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Dissolved organic matter concentration and flux in streams

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Dissolved organic matter (DOM) in streams is important as an energy resource for food webs (Bott et al. 1984, Meyer 1990a), a regulator of nutrient uptake and cycling by heterotrophic microbes (Lock 1981, Meyer et al. 1988), a complexing agent for metals (McKnight and Bencala 1990, Mierle and Ingram 1991), and a determinant of pH and alkalinity (Oliver et al. 1983). DOM has been shown to be an important metabolic substrate in some streams, with DOM use contributing significantly to total stream metabolism (Naiman et al. 1987, Meyer and Edwards 1990). Sources of DOM are both the terrestrial watershed (McDowell and Likens 1988, Hornberger et al. 1994) and instream processes, such as leaching and decomposition of allochthonous particulate organic matter and release by stream algae (Kaplan and Bott 1982, Meyer 1990b). For small streams, the primary site of DOM use is the stream bottom, including the interstitial waters of streambed sediments (Dahm 1981, Hynes 1983, Ford and Naiman 1989, Fiebig and Lock 1991). In larger rivers, the water column may also be an important site for DOM use (Vannote et al. 1980).

Stream DOM is an important indicator of watershed-scale hydrologic and biogeochemical processes. Large water-soluble pools of DOM are present in the upper soil horizons of forests and grasslands (litter, O, and A horizons) and are sources of DOM to drainage waters; however, lower soil horizons (B and C horizons) often contain materials (e.g., iron and aluminum oxides) that effectively sorb and immobilize DOM (McDowell and Wood 1984, Cronan 1990). Hydrologic pathways involving lateral flow of water through or over surface soil layers often have relatively high concentrations of DOM, whereas water flowpaths that pass slowly through lower soil layers usually have low DOM concentrations (Moore and Jackson 1989, Kaplan and Newbold 1993). The commonly observed increase in DOM concentrations during periods of high discharge is at least partly due to shifts in dominant flowpaths from deeper routes to shallow subsurface or surface pathways (Tate and Meyer 1983, Mulholland et al. 1990, Hornberger et al 1994). Wetlands are also an important source of DOM to streams, and several analyses have shown that differences in baseflow DOM concentrations among streams are strongly related to the amount of wetland drainage contributing to streams (Mulholland and Kuenzler 1979, Eckhardt and Moore 1990). Saturated riparian soils and wetlands appear to be particularly important contributors to stream DOM, especially during storms (Fiebig et al. 1990, Hemond 1990).

In this paper I focus on the concentrations and flux of DOM in streams whose organic matter budgets are presented in the preceding chapters. My objective is to define the variation in annual average DOM concentrations and flux and to identify what factors might be most responsible for this variation.

Methods

The data used in this analysis are presented and described in the site-description chapters in this paper with the following exceptions. Values

TABLE 1. Independent variables used in the analysis and the number of streams for which values for the variable were available.

Independent variable	Number of observations
Latitude	33
Stream order	33
Watershed area	32
Average annual precipitation	33
Average annual runoff	32
Average water temperature	32
Average annual discharge	33
Channel slope	32
Average channel width	26
Streambed area above site	23
Gross primary production (instream)	27
Litter input	33
DOM input (groundwater, throughfall)	19
Total organic input	26
Wood standing crop	23
CBOM (excluding wood)	26
Total CBOM	29
FBOM	23
Total BOM	26
Heterotrophic respiration	24
POM concentration	33

of DOM transport for Beaver Creek, Quebec, were calculated from the DOC values presented by Naiman (1982) and the average annual discharge values presented by Naiman and Link (1997). The average annual discharge used for Sycamore Creek, Arizona, was 1350 L/s rather than the 800 L/s given by Jones et al. (1997) because the larger value was the mean discharge for the 5-y period (1989–1993) over which the average annual DOM transport was computed (Jones et al. 1996), whereas the smaller value represents a long-term mean.

Dependent variables in the analyses were mean annual DOM concentration (mg/L), annual DOM transport (kg/y), annual DOM export per unit streambed area (g m^{-2} y^{-1}), and annual DOM export per unit watershed area (g m^{-2} y^{-1}). Independent variables used in the analysis are listed in Table 1. Mean annual DOM and POM concentrations were computed from the data provided on annual DOM or POM transport and average discharge (converted to an annual value) as follows: mean annual concentration = annual transport divided by annual discharge. Annual runoff (cm) was calculated from mean annual discharge (m^3) and watershed area (m^2). DOM export was presented as export per unit of streambed area per year and as export per unit of watershed area per year. DOM export per unit watershed area was calculated as annual transport divided by watershed area and presented in terms of g m^{-2} y^{-1}.

Correlations and stepwise multiple regressions were performed using SAS (PC SAS, release 6.03, SAS Institute, Cary; North Carolina). Because values of many independent variables and some of the dependent DOM variables spanned several orders of magnitude, correlations were performed on log-transformed data where necessary to improve the linear correlation. Multiple regression models were developed for the 4 dependent variables (DOM concentration, DOM transport, streambed-normalized DOM export, and watershed-normalized DOM export). Multiple regressions could not be performed using all of the independent variables because many sites lacked data for 1 or more of these variables. Therefore, multiple regressions were performed using only latitude, stream order, watershed area, annual precipitation, channel slope, average annual discharge, average annual runoff, litter input, and POM (seston) concentration as independent variables, permitting 31 out of 33 streams to be included in the analysis. Average annual discharge and average annual runoff were not used in the correlation and multiple regression analyses for DOM transport and the 2 expressions of DOM export because of autocorrelation between dependent and independent variables. Untransformed and log-transformed values of independent variables were entered in the multiple regression model.

Results

Mean annual DOM concentrations ranged from 0.1 to 36.6 mg/L across sites (Table 2). There were only a few significant correlations between mean DOM concentration and stream characteristics, and almost all of these physical factors related to stream size or channel morphology (Table 3). The strongest correlations ($r > 0.6$) were between DOM concentration and log channel slope (negative), log channel width, and streambed area, although none of these variables were particularly strong predictors of

TABLE 2. Latitude, stream order, and mean annual concentration (mg/L), transport (kg/y), export per unit streambed area (g m^{-2} streambed y^{-1}), and export per unit watershed area (g m^{-2} watershed y^{-1}) of DOM for streams in this analysis.

Stream (location)	Lat.	Order	DOM concentration	DOM transport	DOM export (streambed)	DOM export (watershed)
Q. Toronja (Puerto Rico)	18	1	3.8	1068	—	6.59
R. Icacos (Puerto Rico)	18	3	5.1	61,266	—	18.79
Q. Sonadora (Puerto Rico)	18	3	5.9	38,951	—	14.87
Ogeechee R. (Georgia)	32	6	28.6	6.0×10^7	4526	8.76
Sycamore Cr. (Arizona)	33	5	11.9	506,000	1529	1.00
Creeping Swamp (North Carolina)	35	3	36.6	1.3×10^6	—	16.25
Hugh White Cr. (North Carolina)	35	2	3.0	1796	222	2.94
Satellite Br. (North Carolina)	35	1	1.0	56	149	0.74
Walker Br. (Tennessee)	36	1	1.7	640	500	1.66
Buzzards Br. (Virginia)	37	1	20.2	38,248	3122	9.56
Keppels Cr. (Australia)	37	4	5.2	27,800	1690	1.95
Kings Cr.—gallery (Kansas)	39	5	2.5	4720	17.6	0.45
Kings Cr.—prairie (Kansas)	39	3	2.5	660	30.1	0.49
White Clay Cr. (Pennsylvania)	40	3	7.6	27,600	1150	3.81
Augusta Cr. (Michigan)	42	1	8.4	3444	3280	9.06
Fort R. (Massachusetts)	42	4	6.3	538,000	—	5.03
Bear Br. (New Hampshire)	44	2	4.3	514	80.6	3.89
Devils Club Cr. (Oregon)	45	1	1.6	86	286.7	0.43
Watershed 10 (Oregon)	45	1	1.2	203	677	1.99
Mack Cr. (Oregon)	45	3	0.7	2031	—	0.34
Lookout Cr. (Oregon)	45	5	0.7	80,800	—	1.33
McKenzie R. (Oregon)	45	7	1.1	1.9×10^6	—	1.47
Rattlesnake Sp. (Washington)	47	1	0.7	670	158	0.002
First Choice Cr. (Quebec)	50	1	8.1	1293	8620	5.17
Beaver Cr. (Quebec)	50	2	25.8	26,849	2636	14.67
Muskrat R. (Quebec)	50	5	25.2	5.15×10^6	1798	24.89
Matamek R. (Quebec)	50	6	30.6	1.32×10^7	—	19.60
Moisie River (Quebec)	50	9	11.6	1.7×10^8	—	8.56
Breitenbach (Germany)	51	1	4.0	4780	1040	0.58
Caribou Cr., C–2 (Alaska)	65	1	6.2	6133	—	1.18
Caribou Cr., C–3 (Alaska)	65	1	18.7	14,276	—	2.50
Kuparuk R. (Alaska)	70	4	21.8	640,000	1306	4.48
Canada Stream (Antarctica)	78	1	0.5	54	1.7	—

DOM concentration (Fig. 1A,B,C). DOM concentration was also significantly correlated with average annual discharge and watershed area, suggesting that larger streams have generally higher DOM concentrations than smaller streams (Fig. 1D). DOM concentration was not significantly correlated with mean annual runoff ($r = -0.246$, $p = 0.176$) also suggesting that the DOM concentration-discharge relationship was due more to stream size than to watershed wetness. Multiple regression analysis showed that DOM concentration was best predicted by channel slope and that inclusion of no other variables improved the model (Table 4).

DOM concentrations were unrelated to latitude (Fig. 2). However, DOM concentrations were substantially higher in streams draining watersheds with extensive wetlands (Creeping Swamp, North Carolina; Buzzards Branch, Virginia; Ogeechee River, Georgia; Beaver Creek and Muskrat River, Quebec) or permafrost (Kuparuk River and Caribou Creek C–3, Alaska) than in the other streams, although variables quantifying wetlands and permafrost per se were not included in the dataset. Among the Quebec streams, Beaver Creek is described as a series of beaver ponds and wetlands and the Muskrat River drains a large muskeg, whereas

TABLE 3. Significant ($p < 0.05$) correlations between DOM concentration, DOM transport, DOM export per unit streambed area, and DOM export per unit watershed area, and various physical, chemical, and biological characteristics of streams. Type refers to whether correlations were strongest for untransformed (un) or log-transformed values (log) of the indendent variable, or log-transformed values of the dependent and independent variables (log–log).

Dependent variable	Independent variable (type)	r	p	n
DOM concentration	Watershed area (log)	0.446	0.0106	32
	Average discharge (log)	0.453	0.0081	33
	Channel slope (log)	−0.665	0.0001	32
	Channel width (log)	0.604	0.0012	26
	Streambed area (un)	0.661	0.0008	22
	POM concentration (log–log)	0.422	0.0145	33
DOM transport	Stream order (log–log)	0.835	0.0001	33
	Watershed area (un)	0.997	0.0001	32
	Channel slope (log–log)	−0.754	0.0001	32
	Channel width (log–log)	0.875	0.0001	26
	Streambed area (log–log)	0.758	0.0001	23
	Litter input (log)	−0.551	0.0011	32
DOM export	Channel slope (log–log)	−0.527	0.0169	20
(per unit streambed area)	Total organic input (log–log)	0.447	0.0424	21
	CBOM (excl. wood) (log–log)	0.526	0.0249	18
	Total CBOM (log–log)	0.496	0.0261	21
	Total BOM (log–log)	0.557	0.0087	21
	POM concentration (log–log)	0.490	0.0241	21
DOM export	Annual precipitation (log–log)	0.431	0.0173	30
(per unit watershed area)	Channel slope (log)	−0.505	0.0044	30
	Channel width (log)	0.453	0.0262	25
	Streambed area (un)	0.598	0.0042	21
	POM concentration (log–log)	0.475	0.0080	30

First Choice Creek has little wetland drainage and the Moisie River drains a large heterogenous watershed (Naiman 1982, Namain and Link 1997). Matamek River DOM concentration was also high (30.6 mg/L), but it was not clear how much wetland drainage is included in its watershed and therefore it was not included in either group in this analysis. Kuparuk River (Harvey et al. 1997) and Caribou Creek C–3 (Irons and Oswood 1997) have extensive permafrost in their watersheds, whereas Caribou Creek C–2, although draining a watershed adjacent to Caribou Creek C–3, has very little permafrost (Irons and Oswood 1997). Average DOM concentration for the 7 wetland and permafrost streams was 25.4 mg/L (range: 18.7–36.6 mg/L), considerably greater than the average DOM concentration for the other 25 streams of 4.2 mg/L (range: 0.1–11.9 mg/L). Although it appears that DOM concentration declines with latitude in the wetland/permafrost streams (Fig. 2), the DOM/latitude regression for these streams was not significant ($F = 3.04$, $p = 0.142$).

Annual DOM transport was correlated primarily with characteristics related to stream size (e.g., stream order, watershed area, channel width, streambed area) as is expected (Table 3). DOM transport was also negatively correlated with channel slope and litter input. The negative correlation between DOM transport and litter input appears to be simply a matter of the independent effects of stream size on litter input (litter input per unit area of streambed generally declines with increasing stream size) and on DOM transport (higher DOM transport in larger streams). Multiple regression analysis indicated that watershed area explained 78% of the variation in DOM transport, as expected because of the strong influence of discharge on watershed area (Table 4). Inclusion of log POM concentration and log annual precipitation in the multiple regression model improved the prediction of DOM transport by about 9%.

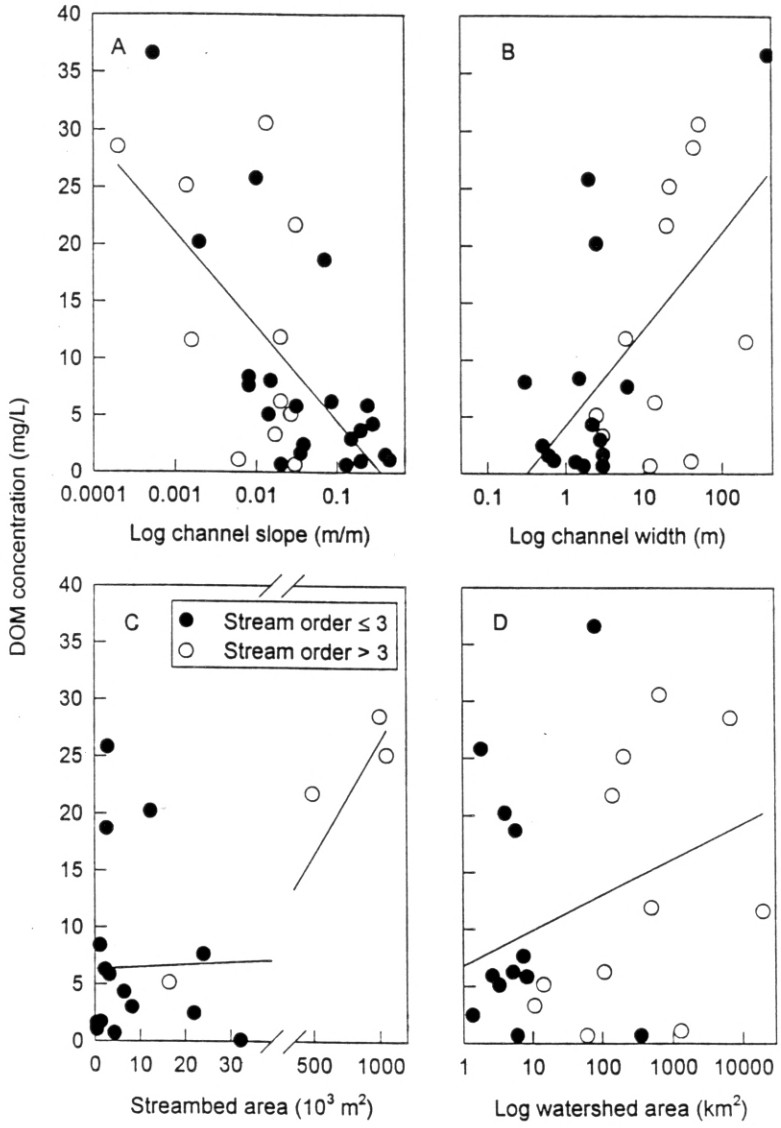

FIG. 1. Relationships between DOM concentration and (A) channel slope, (B) channel width, (C) streambed area, and (D) watershed area. Lines show least-squares regression fits.

Annual DOM export per unit streambed area was negatively correlated with channel slope and positively correlated with characteristics related to organic matter input and storage (Table 3). Approximately 74% of the variation in streambed-normalized DOM export was explained by a multiple regression model that included channel slope and POM concentration (Table 4).

Annual DOM export per unit watershed area was positively correlated with mean annual precipitation as expected because of its strong effect on discharge, and hence material export (Table 3). Annual watershed-normalized DOM export was also negatively correlated with channel slope and positively correlated with mean channel width, streambed area, and POM concentration. Approximately 55% of the variation in watershed-normalized DOM export was explained by a multiple regression model that included channel slope, annual precipitation, litter input, and POM concentration (Table 4). Although

TABLE 4. Multiple regression models for annual average DOM concentration (mg/L), annual DOM transport (kg/y), streambed-normalized DOM export (g m^{-2} y^{-1}), and watershed-normalized DOM export (g m^{-2} y^{-1}). A criterion of $p < 0.05$ was used for entry of independent variables into the model. Models were developed for log-transformed values of DOM transport and streambed-normalized DOM export because the untransformed values of these variables spanned ≥3 orders of magnitude. Both untransformed and log-transformed values of the independent variables were evaluated for entry into the model.

Dependent variable	Independent variable	Parameter estimate	Partial r^2	Model r^2	F	p
DOM concentration	Intercept	−3.707				
	Log channel slope	−8.282	0.442	0.442	23.77	0.0001
Log DOM transport	Intercept	−1.616				
	Log watershed area	1.181	0.780	0.780	106	0.0001
	Log POM conc.	0.787	0.050	0.830	8.49	0.0068
	Log annual precipitation	1.134	0.045	0.874	9.94	0.0038
Log DOM export	Intercept	2.252				
(per unit streambed)	Log channel slope	−0.392	0.297	0.297	7.19	0.0158
	Log POM conc.	1.388	0.195	0.492	6.13	0.0249
	POM conc.	−0.135	0.214	0.735	10.89	0.0049
DOM export	Intercept	−4.011				
(per unit watershed)	Log channel slope	−4.872	0.230	0.230	8.99	0.0054
	Annual precipitation	0.0384	0.162.	0.392	7.73	0.0094
	Litter input	−0.0105	0.086	0.479	4.64	0.0399
	Log POM conc.	3.8795	0.076	0.554	4.58	0.0416

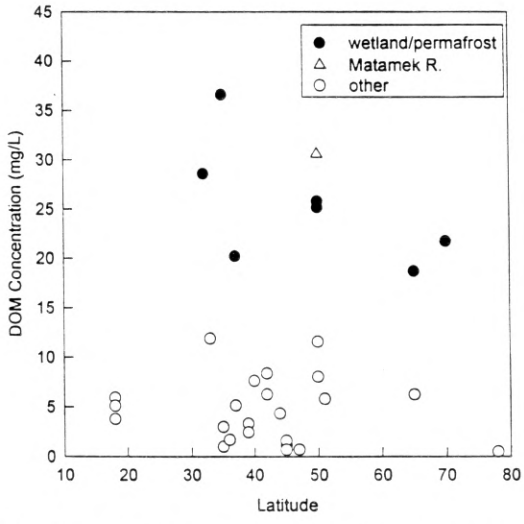

FIG. 2. Plot of DOM concentration versus latitude. Streams draining wetlands or permafrost watersheds are indicated by solid symbols, all other streams by open symbols. The Matamek River (plotted separately) is similar to the wetland/permafrost streams, but it was not clear if it represented a wetland drainage stream.

there was no relationship between watershed-normalized DOM export and runoff for the entire dataset, when the streams were separated into 2 groups based on the presence or absence of wetlands/permafrost, watershed export was closely related to runoff within each group (Fig. 3). The slope of the export-runoff relationship was about 6 × greater for the wetland/permafrost streams than the other streams.

Discussion

While it is known that both instream processes (e.g., detritus processing, algal excretion) and watershed processes produce streamwater DOM (Kaplan and Bott 1982, McDowell and Likens 1988, Meyer 1990b), the general lack of relationships between DOM concentration and measures of organic matter input and instream storage suggests that instream processes are not as important as watershed processes in controlling streamwater DOM. The prominence of channel slope as a predictor of DOM concentration and export and the sharp differences in concentrations between streams draining watersheds with significant wetland or permafrost and others suggests that watershed characteristics related to organic storage and surface

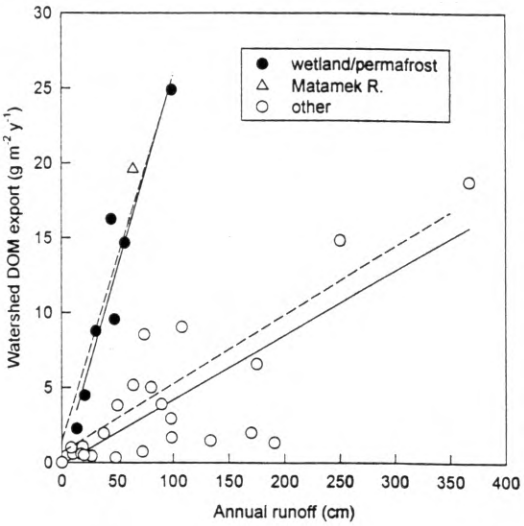

FIG. 3. Relationship between watershed-normalized annual stream DOM export and annual runoff. Solid symbols denote wetland or permafrost watersheds and open symbols denote other watersheds (Matamek River is plotted separately, but falls along the wetland/permafrost line). Lines are least-squares linear regressions for each watershed type (wetland/permafrost streams: DOM export = 0.0177 + 0.259 × runoff, F = 48.83, r^2 = 0.907, p = 0.0009; other streams: DOM export = −0.1515 + 0.043 × runoff, F = 36.94, r^2 = 0.383, p = 0.0001). Dashed lines are the export–runoff relationships for wetland and upland streams reported by Mulholland and Kuenzler (1979).

flowpaths are the most important factors controlling stream DOM. In general, high stream DOM concentrations (exceeding 12 mg/L) were found only in watersheds with sizeable riparian wetlands, or with main hydrologic flowpaths through organic-rich surface soil horizons, or both. Such watersheds generally have channels with low slopes and broad floodplains or have physical restrictions limiting vertical drainage in watershed soils (e.g., permafrost). Examples in this dataset are the swamp-draining streams in the Coastal Plain of the southeastern US, streams draining wetlands in Quebec, and streams draining permafrost areas in Alaska.

The striking difference in DOM concentrations among the Quebec streams and the Alaska streams further highlights the effect of hydrologic flowpath. First Choice Creek (DOM = 8.1 mg/L) drains a small watershed and is fed primarily from springs that presumably are fed from groundwater pools in the lower mineral soil. The Moisie River (DOM = 11.6 mg/L) drains a very large heterogeneous watershed. In contrast, 2 other Quebec streams, Beaver Creek (DOM = 25.8 mg/L) and Muskrat River (DOM = 25.2 mg/L), drain extensive wetlands and thus have a larger proportion of surface and shallow subsurface flowpaths (Naiman 1982, Naiman and Link 1997). Caribou Creek C–2 (DOM = 6.2 mg/L) drains a south-facing watershed having only about 3.5% permafrost, and consequently the dominant water flowpaths are deeper and soil organic layer thinner (5–10 cm) than Caribou Creek C–3 (DOM = 18.7 mg/L), which drains an adjacent northeast-facing watershed having about 55% permafrost and consequently a deep organic layer (about 1 m) and shallow water flowpaths (Irons and Oswood 1997). The Kuparuk River (DOM = 21.8 mg/L) also drains a permafrost watershed (Harvey et al. 1997).

The strong effect of wetland drainage on stream DOM concentrations was also emphasized by Eckhardt and Moore (1990) who presented a regression model relating DOC concentration to the percentage of wetlands in the watershed for streams in southern Quebec. Johnston et al. (1990) reported a strong positive correlation between TOC concentration (presumably mostly DOC) and percentage of herbaceous wetlands in the watersheds of streams in Minnesota. A quantitative analysis of the effect of wetlands cannot be done in this study because data were not available on the wetland percentage in each watershed. However, using the regression equation developed by Eckhardt and Moore relating DOC to % wetland area (ln DOC = 2 + 0.025 × % wetland), the wetland percentage in the watersheds of the 5 wetland streams in this study are predicted to range from 12.9% for Buzzards Branch to 36% for Creeping Swamp. Although the relationship developed by Eckhardt and Moore may not be representative of the southeastern US, the wetland percentages I have calculated here appear reasonable.

Sycamore Creek has relatively high DOM concentration but does not possess the watershed characteristics common to other high-DOM streams. Sycamore Creek is a productive, desert stream that can accumulate large standing stocks of algae during periods between floods (Grimm 1987). Instream production of DOM may be high in Sycamore Creek due to

high rates of algal production and subsequent excretion (Jones et al. 1996). The higher average DOM concentrations in Sycamore Creek may also be the result of an extremely variable flow regime in which a large fraction of the annual discharge is during a few large stroms. As is the case with most streams, DOM concentration is considerably greater during high discharge (mean 13.2 mg/L) than at low discharge (mean = 9.6 mg/L) in Sycamore Creek (Jones et al. 1996), presumably because of the greater importance of shallow subsurface and surface flowpaths at high flow. Finally, the relatively high DOM concentrations in Sycamore Creek may be a result of watershed characteristics; specifically, lower rates of organic matter mineralization in the terrestrial environment of arid lands due to moisture limitations, limited geochemical sorption of DOM in the sandy soils, and rapid transport of water through the terrestrial system to the stream during intense storms. In most humid watersheds only a very small proportion of the annual primary production (about 1%) is exported as DOM and POM in streams (Meybeck 1982) due to efficient biological remineralization and sorption in clay-rich soils (McDowell and Wood 1984). However, in semi-arid watersheds, Meybeck (1982) reported that > 10% of annual primary production is exported as stream DOM and POM. Jones et al. (1996) estimated that export of total organic matter in Sycamore Creek accounted for 2–33% of terrestrial NPP in its watershed. Thus, watersheds in arid temperate regions may export as DOM a larger fraction of their primary production due to inefficient biological and geochemical retention and rapid water movement through soils during infrequent and intense storms.

The export of DOM, whether normalized to streambed area or watershed area, was best predicted by channel slope (Table 4). Although streambed-normalized DOM export was correlated with measures of benthic organic matter storage (Table 3), suggesting that decomposition of stored organic matter influences the production of DOM, multiple regression analysis indicated that only channel slope and POM concentration were significant predictors of streambed DOM export. Watershed-normalized DOM export was primarily related to factors controlling runoff (e.g., precipitation) and factors controlling DOM concentration (e.g., morphology, as indicated by channel slope). This is not surprising because watershed export is the product of runoff and concentration. What is interesting, however, is that there appear to be 2 distinct watershed-normalized DOM export–runoff relationships (Fig. 3). In watersheds where the channel or landscape morphology generates primarily shallow flowpaths through organic soil layers (e.g., wetlands, permafrost), the DOM export–runoff relationship is much steeper than in watersheds with deeper flowpaths through mineral soil layers. Mulholland and Kuenzler (1979) also reported a much steeper relationship between DOC export and runoff for swamp-draining watersheds than upland watersheds. When the DOC exports are converted to DOM by multiplying by 2, slopes of the DOM export–runoff relationship for swamp-draining watersheds (0.27) and for upland watersheds (0.04) presented by Mulholland and Kuenzler are similar to DOM export–runoff slopes determined for wetland/permafrost watersheds (0.259) and for other watersheds (0.043) in this study (Fig. 3). The strength of the export–runoff relationships and the range of runoff values over which the relationships remain linear (up to about 400 cm for non-wetland watersheds) is striking, suggesting relatively tight controls on DOM concentration within each of 2 types of watershed morphology over a large range of hydrologic outputs. However, this finding conflicts with an earlier report by Schlesinger and Melack (1981) which showed a curvilinear relationship between watershed-normalized DOC export and runoff in upland basins, suggesting a depletion effect on DOC generation in catchments with high runoff.

Latitude was a poor predictor of DOM concentration and watershed-normalized export, even after removing the 7 wetland/permafrost streams from the analysis. This result contrasts somewhat with previous regional and global studies of carbon transport in rivers. Meybeck (1982) summarized data primarily from the larger rivers of the world and concluded that watershed export of TOC, most of which was DOC, decreased with increasing latitude from a value of 6.5 g C m^{-2} y^{-1} for the tropics to 0.5 g C m^{-2} y^{-1} for the high latitude tundra. Schlesinger and Melack (1981) in their analysis of global river carbon transport, also reported relatively high TOC export from the tropics (5 g C m^{-2} y^{-1}) and low exports from the tundra (1 g C m^{-2} y^{-1}). However, in contrast to Meybeck's analysis, Schlesinger and Melack reported rela-

tively high exports from boreal watersheds (5 g C m^{-2} y^{-1}) primarily because they used higher runoff values than did Meybeck. In an analysis of North American rivers, Mulholland and Watts (1982) showed a general decline in river TOC exports southward from the boreal region of northeastern Canada to the warm temperate regions of the United States. The dataset I analyzed consisted primarily of small, temperate-zone watersheds, and these may not necessarily be a representative sample of all temperate watersheds. The mean watershed DOM export for the temperate watersheds in this study (with latitudes from 32 to 51, but excluding the Quebec watersheds) was 3.4 g m^{-2} y^{-1} (1.7 g C m^{-2} y^{-1}), less than half the temperate zone average of 4 g C m^{-2} y^{-1} given by both Schlesinger and Melack (1981) and Meybeck (1982). This discrepancy may be a result of a bias in my analysis toward smaller streams, which tend to have lower DOM concentrations. The average DOM export for the 3 tropical watersheds in the dataset I analyzed (Puerto Rico streams) was 13.4 g m^{-2} y^{-1} (6.7 g C m^{-2} y^{-1}), reasonably close to the value for the tropics given by Meybeck but somewhat less than the value given by Schlesinger and Melack. However, in a recent study Newbold et al. (1995) reported relatively low DOC export from 6 tropical montane watersheds in Costa Rica (mean of 3.6 g C m^{-2} y^{-1}), suggesting that DOM export from tropical watersheds is not necessarily large. Average DOM export from the 5 Quebec watersheds that are described as having boreal vegetation (Naiman and Link 1997) was 14.6 g m^{-2} y^{-1} (7.3 g C m^{-2} y^{-1}), much closer to the relatively high value given by Schlesinger and Melack than the lower values given by Meybeck for the taiga. Average DOM export for the 3 Alaskan watersheds was low (2.7 g m^{-2} y^{-1}, 1.4 g C m^{-2} y^{-1}), primarily because runoff in this region was low, as has also been shown in the large-scale analyses. Therefore, latitude appears to be of minor importance as a determinant of watershed DOM export, except for its effect on precipitation and runoff.

Estimates of DOM export in streams, particularly small streams, may be low because of the strong positive relationship commonly observed between DOM concentrations and discharge during storms and the difficulty in adequately sampling storm events. Although the data that I analyzed included some attempt to account for short-term storm fluxes of DOM in annual budgets (28 of 33 streams), annual DOM transport and export values in my analysis (as well as other previously published studies) may be underestimates due to inadequate accounting for storm fluxes. The potential underestimate of DOM export from a particular watershed is probably greater for wet years, when a greater fraction of the annual discharge is stormflow, than for dry years when a greater fraction of discharge is baseflow. The lack of a significant relationship between annual DOM concentration and annual runoff in my analysis is not germane to this issue because it was an intersite comparison rather than a comparison among years at particular sites.

The dependence of DOM concentration and export on watershed characteristics suggests that the source of much of the stream DOM is the terrestrial system and DOM is largely refractory within streams. However, Meyer et al. (1987) showed that a significant portion of the DOM produced in floodplain wetlands of low-gradient Coastal Plain streams in southeastern USA is metabolized by bacteria in the stream. Newbold et al. (1982) calculated that, on average, the organic carbon transported in Bear Brook and in Creeping Swamp (most of which is dissolved) is remineralized within about 3–5 km of travel distance in the stream. In a study of streams at the Hubbard Brook Experimental Forest (including Bear Brook), it appeared that epilithic bacteria were supported primarily by DOM from terrestrial sources rather than by autochthonous DOM production by epilithic algae (Findlay et al. 1993). Thus, there is a need to better understand the role of terrestrial sources of DOM in stream organic matter budgets and its importance in supporting microbial metabolism and food webs in streams.

Among the independent variables used in this analysis (Table 1), channel slope proved to be the best predictor of DOM concentration and export. The strength of channel slope as a predictor of DOM variables (inverse relationship) is probably a result of its close relationship with watershed and riparian topography (importance of wetlands) and hydrology (surface and shallow subsurface flowpaths). Future studies on controls of stream DOM concentration and export should focus particularly on the effect of wetlands of different types and on hydrologic flowpaths, particularly in the riparian zone.

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Organic matter budgets for streams: a synthesis

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Estimating the efficiency of ecological processes has been a goal of ecologists since publication of Lindeman's paper on Cedar Bog Lake (Lindeman 1942, but note that for his definition of efficiency Lindeman cited an unpublished manuscript by G. E. Hutchinson). Many different definitions and kinds of ecological efficiencies have been determined in the ensuing years (e.g., Kozlovsky 1968). In an analysis of ecosys-

STREAM ORGANIC MATTER BUDGETS

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Stream organic matter budgets[1,2]

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Abstract. This analysis of organic matter dynamics in streams has 3 objectives: 1) to explore the relationships between physical characteristics of streams and their watersheds (climate, geomorphology) and stream organic matter dynamics using data from a broad geographic area; 2) to compare stream organic matter dynamics in a diverse array of streams in order to suggest determinants of observed patterns; and 3) to reveal deficiencies in currently available data on organic matter dynamics in streams. Streams were included in this analysis not to represent the global diversity of stream types but because organic matter data were available. In the introductory chapter we describe the kinds of data included for each stream and provide brief descriptions of previously published organic matter data for streams included in the comparative analysis but not described in individual chapters. The next 16 chapters present organic matter data for streams from North America, Europe, Australia, and Antarctica. Most of the streams represented are in the temperate zone of North America. Data presented include climate and geomorphic variables and organic matter inputs, exports, and standing crops. The chapters on individual streams are followed by 7 chapters analyzing physical features of these streams and specific components of the organic matter budgets. Stream size, water temperature, and precipitation were the most important variables setting the physical template for organic matter processes occurring in the streams. Watershed area was the best predictor of gross primary productivity (GPP), which increased with increasing watershed area. Watershed area, discharge, and soluble reactive phosphorus concentration explained 71% of the variation in GPP. Climate (latitude) and vegetation type were more important than stream order in predicting litter inputs across a broad geographic range of streams, although, within a river basin, litterfall decreased with increasing stream order. Regression of benthic organic matter (BOM) and latitude and precipitation proved useful in predicting BOM standing crop in streams at a continental scale, although BOM was also related to channel characteristics such as gradient and woody debris. Benthic respiration increased dramatically with increasing temperature (Q_{10} = 7.6), suggesting a response related not only to metabolism but also to changes in BOM quality in response to latitudinal shifts in vegetation. Terrestrial and riparian vegetation was found to play an important role in regulating suspended particulate organic matter (POM) concentration and export, with higher values observed in forested streams and in lower gradient streams with extensive floodplains. Channel slope was the best predictor of dissolved organic matter (DOM) concentration and export, probably because of its relationship with riparian wetlands and hydrologic flowpaths. In the final chapter, a synthesis of the organic matter budgets, we reached two conclusions: 1) At a global level, stream organic matter dynamics are driven primarily by climate through its effect on terrestrial vegetation. 2) Despite significant progress in understanding organic matter processes in streams, many of the differences we found among streams reflect omissions of important components of the budget, especially accurate measures of streambed area, heterotrophic respiration, standing stock of fine BOM, and groundwater inputs of DOM.

Key words: stream, organic matter, budget, primary production, litterfall, BOM, DOM, POM, respiration.

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