THE EFFECTS OF WATERSHED DISTURBANCE ON DISSOLVED ORGANIC CARBON DYNAMICS OF A STREAM

JUDY L. MEYER AND CATHY M. TATE
Institute of Ecology and Zoology Department, University of Georgia, Athens, Georgia 30602 USA

Abstract. The response of a stream ecosystem to disturbance in its watershed was investigated by comparing mass balances of dissolved organic carbon (DOC) for a stream draining an undisturbed watershed with a stream draining a watershed that was clear-cut 2 yr before the study began. These second-order streams are in the Coweeta Hydrologic Laboratory, North Carolina. Both streams had similar, elevated DOC concentrations (from <1 to 5 mg/L) during storms. Rising and falling limbs of the hydrograph also had similar DOC concentrations. During the growing season DOC concentration increased from headwater seep to the weir in the undisturbed stream under baseflow conditions. No significant longitudinal change was observed in the stream draining the clear-cut watershed. Hence concentration was consistently lower in baseflow samples during the growing season in the stream draining the clear-cut watershed. As a result annual DOC export from the clear-cut watershed was less (9.8-11.5 kg/ha) than from the reference watershed (14.6-15.1 kg/ha). The lower DOC export was partly due to reduced DOC inputs from throughfall and leaching of fresh litter, but most importantly to lower DOC inputs in subsurface water and probably also less in-stream generation of DOC.

INTRODUCTION

The location of a stream in a drainage network and the nature of the surrounding terrestrial ecosystem are major determinants of stream ecosystem structure and function (Hynes 1975, Vannote et al. 1980). Disturbance of the terrestrial ecosystem is reflected in alteration of the stream ecosystem, and the rate at which aspects of ecosystem function return to predisturbance levels is closely linked to recovery of the terrestrial system (e.g., Webster and Patten 1979, Gurtz et al. 1980). Numerous studies have documented that disturbing a forested ecosystem by clear-cutting can initially result in increased elemental export from streams (e.g., Likens et al. 1970, Hobbie and Likens 1973, Aubertin and Patric 1974). From the perspective of stream ecosystem function, the relevant question is not merely the magnitude of export, but rather the magnitude of the net balance of inputs to and exports from the stream.

In this study we have addressed the question of the effects of watershed disturbance on stream ecosystem function by determining annual mass balances of dissolved organic carbon (DOC) in an undisturbed stream and in a stream draining a recently clear-cut watershed. DOC is an important carbon source in stream ecosystems (Fisher and Likens 1973, McDowell and Fisher 1976, Fisher 1977, Wetzel and Manny 1977, Mulholland 1981). Previous studies have demonstrated an increase in DOC export after forest clear-cutting (Hobbie and Likens 1973, Dahm 1980), but the mechanisms responsible for the increase are not known. Our purpose in determining annual mass balances for DOC was twofold: (1) to determine if there was a change in DOC export after clear-cutting in this southern Appalachian watershed, and (2) to ascertain if a change in DOC export was due simply to altered DOC inputs.

Mass balances have been calculated for total organic carbon in several stream ecosystems (Fisher and Likens 1973, Fisher 1977, Mulholland 1981, Cummins et al., in press), while McDowell and Fisher (1976) have calculated a budget for DOC alone. In the mass balances presented here, sources of DOC to the stream included precipitation and throughfall, subsurface water, leaching of allochthonous litter and in some cases tributary inputs, whereas the only loss monitored was export downstream. Hence we have measured the net effect of a number of processes that alter the form or remove DOC from the water column in streams. These processes include flocculation, biological uptake, and chemical sorption by seston and sediments, as well as respiratory losses. By calculating an annual mass balance, we can assess the net effect of disturbance on DOC inputs and fluvial exports, although we cannot distinguish which of the above processes are most affected by disturbance.

STUDY SITE

The two second-order streams studied drain watersheds in the Coweeta Hydrologic Laboratory, North Carolina. For general information on Coweeta watersheds see Swank and Douglass (1977). The undisturbed watershed (WS 14) is 61 ha, has a northwestern...
aspect, and consists of a mature forest of oaks, hickories, and yellow poplar with a dense rhododendron understory. The forest has had no human disturbance at least since 1924. The clear-cut watershed (WS 7) is 59 ha and has a southern aspect. Six cattle were allowed to graze on this watershed from 1941 to 1949, but there was little long-term impact on vegetation or streamwater chemistry (Swank and Douglas 1977). WS 14 was selected as the reference stream because, of all the Coweeta gaged watersheds, its stream discharge, elevation, and watershed area were most similar to that of WS 7 prior to cutting (Gurtz et al. 1980). The invertebrate communities of the two streams were also similar before disturbance (Gurtz 1981).

During April through June 1976, three logging roads were built on WS 7, disturbing ~5% of the watershed area. Two of the roads cross the stream. The watershed was clear-cut and cable-logged between January and June 1977. Logging debris that fell into the main stream channel was removed in August 1977, but the existing debris dams and debris falling into tributaries were left in place.

Several changes in the stream were apparent after cutting and are presented in greater detail in Webster et al. (in press). Discharge increased and water temperatures rose. Mean monthly temperatures during two summers after cutting were 1.5°–3.5°C higher than predicted from stream temperatures in an adjacent reference watershed (Webster et al., in press). Although there was little change in pH or phosphorus concentration, NO$_3$-N concentration in streamwater increased from 2 to 50 µg/L (W. Swank, personal communication). There was a slight increase in algal biomass in the stream, but the change was primarily in the seeps adjacent to the main channel (Hains 1981). The stream received high inputs of sediment during road construction. Significantly higher concentrations of both organic and inorganic seston were found in the clear-cut watershed than in the undisturbed watershed (Gurtz et al. 1980). Sediment accumulation in the weir pond was 13 times that accumulating prior to cutting (Webster et al., in press). As a consequence of higher discharge, warmer water temperatures, changing food resources, and high sediment input, the invertebrate communities of the two streams differed after cutting. In general, the dominant shredders declined, while collector-gatherers increased (Gurtz 1981).

**METHODS**

On the undisturbed watershed, the main channel was sampled at six sites, tributaries at four sites, and subsurface water seeps at six sites (Fig. 1). One of the sites included as a seep was actually a tributary that flowed underground for much of its length. It was treated as a seep because its DOC concentrations were not significantly different from that of seeps, and because it did not receive direct litter and throughfall inputs as did other tributaries. Sampling sites on the clear-cut watershed included four main channel sites, four tributary sites, and seven subsurface water seeps (Fig. 1).

Water samples were taken at each of these sites every 2 wk from 1 July 1979 to 30 June 1980. Seeps were sampled using a pipette; care was taken to sample the water just as it flowed out of the ground and to minimize disturbance of the substrate. Porous cup lysimeters were sampled biweekly when they contained adequate water. Lysimeters were at a depth of 30 cm, which is at the bottom of B horizon, below the primary rooting zone. Six lysimeters were on the clear-cut watershed and six were on watershed 2, an undisturbed watershed adjacent to watershed 7 and similar to watershed 14 except that it is much smaller (12.1 ha) and has a southern aspect. All samples were collected in precombusted glass bottles, filtered within 4 h of collection through precombusted Gelman A/E glass fiber filters, and stored in precombusted glass bottles at 4°C until analysis.
DOC concentration in samples was determined in duplicate, using a Dohrmann DC 54 Carbon Analyzer, which uses UV catalyzed oxidation in the presence of persulfate. The instrument yielded reproducible results: the coefficient of variation of triplicate determinations of carbon standards (1.8 mg/L) run on 42 occasions ranged from 0.2 to 2.2% with a mean of 0.5%. To check the completeness of oxidation using the UV method, we compared it with pyrolysis at 850°C (Dohrman DC 52 analyzer) on streamwater samples concentrated in a freeze dryer. The mean difference in carbon values obtained with the two methods was 0.05 mg/L, and in no case were the values significantly different.

In addition to the biweekly samples, we sampled the streams at the sites just above the weir pond during 11 storms throughout the year. A total of 238 storm samples was taken at intervals from 5 min to 5 h, depending on discharge and its rate of change. DOC concentration in these samples was analyzed as described above.

Some streamwater samples were partitioned into low- and high-molecular mass fractions by ultrafiltration through Amicon UM10 filters with a nominal 10 000 molecular mass cutoff. Filters were soaked and rinsed before use (Schindler and Alberts 1974).

Stream discharge was continuously recorded by the United States Forest Service, using V-notch weirs. Volume of water entering from tributaries was estimated by multiplying the discharge per hectare (measured at the weir) times the number of hectares drained by each tributary. Precipitation data were gathered by the United States Forest Service, using rain gauges located on each watershed. To calculate volume of subsurface water entering daily, we subtracted volume of water entering in tributaries and volume of precipitation (channel interception) from volume of water leaving at the weir. Evaporation from the stream channel was not considered.

DOC concentration in throughfall was measured in samples from 5 collectors on the undisturbed watershed and 10 collectors on the clear-cut (5 under slash and 5 under vegetation). Each collector was a 2 x 0.15 m stainless steel or galvanized metal trough which drained into a 22-L plastic carboy. The trough was covered with fiberglass screening to exclude litter. Deionized water run through the system and allowed to sit for a week gained carbon in the amount of 0.9 mg/L, far below the throughfall concentrations observed. Collectors on the clear-cut watershed were emptied after each storm from July to October 1979; at other times and on the undisturbed watershed, they were emptied biweekly.

Litter falling into the channel was collected in 6 0.40-m² baskets randomly placed alongside lower, middle, and upper reaches of the stream channel on the clear-cut watershed, and in 12 0.13-m² baskets on the undisturbed watershed. These were emptied three times during the year on the undisturbed watershed, and once on the clear-cut watershed. Litter blowing into the channel (lateral movement) was collected with 12 baskets (0.4 x 0.09 m) oriented upslope on the clear-cut watershed and 11 baskets (0.3 x 0.18 m) on the undisturbed watershed. These collectors were emptied five times during the year on the clear-cut watershed and three times on the undisturbed watershed. The percentage of carbon leached from the leaves was calculated as 50% of the loss in mass of leaves held in the stream channel for one week (J. L. Meyer and C. Johnson, personal observation).

**Budget calculations**

Daily exports and inputs of DOC were calculated and summed to obtain monthly and annual values. To calculate fluvial exports, we multiplied stream discharge recorded from 6 to 120 times daily (frequency depended on rate of change of discharge) times the appropriate DOC concentration. When discharge was changing due to storms, DOC concentration was determined from the concentration–discharge regressions presented below for each watershed and season. Under nonstorm conditions, DOC concentration was taken as the mean of DOC concentrations measured on biweekly samples for that season from stations at the base of the watershed.

Daily DOC inputs from tributaries were calculated as the product of water volume times DOC concentrations at the base of the watershed times a factor for each tributary. The factor was determined as the seasonal mean of the ratio of tributary DOC concentration to DOC concentration at the base of the watershed calculated for each biweekly sample. (Factors varied from 0.687 to 1.210, with a mean of 0.951.) Hence, the tributary DOC concentrations were allowed to vary as DOC concentration in the main channel varied. The same approach was used to calculate DOC inputs from seeps. (These factors varied from 0.409 to 1.011, with a mean of 0.643.) By using this procedure, we assumed that the ratio of tributary or seep concentration to main channel concentration was the same during storm and baseflow conditions. This may underestimate seep and tributary inputs during storms, since water with high DOC levels may be flushed from terrestrial storage sites and enter the stream when in-stream uptake of DOC is low due to the high discharge.

Daily inputs of DOC in throughfall were calculated as volume of precipitation (channel interception) times DOC concentration measured during the appropriate 2-wk time period. On the undisturbed watershed, volume of precipitation was corrected for canopy interception (Helvey and Patric 1965). Approximately 40% of precipitation reaching the stream channel on the clear-cut watershed would be falling through slash, while ~10% would be falling through riparian vegetation. These percentages were determined from a series of 30 photographs taken (by M. Gurtz and J. Web-
Hence, on the clear-cut watershed, throughfall inputs were calculated as 

\[ 0.4 C_s + 0.1 C_v + 0.5 C_o \]

where \( C_s, C_v, \) and \( C_o \) were the DOC concentrations in collectors under slash, under vegetation, and in the open, respectively, and \( V \) was the total volume of water in precipitation during the time interval.

RESULTS AND DISCUSSION

The annual budget and export figures reported below are for the period 1 July 1979 to 30 June 1980, although the water year at Coweeta is 1 May through 30 April. We have designated the period May through October as growing season and the period November through April as dormant season.

Subsurface water inputs

DOC concentration in subsurface water seeps on both watersheds was typically lower than DOC concentration in streamwater. Some seasonal change in seep DOC concentration was apparent (Fig. 2). On the undisturbed watershed, the mean DOC concentration (with 95% confidence limits, used throughout this paper unless otherwise noted) during the growing season was 0.673 ± 0.141 mg/L, while during the dormant season it was 0.339 ± 0.027 mg/L. Hence, DOC concentration in seeps during the growing season was higher and more variable than during the dormant season. On the clear-cut watershed, mean DOC concentration was 0.346 ± 0.027 mg/L during the growing season and 0.259 ± 0.019 mg/L during the dormant season. Thus there was less seasonal difference in DOC concentration in subsurface water seeps on the clear-cut watershed. Significantly higher DOC concentrations were observed on the undisturbed watershed when all seasons were considered together (ANOVA, \( P < .002 \)). Mean DOC concentrations were twice as high on the undisturbed compared with the clear-cut watershed during the growing season and only 1.3 times as high during the dormant season.

DOC concentrations in the lysimeter samples from the two watersheds were considerably higher than the concentrations observed in the subsurface water seeps (Fig. 3 cf. Fig. 2), perhaps because lysimeters sampled soil water that had been in more intimate contact with the active root zone. This has also been reported for an Alberta watershed (Wallis et al. 1981) and another Appalachian watershed, although concentrations observed here are considerably higher (Comiskey 1978). Seasonal differences in DOC concentration were apparent in the lysimeter samples, particularly on the undisturbed watershed. A distinct peak in DOC concentration existed during autumn on the undisturbed watershed, with no real change in concentration on the clear-cut watershed (Fig. 3); this may have been due to leaching of greater amounts of newly fallen leaf litter on the undisturbed watershed. A secondary peak in DOC concentration occurred on both watersheds during the spring. No significant differences in DOC concentration in lysimeter samples were found between the two watersheds on an annual basis (ANOVA \( P > .05 \)), primarily because of high variability among lysimeters on a single watershed.

Throughfall

The mean DOC concentration in incident precipitation measured on nine occasions was 1.032 ± 0.304 mg/L, whereas throughfall collected under vegetation and slash showed much higher DOC concentrations. DOC concentrations of throughfall collected under slash were significantly (\( P < .05 \)) higher than that collected under vegetation on the clear-cut watershed (Fig. 4). DOC concentration in throughfall collected under vegetation on the clear-cut watershed was not significantly different from that collected on the undisturbed watershed. All throughfall samples showed an autumn
peak in DOC concentration, and samples taken under vegetation showed a secondary spring peak (Fig. 4). This pattern is similar to that presented earlier for the lysimeter samples.

**Fluvial transport of DOC during baseflow**

DOC concentrations in samples taken during non-storm periods at the base of each watershed are plotted in Fig. 5. DOC concentrations were consistently higher during the growing season on the undisturbed watershed, whereas little difference in concentration occurred during the dormant season. The seasonal changes in DOC concentrations were greater than any diel changes measured under nonstorm conditions. During a 24-h period in August 1979 under baseflow conditions, DOC concentrations in samples collected at 4-h intervals varied from 0.337 to 0.355 mg/L on the clear-cut and 0.652 to 0.760 mg/L on the undisturbed watershed. No regular pattern of variation that could be attributed to in-stream biological activity was apparent.

We also examined DOC concentrations at stations along the main channel in both watersheds (Fig. 6). On every sampling date during the growing season, concentrations on the undisturbed watershed consistently increased downstream. Samples taken from the headwater seep were significantly lower than those from all other stations. The four intermediate stations were not significantly different from each other, but they were lower than the station farthest downstream (Duncan's multiple range test, $P < .05$). During the dormant season, DOC concentration in the headwater seep was still significantly lower than other stations, but there were no differences between the other stations. This trend of increasing DOC concentration downstream was also observed in other undisturbed streams (Kaplan et al. 1980, Wallace et al. 1982) and in streams draining watersheds with successional forests > 10 yr old (Tate and Meyer 1982). This longitudinal pattern was different on the clear-cut watershed, where the only significant difference between DOC concentrations at stations on the main channel was that the headwater seep had a lower concentration during the dormant season.

Samples from stations along the main channel of the two streams were taken during August 1979 and separated into low (<10000) and high molecular mass fractions using ultrafiltration. These data are presented in Table 1 and compared with similar data from the headwaters of Dryman Fork, another undisturbed stream in the Coweeta Hydrologic Laboratory (described in Wallace et al. 1982). It is clear that in these undisturbed watersheds, as well as in others (Kaplan et al. 1980), the downstream increase in DOC concentration is due to an increase in concentration of high molecular mass fractions. This increase in the high molecular mass fraction is less apparent on the clear-cut watershed.

**Fluvial transport during storms**

Eleven storms were sampled intensively, including the highest discharge of the year. DOC concentration increased markedly during storms (Fig. 7), as has been noted in other streams (Manny and Wetzel 1973, McDowell and Fisher 1976, Comiskey 1978). We observed much higher concentrations during storms than were observed under nonstorm conditions. During three storms DOC concentrations were slightly higher on the rising limb, while during three other storms they were higher on the falling limb. During the other storms and when data from all storms are plotted together (Fig. 7), there was no significant difference between concentrations on rising and falling limbs. This similarity was also observed in a Tennessee stream (Comiskey 1978), although DOC concentrations were
Fig. 6. Changes in DOC concentration (x and 95% CL) in streamwater from the source (a seep) along the main stream channel on a clear-cut (■) and on an undisturbed (○) watershed during dormant and growing seasons. Each point is the mean of 11-14 samples. On the clear-cut watershed data from stations 1, 2, 4, and 6 are shown, while on the undisturbed watershed data from stations 1, 2, 4, 5, 9, and 10 are shown. (See Fig. 1 for station locations.)

higher on the rising limb in a Massachusetts stream (McDowell and Fisher 1976). The pattern of DOC concentration we observed during storms is thus very different from the behavior of fine particulate organic carbon concentration, which is consistently much higher on the rising limb in these and other streams (Comiskey 1978, Bilby and Likens 1979, Gurtz et al. 1980).

The regressions of DOC concentration vs. discharge during storms were different for the two seasons; higher DOC concentrations were observed in storms on both watersheds during the growing season than during dormancy. The dormant season data were fit with two regressions: one for data from a late-March storm that came after a fairly long wet period and reached a much lower maximum DOC concentration than had previously been observed, and a second for data from all other dormant-season storms. It is surprising that there...
was no difference in concentration vs. discharge regressions for the two watersheds (Fig. 8). This is also in contrast to what has been observed with particulate organic carbon concentration on these watersheds (Gurtz et al. 1980).

The causes of increasing DOC concentrations during storms are unclear. There are at least four potential sources for the increased DOC during storms:

1) Increased amounts of DOC are flushed from storage sites in the terrestrial system and enter the stream via subsurface water. Lysimeter samples showed elevated DOC concentrations (Fig. 3), and storm-induced flushing of soil water into streams would lead to increased streamwater DOC concentrations. Some direct evidence exists for increasing DOC concentration in subsurface water entering the stream during storms. Subsurface seeps on the undisturbed watershed were sampled during one growing season storm. All seeps showed elevated DOC concentrations: mean seep concentration on that day was 2.893 ± 0.750 mg/L, with the overall growing season mean of 0.673 ± 0.141 mg/L. Increased DOC concentration in seeps during storms has been reported for Bear Brook, New Hampshire (Fisher and Likens 1973), and during one storm in Walker Branch, Tennessee (Comiskey 1978). However, we also sampled one seep on the clear-cut watershed at 10-min intervals for an hour during a storm, and it showed no change in DOC concentration despite changes in DOC concentration in the adjacent stream water.

2) Throughfall on the stream channel is adding some DOC to the stream. The contribution of DOC from throughfall would occur primarily on the rising limb of the hydrograph. However, throughfall appears to be only a minor fraction of the observed increase in DOC concentration during storms. For example, during one summer storm, DOC from throughfall contributed a maximum of 4% of the increase in DOC concentration observed on the rising limb of the hydrograph. In Walker Branch, contributions of DOC in throughfall during summer storms were more significant (Comiskey 1978).

3) Some DOC is leached from particulate organic matter in previously dry portions of the stream channel. The magnitude of this source is, however, difficult to assess.

4) DOC is also coming from storage in the streambed and in intermittent channels. We have no data on interstitial DOC concentration, although it is generally higher than the concentration in overlying water in most aquatic systems (Wetzel 1975). When organic debris dams were experimentally removed from a New Hampshire stream channel, increased concentration and export of DOC were observed (Bilby and Likens 1980). Hence, it would appear that DOC storage sites exist in the channel and can be cleared by a benthic disturbance such as high flow. This is further supported by the fact that the March storm coming after a period of wet conditions and relatively high flow did not reach as high a DOC concentration as earlier storms. Presumably, both terrestrial and aquatic storage areas were depleted prior to this storm. A similar phenomenon has been observed during some storms in a Tennessee stream (Comiskey 1978).

The amount of DOC added to the stream via throughfall, leaching of particles, and flushing of streambed storage sites (sources 2, 3, and 4 above) should be maximal on the rising limb of the hydrograph, whereas the flushing of terrestrial storage areas (source 1 above) would be more delayed and prolonged. This could explain the absence of a concentration difference on rising and falling limbs of the hydrograph. On the rising limb, sources 2 through 4 may contribute, while source 1 is increasing in importance and predominates on the falling limb. Studies in an Alberta watershed have demonstrated that most of the DOC exported during storms was from subsurface water sources (Wallis et al. 1981). We suspect the same to be true in Coweeta streams, since subsurface water generally dominates the runoff hydrograph (Hewlett and Helvey 1970, Skalet and Farvolden 1979). The contribution of subsurface DOC to streams during storms is currently under study at Coweeta.
Annual DOC export was calculated using the concentration–discharge regressions (Figs. 7 and 8) to estimate DOC concentration during storms and the seasonal mean concentrations under low-flow conditions, as described previously. A more accurate method for calculating export is to use concentration data from a sampler that samples a volume of water proportional to stream discharge. DOC samples were also taken weekly from a proportional sampler (Frederiksen 1969) on the clear-cut watershed for a 10-mo period during and after this study. Discharge-weighted DOC concentrations from the proportional sampler can be compared with discharge-weighted concentrations predicted using the regressions (Fig. 9). The agreement is good and certainly much better than if only biweekly grab samples are used. Grab samples consistently underestimated DOC concentrations, particularly during periods when there were storms (Fig. 9).

Export calculated from the proportional sampler data was also compared with export calculated using the regression-based method described above. During the dormant season, the regression-based method predicted export to be 99% of that calculated with the proportional sampler. During the growing season, results were more sensitive to the criteria used to determine if there was storm flow. If the gage height changed by a certain amount (0.213 or 0.183 cm) between readings, we considered it to be storm flow. Depending on the change in gage height specified, export during the growing season was 86–123% of that calculated using the proportional sampler. Annual export was 94–104% of that calculated using the proportional sampler data. We feel that this is reasonable agreement. The range of export values presented in the tables below represent the values obtained using the two criteria for determining storm flow.

### Table 2. Annual discharge and DOC export from two Coweeta watersheds for the period 1 July 1979–30 June 1980.

<table>
<thead>
<tr>
<th></th>
<th>Undisturbed watershed</th>
<th>Clear-cut watershed</th>
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<tbody>
<tr>
<td><strong>DOC export</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>14.6–15.1 kg/ha</td>
<td>9.8–11.5 kg/ha</td>
</tr>
<tr>
<td>November–April</td>
<td>52–55%</td>
<td>43–50%</td>
</tr>
<tr>
<td>May–October</td>
<td>45–48%</td>
<td>50–57%</td>
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<tr>
<td><strong>Discharge (m^3)</strong></td>
<td></td>
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</tr>
<tr>
<td>Annual</td>
<td>926 000 m^3</td>
<td>943 000 m^3</td>
</tr>
<tr>
<td>November–April</td>
<td>65%</td>
<td>58%</td>
</tr>
<tr>
<td>May–October</td>
<td>35%</td>
<td>42%</td>
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Annual DOC export from the clear-cut watershed was ~70% of that from the undisturbed watershed, despite only a 2% difference in discharge (Table 2). DOC export from both watersheds showed less seasonal difference than did discharge, primarily because DOC concentrations tended to be lower during the dormant season, when total runoff was greater. These export values were higher than values calculated using only biweekly samples. When changes in DOC concentration during storms were not taken into account, DOC export was underestimated by 35% in the undisturbed watershed and 50% on the clear-cut watershed. Similarly, Dahm (1980) reported a 60% underestimate of DOC export from an Oregon clear-cut watershed when storm-induced changes in DOC concentration were not taken into account.

The finding of lower DOC export from the clear-cut watershed was unexpected and at variance with results of previous studies, although older successional watersheds at Coweeta showed slightly depressed export values for as long as 20 yr after cutting (Tate and Meyer 1982). Hobbie and Likens (1973) reported slightly greater DOC export from a New Hampshire watershed that was clear-cut without timber removal and then sprayed with herbicide for three summers. The New Hampshire study was conducted during the 3rd and 4th yr after cutting, and the greater DOC export was attributed primarily to increased runoff. In a comparison between a commercially clear-cut and an undisturbed watershed in Oregon, Dahm (1980) reported DOC export from the clear-cut watershed was 190% higher than that from the undisturbed forest the 2nd yr after cutting. By the 3rd yr the clear-cut watershed showed only 37% greater export. The decrease in DOC export from the clear-cut watershed was largely due to lower DOC concentrations, which dropped 47% on the clear-cut watershed and only 8% on the undisturbed watershed between years two and three (Dahm 1980).

When the above results are combined with the data presented here, an apparent pattern of changes in DOC...
export after clear-cutting emerges. With the increased runoff and large inputs of detritus to the stream, DOC export is very high immediately after clear-cutting. As the vegetation begins to recover, as runoff declines to more normal values, and as the supply of easily leached DOC declines, so does DOC export. Hence, at some time after cutting, export is less than it was prior to cutting. Eventually, the supply of DOC to the stream will return to precut levels, as will export. The recovery is thus closely linked to recovery of the terrestrial ecosystem. However, we do not yet have long-term data from one system to corroborate this hypothesized pattern, which is similar to that proposed for changes in export of essential nutrients during succession, although the causal factors are different (Vitousek and Reiners 1975, Bormann and Likens 1979). If this pattern is correct, the data that exist suggest that recovery proceeds at different rates in different ecosystems: faster in the southern Appalachians than in the Pacific Northwest or the Northeast. This is supported by the observation that recovery of net primary productivity after clear-cutting of southern Appalachian forests is more rapid than has been reported for other forests (Boring et al. 1981).

**DOC mass balance**

One reason for the reduced DOC exports from the clear-cut watershed is apparent when the annual mass balances are compared for the two streams (Table 3): less DOC was entering the stream on the clear-cut watershed. The mass balances also indicate that exports exceeded inputs in both streams. As is common in budgetary calculations, we do not have precise error estimates for these figures; hence we cannot be certain that the calculated difference between exports and inputs is significant. However, given the fact that losses of DOC from the system due to respiration, flocculation, sorption, and biological uptake have not been included, it is surprising that DOC inputs do not exceed exports.

One possible reason for the net losses observed is that we have underestimated or overlooked DOC sources to the stream. These sources include:

1) Subsurface water inputs may have been underestimated by using DOC concentrations from seeps (Wallis et al. 1981) and by our method of calculating subsurface inputs during storms, as discussed earlier.

2) We have overlooked DOC leached from algae. If we assume that 10% of the carbon fixed is leached (Sharp 1977), this would increase DOC inputs by 1.8% in the clear-cut watershed and 0.6% in the undisturbed stream (based on 14C data from Webster et al., in press).

3) We have not considered DOC leached from organic matter stored in stream channels. Based on a leaching rate of 0.1%/yr (Cummins et al., in press), wood in the amounts of 19 and 41 kg/m$^2$ would have to be stored in the undisturbed and disturbed streams, respectively, to account for the calculated differences in input and export (Table 3). It is unlikely that wood storage is that great in these streams, since in Oregon streams with large Douglas fir logs, wood storage is $\sim$10 kg/m$^2$ (Froehlich 1973). However, leaching rates may be $>0.1\%$/yr, especially for stored POC other than wood. This slow leaching of stored POC was not included in the budget.

4) We have not included DOC generated by consumers. Leaf-shredding insects generate DOC per unit body mass at the rate of 0.2-140 mg·mg$^{-1}$·d$^{-1}$, with rate an inverse function of body size (Meyer and O’Hop, in press). With an ash-free dry biomass of 1 g/m$^3$ (J. B. Wallace, personal communication), shredders alone could produce DOC at from 1 to 50 g·m$^{-2}$·yr$^{-1}$. Microbial production of DOC would be even greater.

The in-stream sources of DOC that we have not included in the budget deserve further investigation, for they appear potentially significant. The consistent

| Table 3. Annual DOC budgets (1 July 1979-30 June 1980) for two streams draining an undisturbed and a clear-cut watershed. The budgets are calculated for the main stream channel only and for the entire stream network (main channel plus tributaries). The range of values reflects the two different criteria used to determine when there was storm flow as described in the text. |
|---|---|---|---|---|---|---|---|
| **Main channel** | **Entire network** | **Undisturbed** | **Clear-cut** | **Undisturbed** | **Clear-cut** |
| **Inputs** | | **C (kg)** | **% of total** | **C (kg)** | **% of total** | **C (kg)** | **% of total** | **C (kg)** | **% of total** |
| Subsurface water | | 223-235 | 26-27% | 191-228 | 36-37% | 522-548 | 69-70% | 392-467 | 80-83% |
| Tributaries | | 499-526 | 56-60% | 285-335 | 53-54% | ... | ... | ... | ... |
| Litter leaching | | 82 | 9-10% | 28 | 5-6% | 164 | 21-22% | 49 | 9-10% |
| Throughfall | | 39 | 4-5% | 30 | 5-6% | 74 | 9-10% | 48 | 9-10% |
| Total | | 843-882 | 524-621 | 760-786 | 489-564 | 9-10% |
| **Exports** | | **Total** | **873-923** | **575-674** | **873-923** | **575-674** |
| **Exports/inputs** | | **104-105%** | **108-109%** | **115-117%** | **118-120%** |
increase in DOC concentration from headwater seep to weir in the undisturbed stream (Fig. 6) attests to their importance. Further evidence is provided by a comparison of the budget calculated for the main channel with that calculated for the entire stream network on each watershed (Table 3). Total inputs are less for the network budgets, even though we are considering a greater area of stream. This is partly because in-stream generation of DOC in tributaries would be included as measured tributary inputs when a budget is calculated for the main channel, but not in a budget for the whole stream network. One might expect these in-stream sources to be maximal in tributaries, where the ratio of benthic surface area/water volume is maximal, and where shredder densities are greatest.

In addition to DOC sources not included in the budget, hydrologic conditions may be partly responsible for the net losses observed. The year for which these budgets were calculated was relatively wet; annual runoff was 37% above the 44-yr average (Coweeta Hydrologic Laboratory data files). The recurrence interval for the maximum discharge of the year was 30 yr (calculated using regressions given in Douglas [1974]). During such wet years one would expect a flushing of stored material from the system (e.g., Meyer and Likens 1979). It is unlikely that flushing of stored material during this year is the only reason for the observed net export, because the years preceding this one were also fairly wet with a 100-yr flood during 1976. Hence long-term storage areas for leachable particles within the stream channel would have been depleted by the high flows prior to the year studied.

Problems in comparing stream ecosystem budgets

A comparison of DOC processing in two streams using a mass balance approach is sensitive to the units used for calculating the budget. The main channels of the two streams studied here were similar with respect to watershed size, amount of runoff, and stream length, but they had different bankful widths. The main channel on the clear-cut watershed was 59% of the area of the undisturbed stream. Hence inputs and exports per square metre were less in the undisturbed area, which is the reverse of the conclusion reached earlier (Table 3). The rationale for expressing the budget on an areal basis is that much of the activity in a stream is associated with the substrate. However, the area used in these calculations is bankful area, and during most of the year only a small part of that area is under water. Calculations should be based on area of wetted surface, but this area changes with discharge, is influenced by channel roughness, and is logistically unfeasible to measure accurately for annual budget calculations.

Because of these problems the unitless export/input ratio may be the most appropriate measure to use for comparisons. However, using a mass balance approach and comparing the ratio of exports/inputs in two streams biases one's conclusions toward hydrologic processes (Cummins et al., in press), because total fluvial exports are predominantly determined by losses during storms, and net exports tend to be greater during storms (Meyer and Likens 1979). Thus biologically caused differences between ecosystems can be obscured by hydrologic events. As Cummins et al. (in press) conclude, a budgetary approach toward comparing two stream ecosystems may be inappropriate if one is trying to assess differences in biological processes in the streams. An input—output analysis of DOC in these streams can obscure important in-stream processes such as DOC generation and utilization.

The effects of clear-cutting on stream DOC dynamics

This study was begun 2 yr after logging was completed and 3 yr after roads were built on the watershed. Hence we were studying a system that had already begun to recover from disturbance: algal production in the stream was reduced from the rates observed immediately following clear-cutting (Webster et al., in press), net primary productivity of the forest had returned to 86% of predisturbance levels (L. R. Boring, personal communication), and leaf fall had risen from 2% of precut amounts immediately after cutting to 17% of precut quantities at the time of the study (Webster and Waide 1982). Data available from other clear-cutting studies (e.g., Dahm 1980) suggest that DOC dynamics immediately after logging will be different from those observed here.

In the stream on the clear-cut watershed, annual DOC export was reduced and DOC concentrations in streamwater were lower during the growing season than in an undisturbed stream. There are at least three reasons for this reduction in DOC concentration and export:

1) Reduced inputs of DOC from the riparian zone in the disturbed stream (e.g., lower litter inputs, Table 3).

2) Reduced DOC input from subsurface water sources. Subsurface water inputs in the disturbed stream were 86% of inputs in the reference stream (Table 3). This reflects reduced concentrations of DOC in the seep and soil water (e.g., Figs. 2 and 3), which are presumably a consequence of lower litter fall and slower litter decomposition on the clear-cut watershed (Seastedt and Crossley 1981).

3) Reduced in-stream generation of DOC. We have no direct evidence for this, although several observations are consistent with it. For example, there is an increase in DOC concentration along the length of the reference stream during the growing season, whereas there is little increase in the disturbed stream (Fig. 6). The discrepancy between main channel and
whole network budgets (Table 3) discussed previously provides additional evidence. This discrepancy is greatest in the stream draining the clear-cut.

Thus the major effect of this disturbance of the terrestrial ecosystem on DOC dynamics in the stream was reduced inputs of both DOC and leachable POC and increased export of the POC. Therefore, the rate of recovery of the stream ecosystem to predisturbance DOC dynamics will reflect the rate at which inputs from the terrestrial ecosystem return to predisturbance levels. This dependence on the rate of recovery of the terrestrial ecosystem has also been observed with particulate organic matter in this stream (Gurtz et al. 1980). It provides clear demonstration of the tight linkages between streams and their watersheds.

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