Tellus (1982), *34*, 176–186

Transport of organic carbon to the oceans by rivers of North America: a synthesis of existing data [1,2]

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(Manuscript received February 3; in final form July 8, 1981)

ABSTRACT

Transport of organic carbon in rivers of North America to the oceans was assessed by compiling and analyzing data from 82 North American rivers draining 60% of Canada and the United States. These data were collected by the U.S. Geological Survey and the Water Resources Branch of Canada's Inland Waters Directorate. Mean annual concentrations of total organic carbon showed considerably less variation than did annual specific export (gC m^{-2} yr^{-1}). Regional variation in annual specific export of total organic carbon was attributed primarily to differences in annual runoff. Transport of total organic carbon to coastal regions by North American rivers totalled about $35 \times 10^{12} \pm 5 \times 10^{12}$ gC yr^{-1} in 1977 and 1978. The total organic carbon flux to the oceans associated with the long-term average annual flow in North American rivers was computed to be about 40×10^{12} gC yr^{-1}, slightly larger than that in 1977 and 1978 because of the lower-than-average runoff in some regions those years.

1. Introduction

There has been considerable interest recently in the role of rivers in the global carbon cycle, specifically their role in the transfer of plant nutrients (Walsh, 1980) and carbon (United States Department of Energy, 1981) from inland regions to continental margins and the oceans. Recent estimates of the flux of organic carbon in the world's rivers to the oceans range from 0.2 to > 1.0 $\times 10^{15}$ gC yr^{-1} (Kempe, 1979; Richey et al., 1980; Schlesinger and Melack, 1981; Meybeck, 1981). These estimates are based either on data from a few large rivers or on extrapolations of data from small rivers and streams, mostly in temperate regions. To our knowledge, a systematic compilation of river organic carbon flux to the oceans from individual continents or regions of the world has not been made.

The purpose of this paper is to make an estimate of river organic carbon transport from North America to the oceans. Riverflow and organic carbon concentration data for most of the larger rivers draining the North American continent are available from sources in the United States and Canada. In this paper we present a systematic compilation and analysis of these data.

2. Data compilation

Annual riverflow and total organic carbon (TOC) concentration data were collected for 82 of the largest rivers in North America which discharge to the oceans (Fig. 1). Annual riverflows for United States rivers were obtained from the United States Geological Survey (U.S.G.S. Water Resources Data for the various states) from

[1] Research sponsored by the Institute for Energy Analysis of Oak Ridge Associated Universities under contract DE-ACO5-760R00033 with the U.S. Department of Energy and by the Office of Health and Environmental Research, U.S. Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation.

[2] Publication No. 1753, Environment Sciences Division, ORNL.

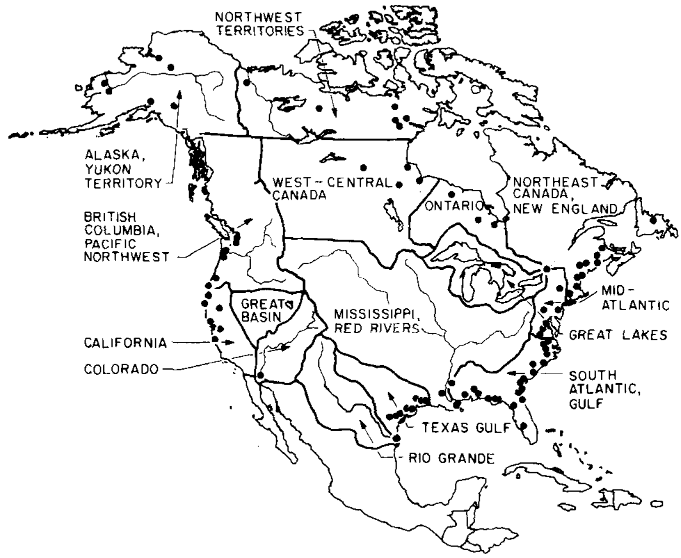

Fig. 1. Distribution of river sampling stations and drainage regions of North America.

stations at or near the river mouth. Organic carbon concentrations and instantaneous riverflow data were retrieved from the United States Environmental Protection Agency's STORET system (U.S. Environmental Protection Agency, 1975). These data were collected by the U.S. Geological Survey as part of their NASQAN program, with the exception of those for the Potomac, Santee, and Sacramento Rivers which were collected by state agencies. Annual riverflow, instantaneous riverflow, and TOC concentrations for the Canadian rivers were obtained from the Canadian Inland Waters Directorate's NAQUADAT system (Demayo and Hunt, 1975).

In this review we have used organic carbon concentrations measured and reported as TOC. Detrital organic carbon in aquatic systems is often divided into two fractions by size, dissolved organic carbon (<0.5 μm) and particulate organic carbon (>0.5 μm). By definition, TOC is the sum of the dissolved and particulate organic carbon fractions. However, various steps in sample collection and analysis effectively limit the upper size of organic particles measured. Thus, the TOC values compiled here include both the dissolved and smaller particulate (< about 1–10 mm in size) organic carbon fractions. This size limitation may result in only a small underestimate of true TOC since material > 1 mm in size has been reported to comprise only a minor portion of the TOC in transport in smaller streams and rivers (Fisher, 1977; Naiman and Sibert, 1978; Sedell et al., 1978).

Methods of sample collection and chemical analysis for organic carbon are standardized; however, there are differences between methods used by the U.S. Geological Survey (Goerlitz and Brown, 1972) and those of Canadian researchers (Environment Canada, 1979). The U.S. Geological Survey took depth integrated samples usually at several stations across the river width. Samples were preserved by the addition of concentrated H_2SO_4 (2 ml per liter of sample) and stored at 4 °C in glass bottles. Samples were homogenized, further acidified, purged with an inert gas to remove inorganic carbon, and combusted at high temperature (950 °C). The evolved CO_2 was measured with a nondispersive infrared analyzer (Van Hall et al., 1963). Organic carbon samples taken from Canadian rivers were generally grab type. Methods of sample preservation and analysis were identical to those used by the U.S. Geological Survey, with the exception of the separation of inorganic carbon. Inorganic carbon was measured directly by infrared analysis after acidification and low temperature combustion (150 °C) (Beckman Model

915 Total Carbon Analyzer). Inorganic carbon concentration was then subtracted from total carbon (950 °C combustion) to obtain organic carbon.

Mean annual TOC concentrations for the rivers tabulated here were computed from available data collected during 1977 and 1978. Sampling frequencies were variable, but most commonly bimonthly to monthly. In cases where there were less than three samples taken during 1977 or 1978, we also used data collected in other years at that particular station to compute a mean TOC concentration. At all stations the samples taken were spread out over the period of flow (i.e., not confined to only a brief period each year). TOC concentrations were weighted by instantaneous riverflow wherever possible. This weighting procedure gave those concentrations measured during high flow greater importance in the calculation of mean annual concentration, and hence, annual transport. Thus, for most stations, flow-weighted mean TOC concentrations were calculated each year, and these multiplied by annual riverflow to obtain annual TOC export.

3. Results and discussion

Data are presented for 82 rivers in the United States and Canada which discharge to the oceans (Table 1). The rivers are grouped among 14 regions (Fig. 1), selected either on the basis of similar TOC fluxes or on geographical or political boundaries. Annual specific export of TOC ranges from about 0.01 $gC\ m^{-2}\ yr^{-1}$ from the Rio Grande and Colorado River basins to 8.4 $gC\ m^{-2}\ yr^{-1}$ from the Exploits River basin. Unweighted and weighted (by instantaneous riverflow) mean annual TOC concentrations show less variation, however, ranging from 1.6 $gC\ m^{-3}$ in the Umpqua River to 21.2 $gC\ m^{-3}$ in the Nueces River.

As is the case for most other substances (Elwood and Henderson, 1975; Likens et al., 1977), concentrations of organic carbon in running waters are not independent of flow rate. Both particulate and dissolved organic carbon concentrations have been reported to increase with increasing streamflow in most streams; however, positive correlations between concentration and flow are usually weak (Fisher and Likens, 1973; Larson, 1978; Lewis and Grant, 1979). This is primarily the result of strong hysteresis effects in streams. Organic carbon concentrations increase rapidly on the rising limb of the hydrograph, peak prior to the peak in the hydrograph, and decline more rapidly than streamflow (Fisher and Likens, 1973; Baker et al., 1974; Comiskey, 1978; Bilby and Likens, 1979; Gurtz et al., 1980). Although hydrographs of large rivers are much less variable than those of streams, organic carbon concentration patterns may be similar. Data presented here indicate there is at least a weak pattern of higher concentrations at higher riverflows. Flow-weighted mean annual TOC concentrations for 22 of the rivers compiled in Table 1 in 1977 were > 10% higher than unweighted mean concentrations, whereas weighted mean concentrations were > 10% lower than unweighted mean concentrations for only six rivers. In addition, of the 45 rivers compiled in this study for which there was simultaneous concentration and flow data, 15 showed significant ($P < 0.05$) positive correlations between TOC concentration and riverflow during 1977. Most of these correlations (13 of the 15), however, were relatively weak ($r < 0.6$). In no rivers were TOC concentrations significantly negatively correlated with riverflow. A number of other investigators studying rivers have also reported that organic carbon concentrations tend to increase during periods of increasing riverflow, particularly after long periods of low flow (Brinson, 1976; Naiman and Sibert, 1978; Dahm, 1980). Malcolm and Durum (1976) have reported weak positive correlations between DOC concentration and riverflow in the Mississippi, Neuse, and Sopchoppy Rivers.

There is wide variation in annual TOC export from drainage basins in different regions of North America (Table 2). Regional specific export of TOC is highest in northeastern North America, lowest in the southwestern sections, and spans almost 3 orders of magnitude (0.01 to 6.3 $gC\ m^{-2}\ yr^{-1}$). Differences in mean annual TOC concentration explain some of the variation. In general, mean TOC concentrations are higher in the eastern and central regions of North America than in the western and northern sections, with the exception of a few of the Alaskan and California rivers (Table 1). Our estimates of TOC export from regions dominated by boreal or temperate forests (Northeast Canada and New England, Mid-Atlantic, South Atlantic and Gulf, Ontario, and the Pacific Northwest and British Columbia) range

Table 1. *Annual flow, total organic carbon (TOC) concentration (weighted by instantaneous riverflow), and annual export in selected rivers of North America in 1977 and 1978. Annual flow data is from the U.S. Geological Survey (U.S.) and from the Water Resources Branch of the Inland Waters Directorate (Canada). Carbon concentration data is from the U.S. Environmental Protection Agency's STORET data bank (U.S.) and from the Inland Waters Directorate's NAQUADAT system (Canada)*

River	Station location	Drainage area (km^2)	Specific runoff (cm)		Weighted mean TOC conc.* ($gC\ m^{-3}$)		TOC export† ($gC\ m^{-2}\ yr^{-1}$)	
			1977	1978	1977 (*n*)	1978 (*n*)	1977	1978
Northeast Canada, New England (2,230,000 km^2)								
Sw. Miramichi	Blackville, N.B.	5,050	82	60	6.8 (15) (1974–1979)‡		5.6	4.1
Exploits	Grand Falls, Nfld.	8,640	114	83	7.4 (14) (1968)‡		8.4	6.1
St. John	Mactaquac, N.B.	39,900	75	55	10.9 (18))1972)		8.2	6.0
St. Croix	Milltown, Me.	3,780	80	64	7.5 (8)	7.8 (7)	6.0	5.0
Penobscot	W. Enfield, Me.	17,280	76	58	7.2 (8)	9.3 (6)	5.5	5.4
Kennebec	Bingham, Me.	7,045	64	67	6.9 (6)	6.7 (6)	4.4	4.5
Androscroggin	Brunswick, Me.	8,832	76	70	7.8 (6)	7.1 (7)	6.0	5.0
Saco	Cornish, Me.	3,362	80	73	7.2 (6)	7.0 (7)	5.8	5.1
Merrimack	Lowell, Ma.	12,005	63	58		8.1 (8)	5.1	4.7
Connecticut	Thompsonville, Ct.	25,022	71	56	6.9 (11)	7.1 (12)	4.9	4.0
Housatonic	Stevenson, Ct.	3,991	77	56	6.8 (12)	5.5 (12)	5.2	3.1
		Σ = 134,907						
Mid-Atlantic (264,000 km^2)								
Hudson	Green Island, N.Y.	20,953	82	60	8.9 (3)	8.3 (6)	7.3	5.0
Delaware	Trenton, N.J.	17,560	72	65	6.3 (9)	5.1 (8)	4.5	3.3
Susquehanna	Conowingo, Md.	70,190	64	58	8.1 (21)§	8.2 (12)§	5.2	4.8
Potomac	Washington, D.C.	29,940	27	42	7.1 (8) (1975–1977)‡		1.9	3.0
Rappahannock	Fredericksburg, Va.	4,134	22	42	4.4 (15) (1978–1979)‡		0.9	1.8
James	Cartersville, Va.	16,206	26	45	6.4 (21)	4.3 (19)	1.7	1.9
		Σ = 158,983						
South Atlantic, Gulf (700,000 km^2)								
Roanoke	Roanoke Rapids, N.C.	21,780	21	49	4.7 (4)	7.1 (7)	1.0	3.5
Nottoway	Sebrell, Va.	3,680	32	56	7.0 (9)		2.2	3.9
Tar	Tarboro, N.C.	5,540	27	45	6.6 (5)	13.7 (8)	1.8	6.2
Neuse	Kinston, N.C.	6,970	27	43	6.9 (5)	8.7 (8)	1.9	3.7
Cape Fear	Kelly, N.C.	13,520	28	46	7.9 (4)	7.2 (8)	2.2	3.3
Pee Dee	Georgetown, S.C.	32,770	36	43	11.0 (9)‡		3.9	4.7
Santee	Jamestown, S.C.	38,600	7	30	6.9 (5)‡	8.4 (7)‡	0.5	2.5
Savannah	Cyclo, Ga.	25,510	44	38	5.1 (12)	4.6 (17)	2.2	1.7
Ogeechee	Eden, Ga.	6,860	29	26	9.5 (6)	13.9 (8)	2.8	3.6
Altamaha	Everett City, Ga.	36,300	36	32	7.3 (14)	6.7 (17)	2.6	2.1
Satilla	Atkinson, Ga.	7,230	31	26	14.0 (10)	17.9 (10)	4.4	4.7
St. Johns	Jacksonville, Fla.	22,673	13	28	13.7 (7) (1973–1977)‡		1.7	3.8
Peace	Arcadia, Fla.	3.561	12	25	17.7 (6)	21.7 (8)	2.1	5.4
Suwannee	Wilcox, Fla.	25,000	38	38	9.9 (6)	12.4 (6)	3.8	4.7
Apalachicola	Blountstown, Fla.	45,600	45	49	7.9 (12) (1979)‡		3.6	3.9
Choctawatchee	Bruce, Fla.	11,355	54	80	6.0 (6)	9.0 (6)	3.3	7.2
Escambia	Century, Fla.	9,886	52	73	7.2 (7)	7.4 (6)	3.7	5.4
Alabama	Claiborne, Ala.	55,700	64	44	7.4 (6)	6.6 (10)‡	4.5	2.9
Pascagoula	Benndale, Ms.	17,300	64	40	9.7 (3)	7.9 (3)‡	6.3	3.2
Pearl	Bogalusa, La.	17,170	65	43	5.8 (9) (1979)		3.8	2.5
		Σ = 407,005						

Table 1—*contd.*

River	Station location	Drainage area (km^2)	Specific runoff (cm) 1977	1978	Weighted mean TOC conc.* ($gC\ m^{-3}$) 1977 (*n*)	1978 (*n*)	TOC export† ($gC\ m^{-2}\ yr^{-1}$) 1977	1978
Ontario (1,069,000 km^2)								
Albany	Hat Island, Ont.	118,000	26	23	9.0 (7) (1972–1973)		2.3	2.1
Winisk	Asheweig R., Ont.	50,000	16		8.0 (4) (1972–1973)‡		1.3	
Abitibi	Onakawana, Ont.	27,500	41	49	12.7 (9) (1972–1973)‡		5.3	6.2
		$\sum =$ 195,500						
Great Lakes (774,000 km^5)								
St. Lawrence	Cornwall, Ont.	773,890	30	32	7.9 (3)	4.4 (9)	2.4	1.4
Mississippi and Red Rivers (3,175,000 km^2)								
Mississippi	Belle Chase, La.	2,926,500	12	14	5.7 (11)‡	6.4 (7)	0.7	0.9
Atchafalaya (Red)	Simmesport, La.	226,810	64	80	12.0 (3)‡	9.2 (10)	7.7	7.4
		$\sum =$ 3,153,310						
Texas—Gulf (450,000 km^2)								
Sabine	Ruliff, Tx.	24,162	22	13	6.1 (11)	8.3 (6)	1.3	1.1
Neches	Evadale, Tx.	20,593	19	10	7.1 (11)	11.0 (6)	1.3	1.1
Trinity	Romayor, Tx.	44,512	14	5	6.9 (10)	8.3 (8)	0.9	0.4
Brazos	Rosharon, Tx.	117,428¶	6	1	9.8 (5)	7.0 (8)	0.6	0.1
Colorado	Wharton, Tx.	107,170¶	3	1	3.9 (11)	4.6 (8)	0.1	0.1
Guadalupe	Victoria, Tx.	13,463	19	10	6.2 (6)	7.0 (8)	1.2	0.7
San Antonio	Golial, Tx.	10,155	12	5	9.2 (12)	20.2 (8)	1.1	1.0
Nueces	Three Rivers, Tx.	40,400	2	1	6.9 (12)	21.2 (8)	0.1	0.2
		$\sum =$ 377,883						
Rio Grande (457,000 km^2)								
Rio Grande	Brownsville, Tx.	456,702	0.4	0.4	3.5 (6)	5.8 (10)‡	<0.1	<0.1
Colorado (640,000 km^2)								
Colorado	Andrade, Ca.	639,000	0.3	0.3	3.2 (23)	3.3 (19)	<0.1	<0.1
West Central Canada (2,113,000 km^2)								
Churchill	Red Head Rapids, Man.	287,000	11	7	8.8 (22) (1973–1979)‡		1.0	0.6
Nelson	Kelsey Gen. Sta., Man.	1,010,000	4	5	8.7 (30) (1973–1979)‡		0.4	0.4
Hayes	Gods R., Man.	103,000	14	22	10.7 (12) (1974–1977)‡		1.4	2.4
		$\sum =$ 1,400,000						
California (310,000 km^2)								
Salinas	Chular, Ca.	10,469	0.5	9	12.9 (7)	11.3 (8)	0.1	1.0
San Joaquin	Vernalis, Ca.	35,058	1	18	5.6 (3)	5.2 (4)	0.1	0.9
Sacramento	Sacramento, Ca.	60,870	11	38	5.5 (13))1970–1974)‡		0.6	2.1
Eel	Scotia, Ca.	8,063	29	96	6.2 (6) (1979)		1.8	6.0
Russian	Guerneville, Ca.	3,465	12	81	3.3 (7)	5.9 (10)	0.4	4.8
Klamath	Klamath, Ca.	31,340	28	47	9.6 (6)	2.4 (8)	2.6	1.1
		$\sum =$ 149,265						

Table 1—*contd.*

River	Station location	Drainage area (km²)	Specific runoff (cm) 1977	Specific runoff (cm) 1978	Weighted mean TOC conc.* (gC m⁻³) 1977 (*n*)	Weighted mean TOC conc.* (gC m⁻³) 1978 (*n*)	TOC export† (gC m⁻² yr⁻¹) 1977	TOC export† (gC m⁻² yr⁻¹) 1978
Pacific Northwest, British Columbia (1,650,000 km²)								
Rogue	Agness, Or.	10,202	26	39	3.5 (5)	1.8 (8)	0.9	0.7
Umpqua	Elkton, Or.	9,539	46	47	3.4 (6)	1.6 (7)	1.6	0.8
Columbia	Bradwood, Or.	665,900	17	25	2.2 (10)‡	2.6 (12)‡	0.4	0.6
Skagit	Mt. Vernon, Wa.	8,011	155	158	3.6 (5)	2.8 (8)	5.6	4.4
Chehalis	Porter, Wa.	3,351	98	78	3.7 (5)	3.8)8)	3.6	3.0
Snohomish	Monroe, Wa.	3,981	205	166	2.0 (5) (1979–1980)		4.0	3.3
Fraser	Mission City, BC	228,000	38	36	6.3 (18) (1973)		2.4	2.3
		Σ = 928,984						
Northwest Territories (3,380,000 km²)								
Mackenzie	Arctic Red R., NWT	1,660,000	17	15	7.5 (25) (1973–1978)‡		1.3	1.1
Back	Deep Rose L., NWT	98,200	15	14	3.2 (9) (1972–1979)‡		0.5	0.4
Thelon	Baker L., NWT	154,000	16	17	4.0 (10)** (1972–1979)‡		0.6	0.7
Coppermine	Point L., NWT	20,300	14	12	4.1 (5) (1970–1972)‡		0.6	0.5
Kazan	Kazan Falls, NWT	72,300	16	23	4.2 (5) (1972–1977)‡		0.7	1.0
Quoich	St. Clair Falls, NWT	28,700	21	16	2.7 (6) (1972–1977)‡		0.6	0.4
		Σ = 2,033,500						
Alaska, Yukon Territory (2,055,000 km²)								
Stikine	Wrangell, Ak.	51,000	94	88	2.4 (15) (1976–1979)‡		2.2	2.1
Copper	Chitina, Ak.	53,400	73	58	6.3 (4) (1978–1979)‡		4.6	3.7
Susitna	Susitna Sta., Ak.	50,200	99	75	3.9 (4)	2.8 (3)	3.8	2.1
Kuskokwim	Crooked Cr., Ak.	80,500	48	30	4.1 (5) (1977–1978)		2.0	1.2
Yukon	Pilot Sta., Ak.	831,000	23	19	7.2 (6) (1977–1978)		1.7	1.4
Kobuk	Kiana, Ak.	24,660	37	46	5.4 (4) (1976–1977)‡	2.7 (5)	2.0	1.2
Kuparuk	Deadhorse, Ak.	8.107	17	15	9.9 (3)	12.0 (4)	1.7	1.8
		Σ = 1,098,867						

* Weighted by instantaneous riverflow.

† Computed using drainage area, annual flow, and weighted mean annual TOC concentration (unless $n < 3$, in which case used unweighted mean conc.).

‡ Unweighted mean TOC concentration.

§ TOC concentration is for a station (Harrisburg) 90 km upstream of that for flow.

‖ Flow at TOC sampling station was computed by multiplying flow at an upstream station by the drainage area increase factor between the two stations (area at TOC sampling station/area at flow station).

¶ Includes noncontributing drainage areas.

** TOC at a station well upstream (65,000 km² drainage) of flow station.

from 1 to 6 gC m⁻² yr⁻¹ (Table 2) and are roughly similar to the 4 to 5 gC m⁻² yr⁻¹ estimated by Schlesinger and Melack (1981) for such systems. However, our values of TOC export from arid regions (Rio Grande and Colorado River drainages) are considerably lower than the 0.5 to 1 gC m⁻² yr⁻¹ estimated by Schlesinger and Melack.

Meybeck (1981) has suggested that organic carbon export in rivers is directly related to net primary production in the drainage basin. The low

Table 2. *River TOC export in 1977 and 1978 from the various regions of North America (Rio Grande drainage basin and north). Values are compiled from data in Table 1*

Drainage region*	Total drainage area (km^2)	Number of rivers surveyed	Drainage area surveyed (% of regional total)	Mean TOC export† ($gC\ m^{-2}\ yr^{-1}$) 1977	Mean TOC export† ($gC\ m^{-2}\ yr^{-1}$) 1978	Total Regional TOC export ($\times 10^{12}\ gC\ yr^{-1}$) 1977	Total Regional TOC export ($\times 10^{12}\ gC\ yr^{-1}$) 1978
Northeast Canada, New England	2,230,000	11	6%	6.3	5.1	14.0	11.4
Mid-Atlantic	264,000	6	60%	4.3	3.9	1.1	1.0
South Atlantic, Gulf	700,000	20	58%	3.0	3.5	2.1	2.4
Ontario	1,069,000	3	18%	2.4	2.9	2.6	3.1
Great Lakes	774,000	1	100%	2.4	1.4	1.9	1.1
Mississippi, Red Rivers	3,175,000	2	99%	1.3	1.4	4.1	4.4
Texas-Gulf	450,000	8	84%	0.6	0.3	0.3	0.1
Rio Grande	457,000	1	100%	<0.1	<0.1	<0.1	<0.1
Colorado R.	640,000	1	100%	<0.1	<0.1	<0.1	<0.1
Great Basin	480,000	0	—	0	0	0	0
West Central Canada	2,113,000	3	66%	0.6	0.6	1.3	1.3
California	310,000	6	48%	0.9	2.0	0.3	0.6
Pacific Northwest, British Columbia	1,650,000	7	56%	1.0	1.1	1.6	1.8
Northwest Territories	3,380,000	6	60%	1.0	1.0	3.4	3.4
Alaska, Yukon Terr.	2,055,000	7	53%	2.0	1.6	4.1	3.3
TOTAL	19,747,000					36.8	33.9

* Drainage regions are the same as those appearing as headings in Table 1.
† Mean of TOC exports from rivers within each region weighted by the size of each river's drainage basin.

mean annual TOC exports we report for most rivers draining the arid southwestern portions of North America (Colorado River, Rio Grande) and the cold northern sections (Northwest Territories, Yukon Territory, Alaska) are probably the result of low annual net primary productivity in these regions. Low TOC exports in rivers draining the Pacific Northwest and British Columbia are somewhat more difficult to explain. Much of Columbia River drainage lies in the arid portion of this region east of the Cascade Mountains and this may limit its TOC inputs. Many of the other rivers draining the Pacific Northwest originate in the mountains of the Cascade and Coast Ranges and descend steeply to the coast. The high seasonal rainfall of the coastal region (120 to 250 mm yr^{-1}, U.S. Geol. Survey, 1979) and the steep topography result in relatively short residence time for water in and on watershed soils. The short residence time of water within the terrestrial portions of these mountainous watersheds and their proximity to the coast may result in reduced leaching of litter and soil organic carbon and hence lower river TOC concentrations. Also, in the wet, highly productive coniferous forests of the western portions of the Pacific Northwest, ecosystem processes which result in efficient nutrient retention and recycling (Waring and Franklin, 1979) may also result in efficient retention of organic carbon. Lower organic carbon sources in conjunction with high rates of annual runoff and short water residence time result in low TOC concentrations in rivers draining this region compared to those in other regions of North America.

Despite regional variation in mean annual TOC concentrations, most of the regional variation in annual specific TOC export ($gC\ m^{-2}\ yr^{-1}$) is the result of large differences in annual runoff across

North America. Among the river basins presented in Table 1, annual runoff varied from lows of < 1 cm, for some of the rivers draining the arid southwestern United States, to highs of > 150 cm for two rivers in Washington State. Brinson (1976) and Mulholland and Kuenzler (1979) have suggested that organic carbon export is linearly related to annual runoff; however, their analyses were based upon data from a small number of mostly low order streams. When 1977 TOC exports (gC m^{-2} yr^{-1}) from the drainage basins of rivers compiled in this study are plotted against annual runoff (cm), more variation is observed (Fig. 2). If data from three Washington rivers (Skagit, Chehalis, and Snohomish) and two Alaskan rivers (Stikine and Susitna) draining coastal mountainous regions are omitted, the export-runoff relationship of Fig. 2 appears to be linear ($r = 0.92$), at least over the runoff range from about 10 to 80 cm. However, the data plot well above the relationship suggested by Mulholland and Kuenzler (1979), particularly for runoff values > 20 cm. Schlesinger and Melack (1981) have proposed a curvilinear relationship between TOC export and runoff, with export approaching a maximum value at high runoff values. Although our data (Fig. 2) suggest a linear relationship at runoff values < 80 cm yr^{-1}, data plotted from three drainages with runoff $>$ 120 cm yr^{-1} seem to indicate a similar saturation-type effect.

The strong dependence of river organic carbon transport on flow is further demonstrated in Fig. 3. A logarithmic plot of annual transport (gC yr^{-1}) versus annual riverflow (m^3 yr^{-1}) for North American rivers compiled in this study shows a strong linear relationship ($r = 0.96$) very similar to that presented by Schlesinger and Melack (1981). Because the slope of the linear regression is approximately 1.0, the weighted mean annual TOC concentration inherent in this relationship, about 6.5 gC m^{-3}, is approximately constant over the range of annual flows compiled (Fig. 3).

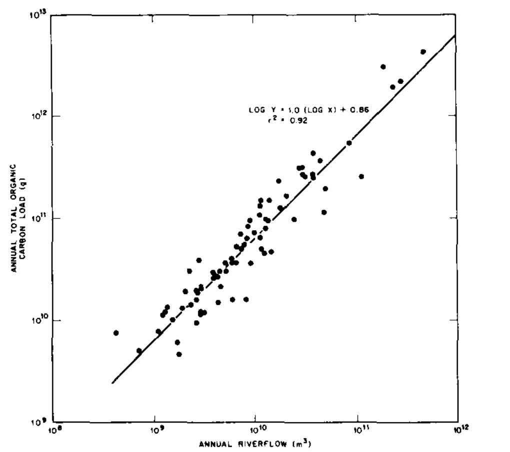

Fig. 3. Annual total organic load shown as a logarithmic function of total annual riverflow for rivers of North America in 1977.

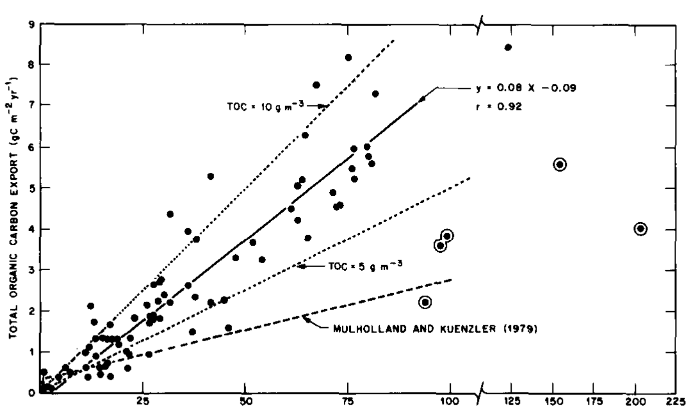

Fig. 2. Annual total organic carbon export plotted as a function of annual runoff from large North American watersheds in 1977. Circled data points are from mountainous watersheds on the Pacific coast. Also shown are export-runoff relationships for mean total organic carbon (TOC) concentrations of 5 and 10 g m^{-3} and the export-runoff relationship proposed by Mulholland and Kuenzler (1979).

Annual export of TOC from each of the drainage regions of North America via rivers is presented in Table 2. The rivers surveyed in this study drain a total of 11,907,800 km^2, approximately 60% of the North American continent to the north of and including the Rio Grande basin. Based upon the computations of mean regional TOC exports from the rivers surveyed, we calculate 37×10^{12} gC was exported from the North American continent by rivers in 1977 and 34×10^{12} gC in 1978. Most of this loss was from the eastern and northwestern portions of the continent, those with the greatest annual runoff.

Since annual TOC export is largely dependent on annual runoff, large year-to-year variation in riverflow would result in similarly large variation in TOC export. This is particularly evident comparing TOC exports in 1977 and 1978 in the San Joaquin, Eel and Russian Rivers of California, which had 18, 3.3 and 6.8 times greater flow, respectively, in 1978 than in 1977. Although California rivers, and to a lesser extent many of the rivers in the Southeastern United States, had substantially greater flows in 1978 compared to 1977, rivers in northeast Canada and New England, Texas, and Alaska generally had less flow (Table 1). Since many of the latter regions have relatively high TOC export, the net result of differences in the distribution of runoff in the two years considered was a slight decrease in TOC export from 1977 to 1978 (Table 2).

In order to estimate TOC export associated with the long-term average riverflow, flows during 1977 were compared with long-term annual averages for rivers in each region (Table 3). Assuming TOC export varies directly with annual flow, the long-term average export of TOC amounts to about 39×10^{12} gC yr^{-1}, or about 5% greater than that in 1977 and 15% greater than in 1978. These results indicate that TOC export from the portion of North

Table 3. *Computation of long-term average annual TOC export in rivers of North America*

Drainage regions*	Number of rivers surveyed†	Drainage area surveyed (% of regional total)	1977 riverflow (% of long-term average)‡	1977 TOC export ($\times 10^{12}$ gC yr^{-1})	Long-term average TOC export ($\times 10^{12}$ gC yr^{-1})§
Northeast Canada, New England	16	17	113	14.0	12.4
Mid-Atlantic	6	60	109	1.1	1.0
South Atlantic, Gulf	20	58	100	2.1	2.1
Ontario	5	30	82	2.6	3.2
Great Lakes	1	100	108	1.9	1.8
Mississippi, Red Rivers	2	99	70	4.1	5.9
Texas-Gulf	8	84	98	0.3	0.3
Rio Grande	1	100	—	<0.1	<0.1
Colorado	1	100	—	<0.1	<0.1
West-Central Canada	3	66	70	1.3	1.9
California	5	45	38	0.3	0.8
Pacific Northwest, British Columbia	7	56	72	1.6	2.2
Northwest Territories	6	60	96	3.4	3.5
Alaska, Yukon Terr.	3	7	111	4.1	3.7
TOTAL				36.8	38.8

* See Figure 1.

† Rivers are the same as those in Table 1, but include some additional rivers in Canada and some deletions in Alaska and California.

‡ Average of that for each river surveyed in each region and weighted by river drainage basin size.

§ Computed by dividing 1977 TOC export by 1977 riverflow as a fraction of the long-term average riverflow.

America, to the north of and including the Rio Grande basin, amounts to about 40 × 10^{12} gC yr^{-1} with year to year variation of from about 5 × 10^{12} to 10 × 10^{12} gC yr^{-1}. In addition, as a result of the potential errors involved in TOC and riverflow measurement, as well as those introduced in deriving mean annual values and extrapolating to other areas, the annual exports computed here have an uncertainty associated with them of roughly 10 to 20%.

Very low frequency floods may transport extremely large amounts of organic carbon, especially particulate organic carbon, over a very short period of time. Nordin and Meade (1981) have reported that one large flood in the Eel River in California, lasting only four days during 1965, resulted in a sediment load greater than the combined total for the previous seven years. However, the impact of extreme flood events on sediment and presumably organic carbon flux in large rivers is not as great as in small rivers. For example, Nordin and Meade (1981) report that a 100-year flood in the Mississippi River during 1973 resulted in an annual sediment load of only about 1.5 times the average for the period 1963–1978.

North America, to the north of and including the Rio Grande drainage basin, comprises 19.7 × 10^6 km^2, or 13.2% of the earth's continental land mass. Assuming North American rivers carry 13.2% of the earth's river organic carbon load, global annual river flux to the oceans is about 0.3 × 10^{15} gC. Global extrapolations of river organic carbon flux, based upon our data alone, are probably low. While mean annual runoff from the North American continent is similar to the world average (Todd, 1970), tropical ecosystems are unrepresented in our data. Organic carbon loss from tropical areas via rivers appears to be somewhat greater than from cooler regions (Richey et al., 1980; Schlesinger and Melack, 1981). With this in mind, our North American estimate, based upon an extensive compilation of 82 rivers (draining about 60% of Canada and the United States), seems to be in rough agreement with global river flux estimates of about 0.4 × 10^{15} gC yr^{-1} (Schlesinger and Melack, 1981; Meybeck, 1981). These estimates, however, are probably lower bounds since methods of sampling and measurement of organic carbon in rivers, especially large rivers, probably underestimate to an unknown extent the concentrations transported at a particular time and over the annual period.

4. Acknowledgements

We thank Maureen Lamb, (Water Quality Branch, Inland Waters Directorate) and Douglas Kirk and William Ozga (Water Resources Branch, Inland Waters Directorate) for helping to retrieve data from Canadian rivers. We also thank Drs John Trabalka and Ralph Turner (Environmental Sciences Division, Oak Ridge National Laboratory) and Dr William Schlesinger (Duke University) for critical reviews of the manuscript. Data used in this synthesis was collected by the Water Resources Division of the United States Geological Survey and by the Water Quality and Water Resources Branches of the Inland Waters Directorate, Canada.

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