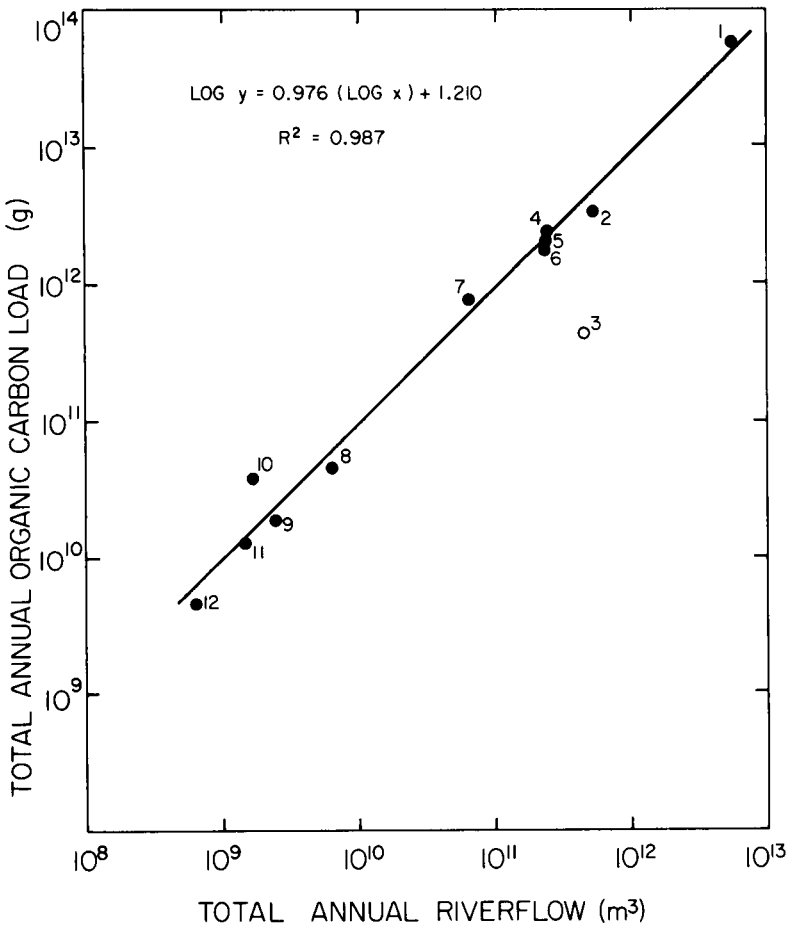

Fig. 1. Total annual load of organic carbon (dissolved and particulate) shown as a logarithmic function of total annual riverflow for rivers of the world. Rivers 1–7 are among the 50 largest, as follows (with source of data): 1 = Amazon (Richey et al., 1980), 2 = Mississippi (Malcolm and Durum, 1973), 3 = St Lawrence (Robertson and Eadie, 1975), 4 = MacKenzie (Reeder et al., 1972), 5 = Danube and others comprising the Black Sea watershed (Deuser, 1971), 6 = Volga (Skopintsev, 1979), 7 = Rhine (Postma, 1973). Rivers 8–12 are smaller rivers draining to the ocean for which data were available: 8 = Brazos (Malcolm and Durum, 1973), 9 = Neuse (Malcolm and Durum, 1973), 10 = Satilla (Beck et al., 1974), 11 = Nanaimo (Naiman and Sibert, 1978), 12 = Shetucket (Klotz and Matson, 1978). Except for nos. 5 and 12 which give DOC only, all studies include TOC or DOC and FPOC. Riverflows are from Todd (1970). Datum from the St Lawrence is not included in calculated regression (see text).

calculate the carbon load for those rivers among the fifty largest for which no carbon data are available. We used the annual riverflows given by Todd (1970) for these rivers as the independent variable. Predicted carbon loads (n = 43) and measured carbon loads (n = 7) were summed to give 0.16 × 10^{15} gC yr^{-1} as the transport for the fifty largest rivers which carry 43% of the world's annual freshwater runoff of 4.2 × 10^{13} m^3 yr^{-1} (Lvovitch, 1973). The estimate can therefore be increased to 0.37 × 10^{15} gC yr^{-1} to yield a first approximation of the total world value.

This value should not be accepted uncritically. None of the rivers used in calculating the regression of Fig. 1 was carefully studied during all stages of riverflow comprising a hydrologic year. There are no data for the high sediment rivers of Asia. The methods for separating and measuring dissolved

and particulate carbon often differed between studies and were frequently only vaguely outlined. There are no data which include the coarse particulate carbon of riverflow, including fallen trees and large mats of aquatic weeds.

3.3. *A second approximation*

Our second approximation of total organic carbon transported from terrestrial ecosystems to the oceans via streamflow is based on the denudation rate of terrestrial watersheds with respect to organic carbon. Since the losses of organic carbon are based on samples taken at downstream sites, these denudation rates are minimum estimates of the loss of organic carbon from terrestrial ecosystems because the carbon oxidized during transport is not measured (cf. Richey et al., 1980). The estimates are too high to the extent that autochthonous production of organic carbon is important. Fig. 2 shows the total annual transport of organic carbon as a function of watershed size for some large rivers of the world. The double logarithmic regression shows a lower correlation ($R^2 = 0.90$) than that relating transport to flow (Fig. 1). The slope of this regression indicates a mean denudation rate of 7.2 gC m^{-2} yr^{-1} for terrestrial watersheds of the world. Most of these data are from rivers draining forested regions; certainly large areas of desert and semi-desert have lower rates of loss. None of the data plotted in Fig. 2 is derived from arid regions; notably, the datum from the Brazos River (Texas, U.S.A.) that drains shortgrass prairie lies distinctly below the general regression.

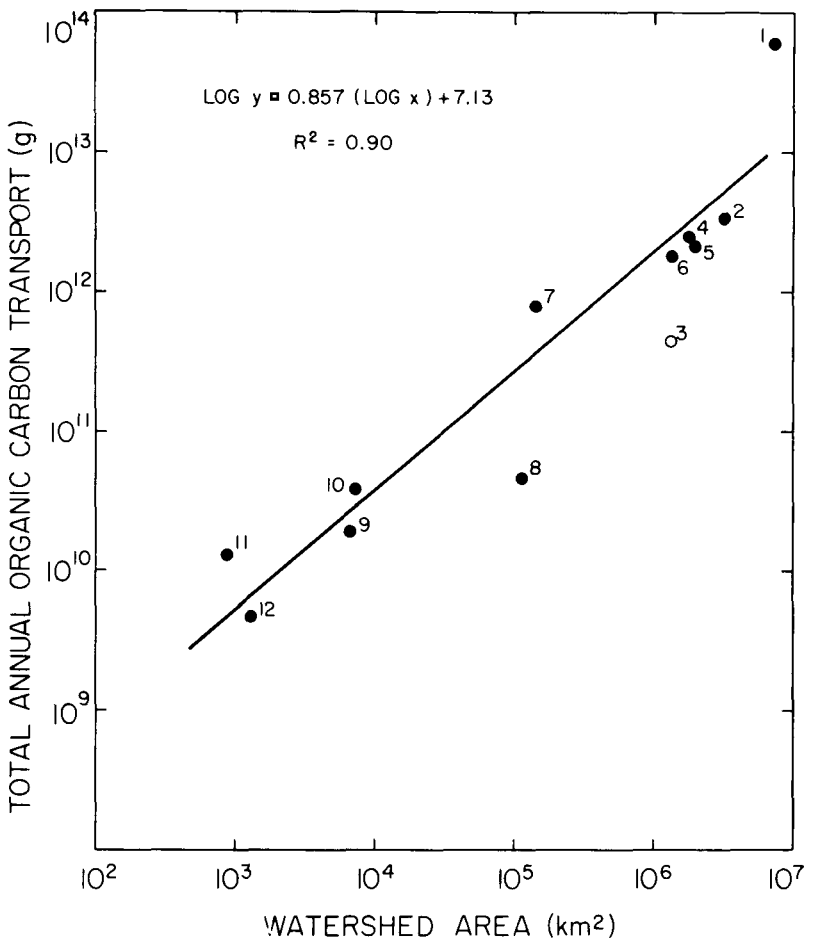

Fig. 2. Total annual load of organic carbon shown as a logarithmic function of watershed area for rivers of the world. See additional specifications for Fig. 1.

Alternatively, we have gathered data from studies in which the annual output of dissolved and particulate carbon in small streams has been measured and expressed as the loss per m^2 of watershed. Most of these watersheds do not drain directly into the oceans. The data are compiled by ecosystem type in Table 2. Also included for comparison are some values for large watersheds, calculated by dividing the carbon load of rivers in Fig. 2 by their watershed area. We have included values in the appropriate categories of Table 2 without regard to the current disturbance of the natural vegetation by man. Several of the larger rivers draining different types of ecosystems appear in more than one category.

The values in Table 2 range from 1.0 to 10.0 gC m^{-2} yr^{-1} with only a few exceptions. There is no great difference among the rates at which tropical, temperate and boreal forest watersheds are denuded of organic carbon. Watersheds with great topographic relief and high runoff show relatively large losses of organic carbon in both tropical and temperate regions (e.g., Bishop, 1973 and Richey and Wissmar, 1979, respectively). Grassland and tundra ecosystems have low rates of loss, based on data from only a few studies. These systems have relatively low precipitation and runoff, reducing the transport of organic carbon (Brinson, 1976). Low rates of loss may also be due to their lower primary productivity or to the tendency for detritus to be produced belowground in grassland systems by the death of roots *versus* the fall of leaves in forests (Schlesinger, 1977). Wetland watersheds, including swamps and estuaries, release large amounts of organic carbon to their drainage waters (Mulholland and Kuenzler, 1979).

The data from temperate forests are numerous enough to permit a more incisive analysis for this ecosystem type. The mean rate of denudation of organic carbon from temperate forest watersheds less than 10,000 km^2 in area is 3.57 ± 0.34 gC m^{-2} yr^{-1} (S.E.). While larger rivers transport greater total amounts of organic carbon (Figs. 1 and 2), the rates of loss per unit area of watershed (gC m^{-2} yr^{-1}) do not differ consistently among temperate watersheds of widely different sizes. Thus, denudation rates for small watersheds can be used to calculate mean rates for world ecosystem types.

With increasing residence time in fresh waters, organic carbon, particularly POC, is decomposed and transformed by stream heterotrophs. Thus, one might expect lower rates of loss to be calculated for the watersheds of larger rivers than for their small headwater watersheds (e.g., Table 2, Naiman and Sedell, 1979). Among the temperate forest data the fact that the loss rates are not significantly correlated with watershed size has several possible explanations and implications. First, this may reflect the refractory nature of compounds comprising the bulk of the organic carbon transport, especially the DOC. Secondly, the amount of allochthonous organic carbon that has been oxidized in large rivers may be balanced by the autochthonous production of organic carbon. Finally, particulate organic carbon may simply be degraded to an equivalent amount of refractory dissolved organic compounds. Surprisingly, however, there is no indication of a positive correlation between the DOC/POC ratio and increasing stream order among the smaller temperate forest watersheds in Table 2 (cf. Fisher and Likens, 1973; Naiman and Sedell, 1979). The DOC/POC ratios vary widely, although the mean for small temperate forest watersheds is close to 10:1, as proposed by Wetzel and Rich (1973). For rivers draining predominantly grassland areas, DOC/POC ratios may be closer to 1:1 (e.g., Malcolm and Durum, 1973). POC transport may also be important in tropical regions (Richey et al., 1980).

As a means of integrating the characteristics of size and total runoff volume for watersheds, we have plotted the rate of loss of organic carbon (gC m^{-2} yr^{-1}) from various upland watersheds as a function of the rate of runoff per unit area of watershed (cm yr^{-1}; where 100 cm yr^{-1} = 1 m^3 m^{-2} yr^{-1}. For a variety of ecosystem types, the rate of loss of organic carbon shows a curvilinear increase with increases in runoff (Fig. 3). This relation shows a great amount of scatter compared to that found in similar attempts using linear regression with more limited sets of data by Brinson (1976) and Mulholland and Kuenzler (1979). Nevertheless, it is obvious that the rate of runoff is important in determining the rate of loss of organic carbon from upland ecosystems. Nearly all these data lie below a line with a slope of 0.1, a value which would result from a mean concentration of 10 g m^{-3} of TOC in runoff water. Thus, this compilation suggests a mean concentration of organic carbon in world riverflow from upland

Table 2. *Rate of loss of organic carbon from terrestrial watersheds arranged by world ecosystem types. Areas for some watersheds were determined by planimetery of topographic maps*

Ecosystem type locale and reference	Data reported				Runoff (cm)	Watershed size (km^2)	Loss of organic carbon ($gC\ m^{-2}\ yr^{-1}$)
	TOC	DOC	POC	DOC/POC			
Tropical forests							
Guatemala, small streams (Brinson, 1976)		×	×		85	170	2.20
					86	300	3.20
					194	5247	4.75
Malaysia, small rainforest streams, cleared (Bishop, 1973)*		×	×	4.9	127	28	14.4
		×	×	2.8	127	103	23.4
Brazil, Amazon rising water R. high water (Richey et al., 1980)		×	×	0.3	84	7,050,000	8.51
		×	×	3.3			
Brazil, Amazon R. (Williams, 1968)		×	×	2.8	84	7,050,000	4.40
Zaire, Zaire R. (Eisma et al., 1978a, b)			×		35	4,012,950	1.71
Temperate forests (watersheds <10,000 km^2)							
Canada							
L. Marion watershed, B.C. (Richey et al., 1978) (Efford, 1972)		×	×	8.7	200	13	8.10
Canagagigue Creek, Ontario (Dance et al., 1979)		× (est.)	×	36.0	15	25	1.84
Scotland							
River Stinchar		×			62	420	4.69
River Cree		×			94	470	3.83
Water of Luce (Sholkovitz, 1976)		×			79	190	5.26
Poland							
Mikolajskie L., watershed (Pieczyńska, 1972)		×	×	—	—	8	2.66
U.S.A.							
Little Miami R., Ohio (Weber and Moore, 1967)		×	×	2.7	34	4545	3.00
Neuse R., N.C. (Malcolm and Durum, 1973)		×	×	3.0	36	6694	2.72
Shetucket R., Conn (Klotz and Matson, 1978)		×	—	—	60	1330	3.42
Bear Brook, N.H. (Fisher and Likens, 1973)		×	×	10.2	72	1	1.95
Mirror L., watershed, N.H. (Jordan and Likens, 1975)		×	×	25.2	70	1	1.89
Hubbard Brook, N.H. forest Bormann et al., 1974) cleared (Hobbie and Likens, 1973)		×	×	3.5	70	0.1	1.52 (2.67)
Fort River, Mass. (Fisher, 1977)		×	×	3.3	80	107	3.30
Un-named stream, PA (Larson, 1978)		×		—	82	7	5.24

* Recalculated from original source.

Table 2—*contd.*

Ecosystem type locale and reference	Data reported TOC	DOC	POC	DOC/POC	Runoff (cm)	Watershed size (km^2)	Loss of organic carbon ($gC\ m^{-2}\ yr^{-1}$)
Lawrence L. watershed, Mich. (Wetzel et al., 1972)		×	×	5.0	120	0.3	3.62
Augusta Creek, Mich. (Wetzel and Manny, 1977)		×	×	3.0	47	68	2.72
Findley L. watershed, Wash. (Richey et al., 1978) (Richey and Wissmar, 1979)		×	×	4.9	448	1	6.14
Un-named stream, Ohio (Chichester et al., 1979)	×			—	85	?	3.33
Devils Club Creek		×	×	3.5	205	0.2	4.43
Mack Creek		×	×	5.5	205	6.0	3.96
Lookout Creek		×	×	4.1	211	60.5	3.12
MacKenzie R., Oregon (Naiman and Sedell, 1979)		×	×	1.8	173	1287	1.78
Temperate forests (watersheds >10,000 km^2)							
U.S.A.							
Mississippi R. (Malcolm and Durum, 1973)		×	×	0.9	18	3,220,716	1.06
St Lawrence R. (Robertson and Eadie, 1975)	×				31	1,289,322	0.34
U.S.S.R.							
Volga R. (Skopintsev, 1979)	×				18	1,360,000	1.29
U.S.A.							
Columbia R. (Gross et al., 1972)			×		34	670,000	0.24
Susquehanna River (Flemer and Biggs, 1971)			×		42	72,492	1.16
Europe							
Black Sea watershed (Deuser, 1971)		×			13	1,980,000	1.04
Rhine R. (Postma, 1973)	×				47	145,000	5.34
Boreal forest							
Canada							
MacKenzie R. (Reeder et al., 1972)	×				17	1,804,776	1.40
Rawson L. watershed (Schindler et al., 1976)		×			28	3	5.50
Finland							
Baltic Sea watershed (Wartiovaara, 1978)	×				—	230,000	4.00
U.S.S.R.							
L. Baikal watershed (Moskalenko and Votinsev, 1972)	×				—	31,500	9.65
Sweden							
River Ricklean (Karlström and Backlund, 1977)			×		—	1673	0.45

Table 2—*contd.*

Ecosystem type locale and reference	Data reported				Runoff (cm)	Watershed size (km^2)	Loss of organic carbon ($gC\ m^{-2}\ yr^{-1}$)
	TOC	DOC	POC	DOC/POC			
Temperate grasslands							
U.S.A.							
Brazos R. (Malcolm and Durum, 1973)		×	×	0.9	5.5	113,968	0.41
Missouri R. (Malcolm and Durum, 1973)		×	×	0.3	3.5	1,084,545	0.67
Mississippi R. (Malcolm and Durum, 1973)		×	×	0.9	18	3,220,716	1.06
U.S.S.R.							
Volga R. (Skopintsev, 1979)	×				18	1,360,000	1.29
Europe							
Black Sea watershed (Deuser, 1971)		×			13	1,980,000	1.04
Tundra							
Canada							
Char. L. watershed (de March, 1975)		×	×	19.2	14	4	0.25
MacKenzie R. (Reeder et al., 1972)	×				17	1,804,776	1.40
Norway							
Øvre Heimdalsvatn (Larsson and Tangen, 1975)			×		—	24	0.75
Wetlands							
Canada							
Nanaimo River & estuary (Naiman and Sibert, 1978)		×	×	35.2	168	894	14.6
U.S.A.							
Saltmarsh, Maryland (Heinle and Flemer, 1976)		×	×	1.0	—	1.27	14.6
Saltmarsh, Rhode Island (Nixon and Oviatt, 1973)	×				—	0.02	14.1
Saltmarsh and estuary, N.Y. (Woodwell et al., 1977)		×	×		—	0.57	−53.0
Swampforests N.C. (Mullholland and Kuenzler, 1979)		×	×	37.0	22	80	3.37
				19.0	40	80	8.37
				20.0	18	32	1.89
				174.0	39	32	6.81
				13.0	22	54	2.49
				—	22	141	2.72
				—	22	132	3.39
				4.8	22	110	3.23
Satilla R., Ga (Beck et al., 1974)	×			—	23	7456	5.28
Sopchoppy River Swampforest, FLA (Malcolm and Durum, 1973)		×	×	23.6	27	750	4.47
Swampforest, LA. (Day et al., 1977)	×	×			89	770	10.4
Mountain fen/bog, CA (Erman and Chouteau, 1979)			×		—	—	4.7–20.4

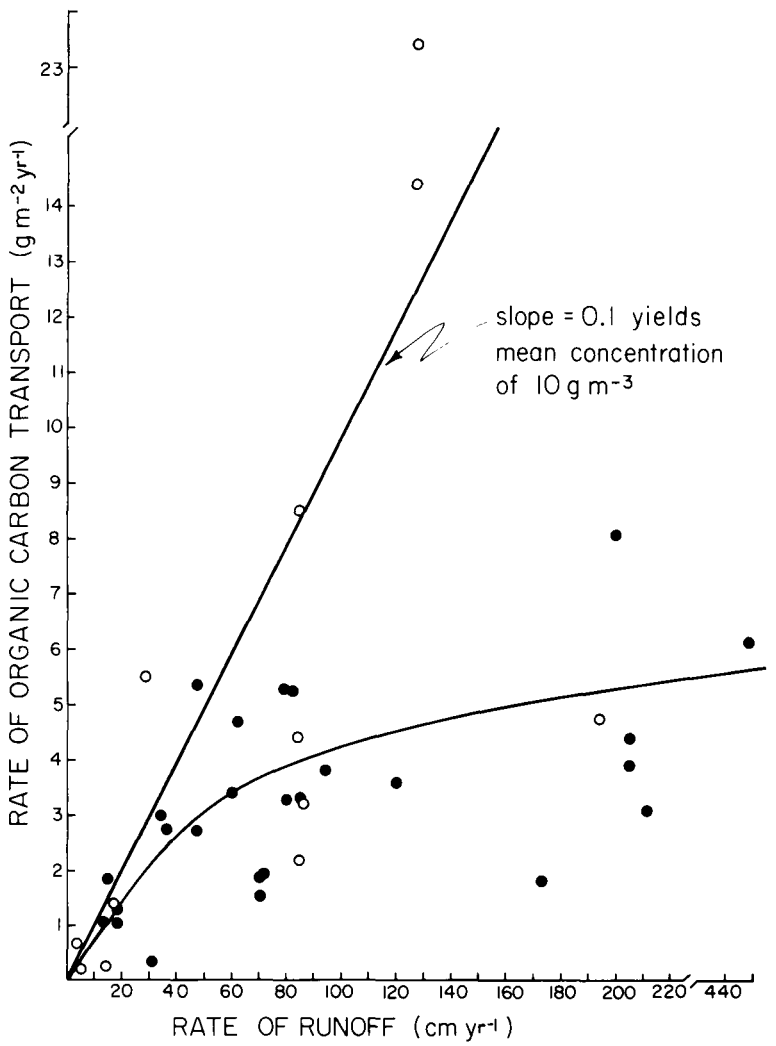

Fig. 3. Rate of organic carbon loss from upland terrestrial watersheds (gC m^{-2} yr^{-1}) as a function of the rate of runoff (cm yr^{-1}). Temperate forest watersheds are shown with solid circles; data from other systems are shown with open circles. The plotted curve is the subjective best fit to the temperate forest data. The plotted line shows the theoretical relationship assuming a weighted mean concentration of 10 g m^{-3} organic carbon in the world's rivers.

watersheds that is considerably less than the 10 g m^{-3} value implied in Fig. 1. Similarly, nearly all the rates of loss (Table 2, Fig. 3) are less than the 7.2 gC m^{-2} yr^{-1} mean world value calculated from Fig. 2. Wetland areas, including swamps and estuaries, are exceptions (Table 2). In a graphical compilation similar to Fig. 3, Mulholland and Kuenzler (1979) have recently shown high rates of organic carbon loss from various wetland watersheds. Concentrations of organic carbon in runoff from these areas often exceed 10 g m^{-3}. Swamp forests show particularly high rates of loss (Beck et al., 1974). Salt marsh estuaries also show high rates of organic carbon release, although much of the loss in estuarine and other wetland systems may be terrestrial in origin (Haines, 1977).

Due to limited data in Table 2, we assessed subjective mean annual denudation rates (gC m^{-2} yr^{-1}) of organic carbon for ecosystems of the world (Table 3). These rates were multiplied by the world land area of each type (Whittaker, 1975)

Table 3. *A second approximation of total organic carbon transport from terrestrial watersheds to the world's oceans based on world land areas and rates of carbon loss per unit area*

Ecosystem type	Area (10^{12} m^2)	Rate of organic carbon loss (gC m^{-2} yr^{-1})	Total transport (10^{12} gC yr^{-1})
Tropical forest	24.5	5	122.5
Temperate forest	12	4	48
Boreal forest	12	5	60
Woodland and shrubland	8.5	4	34
Tropical grassland	15	1	15
Temperate grassland	9	1	9
Tundra and alpine	8	1	8
Desert and semidesert	8‡	0.5*	4
Cultivated	14	5†	70
Swamp and marsh	2	20	40
			410 = 0.41 × 10^{15} gC yr^{-1}

* Assumed to be one-half the grassland value.

† Conservative estimate based on losses from studies (Table 2) indicating some current disturbance of natural vegetation. See text for alternative, maximum estimates.

‡ Whittaker's (1975) area for world deserts has been reduced by the area of endorheic basins and deserts with no runoff (Holeman, 1968).

to yield our second approximation of the total world transfer of carbon from land to the oceans in organic form in riverflow (0.41 × 10^{15} gC yr^{-1}). The majority of the transport is from forested ecosystems, particularly tropical forests. Certainly this approach would benefit from a larger set of data allowing for calculation of means for finer subdivisions of land area. If our estimates of the rates of loss of organic carbon are revised substantially, changes in the values from forested regions will have a much greater effect on the world total than large changes in the values for arid regions.

4. Discussion

Our estimates of the organic carbon transported in the world's rivers, 0.37 – 0.41 × 10^{15} g yr^{-1}, fall within the range suggested by most previous workers (Table 1). Transport of organic carbon rivals the flux of dissolved inorganic carbon in the world's rivers, which is estimated as 0.45 × 10^{15} gC yr^{-1} by Kempe (1979). These transports are rather small fluxes in the global carbon cycle. There is a considerable range in estimates of primary production in the world's oceans (Duce and Duursma, 1977; de Vooys, 1979); we will cite the 31 × 10^{15} gC yr^{-1} value of Platt and Subba Rao (1975). Nearly all marine primary production is later metabolized in the upper water column. Eppley and Peterson (1979) estimated that only 3.4 – 4.7 × 10^{15} gC yr^{-1} may sink through the thermocline to the deep ocean as dead organic particles. Thus, the organic carbon transported in rivers could represent up to 10% of the flux of carbon to ocean sediments.

The fate of freshwater organic carbon upon entering the oceans is poorly understood (Duce and Duursma, 1977; Handa, 1977). Some organic carbon is undoubtedly oxidized in the ocean, but this amount is probably small since only the most refractory compounds are likely to resist oxidation during freshwater transport. Thus, compared to the organic matter derived from oceanic production, the organic matter from rivers may be less likely to decay upon sinking through the thermocline to lower layers. Based on studies of carbon isotope ratios in sediments, there is evidence which suggests that much of the sedimentation of terrestrial carbon occurs in estuarine and near-shore environments (Gardner and Menzel, 1974; Hedges and Parker, 1976; Shultz and Calder, 1976; Handa, 1977). These studies suggest that organic carbon in riverflow is a very small source of the carbon in deep ocean sediments. Pocklington

and Leonard (1979), however, caution against the ease with which sedimentary isotope measurements are interpreted. Sholkovitz (1976) found that rather small percentages of dissolved organic matter were flocculated upon mixing with ocean water, suggesting that organic carbon from rivers might be widely transported through the oceans.

The flux of carbon to the oceans has undoubtedly been augmented by man's activities which have increased atmospheric CO_2 levels and rates of terrestrial erosion. The ocean is a net sink for at least 2×10^{15} gC yr^{-1} due to enhanced CO_2 dissolution by increasing atmospheric concentrations (Broecker et al., 1979). Several workers have suggested that man's activities may be enhancing marine photosynthesis as a result of increasing the combined availability of CO_2, P and N in surface waters (Broecker et al., 1979; Garrels et al., 1975). However, Peterson (in press) has calculated that this process would result in a net increase of only $0.1 - 0.2 \times 10^{15}$ gC yr^{-1} entering the deep oceans by sinking particulates (cf., Broecker et al., 1979; Bolin, 1977b).

In a temperate deciduous forest in Tennessee (U.S.A.), groundwater losses of dissolved organic (DOC) and inorganic carbon were 1.25 and 1.66 gC m^{-2} yr^{-1}, respectively. These values were less than 0.3% of the total annual release of CO_2 from soil to the atmosphere as a result of decomposition (Edwards and Harris, 1977; see also Maier et al., 1976). Most of the carbon lost from soils is probably lost through increased oxidation rather than erosion (Schlesinger, 1980); nevertheless even small erosional losses can be important inputs to rivers. We have no estimate of the extent to which the transport of organic carbon in rivers may currently be augmented by man's activities, but the data of Spalding et al. (1978) suggest that these losses may increase in cultivated soils. In intensively farmed Wisconsin (U.S.A.) watersheds, Brink et al. (1977) reported mean soil losses due to erosion range from 1.2 to 1.9 kg m^{-2} yr^{-1}. These values are typical of all but the most careless of land clearing operations (see Pimentel et al., 1976; Bormann et al., 1974). If we assume that these soils contain an average carbon content of 2–5%, the resulting carbon loss by erosion might deliver up to 100 gC m^{-2} yr^{-1} to drainage waters. While this rate is large compared to the values in Table 2 and it probably declines as the period of cultivation continues, increased rates of soil disturbance and erosion may significantly increase the riverine flux of organic carbon worldwide.

Although Asian rivers carry about 80% of the suspended solids to the oceans (Holeman, 1968), we have no measurements of TOC transport by the major Asian rivers. We suggest two estimates of POC transport by the Yangtze, Bramaputra, Mekong, Ganges, Irrawaddy and Indus based on their yields of suspended sediments summarized in Holland (1978). The drainage-area-weighted yield for these six rivers is 745 g TSS m^{-2} yr^{-1}. As a first estimate we used the POC/suspended sediment ratio of 5% for the Amazon (Richey et al., 1980) and calculated a POC export of 37 gC m^{-2} yr^{-1}. This value appears high compared to the empirical values in Table 2. Our second estimate assumed that the average organic carbon content of shales (0.9%, Holland, 1978) represents the deposition of organic carbon associated with suspended solids. We used shales instead of other sedimentary rocks because of the similarity between the major chemical components of shales and of the suspended solids in the Asian rivers (Martin and Meybeck, 1979). By this procedure we calculate a POC export of 6.7 gC m^{-2} yr^{-1}. This value is similar to values in Tables 2 and 3.

In summary, we are encouraged by the similarity of our two largely independent estimates of organic carbon transport by the world's rivers. To substantially improve the estimate will require considerable effort by geochemists and limnologists because we need studies in many ecosystems that span several hydrologic years, including rare hydrologic events of great magnitude. Particularly in larger rivers these samplings should include depth integrated measurements of coarse particulate carbon as well as POC and DOC and should assess the oxidation of organic carbon during downstream transport. These measurements must be made in large rivers such as the Ganges, Zaire, Orinoco and Yangtze and should include ecosystems subjected to large-scale human disturbance. Careful and precise documentation of the export of total organic carbon from tropical rainforests such as the Amazon basin may provide an indication of the effects of deforestation in the basin. As a major link between the land and the oceans, rivers deserve further scrutiny as a component of the world's carbon budget.

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6. Note

While there are no data currently available for the transport of organic carbon in the large rivers of China, Professor Liu Jian-kang (Institute of Hydrobiology, Luojiashan, Wuhan, Hubei, China) has recently informed us that measurements of TOC are soon to begin on the River Chang Jiang (Yangtze).

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ПЕРЕНОС ОРГАНИЧЕСКОГО УГЛЕРОДА РЕКАМИ МИРА

Путем подсчета и экстраполяции данных по двенадцати средним и большим рекам полный перенос реками органического углерода в мировой океан в растворенном виде и в виде частиц оценен в 0.39×10^{15} г/год. Другая оценка в 0.41×10^{15} г/год получена из измерений флювиальных потерь органического углерода с единицы площади суши в экосистемах различного типа. Скорости потерь находятся в пределах от 1 г/м^2 год для травяных систем до 10 г/м^2 год для некоторых лесов. Перенос органического углерода реками является малым потоком в глобальном углеродном цикле, однако, наше современное понимание проблемы ограничено неадэкватной выборкой и малым количеством данных по основным рекам мира.