Biogeochemistry **24**: 1–19, 1994.

Forest sources and pathways of organic matter transport to a blackwater stream: a hydrologic approach

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Received 4 June 1993; accepted 13 October 1993

Abstract. Quantitative information regarding landscape sources and pathways of organic matter transport to streams is important for assessing impacts of terrestrial processes on aquatic ecosystems. We quantified organic C, a measure of organic matter, flowing from a blackwater stream draining a 12.6 km^2 watershed on the upper Atlantic Coastal Plain in South Carolina, and utilized a hydrologic approach to partition this outflow between its various pathways from upland and wetland forest sources. Results of this study indicate that 28.9 tonnes C yr^{-1} were exported in stream flow, which was estimated to be 0.5% of the annual C input from forest detritus to the watershed. Upland forest, which covers 94% of the watershed area, contributed only 2.0 tonnes C yr^{-1} to stream flow, which amounted to 0.04% of detritus annually produced by the upland forest. Organic matter was transported from uplands to the stream almost entirely through groundwater. Apparently, upland soils are too sandy to support overland flow, and the sloping topography insufficiently extensive or steep enough to drive important quantities of interflow. Riparian wetland forest, which covers only 6% of the watershed area, contributed 26.9 tonnes C yr^{-1} to stream flow, amounting to about 10.2% of detritus annually produced by the wetland forest. Dissolved organic C leached from wetland soil accounted for 63% of all organic C entering the stream, and was transported chiefly in baseflow. These results indicate that upland detritus sources are effectively decoupled from the stream despite the sandy soils and quantitatively confirm that even small riparian wetland areas can have a dominant effect on the overall organic matter budget of a blackwater stream. In view of the recognized importance of dissolved organic matter in facilitating transport of other substances (e.g., cation nutrients, metals, and insoluble organic compounds), our results suggest that the potential for movement of these substances through wetland soils to streams in this region is high.

Key words: Atlantic Coastal Plain, blackwater stream, carbon budget, dissolved organic carbon, riparian wetlands, water quality

Introduction

It is widely recognized that aqueous transport of organic matter through forested landscapes establishes an important link between terrestrial and aquatic ecosystems (Cummins et al. 1983; Meyer 1990). Dissolved forms of organic matter contain plant nutrients, form water-soluble complexes with metals and insoluble organic compounds, and are important mobile anions for cation movement, thus facilitating the transport of many other substances through soils (Cronan et al. 1978; Pohlman & McColl 1988; Qualls et al. 1991; Schoenau & Bettany 1987; Schnitzer 1978). Both dissolved and particulate organic matter from terrestrial sources are important food sources in the aquatic food web (Meyer 1990).

The quantity of organic matter that flows to forest streams, and its sources and pathways, provides important information for assessing the impact of surrounding forests on aquatic systems (Cronan & Aiken 1985; Meyer 1990). A study of a small montane watershed in the northeastern U.S. indicated that about 1% of forest detritus production was transported to, and exported by, the stream (Fisher & Likens 1973). This proportion is similar to what is transported by major rivers worldwide (Thurman 1985).

Little is known about the quantities of organic matter transported from different portions of watersheds or the important transport pathways to streams (Hemond 1990). Riparian wetland or floodplain forest is considered an important source of organic matter to streams (Meyer 1990; Mulholland & Kuenzler 1979), transporting particularly large amounts from the soil in floodwaters (Meyer 1986; Mulholland 1981). Upland forest, which may produce the majority of detritus in watersheds, is more restricted in transporting organic matter to streams because soils filter and immobilize organic matter leached from the detritus by percolating rainwater (McDowell & Likens 1988). However, situations in which water flow may shortcut the soil pathway, such as during high intensity rainstorms when overland flow and shallow interflow through hillslopes become important, could allow greater transport from upland sources to streams (Cronan 1990). For example, Fisher & Likens (1973) found substantial input of organic matter to a segment of a mountain stream via groundwater and interflow (32% of the non-upstream input), presumably due to the shallow soils and steep slopes within the watershed. Soils having low capacity to immobilize organic matter may also allow greater transport of upland organic matter to streams. Leenheer (1980) and St. John & Anderson (1982) observed that blackwater streams in the Amazon basin, typified by high concentrations of dissolved organic matter, tended to flow from watersheds dominated by sandy soils, while whitewater streams, with lower dissolved organic matter concentrations, drained watersheds dominated by clayey soils. Similar observations have been made for streams in the southeastern U.S. (Meyer 1986) and in Australia (Nelson et al. 1993). These researchers have suggested that sandy soils have a lower capacity than finer textured soils to immobilize organic matter. Clearly, organic matter transport to streams depends upon soil and topographic conditions that determine the importance of various surface and subsurface hydrologic pathways (Cronan 1990).

We quantified organic matter transport through various hydrologic pathways from upland and wetland forests to a stream on the upper Atlantic Coastal Plain in order to determine the origin of organic C on the landscape and the dominant pathways which transport it to the stream. Our study watershed is comprised of upland forest with sandy soils dissected by wide strips of floodplain wetland forest adjacent to a blackwater stream. Based upon observations reported in the literature, we expected a substantial contribution of organic matter from the wetland forest to the stream, and hypothesized that during frequent high intensity rainfalls, the uplands would also transport a large amount of organic matter to the stream through the sloping sandy soils. We are aware of no previous study which has quantitatively assessed the separate contributions made by uplands and wetlands to the organic matter of a stream and the particular pathways involved.

Site location and description

This study was conducted on the U.S. Department of Energy's Savannah River Site, in South Carolina (Fig. 1). At our study site, Fourmile Branch is a 2nd order stream which drains a 12.6-km^2 watershed in the Sandhill region of the upper Atlantic Coastal Plain. Fourmile Branch is a low gradient, sandy bottom, blackwater stream typical of the upper Coastal Plain (Newman 1986). The topography of the watershed is gently rolling with broad ridges separating moderately sloping valleys (Fig. 2). There is 45 m of relief between the ridge tops at the upper end of the watershed and the outflow 5 km to the west. Mean annual rainfall is 121 cm and is evenly distributed throughout the year (NOAA 1982).

The upland portion of the watershed, which covers about 11.9 km^2 based on a recent soil survey (Rodgers 1990), supports pine and southern mixed hardwood forest. The broad ridge tops are covered by longleaf pine (*Pinus palustris*), loblolly pine (*P. taeda*) and slash pine (*P. elliottii*) plantations and natural mixed pine-oak forest (Workman & McLeod 1990). More sloping areas near stream courses are dominated by deciduous forest of various oaks (*Quercus* spp.), hickorys (*Carya* spp.) and sweetgum (*Liquidambar styraciflua*), among others. Upland soils have sandy surface horizons (up to 2 m depth) with low organic matter content (< 2%) over clay-enriched, low permeability subsoils. They are primarily Blanton sands (Grossarenic Paleudults), Fuquay and Dothan loamy sands (Arenic and Plinthic Paleudults, respectively) and Vaucluse sandy loams (Typic Hapludults; Rodgers 1990). Rainfall infiltration is rapid, and overland flow events are uncommon even on steeper slopes (Williams & Pinder 1990). However, significant lateral flow (interflow) might occur through sand atop the clayey subsoil. Upland soils are well drained and are subject to periodic drought during late summer and autumn.

Riparian wetlands are a distinctive feature of the watershed, comprising 0.7 km^2 or about 6% of the watershed area. These wetlands are a low, flat floodplain, 50 to 100 m wide, running the length of the stream valley bottom. The area supports dense forest containing sweetgum, tupelos (*Nyssa sylvat-*

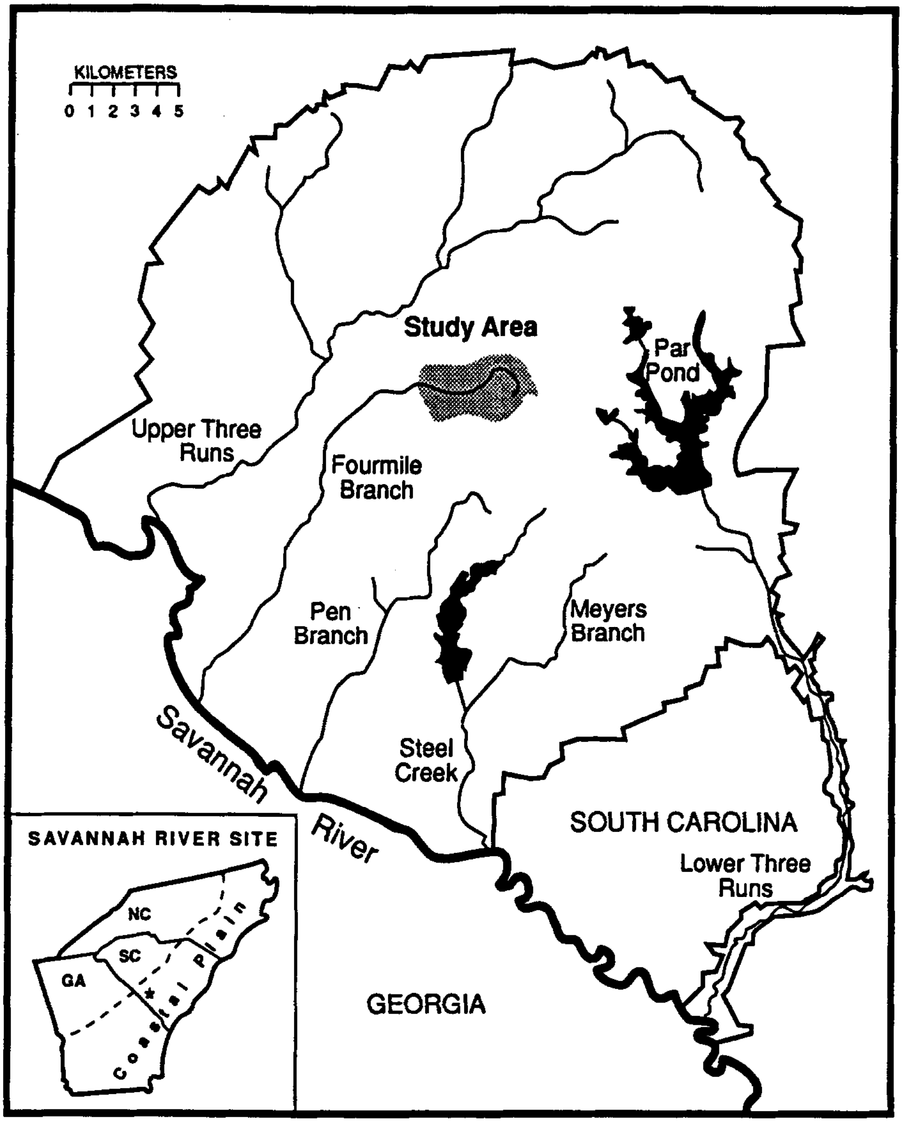

Fig. 1. Location of the Savannah River Site and upper Fourmile Branch watershed on the Atlantic Coastal Plain physiographic province in South Carolina.

ica var. biflora and *N. aquatica*), oaks (*Quercus nigra* and *Q. laurifolia*), red maple (*Acer rubrum*) and cypress (*Taxodium distichum*), among others (Workman & McLeod 1990). Soils in these wetlands are primarily Fluvaquents and Cumulic Humaquepts, which have an organic-rich surface layer (up to 1 m or more deep) over sandy subsoil (Rodgers 1990). The water table fluctuates between 30 cm above and 30 cm below the soil surface, keeping

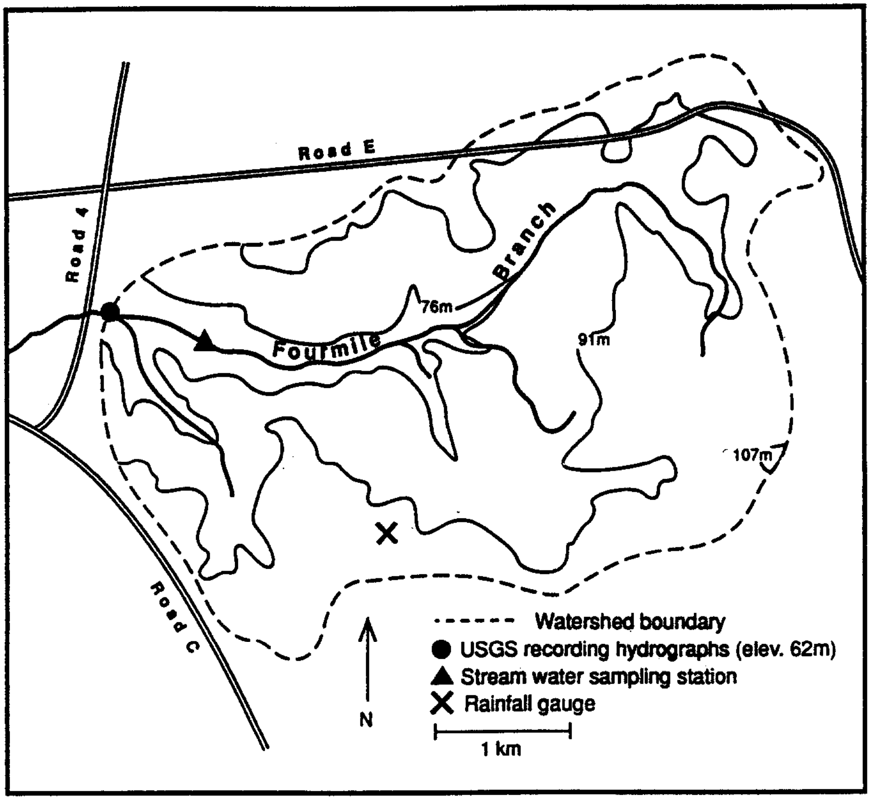

Fig. 2. Topographic map of upper Fourmile Branch watershed showing the locations of hydrograph recorder, stream water sampling and rainfall gauge stations.

the soil profile nearly saturated throughout the year. Flooding is frequent, and occurs year-round during larger rainfall events.

Methods

Overview

Our approach was to create an organic matter budget by, first, quantifying the annual export of organic matter from the watershed by the stream and, then, partitioning this export among baseflow and runoff and their contributing hydrologic pathways. Finally, we tallied those pathways which originated from upland and wetland sources. For comparison, we estimated detritus production rates in uplands and wetlands in order to assess the general mobility of organic matter from these landscape sources. Organic C was used throughout this study as the measure of organic matter because the various forms of plant,

Table 1. Budget worksheet for sources and pathways of stream-exported water and organic carbon from 12.6 km^2 Fourmile Branch watershed. Total, particulate and dissolved organic carbon are signified by TOC, POC and DOC, respectively.

Pathways	Water	Organic carbon concentration			Organic carbon flux		
	volume	TOC	POC	DOC	TOC	POC	DOC
	GL yr^{-1}	—mg C L^{-1}—			—tonnes C yr^{-1}—		
Stream	4.07	7.1	1.8	5.3	28.9	7.3	21.6
Baseflow	3.74	6.2	1.5	4.7	23.2	5.6	17.6
Upland groundwater	3.74			0.5	1.9	0	1.9
Wetland soil leaching	0				14.6	0	14.6
Stream channel debris	0				6.7	5.6	1.1
Stream autotrophs	0				0	0	0
Runoff	0.33				5.7	1.7	4.0
Wetland overland flow	0.23				1.7	1.7	0
Wetland soil leaching	0				3.7	0	3.7
Throughfall onto channel	0.01				0.2	0	0.2
Upland overland flow	0				0	0	0
Upland interflow	0.09			1.2	0.1	0	0.1

soil and aquatic organic matter have generally similar C contents (Schnitzer 1978; Thurman 1985; Vogt 1991).

The methods detailed below represent a synthesis of previously published data within our partitioning framework (shown in Table 1). Most of the data were determined in the course of previous research and monitoring of Fourmile Branch and of other streams and groundwater on the Savannah River Site. Other data were derived from studies conducted elsewhere on the Coastal Plain, while some additional data were collected by us.

Quantity of stream-exported organic carbon

The quantity of organic C exported annually from Fourmile Branch watershed by the stream was estimated by multiplying annual stream discharge volume by the median organic C concentration of stream water. Values for stream discharge and organic C concentration were determined in previous studies of Fourmile Branch, as outlined below, and are reported in Table 1.

Williams & Pinder (1990) analyzed mean daily discharge data collected by the U.S. Geological Survey during 1973–86 at gauge stations along Fourmile Branch. They determined average annual stream discharge to be 4.07 GL from the upper 12.6 km^2 of the watershed.

Newman (1986) measured organic C concentrations (total [TOC], particulate [POC] and dissolved [DOC]) in stream water samples collected 700 m upstream of the USGS gauge station marking the outflow from the upper Fourmile Branch watershed (Fig. 2). Based on grab samples collected biweekly for 18 months during 1983–85, Newman (1986) determined median TOC concentration in Fourmile Branch was 7.1 mg L^{-1}. Newman (1986) also determined that DOC accounted for 75% of TOC, as defined by filtration through Whatman GF/F glass fiber filters (nominal pore size 0.7 um).

Based on the above findings, we estimated that the average annual flux of organic C by Fourmile Branch was 28.9 tonnes C yr^{-1} (Table 1). This estimate may contain some error associated with using median organic C concentrations instead of flow-weighted averages in our calculation. However, this error is probably minor for Fourmile Branch because stream concentrations were fairly stable. Median concentrations differed by less than 16% between baseflow and stormflow (baseflow + runoff) periods (Newman, unpublished data). By using median concentrations, we greatly simplified the computational process.

Partitioning stream-exported organic carbon among contributing pathways

Figure 3 shows the possible flow pathways of water and organic C to Fourmile Branch. Each of these pathways was considered within the framework of their contributions to stream baseflow and runoff.

Baseflow and baseflow pathways

Williams & Pinder (1990) defined baseflow as water delivered to Fourmile Branch via groundwater. Utilizing both hydrograph separation and streamflow partitioning procedures on 15-minute flow data for the period 1983–86, they determined that 92% of annual stream discharge (3.74 GL yr^{-1}) was groundwater-driven baseflow. The remaining 8% of annual stream discharge (0.33 GL yr^{-1}) was runoff (Table 1). According to their procedures, both baseflow and runoff contributed water to streamflow during runoff periods. All runoff to Fourmile Branch was assumed to occur within 48 hrs following rainfall events (Williams & Pinder 1990).

Baseflow organic C concentrations were determined from Newman's (1986) raw data for stream water. Stream water samples which were collected more than 48 hrs after the end of a preceding measurable rainfall

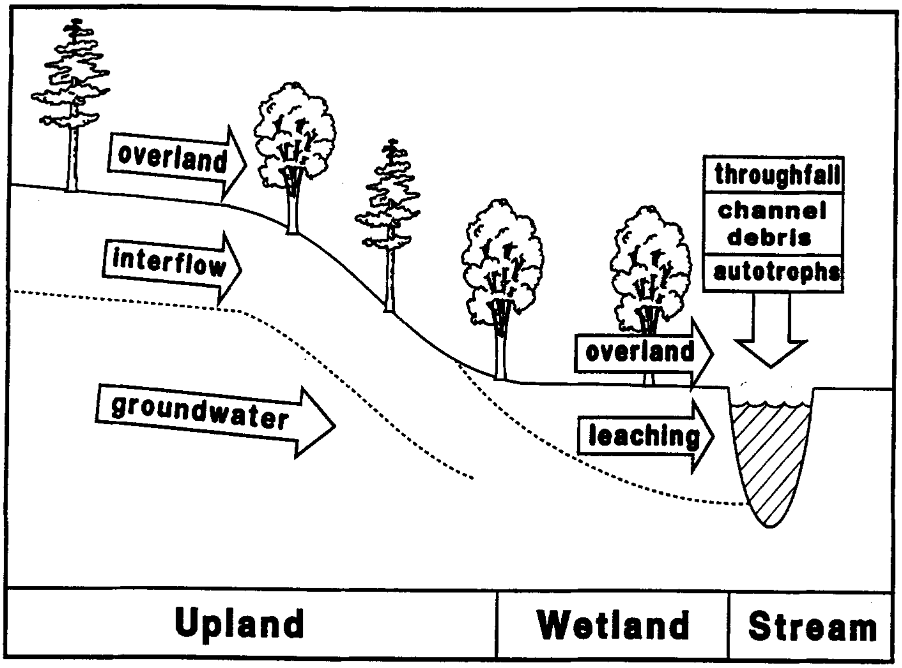

Fig. 3. Schematic diagram showing possible flowpaths of water and organic carbon to Fourmile Branch.

were considered to represent baseflow only. To account for rainfall events, sampling dates and times were compared to daily rainfall records collected at Rainbow Bay on the southern edge of the watershed. There were 19 measurements made during baseflow-only periods, and they were evenly distributed over a calendar year. Median baseflow TOC concentration was 6.2 mg C L^{-1}, which when multiplied by annual baseflow water discharge yielded an annual baseflow TOC flux of 23.2 tonnes C yr^{-1} (Table 1). The proportion of TOC which was dissolved (DOC) was not materially different in baseflow (76%) than the annual stream average (75%; Newman, unpublished data).

The concentration of organic C in groundwater in this area is very low compared to that in stream baseflow. Cummins et al. (1990) showed that DOC concentrations in groundwater from the Savannah River Site are consistently less than 1 mg L^{-1}, the detection limit of their analyses. Their data are a summary of regular groundwater monitoring during 1990 of 1,100 wells at 85 locations within a 13 km radius around Fourmile Branch watershed. Groundwater DOC levels have been monitored in this area since 1975, though in fewer wells, with the same results as the 1990 data. More precise groundwater measurements at other locations on the southeastern Coastal Plain have shown DOC concentrations of 0.1 to 2.5 mg L^{-1}, with most locations being < 0.7 mg C L^{-1} (Leenheer et al. 1974). Based on these studies, we assumed groundwater DOC was 0.5 mg L^{-1} and calculated that this pathway transported 1.9 tonnes C yr^{-1} to Fourmile Branch (Table 1). We assumed that POC transport in groundwater was negligible.

A large quantity of organic C exported in baseflow (21.3 tonnes C yr^{-1}) was not accounted for by inflowing groundwater. This remaining organic C could be contributed to baseflow by three other pathways: (i) autotrophic production in the stream, (ii) mobilization of channel debris, and (iii) wetland soil leaching. Each of these pathways could contribute organic C to the stream without contributing significant amounts of water.

Autotrophic production in Fourmile Branch was assumed to be negligible compared to other organic matter sources in the watershed. Autotrophic production for headwater streams is normally very small, due, in part, to forest shading (Minshall 1978). In Fourmile Branch, autotrophic production is further restricted by the shifting sandy bottom, which provides a poor substrate for anchoring algal populations (J.V. McArthur, pers. comm.).

Channel debris is organic matter carried free of the stream bank, bed sediments, and leaves and logs accumulated in the stream channel. It was assumed that channel debris contributed all POC found in stream baseflow. Channel debris can also leach a significant quantity of DOC into stream water (Meyer 1990). We estimated the quantity of DOC leached from channel debris as 25% of annual leaffall to the channel, plus a slow leaching rate of 0.1% yr^{-1} from stored leaves, wood debris, and sediment organic matter to a 50 cm depth (Cummins et al. 1983; Meyer 1990). Annual leaffall into Fourmile Branch was estimated to be 215 tonnes C km^{-2}, based on an average of leaffall rates measured in wetland forests on the Coastal Plain in Virginia and North Carolina (Brinson et al. 1980; Megonigal & Day 1988; Mulholland 1981) onto our estimated channel area of 0.012 km^2. We considered this leaffall estimate to be a reasonable approximation for Fourmile Branch since these data were collected in forests with similar vegetation, climate, soils and hydrology. Our estimate of DOC leaching from fresh leaffall to the channel was based on studies by Petersen and Cummins (1974) and Hauer (1985) showing leaching of 5 to 30% of leaf mass within a few days for a wide range of deciduous tree species. The channel debris load was calculated to be 38 kg C m^{-2} based on measurements by Hauer (1985) in Meyers Branch, a stream of similar character though somewhat larger than Fourmile Branch (Newman 1986), located 15 km south of Fourmile Branch watershed. Based on the above estimates, we calculated 1.1 tonnes C yr^{-1} of DOC was leached from channel debris (Table 1) with just over half of this coming from initial leaf leachate.

Wetland soils can contribute organic C to baseflow by drainage of interstitial water during periods of receding water table or by mixing with groundwater as it flows through or passes under the organic horizons toward the stream channel. We implicitly considered water within the organic horizons of wetland soil to be distinct from groundwater, even though most of it remains below the water table year-round. This arbitrary distinction conveniently attributed groundwater to the upland source alone. Interstitial soil water was assumed to transport only DOC. After accounting for all other likely sources of organic C to baseflow (i.e., groundwater, channel debris, autotrophs) the remaining 14.6 tonnes C yr^{-1} of DOC in stream baseflow was allocated to wetland soil leaching.

Runoff and runoff pathways

The annual stream flux of organic C which was not accounted for in baseflow was allocated to runoff. Runoff is non-groundwater flow which occurs during and for 48 hrs after rainfall events and was determined by Williams & Pinder (1990) to comprise 8% of annual stream water discharge (0.33 GL yr^{-1}). Runoff water can be transported from upland and wetland sources by overland flow and interflow. On forested uplands of this watershed, however, overland flow is uncommon, if it occurs at all (Williams & Pinder 1990). Runoff from uplands more likely occurs as interflow on valley slopes through the sandy soil on top of the clay-enriched subsoil. Runoff from wetlands probably moves as overland flow during flooding, since heavier rainfalls cannot percolate into the already nearly-saturated wetland soil. It is unlikely that the very low slope of the floodplain could produce sufficient hydraulic gradient to drive significant interflow. However, DOC in soil interstitial water could reach the stream by leaching and mixing into overland flow. For this analysis, we have separated wetland soil from surface contributions by assuming that the soil contributes only DOC and that POC is mobilized from the wetland surface by overland flow (Table 1). Additional organic C can be transported directly from vegetation to the stream during rain events by leaching into throughfall.

Runoff water was partitioned between upland and wetland sources by computing the volume of rain which falls onto and runs off of the wetland portion of the watershed, with the remainder supplied by interflow from uplands and throughfall directly in the stream channel. Throughfall volume was calculated from rainfall, adjusted for 11% interception (Lull 1964), on to the 0.012 km^2 channel area, and accounted for 0.013 GL yr^{-1}. Wetland runoff was computed as the product of annual rainfall on the wetland area and the proportion of annual rainfall which was lost to the stream. Average annual rainfall for this area is 121 cm and distributed fairly evenly throughout the year (NOAA 1982). We estimated the proportion of rainfall onto the wetlands which was lost to the stream by using the value for the watershed as a whole (27%). This proportion probably underestimates that for the wetlands, since the wetland deciduous forest would be less effective at rainfall interception than the upland pine forest which covers a major portion of the watershed area, especially during winter months (Lull 1964), and upland soils probably store throughfall longer making it more susceptible to transpiration losses. Therefore, we calculated wetland runoff to be a minimum of 0.23 GL yr^{-1}. This leaves a maximum amount of 0.09 GL yr^{-1} as interflow runoff from the upland portion of the watershed.

We measured DOC concentration in interflow water sampled from sandy soil, perched just above the clayey subsoil, at 6 locations on a slope along Fourmile Branch. We collected 10 to 12 samples just after rainstorms in June 1992 and March 1993, using piezometers and suction sampling tubes (Model 1900 with high-flow ceramic tip, Soilmoisture Equip. Corp., Santa Barbara, CA). The samples were filtered through Whatman GF/C glass fiber filters and analyzed on a Shimadzu TOC-500 Carbon Analyzer (Shimadzu Scientific Instruments, Inc., Columbia, MD). Organic C concentrations were all < 3 mg C L^{-1} and averaged 1.2 mg C L^{-1}. Using this average for interflow DOC concentration and the interflow volume computed above, we calculated an annual interflow of 0.1 tonne C yr^{-1} (Table 1).

We estimated DOC flux in throughfall using a value determined by Mulholland (1981) for a deciduous wetland forest on the Coastal Plain in North Carolina with similar vegetation and rainfall as the wetlands along Fourmile Branch. In our analysis, throughfall included only DOC falling directly on the stream channel. Mulholland (1981) determined an annual throughfall flux of 212 kg C ha^{-1} which translates to 0.25 tonnes C yr^{-1} onto a 0.012-km^2 area representing the channel of Fourmile Branch. This quantity probably overestimated actual throughfall DOC flux because measurements by Mulholland included a minor component of fine POC. Furthermore, Brinson et al. (1980) measured throughfall (DOC + fine POC) in a water tupelo (*N. aquatica*) forest on the Coastal Plain in North Carolina and found a much lower flux (91.5 kg C ha^{-1} yr^{-1}) than that found by Mulholland (1981). We considered throughfall onto the wetland surface to be wetland soil DOC.

Tallying contributions from upland and wetland sources

Finally, we computed contributions of organic C by wetlands and uplands to the annual stream-exported C flux by tallying contributions from the various wetland and upland pathways shown in Table 1. In this tally, pathways depositing organic C directly in the stream (throughfall and channel debris) were considered wetland pathways because this organic C most likely origi-

Table 2. Comparison of sources of stream-exported organic carbon from Fourmile Branch watershed. Total, particulate and dissolved components are signified by TOC, POC and DOC, respectively.

Source	TOC	POC	DOC	Water	Area	Detritus input[3]	TOC as % of detritus
	—tonnes C yr^{-1}—			GL yr^{-1}	km^2	tonnes C yr^{-1}	%
Watershed	28.9	7.3	21.6	4.1[1]	12.6	5810	0.50
Upland forest	2.0	0	2.0	3.8	11.9	5545	0.04
Wetland forest[2]	26.9	7.3	19.6	0.2	0.7	265	10.2

[1] total may not agree exactly due to rounding.
[2] includes stream channel debris and throughfall.
[3] estimated from litterfall + root turnover data summarized in Vogt (1991).

Table 3. Comparison of pathways transporting organic carbon from upland and wetland sources to Fourmile Branch. Total, particulate and dissolved organic carbon are signified by TOC, POC and DOC, respectively.

Pathway	Organic carbon flux		
	TOC	POC	DOC
	—tonnes C yr^{-1}—		
From uplands:			
Groundwater	1.9	0	1.9
Interflow	0.1	0	0.1
Overland flow	0	0	0
From wetlands:			
Soil leaching	18.3	0	18.3
Channel debris	6.7	5.6	1.1
Overland flow	1.7	1.7	0
Throughfall onto channel	0.2	0	0.2

nated in the stream-side wetland forest. The results are summarized in Tables 2 and 3.

Organic carbon production in uplands and wetlands

We estimated forest detritus production (litterfall + root turnover) from data summarized by Vogt (1991) for southeastern U.S. upland and wetland forests. Upland detritus production was estimated by averaging the annual amounts for a 27 yr old Florida slash pine forest (444 tonnes C km^{-2} yr^{-1}) and a 53 yr old Tennessee tulip poplar forest (*Liriodendron tulipifera*; 487 tonnes C km^{-2} yr^{-1}). Based on this average (466 tonnes C km^{-2} yr^{-1}), we calculate a detritus input rate of 5545 tonnes C yr^{-1} over a 11.9 km^2 area representing the upland forest portion of Fourmile Branch watershed (Table 2).

A similar estimate for wetland forest detritus production was obtained by averaging amounts produced by a 86 yr old wet cypress forest (356 tonnes C km^{-2} yr^{-1}), a 52 yr old wet maple-gum forest (373 tonnes C km^{-2} yr^{-1}) and a 78 yr old wet mixed-hardwood forest (407 tonnes C km^{-2} yr^{-1}), all located on the Coastal Plain in Virginia (Megonigal & Day 1988; Vogt 1991). Based on this average (379 tonnes C km^{-2} yr^{-1}), we estimated wetland forest detritus production to be 265 tonnes C yr^{-1} over a 0.7 km^2 area (Table 2).

Total detritus production in Fourmile Branch watershed (wetland + upland) was estimated to be 5810 tonnes C yr^{-1} (Table 2). This rate may overestimate actual production due to our use of data from fast-growing slash pine and tulip poplar forests. However, of 19 forests studied throughout the U.S. and in Europe, 16 had detritus production rates between 350 and 600 tonnes C km^2 (Vogt 1991). The other three studies were of a subalpine forest and very young (< 15 yrs old) southern U.S. pine plantations. This suggests that our estimate of detritus production is probably a reasonable one for the general comparisons that are presented below.

Results and discussion

Sources of organic carbon to the stream

Fourmile Branch appears to transport a similar proportion of detrital production from its watershed than streams of other regions. Based on our estimates, streamflow exported 0.5% of forest detritus production (28.9 tonnes C yr^{-1}) from Fourmile Branch watershed (Table 2). In general, rivers export about 1% of watershed net primary productivity (Thurman 1985). Fisher & Likens (1973) estimated 0.7% of forest production is exported by a small montane watershed in New Hampshire. Fourmile Branch watershed, as a whole, functions similarly to others in this regard.

Heterogeneity within Fourmile Branch watershed is revealed when comparing wetland and upland contributions of organic C to the stream. Wetlands, which comprise only 6% of the watershed area, contributed an estimated 26.9

tonnes yr^{-1} of organic C to Fourmile Branch or about 93% of the total stream organic C flux (Table 2). Even if channel debris and throughfall were excluded (comprising 6.9 tonnes C yr^{-1}), wetlands still accounted for 69% of all stream-exported organic C. Uplands were only a minor source of organic carbon to the stream, contributing an estimated 2.0 tonnes C yr^{-1}, or about 7% of the total stream organic C flux (Table 2). We expected a large wetland contribution to the stream organic C flux based on results of earlier studies (Mulholland 1981; Mulholland & Kuenzler 1979; Meyer 1986). We also hypothesized that uplands would be a significant source of organic C to the stream by transport through sandy soils. However, our analysis indicates that uplands did not contribute much organic C to the stream. Wetland forest was clearly the dominant contributor of organic C to Fourmile Branch, despite covering a minor portion of the watershed area. Our results quantitatively confirm that even small wetland areas within a watershed can have a dominant effect on the overall organic C budget of streams.

Wetland forest was the dominant source of organic C to the stream because a much larger proportion of its detritus production was transported to the stream (10.2%) than for upland forest (0.04%; Table 2). In riparian wetlands, such as along Fourmile Branch, slow decomposition rates in combination with frequent flooding and continual groundwater flow probably facilitate transport of detrital organic matter to streams (Mulholland 1981).

Detritus produced in uplands was not transported to the stream to the degree found for wetlands, suggesting that sandy soil texture alone does not determine the propensity for organic C transport through upper Coastal Plain landscapes. Although our calculation for upland transport to the stream was dependent on an estimate of groundwater DOC concentration (0.5 mg C L^{-1}), even a two-fold change in DOC concentration would not materially affect our results. Upland soils in this region appear very efficient at preventing leaching losses of organic C, despite the sandy texture of surface horizons.

Upland pathways of organic carbon transport to the stream

The uplands of Fourmile Branch watershed transported organic C to the stream almost entirely through the groundwater pathway (Table 3). This was due, in part, to groundwater providing almost all the water transported from uplands to the stream. Upland runoff volume was small probably because surface soils of the watershed are too porous to support overland flow (Williams & Pinder 1990) and the slopes are apparently insufficiently steep or extensive enough to drive a significant volume of interflow.

Interflow water also had low DOC concentrations. Several mechanisms may account for strong DOC immobilization in soils, including hydrophobic partitioning, anion and ligand exchange, and complexation and precipitation with Fe and Al hydroxides (Dunnivant et al. 1992; Jardine et al. 1989; McDowell & Wood 1984; Moore et al. 1992; Thurman 1985). Studies of DOC in soil solutions indicate that high DOC concentrations in forest litter (up to 40 mg C L^{-1}) decrease sharply with soil depth to levels approaching groundwater concentrations within 0.5 m or so from the soil surface (Cronan 1990). Our measurements of low DOC concentration in interflow water along Fourmile Branch (1.2 mg C L^{-1}) suggest that immobilization processes are important even in the sandy surface soils of Fourmile Branch watershed. Rapid microbial oxidation of organic matter in these soils, as evidenced by low organic matter contents (< 2%), might also limit the availability of organic matter to soil solution.

Low amounts of runoff water and DOC from uplands can also be attributed, in part, to artifacts of the stream hydrograph partitioning techniques which were used. Williams & Pinder (1990) interpreted typical hydrographs to suggest that runoff periods lasted only 2 days beyond rainfall events. Longer runoff periods would partition greater stream flow to runoff, and ultimately to partitioning greater amounts of stream organic C to the upland interflow pathway. For example, Stricker (1983) utilized a 7 day runoff period for analyzing Upper Three Runs, another stream on the Savannah River Site, and determined runoff to be 15% of total stream flow compared to 4% as determined by Williams & Pinder (1990) using their 2 day period. If a longer interval was used for Fourmile Branch, such as one partitioning 20% of stream flow to runoff (instead of 8%), upland interflow of DOC to Fourmile Branch would still amount to only 0.7 tonnes C yr^{-1}. Therefore, whatever the interval used for Fourmile Branch, interflow organic C remains small compared to groundwater.

Wetland pathways of organic carbon transport to the stream

Leaching of DOC from wetland soil was the dominant pathway of organic C transport from wetlands to the stream, accounting for 18.3 tonnes C yr^{-1} or 68% of the stream organic C originating in the wetlands (Table 3). Wetland DOC was transported in runoff by leaching into floodwaters, and in baseflow by drainage during periods of receding water table or by continual leaching and mixing into groundwater as it passed through or under the organic layers prior to outcropping in the stream channel. Wetland soil leaching in baseflow was clearly the most important single pathway of organic C transport to the stream, accounting for 14.6 tonnes C yr^{-1} or 51% of all stream-exported organic C (Table 1).

Wetland POC from channel debris and surface detritus also comprised a substantial portion of stream-exported organic C. Particulate organic C accounted for 25% of the stream-exported organic C by Fourmile Branch

(Newman 1986). Blackwater streams on the lower Coastal Plain were found to export a smaller proportion of organic C as POC (3 to 5%; Meyer 1986; Mulholland 1981). It has been hypothesized that lower gradient blackwater streams immobilize POC for longer periods, thus allowing greater breakdown of POC to DOC before remobilization by slow-moving water (Mulholland 1981; Mulholland & Kuenzler 1979). The coastal blackwater streams studied by Mulholland (1981) and Meyer (1986) had gradients of 0.02 to 0.05%. Studies of streams in other regions of the U.S. (primarily the northeast and the northwest) showed POC to be 24 to 46% of stream TOC and had higher gradients of 0.2 to 47% (Cummins et al. 1983). Fourmile Branch has an intermediate gradient of about 0.5%. Apparently, Fourmile Branch maintains sufficient gradient to mobilize substantial quantities of POC.

In our hydrologic pathway analysis, we estimated the quantity of DOC transported from wetland soil to the stream by allocating to it all DOC not accounted for by other pathways. As a result, we have partitioned error into wetland soil leaching. We believe we have liberally accounted for inputs of DOC from all other important pathways, so that we did not overestimate the importance of the wetland soil. On the other hand, we may have underestimated the wetland soil DOC pathway, as well as POC pathways, by assuming that in-stream metabolic loss of organic C was negligible. This assumption was necessary in our budgeting method to attribute outflow directly to pathway inputs upstream. We think that respiration losses of organic C from the water column was probably small in Fourmile Branch. Mulholland (1981) estimated water column respiration to be only 2% of fluvial inputs to a blackwater stream on the Coastal Plain. Additional POC could be filtered from the water column by bottom-dwelling bivalves or other macroinvertebrates. However, Leff et al. (1990) concluded that bivalve populations were too small to act as an important sink for POC removal from nearby Meyers Branch. Since in-stream losses of DOC and POC appear to be small, we believe our results have led us to accurate general assessments regarding the important sources and transport pathways of organic C from terrestrial sources to Fourmile Branch.

Our results have important implications with regard to the role of riparian forests in controlling stream water quality. Clearly, wetland forests are the dominant source of organic matter to Fourmile Branch, and as such, are probably the primary source of food in the aquatic food web. The degree to which wetland soils in these forests control transformations from POC to DOC and to various forms of DOC can determine, to a large extent, the populations of aquatic organisms and community structure in the stream (McKnight et al. 1990).

Riparian forests are often also viewed as filters of contaminants transported from uplands, a concept which provides the foundation for many stream restoration programs (Lowrance et al. 1984; Peterjohn & Correll 1984; Osborne & Kovacic 1993). This concept is based primarily on studies of nutrients N and P, but has not been fully investigated for cationic nutrients, metals, and pesticides or other organic contaminants. We know that dissolved organic matter can play an important role in facilitating the transport of these latter substances through soils (*vide supra*). The transport of large quantities of DOC from wetland soils along Fourmile Branch to the stream suggests that the potential for facilitated transport is great, and that riparian wetland forests may not be as effective at retaining the wider range of contaminants as they are for N and P.

Acknowledgements

This study was supported by contract number DE-AC09–76SR00–819 between the U.S. Department of Energy and the University of Georgia. The authors thank Dr. M. Newman and Dr. J. Pinder for providing data used in this study, and Dr. C. Strojan and Dr. J.V. McArthur for reviewing drafts of this manuscript.

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