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THE EFFECTS OF FOREST DISTURBANCE ON STREAM STABILITY

by

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Biology

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February 12, 1988

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(ABSTRACT)

This project was designed to examine the stability of stream ecosystems in response to forest disturbance and subsequent succession. Stability was defined as the ability of streams to retain particulate organic matter and nutrients during storms. I hypothesized that forest streams are least stable during the intermediate stages of forest succession because particulate organic matter accumulations in streams are lowest at that time. This hypothesis was tested by examining stream stability in relation to forest succession.

Stream surveys indicated fewer debris dams and organic matter accumulations in streams draining early and intermediate successional forests compared to reference sites. The abundance of large wood declined within 10 years of forest disturbance and continued to decline for at least 30-40 years through the intermediate stages of forest succession. Comparisons of inputs with standing stocks of organic matter indicated that streams draining early and intermediate successional sites receive less litter from their watersheds and processed it faster. Decreases in stream obstructions combined with changes in litter inputs and processing resulted in relatively high storm transport of fine organic matter from disturbed streams. Storm organic matter export from disturbed streams averaged 4.22 g AFDW/m² and from reference streams averaged 1.83 g AFDW/m². Storm nutrient budgets, constructed by measuring nutrient inputs (soil water, throughfall) and outputs (stream discharge) during individual storms indicated that streams draining early and intermediate successional forest were less retentive of nitrogen and phosphorus than reference sites. Nitrogen loss from disturbed streams averaged 58.04 mg/m²/storm and from reference streams averaged 16.52 mg/m²/storm. Phosphorus loss from disturbed streams averaged 32.52 mg/m²/storm and from reference sites averaged 7.14 mg/m²/storm. A majority of the nitrogen and phosphorus loss

was in association with organic particles. There was no difference between disturbed and reference streams in potassium, calcium, or sulfate retention during storms. However, disturbed streams tended to lose more particulate organic potassium and calcium than reference sites. These results indicate that forest disturbance has a longterm impact on stream ecosystems by reducing their stability for many years following forest clearing.

Acknowledgements

I am grateful to a number of faculty at Virginia Tech who helped with this study. I thank my committee chairman Dr J.R. Webster for his friendship, encouragement, and support during all aspects of this research. The ideas for this project were developed during numerous Coweeta expeditions from 1981-1983 and were the result of a number of extended discussions on stream ecology between Jack and myself. I would also like to thank [redacted] for sharing his enthusiasm for field-work with me and for passing along many of the trade secrets (e.g. methods of surveying ichthyofauna, strategies for storm sampling during droughts, subtleties of sour-dough). [redacted] assisted in the design and execution of this research. I also thank [redacted] for his patient and thorough editing of manuscripts resulting from this project. A number of other faculty served on my advisory committee, I thank Drs. A.C. Hendricks, S.G. Hornor, W.C. Johnson, E.T. Nilsen, and J.R. Voshell for providing advice on experimental design, data analysis, and for critically evaluating manuscripts. I am especially grateful to Dr E.T. Nilsen for agreeing to serve on my committee and for reading this dissertation with relatively short notice.

This research could not have been conducted without access to an excellent experimental site like Coweeta Hydrologic Laboratory. I would like to thank the USDA Forest Service Southeast Station and especially Dr W.T. Swank for making their facilities available. The

staff at Coweeta were extremely helpful in the execution of this research. provided numerous helpful comments on storm sampling strategies. and helped me locate discharge and precipitation data. provided access to the machine shop and numerous ecologically useful implements (e.g. shovels, digging irons, sledge hammers). helped me maintain my precipitation gauges. was very helpful in making the reprint collection and office facilities available to me. Chemical analyses were performed at Coweeta and I thank and for the time they spent adapting and developing methods for this project. I thank for assisting in the field-work and especially for his willingness to help sample storms at all hours of the day. Financial support for this project was provided by the National Science Foundations Ecosystems Studies Program.

Many of my fellow grad students helped in various phases of this work. I thank , , and for assisting with storm sampling and benthic organic matter estimation. I also thank , , and for making extended visits to Coweeta lively occasions.

Finally, I owe a thanks to my family. My parents were constantly supportive of and enthusiastic for one of the longer educational careers on record. I also owe special thanks to my wife, , for her constant encouragement, understanding, and most of all for tolerating an absentee husband during two years of field work.

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Introduction

Headwater streams are closely linked to the areas they drain (Hynes 1975, Vannote et al. 1980), thus watershed disturbance such as logging can cause severe disruption within streams. Logging has been a common disturbance in forested areas of North America and has resulted in a variety of longterm changes in stream ecosystems. Watershed vegetation is an important regulator of the physical environment of streams. Evapotranspiration can account for 40-60% of the annual water loss from a forested watershed (Kovner 1956), thus vegetation regulates streamflow. Removal of terrestrial vegetation decreases evapotranspiration and increases streamflow (Dunford and Fletcher 1947, Kovner 1956, Hewlett and Hibbert 1961) roughly in proportion to the watershed area that is cleared (Hewlett and Hibbert 1961, Rothacher 1971). Streamflow may remain elevated for 30 to 40 years following logging, returning to predisturbance levels at a rate proportional to forest revegetation (Swift and Swank 1981).

The seasonal pattern of streamflow from a forested watershed is determined by the annual distribution of precipitation, watershed hydrologic characteristics (e.g. soil infiltration rate, storage capacity, depth, slope), and aspect of the watershed basin. Following disturbance large increases in streamflow have been observed during baseflows at the end of the

forest growing season when transpiring vegetation would normally deplete most of the water stored in forest soils (Hewlett and Hibbert 1961, Hornbeck et al. 1970, Harr et al. 1975).

Forest disturbance may also affect the pattern of storm runoff. Hewlett and Helvey (1970) reported that stormflow volumes increased 11% and peak discharge increased 7% following forest clearing in a southern Appalachian watershed. Increased stormflows from the disturbed watershed occurred during all seasons and were attributed to greater soil moisture and lower interception losses, which resulted in more water entering stream source areas (Hewlett and Helvey, 1970). Hornbeck (1973), working in the White mountains of New Hampshire, and Harr et al. (1975), working in the Oregon coastal range, also noted increased stormflows and peak discharges in streams draining disturbed watersheds. Increases in stormflow from disturbed streams were greatest at the end of the forest growing season and were attributed to higher soil water storage in disturbed watersheds (Hornbeck 1973, Harr et al. 1975). In the absence of extensive soil disturbance, removal of terrestrial vegetation does not affect soil infiltration rates or time to peak storm discharge in streams draining disturbed areas (Hewlett and Helvey 1970, Hornbeck 1973, Harr et al. 1975).

Headwater streams draining forested areas are typically heavily shaded. Removal of overhanging vegetation increases insolation resulting in increased average stream temperatures, especially during the forest growing season (Brown and Krygier 1970, Swift and Messer 1971, Burton and Likens 1973). The duration of stream temperature increases is typically shortlived (< 5 years) returning to predisturbance levels at a rate proportional to forest regrowth (Brown and Krygier 1970, Swift and Messer 1971, Burton and Likens 1973).

Forest vegetation regulates nutrient inputs to streams by two primary mechanisms: through the uptake of nutrients from soil solution and storage in biomass; and by decreasing water movement through soils (e.g. interception and transpiration) (Bormann et al. 1969, Vitousek and Reiners 1975, Vitousek 1977). Following disturbance, vegetative nutrient uptake is reduced and soil conditions (i.e. increased moisture and temperature) accelerate mineralization of organic matter (Marks and Bormann 1972, Bormann et al. 1974, Covington et al. 1981, Binkley 1984). Following forest disturbance, elevated concentrations of Ca, K, Na,

Mg and NO₃-N in soil solution and streamwater have been widely reported (e.g. Likens et al. 1970, Brown et al. 1973, Neary 1977, Swank 1987). Nutrients that are relatively mobile in soil solution or cycle biologically appear to be most affected, and the nitrogen cycle of forested watersheds is extremely sensitive to disturbance (Vitousek and Reiners 1975, Vitousek 1977, Swank 1986). Disruption of the nitrogen cycle following disturbance results from the mineralization of organic nitrogen to NH₄-N and, in the absence of plant uptake, the subsequent oxidation of NH₄-N by nitrifying bacteria to NO₃-N (Likens et al. 1970, Vitousek and Melillo 1979). Nitrification also releases H⁺, that may displace cations on exchange sites in soils (Likens et al. 1970). NO₃-N and cations can then be flushed from soils and readily transported in streamwater (Likens et al. 1970, Vitousek and Melillo 1979). The magnitude and timing of NO₃-N losses from disturbed forests depends on site specific characteristics such as the availability of organic nitrogen to be mineralized, mineralization rates, and the abundance of populations of nitrifying bacteria (Vitousek and Melillo 1979). Concentrations of NO₃-N in streams draining deforested areas appear to peak within 5 years (Likens et al. 1970, Brown et al. 1973, Swank 1988), although concentrations may remain elevated for 20 or more years (Swank 1987). As vegetation becomes reestablished and nutrients begin to accumulate in biomass, nutrient concentrations in soil solution and streamwater return to reference levels (Likens et al. 1970, Brown et al. 1973, Vitousek 1977).

Soil disturbance associated with road building and timber harvest can result in high sediment yields to streams (Lieberman and Hoover 1948, Tebo 1955, Paustain and Beschta 1979). Soil organic matter, particularly the litter layer, is an important regulator of erodability in forest soils (Bormann et al. 1969). Accumulated litter protects soil from the erosive energy of raindrops, promotes soil particle adhesion, and encourages rain water percolation (Bormann et al. 1969). Disturbances that remove the litter layer or compact forest soils promote overland flow and erosion of mineral soil (sediment) into stream channels. Sediment yields decrease as vegetation regrows; however, instream redistribution and transport of sediment may continue for many years (Brown and Krygier 1971).

Logging also alters the energy base of stream ecosystems. When forests are cut, allochthonous leaf inputs to streams are greatly reduced (e.g. Webster and Waide 1982); however, autochthonous production and standing stocks of periphyton may increase due to the absence of shading and increased nutrient availability (Hains 1981, Murphy and Hall 1981). The periphyton community of shaded, forest streams is typically dominated by diatoms (Hansmann and Phinney 1973, Keithan and Lowe 1985), but following logging filamentous green algae (Chlorophyta) often increase in abundance (Hansmann and Phinney 1973, Likens et al. 1970, Lowe et al. 1986). The pulse of autochthonous production is generally short-lived and the rapid regrowth of riparian vegetation restores detrital inputs within a few years (Swanson et al. 1982, Webster et al. 1983), but the subtle effects of forest disturbance on the energy base of streams may persist for many years. The composition of detrital inputs may change considerably from mostly late successional, decay-resistant litter to rapidly decaying early successional litter (Webster et al. 1987). Also periphyton diversity, density, and productivity may be depressed under the low nutrient conditions typical of streams draining intermediate successional (aggrading) forests (Keithan and Lowe 1985).

Forest ecosystem structure and function is internally generated by the growth of forest vegetation. Thus, cutting or burning represents a short term disturbance to forests because the forest is free to undergo succession or recovery in the absence of further disturbance. However, imported organic matter is an important functional and structural element of stream ecosystems. Thus stream disturbance begins with forest cutting or burning and continues until the predisturbance patterns of vegetation reestablish themselves on the watershed (Webster and Swank 1985), a process that may take 100-400 years depending on the mature forest type of the region (Likens and Bilby 1982, Swanson and Lienkaemper 1978). Declines in the number and size of stream obstructions (large wood and debris dams) have been observed in streams draining logged watersheds (Likens and Bilby 1982, Swanson and Lienkaemper 1978, Golladay et al. 1987). Debris dams have been reported to erode rapidly following watershed logging because small twigs and leaves, which form the internal matrix of debris dams, breakdown and are not replaced (Bilby 1981, Fisher and Likens 1973). Even

though large wood may remain, breakdown of the debris dam matrix may account for increases in particulate organic matter transport observed following logging (Gurtz et al. 1980, Hobbie and Likens 1973, Webster and Golladay 1984). Large woody debris also gradually decays and is not replaced. For the stream, the loss of morphological features during forest recovery causes a gradual reduction in the ability to resist downstream export of material that is most pronounced during storms or seasons of high discharge. Thus, forest disturbance ultimately reduces the ability of streams to resist shorter term natural disturbances. The purpose of this project was to examine longterm effects of forest disturbance on stream ecosystems. This objective was accomplished by examining functional and structural characteristics of streams draining early, intermediate, and late successional forests. In chapters 1 and 3 changes in stream ecosystem function were assessed by examining changes in the ability of streams to retain biologically important material (i.e. organic matter and nutrients) during storms. In chapter 2 changes in stream ecosystem structure were assessed by comparing inputs and standing stocks of organic matter, morphology, and hydraulic characteristics of the streams.

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Chapter 1–Seston Transport

CHANGES IN STREAM MORPHOLOGY AND STORM TRANSPORT OF SESTON FOLLOWING WATERSHED DISTURBANCE

Introduction

Headwater streams are closely linked to the areas they drain (Hynes 1975, Vannote et al. 1980), thus watershed disturbance can cause severe disruption within streams. Logging has been a common disturbance to eastern deciduous forests and has resulted in a variety of longterm effects on streams. Removal of vegetation decreases transpiration and increases streamflow (Hewlett and Hibbert 1961, Kovner 1956). Streamflow may remain elevated for 30-40 years following logging, returning to predisturbance levels at a rate proportional to forest revegetation (Swift and Swank 1981). Logging may also increase stream nutrient concentrations for 10-20 years (Likens et al. 1970, Martin et al. 1984, Swank and Douglass 1975, Vitousek and Melillo 1979). Soil disturbance associated with road building and timber harvest can increase erosion and result in high sediment loading to streams (Lieberman and Hoover

1948, Paustan and Beschta 1979, Tebo 1955). Sediment yields decrease to predisturbance levels as vegetation regrows; however, instream redistribution and transport of sediment may continue for many years (Brown and Krygier 1971).

Logging also alters the energy base of stream ecosystems. When forests are cut, allochthonous leaf inputs to streams are greatly reduced (Webster and Waide 1982); however, autochthonous production may increase due to the absence of shading and increased nutrient concentrations (Hains 1981). The pulse of autochthonous production is generally shortlived and rapid regrowth of riparian vegetation returns the stream to a detritus base within a few years (Swanson et al. 1982, Webster et al. 1983). However, the composition of detrital inputs may change considerably from mostly late successional, decay-resistant, litter to rapidly decaying early successional litter (Webster et al. 1987).

Logs and other organic debris play an important stabilizing role in stream ecosystems. Leaves and twigs accumulate behind logs that are large enough to span stream channels without being displaced by streamflow. These aggregations, called debris dams, cause a stepped pattern of streambed morphology, which reduces stream power and sediment export (Heede 1972, Swanson et al. 1976). Debris dams also filter dissolved and suspended particulate material from the water column (Bilby 1981, Swanson and Lienkaemper 1978, Triska et al. 1982). Rapid erosion of debris dam structure following logging was reported by Bilby (1981) and Fisher and Likens (1973). Small sticks and leaves, which form the internal matrix of debris dams, decay relatively rapidly; and since allochthonous inputs are reduced, the matrix is not replaced. Breakdown in debris dam structure may account, in part, for increased baseflow seston transport observed following logging (Gurtz et al. 1980, Hobbie and Likens 1973, Webster et al. 1983). Webster and Golladay (1984) noted that increased baseflow seston concentration returned to reference levels within 10-20 years following logging, suggesting that debris dam function may be partially restored as allochthonous inputs return to predisturbance levels.

Logging also results in a longterm decline in the number of debris dams in streams draining logged watersheds (Likens and Bilby 1982, Swanson and Lienkaemper 1978, Webster

et al. 1987). Generally, early successional vegetation is not large enough to form stable debris dams as it dies and falls into streams. Thus, the number of debris dams declines as old logs decay, and may remain depressed for 100-400 years depending on the recovery rate of the mature forest type of the region (Likens and Bilby 1982, Swanson and Lienkaemper 1978). Low numbers of debris dams in streams can result in high transport of particulate organic matter, especially during storms. Bilby (1981) and Bilby and Likens (1980) reported that debris dam removal on a 175-m reach of an otherwise undisturbed stream increased the transport of dissolved, fine, and coarse particulate organic matter; greatest increases were observed at high discharges and were attributed to increased stream power and decreased retentiveness.

The major longterm effects of forest disturbance on streams appear to be alteration of the energy base available to stream consumers and a gradual decline in the ability of streams to retain biologically important materials. Low retention efficiency may cause catastrophic loss of organic matter and nutrients during periods of high discharge. The objective of this study was to examine the longterm effects of forest disturbance on streams. This objective was accomplished by characterizing organic matter export during baseflows and storm flows and by examining stream channel morphology in streams draining logged and reference watersheds.

Study Site

This work was conducted at Coweeta Hydrologic Laboratory, Macon County, North Carolina, USA. Four sites were selected for study; two streams draining disturbed watersheds were matched with two streams draining reference watersheds of similar size. Big Hurricane Branch (BHB) drains WS (Watershed)-7, a 58.7-ha experimental watershed, which was grazed by cattle from 1941-1952 and cable logged during the winter of 1976-1977. Regrowth is domi-

nated by hardwood sprouts, herbs, vines, and seedlings (Boring et al. 1981). Carpenter Branch (CB) drains WS-13, a 16.1-ha experimental watershed. Originally mixed hardwoods, all trees and shrubs were cut in 1939-1940 and again in 1962 (Swank and Douglass 1977). No wood was removed from the site and soil disturbance was minimal (Swank and Douglass 1977). The watershed is now covered by a young hardwood forest dominated by yellow poplar (Liriodendron tulipifera) at lower elevations and mixed oaks (Quercus spp.) at higher elevations (Leopold and Parker 1985). Hugh White Creek (HWC) drains WS-14, a 61.1-ha watershed, and Grady Branch (GB) drains WS-18, a 12.5-ha watershed. Watersheds 14 and 18 are mixed hardwood forests and are longterm reference watersheds at Coweeta (Swank and Douglass 1977). Both sites were selectively logged before 1925 and, except for the chestnut blight, have been undisturbed for 60 years. Since many of the measurements we made are influenced by stream size, streams were paired based on similarities in average annual discharge and watershed area (Table 1.). Hugh White Creek was selected as a reference stream for Big Hurricane Branch, and Grady Branch was selected as a reference stream for for Carpenter Branch. All streams are located within two kilometers of each other. They are equipped with V-notch weirs, and continuous records of streamflow are maintained by the Forest Service. Further characteristics of the study sites are presented in Table 1.

Methods

Measurements were made on each stream to assess the effect of watershed disturbance on stream morphology and hydraulics. During September and October 1985, stream width and average depth were measured at three transects within 10-m reaches every 100 meters along each stream. Average velocity was measured for each 10-m reach using dye (rhodamine-B) releases. All measurements were made during stable baseflows. Bed roughness was calculated for each reach according to the Manning formula (Chow 1959).

During March 1986 the main channel of each stream was surveyed for channel features that represented potential obstructions to downstream transport of seston. These features were divided into three categories: 1) organic matter accumulations--accumulations of leaves and sticks supported by rocks or boulders, with no wood > 5 cm diameter; 2) logs--wood alone, with an average diameter > 5 cm; 3) debris dams--sticks and leaves aggregated with supporting logs > 5 cm diameter. Only features that clearly affected stream morphology, i.e., created pools or stair-step patterns of flow, were included in the survey.

From June 1984-June 1985, seston was sampled during eight storms at a single site on each stream just upstream of the weir ponding basin. Stream samples (ca. 500 ml) were collected by ISCO Model 2100 automated water samplers. Intake hoses were positioned above the streambed in well-mixed riffles. Samplers were manually turned on when there appeared to be a possibility of rain. Excess samples collected prior to the onset of precipitation were discarded, the sample bottles were rinsed thoroughly with water collected from below the weir (many of the particulates settle in the weir ponding basin), and bottles were returned to the sampler. All samplers were placed near the stream gaging stations, and during storms streams were sampled at a frequency that varied depending on how fast streamflow was changing. Sampling frequency was greatest during rising flows and continued following storms until streamflow returned to within 5-10% of original baseflow. Sampling frequency varied from 5 minutes during intense thunderstorms to several hours during less intense steady rains. Fifteen to 25 samples were collected from each stream during each storm. Additional grab samples were taken between storms to measure baseflow seston concentrations in each stream.

Water samples were taken to the laboratory and filtered (ashed and tared Gelman type A/E glass fiber filters) within 48 hr of collection. Filters were dried (55°C, 24 hr), desiccated (24 hr), weighed, ashed (550°C, 20 min), rewetted to restore water of hydration, redried, desiccated, and reweighed (Gurtz et al. 1980). Organic seston concentration was determined as weight loss on ashing and expressed as ash free dry weight (AFDW). Storm export was

estimated by integrating the product of seston concentration and discharge over the course of each storm.

Five throughfall collectors (10 X 400 cm pvc troughs draining into 20-L buckets) were placed over each stream to estimate inputs of particulate organic matter during storms. Immediately following storms, throughfall volumes were recorded and subsamples (ca. 250 ml) were returned to the laboratory for processing as described above. Stream area, throughfall particulate organic matter concentrations, and throughfall volumes were used to estimate total organic particle inputs due to channel interception during each storm.

Results and Discussion

Effect of watershed disturbance on stream morphology and hydraulics

Organic matter accumulations and logs are common morphological features in undisturbed Coweeta streams (Table 1). Debris dams are not common due to the rarity of streamflows of sufficient magnitude to move and consolidate large woody debris, therefore logs generally remain where they fall in the stream. A comparison of Big Hurricane Branch and Hugh White Creek revealed significantly fewer organic matter accumulations in the disturbed stream (BHB) (t-test, $P=0.0001$), however there was no significant difference in the number of logs (t-test, $P>0.50$). Carpenter Branch (disturbed) had significantly fewer organic matter accumulations (t-test, $P=0.0003$) and logs (t-test, $P=0.001$) than Grady Branch (reference). In Coweeta streams following logging, there appears to be a twofold disturbance to stream morphological features. Initially, numbers of stick and leaf accumulations are reduced, then there is a more gradual decrease in the amount of large woody debris. The number of debris dams in Big Hurricane Branch (disturbed) was significantly lower than in Hugh White

Creek (reference) (t-test, $p=0.001$) but not significantly different in a comparison of Carpenter Branch and Grady Branch (t-test, $P=0.10$).

Stream hydraulics also appear to change following watershed disturbance (Table 1). The average velocity of Big Hurricane Branch (disturbed) was significantly higher than Hugh White Creek (reference) (t-test, $P=0.011$), and the average velocity of Carpenter Branch (disturbed) was significantly higher than Grady Branch (reference) (t-test, $P=0.014$). The roughness coefficient (Manning's n) was significantly greater for Grady Branch than for Carpenter Branch (t-test, $P=0.014$), but differences in roughness were not significant between Big Hurricane Branch and Hugh White Creek (t-test, $P=0.25$).

Pattern of seston concentration during baseflows and stormflows

Baseflow seston concentrations in the four streams varied seasonally, ranging from 0.1 to 1.0 mg/L in winter and from 3.0 to 7.0 mg/L in summer (Fig. 1). Comparison of disturbed versus reference streams of similar size revealed no significant differences in baseflow seston concentration (paired t-test, $P>0.05$).

Rainfall during the eight storms sampled ranged from 0.5 to 7.0 cm and average rainfall intensities ranged from 0.05 to 1.05 cm/hr (Table 2). Winter and spring storms were of long duration (up to 40 hrs) and moderate in intensity. Summer and autumn storms were generally shorter in duration (1-6 hrs) and were characterized by periods of relatively intense rainfall. Rainfall amounts and intensities were very similar among sites.

A typical pattern of seston concentration during stormflows is illustrated by a storm that occurred on 11 February 1985 (Fig. 2). Rainfall began at 0900 hr and intensified through the afternoon; rainfall ceased at 1700 hr but began again at 1830 hr. Rainfall was heavy through 2400 hr then stopped. Total precipitation was 6.5 cm with an average intensity of approximately 0.5 cm/hr. Seston concentration increased rapidly with increasing discharge in all streams and was highest at or slightly before peak discharge. Once streamflow stabilized,

seston concentration declined and continued to decrease as discharge returned to baseflow. During this storm there were two distinct peaks in seston concentration corresponding to periods of heaviest rainfall. This pattern of seston concentration was observed for each stream during all storms sampled and is similar to that observed by Bilby and Likens (1979), Fisher and Likens (1973), Gurtz et al. (1980), and Meyer and Likens (1979). In all but one case, stormflows had higher average seston concentrations in disturbed streams than in reference streams of similar size (Table 3). Differences in average concentration were significant between Carpenter Branch (disturbed) and Grady Branch (reference) (paired t-test, $P=0.05$, data normalized using natural log transformation) but not between Big Hurricane Branch (disturbed) and Hugh White Creek (reference) (paired t-test, $P=0.09$, data log transformed).

During storms, stream channels expand into backwater areas where fine particles have accumulated since previous storms. Particles trapped in those areas are entrained resulting in increased seston concentrations in the streams. Once stream expansion ceases and no new sources of particles are encountered, seston concentrations decline even though discharge may remain high (Bilby and Likens 1979). Webster (1983, and unpublished data) observed a strong positive relationship between seston concentration and the rate of change in discharge during rising flows in natural and simulated storms in both natural and artificial stream channels. Data from this study were analyzed in a similar manner. Regressions of seston concentration versus the rate of change in discharge (ΔQ) during the rising limb of storm hydrographs were performed on six storms. Two storms with fewer than 4 samples taken on the rising hydrograph were excluded from this analysis. For each stream and storm, seston concentration was regressed separately against the increase in discharge over three time intervals (5, 15, and 60 min) preceding each sample time. In general, seston concentration was positively correlated ($P<0.05$) with ΔQ in all streams (Table 4). Intense storms, with the most rapid increases in discharge, provided the strongest correlations between seston concentration and ΔQ . Furthermore, regressions of concentration versus ΔQ for 60-minute intervals accounted for more of the variation in the data than regressions using ΔQ over either 5- or 15-min intervals. This analysis suggests that the origin of seston particles

transported during storms is not immediately upstream from the sampling site. The median particle size for Coweeta seston ranges from 120-150 μ and the settling velocity for particles < 150 μ ranges from 0.06 to 0.40 cm/sec (Webster et al. 1987). Once suspended, those small, slowly settling particles may travel relatively long distances in turbulent stream water. In 13 out of 72 regression analyses we found significant positive autocorrelation (Durbin-Watson test, $P < 0.05$) or serial dependence between samples. Autocorrelation was most prevalent in regressions of AFDW versus ΔQ for 5- or 15-min intervals during storms with large ΔQ values or extended periods of intense rainfall. Our experimental design did not enable us to isolate the factor causing autocorrelation in this analysis, but we feel its presence provides further evidence for relatively long particle travel distances in Coweeta streams during storms.

In a final analysis, regressions of seston concentration versus ΔQ were combined by season for each stream. The seasons were December-February ("winter") and March-November ("summer"). The data were combined based on the similarities in slope from the preceding analysis. For each season, analysis of covariance was used to compare the slopes of regression lines for the pairs of disturbed and reference streams. For each season and stream, seston concentration was positively correlated with ΔQ ($P < 0.05$) (Table 5). In the larger streams, Big Hurricane Branch and Hugh White Creek, the correlation between seston concentration and ΔQ was generally strongest for the 60-min interval. For 15- and 60-min ΔQ the slopes of the regression lines for Big Hurricane Branch were significantly steeper (analysis of covariance, $P < 0.05$) indicating that a unit increase in discharge resulted in the downstream transport of more material in the disturbed (BHB) compared to the reference (HWC) stream. There was a similar relationship between seston concentration and ΔQ during storms in the smaller streams. However, there was no distinct best ΔQ interval for predicting seston concentration. In all comparisons except 60-min ΔQ during summer storms, the slopes of regression lines were significantly steeper (analysis of covariance, $P < 0.05$) for the disturbed stream (CB) than for the reference stream (GB).

Seston export during stormflows

Carpenter Branch (disturbed) had significantly higher export of seston during storms than Grady Branch (reference) (paired t-test, $P=0.002$, data normalized using a natural log transformation). In a similar comparison of Big Hurricane Branch (disturbed) and Hugh White Creek (reference), there was no significant difference in seston export during storms (paired t-test, $P=0.20$, data log transformed). The absence of a significant difference was due to the effect of an unusual storm (10 November 1984) where export from the reference stream (HWC) was substantially higher than from the disturbed stream (BHB) (Fig. 3). If the 10 November 1984 storm was excluded from the analysis, seston export from the disturbed stream (BHB) was significantly higher than from the reference stream (HWC) (paired t-test, $P=0.03$, data log transformed).

To clarify differences between the streams, seston export during storms was divided by the bankfull stream area to correct for differences in stream size and to permit statistical comparison of treatments to be performed (Fig. 4). In paired comparisons of all storms, storm export ($\text{g AFDW/m}^2 \text{ stream/storm}$) was significantly higher in Carpenter Branch (disturbed) compared to Grady Branch (reference) (paired t-test, $P=0.01$, data log transformed), and significantly higher in Big Hurricane Branch (disturbed) compared to Hugh White Creek (reference) (paired t-test, $P=0.0001$, data log transformed). When combined by treatment, storm export from disturbed streams was significantly higher than from reference streams (ANOVA-followed by Duncan's Multiple Range test, $P<0.05$). This analysis indicates that disturbance (i.e. logging) has resulted in increased export of seston in Big Hurricane Branch and Carpenter Branch.

An exception to the general pattern of seston export occurred during a relatively intense, short-duration storm on 10 November 1984 (Table 2). The storm was the first large storm following leaf fall and 6-8 weeks of relatively dry weather. Seston export was higher in reference streams than in disturbed streams. Although maximum seston concentrations were highest

in Big Hurricane Branch and Carpenter Branch, the disturbed streams, average seston concentrations were highest in Hugh White Creek and Grady Branch, the reference streams. Similar large increases in seston transport during the first large storms following leaf fall were observed by Wallace et al. (1982). Fisher and Likens (1973) observed debris dam shifting, depending on storm intensity, which resulted in increased transport of organic matter. Heede (1972) also noted that submergence or movement of debris dams during storms greatly reduced their efficiency. At Coweeta, accumulations of organic debris are more abundant in reference streams than in disturbed sites (Table 1); therefore a storm powerful enough to shift organic debris could cause release of more material in reference streams. Intense storms may also cause a rapid flushing from disturbed streams, resulting in short periods of very high seston concentration followed by lower concentrations due to depletion of transportable material.

Origin of material transported during storms

Estimates of the input of fine organic material (< 1 mm) to the streams were made for each storm. Possible external sources of particulate organic matter include soil water, springs, overland flow, and throughfall. Concentrations of particulate organic matter in soil water and springs are extremely low (Webster and Golladay 1984, Golladay pers. obs.) and can be excluded from calculations. Soils at Coweeta are highly permeable and infiltration rates can exceed 125 cm/hr, thus overland flow is not a common occurrence (Douglass and Swank 1975). Average throughfall inputs of particulate organic matter were 0.21 g/m² in Big Hurricane Branch, 0.27 g/m² in Hugh White Creek, 0.25 g/m² in Carpenter Branch, and 0.36 g/m² in Grady Branch. Throughfall particulate organic matter contributions were highest during spring and summer when leaf area in the forest canopy was greatest (Table 6). Particulate organic matter contributions in throughfall tended to be inversely related to storm intensity. During long or intense storms the potential throughfall contribution to total

particulate organic matter export was generally less than 20%. However, during low intensity storms, particularly in spring, the potential contribution was as high as 83% of total particulate organic matter export. Contributions of throughfall were generally a higher proportion of total particulate organic matter export in reference streams. This pattern may result from greater scavenging of material in the well developed canopy of reference sites or may be partially an artifact of the generally lower seston export in reference streams, particularly during low intensity storms. In general, most of the particulate organic matter transported during storms originates within streams; however, during low intensity storms substantial amounts of fine particulate organic material may be transferred from forest canopies to streams.

Conclusions

Seston concentration should be strongly correlated with stream power, i.e., the ability of a stream to do work (Bagnold 1966), and many studies have indicated a positive relationship between seston concentration and either stream power or stream discharge (Bormann et al. 1969, Fisher 1977, Fisher and Likens 1973, Meyer and Likens 1979, Webster 1983, Webster and Patten 1979). However, other studies have shown only weak correlation between seston concentration and stream power (Naiman 1982, Naiman and Sedell 1979, Sedell et al. 1978). In headwater streams, seston concentrations are hysteretic during storms, i.e., higher during the rising limb of storm hydrographs than during the descending limbs (Bilby and Likens 1979, Fisher and Likens 1973, Gurtz et al. 1980, Webster et al. 1983). Therefore power might best be considered a measure of potential transport in headwater streams. Actual transport is highly dependent instream factors such as particle availability and channel retentiveness (Bilby and Likens 1979, Fisher 1977, Naiman 1982).

Disturbance of forests by logging should greatly affect instream factors (particle availability, channel retentiveness) that influence seston transport during storms. Because allochthonous inputs decline following logging, and shift from slowly decaying leaf-species to

rapidly decaying ones (Webster et al. 1987), one would expect a decline in rates of particle generation immediately following logging followed by a gradual decline in particle availability. However, our own preliminary observations indicate that fine benthic organic matter levels are similar in the four streams, though slightly lower in Big Hurricane Branch and higher in Carpenter Branch compared to reference sites. Therefore, differences in transport that we observed during storms cannot be readily attributed to differences in particle availability alone. Channel retentiveness is greatly influenced by the presence of debris dams and organic matter accumulations in stream channels and a decline in the efficiency, number, and size of debris dams following logging has been well documented (Fisher and Likens 1973, Gurtz et al. 1980, Likens and Bilby 1982). At our study sites, disturbed streams have fewer organic matter accumulations and debris dams and higher average velocities than reference streams (Table 1). Observed increases in seston export probably resulted from reduced efficiency and number of retention structures in disturbed streams following logging.

Buffer strips, i.e., zones of undisturbed riparian vegetation, have been advocated as a means of maintaining stream water quality in logged areas. As a management tool they have been used primarily to reduce sediment movement from logging roads and disturbed soils to streams, and to maintain normal stream temperatures (e.g. Haupt and Kidd 1965, Trimble and Sartz 1957). More recent studies have demonstrated the effectiveness of buffer strips in maintaining salmonid fisheries (Burns 1972) and normal insect community structure in streams draining logged areas (Newbold et al. 1980). Streamside logging also causes longterm changes in the quality and quantity of allochthonous inputs to streams, which alter the energy base and also reduce the ability of streams to retain biologically important materials. Buffer strips, in addition to maintaining water quality, should reduce the longterm effects of logging by maintaining the predisturbance numbers of debris dams and organic matter accumulations in streams.

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Table 1. Physical and morphological features of the study sites.Values with parentheses are means and 95% (\pm) confidence intervals.

	Big Hurricane Branch	Hugh White Creek	Carpenter Branch	Grady Branch
Watershed #	7	14	13	18
Treatment	Disturbed	Reference	Disturbed	Reference
Area (ha)	58.7	61.1	16.1	12.5
Main Channel length (m)	1225	1125	604	345
Gradient (m/m)	0.19	0.15	0.19	0.20
Streambed Area (m ²)	3274	8085	1330	1116
Average Annual Discharge (L/sec) ¹	18.52 (1.85)	19.37 (1.45)	5.39 (0.32)	4.06 (0.31)
Organic Accumulations (# per 25-m reach)	1.12 (0.40)	2.66 (0.55)	1.94 (0.74)	5.14 (1.39)
Logs (# per 25-m reach)	2.60 (0.53)	2.34 (0.64)	0.65 (0.36)	2.29 (0.83)
Debris Dams (# per 25-m reach)	0.07 (0.08)	0.45 (0.21)	0.18 (0.20)	0.64 (0.54)
Roughness (Manning's n)	0.28 (0.08)	0.34 (0.10)	0.11 (0.04)	0.24 (0.10)
Average Velocity (m/sec)	0.13 (0.03)	0.08 (0.03)	0.19 (0.15)	0.06 (0.02)

¹Based on Forest Service Records

Table 2. Total rainfall and average intensity of storms.

Intensity was calculated by dividing total rainfall amount by the duration of a storm. Values represent averages of all sites.

Storm Date	Total Rainfall (cm)	Intensity (cm/hr)
15 Jun 84	0.50	0.15
20 Jun 84	1.57	1.05
10 Nov 84	3.27	0.55
4 Dec 84	4.04	0.23
11 Feb 85	6.30	0.48
21 Mar 85	2.10	0.06
1 May 85	1.24	0.08
7 May 85	4.19	0.10

Table 3. Flow weighted seston concentrations during storms.

Values are mg/L.

Date	Big Hurricane Branch	Hugh White Creek	Carpenter Branch	Grady Branch
	Disturbed	Reference	Disturbed	Reference
15 Jun 84	8.33	7.46	8.67	3.95
20 Jun 84	40.72	10.21	24.55	15.82
10 Nov 84	17.85	30.79	12.53	18.83
4 Dec 84	4.60	3.35	2.55	2.79
11 Feb 85	6.57	2.82	4.13	3.09
21 Mar 85	3.36	2.44	4.45	2.55
1 May 85	4.74	3.10	6.85	2.90
7 May 85	5.67	4.32	6.52	4.12

Table 4. Seston concentration versus change in discharge during increasing flows.

Values are coefficients of determination (r^2) (* indicates $\beta > 0$, $P < 0.05$).

	ΔQ interval		
	5 min	15 min	60 min
Big Hurricane Branch-Disturbed			
20 Jun 84	0.88*	0.98*	0.97*
10 Nov 84	0.57*	0.67*	0.86*
4 Dec 84	0.62*	0.70*	0.84*
11 Feb 85	0.42	0.50*	0.66*
21 Mar 85	0.16	0.20	0.13
7 May 85	0.17	0.10	0.24
Hugh White Creek-Reference			
20 Jun 84	0.82*	0.86*	0.40
10 Jun 84	0.71*	0.62*	0.43*
4 Dec 84	0.18	0.22	0.65*
11 Feb 85	0.57*	0.56*	0.86*
21 Mar 85	0.60*	0.68*	0.90*
7 May 85	0.25	0.32	0.59*
Carpenter Branch-Disturbed			
20 Jun 84	0.78*	0.77*	0.81*
10 Nov 84	0.76*	0.62*	0.61*
4 Dec 84	0.21	0.73*	0.83*
11 Feb 85	0.94*	0.94*	0.79*
21 Mar 85	0.83*	0.06	0.60*
7 May 85	0.35	0.85*	0.83*
Grady Branch-Reference			
20 Jun 84	0.85*	0.63	0.24
10 Nov 84	0.10	0.14	0.36*
4 Dec 84	0.35*	0.49*	0.85*
11 Feb 85	0.87*	0.52	0.68*
21 Mar 85	0.23	0.31	0.79*
7 May 85	0.27	0.41*	0.63*

Table 5. Regressions of seston concentration and ΔQ for storms combined by season.

Values are slope as mg/L per increase in Q per interval, with n, r^2 in parentheses. All regressions are significant ($P < 0.05$), * indicates slopes are significantly different (analysis of covariance, $P < 0.05$).

	<u>mg/L per ΔQ per interval</u>			<u>mg/L per Δ per interval</u>		
	BHB	HWC	comparison of slopes	CB	GB	comparison of slopes
Winter						
5 min	5.07 (17, 0.42)	2.19 (20, 0.43)	N.S.	29.68 (14, 0.83)	6.68 (12, 0.38)	*
15 min	2.84 (23, 0.42)	0.94 (21, 0.51)	*	8.37 (18, 0.91)	3.82 (17, 0.35)	*
60 min	1.60 (24, 0.68)	0.46 (22, 0.85)	*	4.29 (18, 0.84)	1.51 (12, 0.38)	*
Summer						
5 min	25.14 (31, 0.84)	21.12 (37, 0.65)	N.S.	98.06 (30, 0.75)	55.26 (28, 0.47)	*
15 min	9.71 (36, 0.92)	6.99 (45, 0.66)	*	37.40 (33, 0.61)	20.60 (34, 0.49)	*
60 min	5.03 (48, 0.92)	2.06 (52, 0.62)	*	9.70 (40, 0.63)	8.60 (38, 0.31)	N.S.

Table 6. Throughfall contributions to streams.

Values are amounts (g AFDW/m² of stream area) entering streams during storms and percent of total organic export that could be attributed to throughfall.

	<u>BHB-(Dist.)</u>		<u>HWC-(Ref.)</u>		<u>CB-(Dist.)</u>		<u>GB-(Ref.)</u>	
	input	% of export	input	% of export	input	% of export	input	% of export
15 Jun 84	0.05	1.19	0.04	7.02	0.09	6.52	0.04	8.51
20 Jun 84	0.38	2.70	0.16	21.92	0.20	8.13	0.26	16.77
10 Nov 84	0.24	2.64	0.24	4.70	0.37	12.89	0.39	11.17
4 Dec 84	0.09	1.32	0.12	8.05	0.17	9.60	0.17	10.97
11 Feb 85	0.23	1.04	0.42	19.91	0.32	5.27	0.29	7.53
21 Mar 85	0.11	1.87	0.21	21.88	0.14	4.65	0.19	13.29
1 May 85	0.35	11.25	0.43	82.69	0.38	20.43	0.52	72.22
7 May 85	0.35	4.40	0.58	35.80	0.32	8.63	0.76	34.08

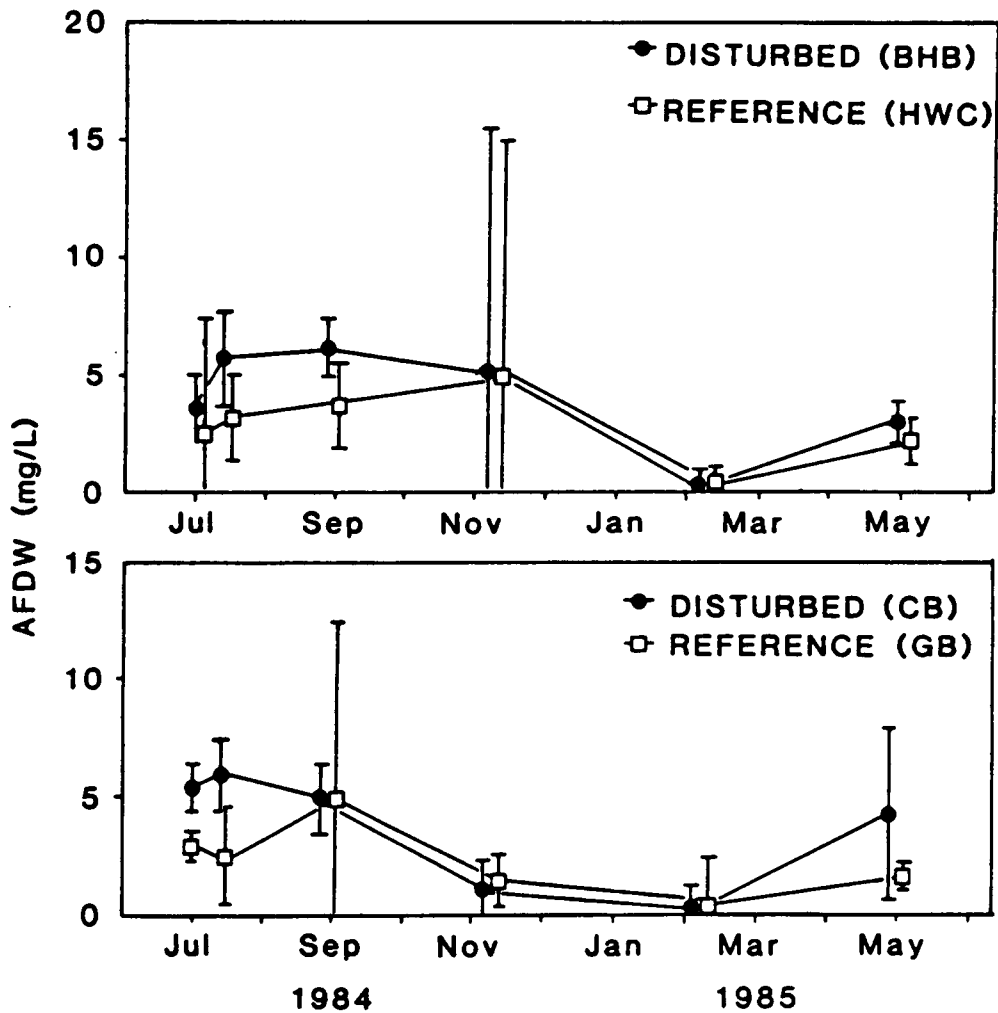


Figure 1. Baseflow seston concentrations in Coweeta streams: Values (mg AFDW/L) are means and 95 % confidence intervals; filled circles represent disturbed streams, open squares represent reference streams.

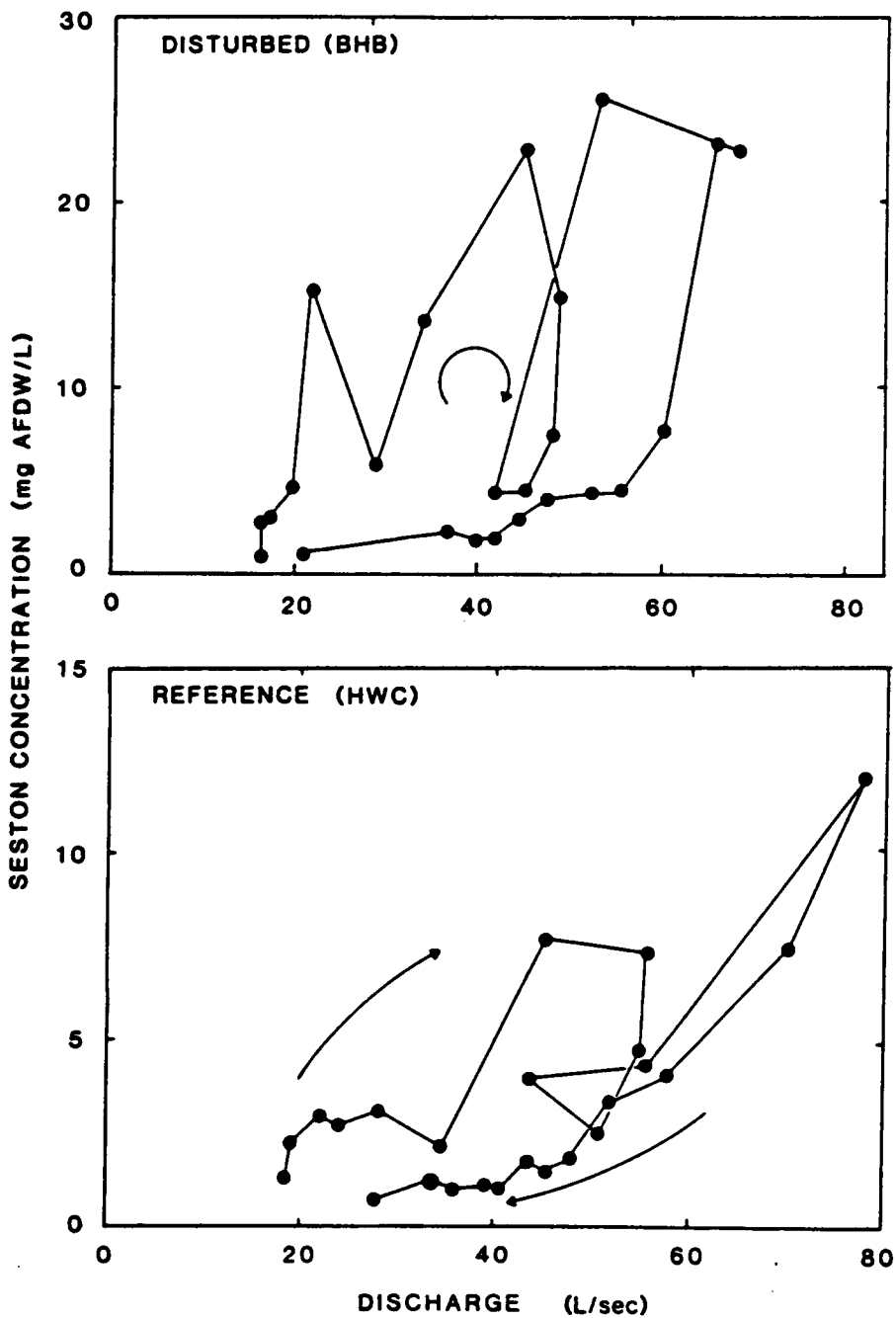


Figure 2. Seston concentration versus discharge during a storm: This storm was sampled 11 February 1985. Arrows indicate the sequence of samples over the course of the storm; note difference in scale for the AFDW axes.

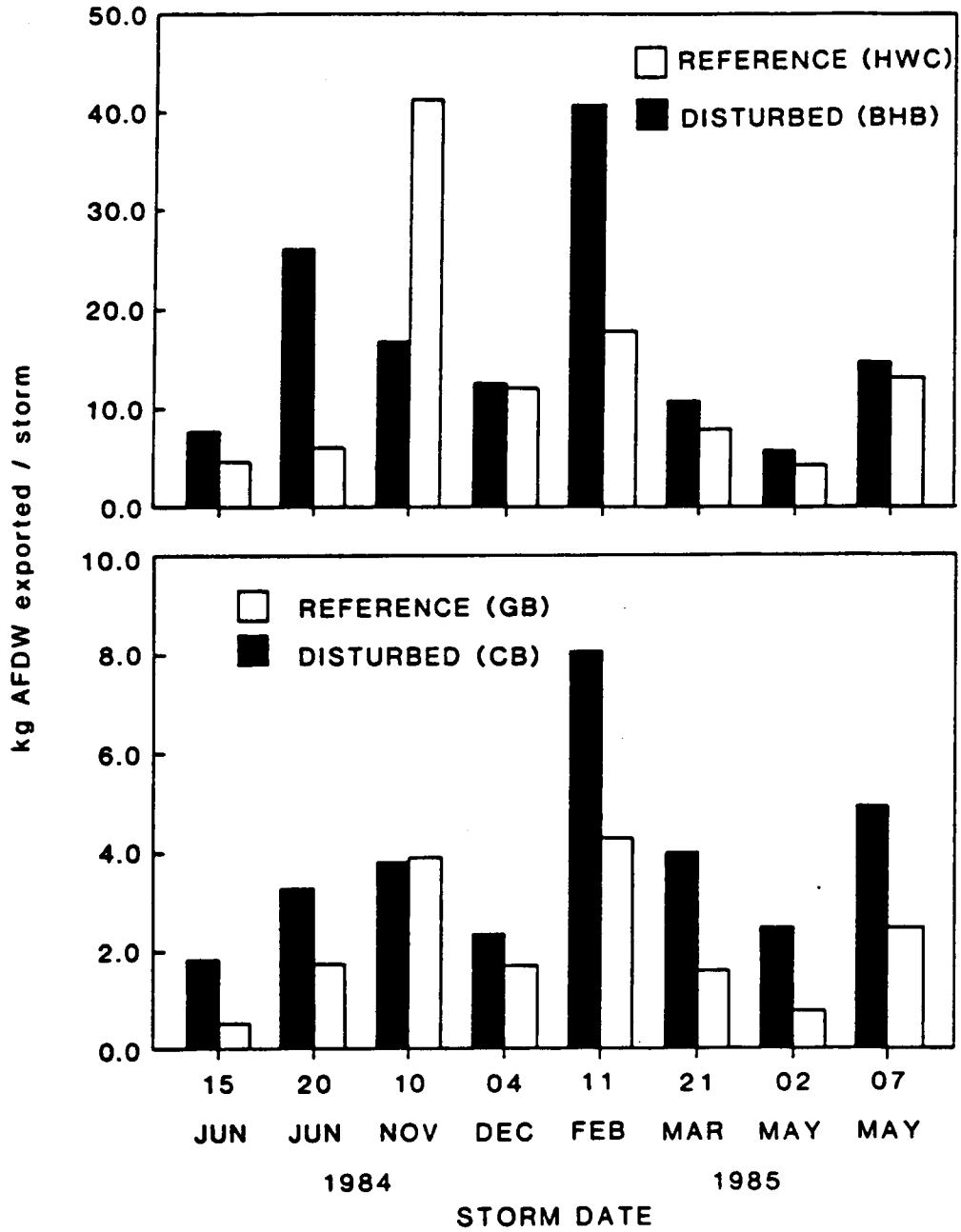


Figure 3. Seston exported from Coweeta streams during storms: Filled bars represent disturbed streams, open bars represent reference streams; note difference in scale for the export axes.

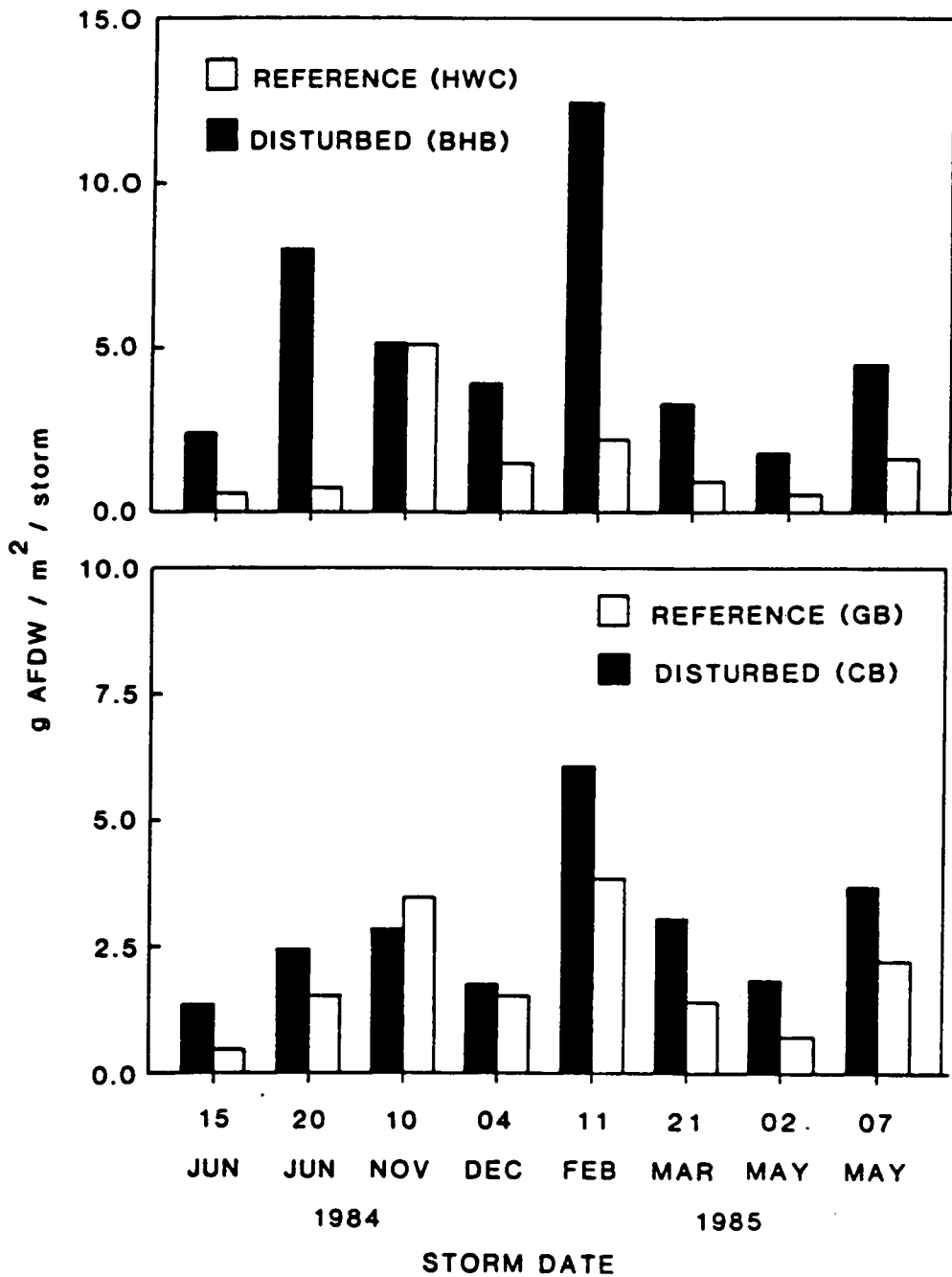


Figure 4. Seston exported from Coweeta streams during storms: Filled bars represent disturbed streams, open bars represent reference streams; note difference in scale for the export axes.

Chapter 2--Benthic Organic Matter

CHANGES IN STREAM BENTHIC ORGANIC MATTER FOLLOWING WATERSHED DISTURBANCE.

Introduction

Low-order temperate forest streams are closely linked to the areas they drain (Hynes 1975, Vannote et al. 1980), and the role of allochthonous organic matter as an energy base for these streams has been well documented (e.g. Nelson and Scott 1962, Minshall 1967, Kaushik and Hynes 1971, Petersen and Cummins 1974). Leaves and wood that accumulate in stream channels are also important habitats for stream biota, decrease stream power and erosiveness, and act as sites of nutrient uptake (e.g. Heede 1972, Swanson et al. 1976, Bilby 1981). The close linkage between streams and their watersheds means that watershed disturbances have profound effects on streams. The purpose of this investigation was to examine the longterm effects of watershed disturbance on stream benthic organic matter abundance.

Forest disturbance may affect stream ecosystems in several ways. Removal of terrestrial vegetation reduces allochthonous inputs (Webster and Waide 1982), but autochthonous production may increase due to the absence of shading and increased nutrient concentrations (e.g. Hains 1981). Stream biota may respond to these changes by switching diet or preferred habitat (e.g. Rounick et al. 1982). Studies at Coweeta Hydrologic Laboratory have shown that stream invertebrate communities are capable of rapid response to disturbance. Forest logging has had little impact on the abundance of invertebrates in Big Hurricane Branch, a second-order stream, even though the dominant shredder was nearly eliminated (Webster et al. 1983, Gurtz and Wallace 1984). Invertebrates shifted habitat, moving from cobble and pebble riffles to moss-covered rock face. Moss-covered rock face appears to be an attractive substrate following disturbance because it provides shelter from scour, traps drifting organic particles, and has relatively high algal densities (Gurtz and Wallace 1984). In general, moss habitat appears to be a site of physical and metabolic stability in streams draining recently logged areas.

Woody debris may also buffer the effects of forest disturbance on stream ecosystems. Gurtz and Wallace (1984) reported that wood became more abundant in Big Hurricane Branch following logging. Golladay and Webster (in press) found that stick breakdown rates were accelerated and invertebrate densities (especially chironomids, collectors, predators, and Lype sp. -a wood inhabiting caddisfly) were high on small woody debris in Big Hurricane Branch following logging. Wood decomposition rates are generally an order of magnitude or more slower than leaf litter, and wood is generally considered to be a low quality food resource. However, its resistance to decay means wood is available for colonization by stream consumers for many years following disturbance.

Taken together these studies demonstrate how stream biota respond to forest disturbance. The adaptability of the biota (either by switching habitat or food source) maintains invertebrate densities and functional group structure, and the persistence of moss habitat and woody debris dating from before disturbance minimizes the effects of watershed disturbance on stream ecosystems. Leaf packs added to Big Hurricane Branch after clear cutting were

rapidly processed by stream consumers (e.g., Webster and Waide 1982) illustrating that ecosystem function, i.e. leaf processing, was preserved despite severe watershed disturbance.

Forest ecosystem structure and function are internally generated by the growth of forest vegetation. Cutting or burning represents a short term disturbance to forests because the forest is free to undergo succession or recovery in the absence of further disturbance. However, imported organic matter is an important functional and structural element of stream ecosystems. Thus stream disturbance begins with forest cutting or burning and continues until the predisturbance patterns of vegetation are reestablished on the watershed (e.g. Webster and Swank 1985), a process that may take 100-400 years depending on the mature forest type of the region (Likens and Bilby 1982, Swanson and Lienkaemper 1978). Disintegration of debris dams in streams occurs rapidly following watershed logging (Likens et al. 1970, Fisher and Likens 1973). Small twigs and leaves, which form the internal matrix of debris dams, decay relatively rapidly, and since allochthonous inputs are low, the matrix is not replaced. Increased invertebrate colonization may accelerate this process. Even though large wood may remain, breakdown of debris dam matrices may account for increased organic matter transport observed following logging (Gurtz et al. 1980, Hobbie and Likens 1973, Webster and Golladay 1984). Large woody debris also gradually decays and is not replaced. Declines in the amount of large woody debris and reduced numbers of debris dams have been observed in streams draining logged watersheds (Likens and Bilby 1982, Swanson and Lienkaemper 1978, Golladay et al. 1987). For streams, loss of woody debris during forest recovery causes the gradual decline of an ecosystem property, i.e. the ability to resist downstream export of material. The result is most pronounced during storms or seasons of high discharge. Thus, forest disturbance ultimately reduces the ability of streams to resist shorter term natural disturbances. In this investigation, the effects of forest disturbance on the abundance of organic matter in streams were examined by measuring standing stocks of woody debris and leaf litter in streams draining clearcut, old-field, intermediate successional, and reference watersheds.

Site Description

This work was conducted at Coweeta Hydrologic Laboratory, Macon County, North Carolina, USA. Five sites were selected for study, three streams draining disturbed watersheds and two streams draining reference watersheds. Big Hurricane Branch (BHB) drains Watershed-(WS)-7, a 58.7-ha experimental watershed, which was grazed by cattle from 1941-1952 and cable logged during the winter of 1976-1977. Regrowth is dominated by hardwood sprouts, herbs, vines, and seedlings (Boring et al. 1981). Carpenter Branch (CB) drains WS-13, a 16.1-ha experimental watershed. Originally mixed hardwoods, all trees and shrubs were cut in 1939-1940 and again in 1962 (Swank and Douglass 1977). The watershed is presently covered by an intermediate successional hardwood forest dominated by yellow poplar (*Liriodendron tulipifera*) at lower elevations and mixed oaks (*Quercus spp.*) at higher elevations (Leopold and Parker 1985). Sawmill Branch (SB) drains WS-6, an 8.9-ha experimental watershed. In 1942 the riparian vegetation was removed from the streamside (12% of watershed area). In 1958 all marketable timber was removed from the watershed and the slash was burned. The watershed was fertilized, limed, and seeded with grass in 1959. Herbicides were applied from 1960-1965 to inhibit the growth of broadleaf vegetation. WS-6 was fertilized again in 1965, and from 1966-1968 all vegetation was killed by herbicide treatment (Johnson and Swank 1973). Finally in 1968 the watershed was permitted to begin natural succession and today it is an old-field, with primarily black locust (*Robinia pseudoacacia*) at the lower elevations and yellow poplar (*L. tulipifera*) at higher elevation sites. Hugh White Creek (HWC) drains WS-14, a 61.1-ha watershed and Grady Branch (GB) drains WS-18, a 12.5-ha watershed. Watersheds 14 and 18 are mixed hardwood forests and are longterm reference watersheds at Coweeta (Swank and Douglass 1977). Both sites were selectively logged prior to 1925 and except for the chestnut blight have been undisturbed for 60 years. Further characteristics of the study sites are presented in Table 7.

Methods

Benthic organic matter was collected quarterly from the 5 streams. Samples were collected on 7-12 July 1985 (summer), 21-26 November 1985 (autumn), 13-18 February 1986 (winter), and 25-29 April 1986 (spring). Hugh White Creek and Big Hurricane Branch were divided into 20 equal segments. The smaller streams, Grady Branch, Carpenter Branch, and Sawmill Branch, were divided into 10 segments. On each date a randomly selected transect within each segment was sampled for benthic organic matter using a 0.071-m² circular sampler. Individual transects were sampled only once. Samples were taken at 1/4, 1/2, and 3/4 of the distance across the channel at each transect. With sampler in place the substrate was stirred to a depth of 10 cm if possible. The resultant slurry of organic matter and fine sediment was pumped with a bilge pump through a 1-mm mesh net into a 20-L bucket. Large organic material (i.e. leaves or sticks > 5 cm in diameter) was removed from the core by hand. This material and particles > 1 mm retained by the net (LBOM) were placed in paper bags and returned to the laboratory, dried, weighed, subsampled, ashed, and reweighed to determine organic content as ash free dry weight (AFDW). Material passing through the net (FBOM) was subsampled, returned to the laboratory, filtered (Gelman type A/E glass fiber filter) weighed, and ashed to determine organic content as AFDW.

During the summer of 1985, estimates of large (> 5 cm diameter) and small (< 5 cm diameter) woody debris were obtained for each stream. Small and large wood standing stocks were determined in randomly selected 1-meter wide cross sections. Cross sections were selected using a stratified random sampling regime, with one cross section sampled per stream segment. All wood debris < 5 cm in diameter was removed from each cross section and weighed wet. Subsamples were returned to the laboratory, air dried to a constant weight, ashed (550°, 40 min), and the residue weighed to determine organic content as ash free dry weight. The AFDW of the original sample was estimated by correcting for moisture and ash using the lab measurements. The AFDW of the original sample was then divided by the

transect area so fine wood standing stocks could be expressed on an areal basis (g AFDW / m² stream channel).

Large woody debris was handled in a similar manner. Small logs were weighed individually and subsampled, and AFDW determined as previously described. For logs too large to weigh, diameter and length were measured to determine volume. Subsamples were returned to the laboratory, dried, weighed, immersed in a graduated cylinder of water to determine volume, ashed, and the residue weighed to determine AFDW. The density of the subsample and the volume of the original log were used to estimate AFDW. The weights of all logs in a particular transect were summed, then divided by transect area to determine large wood standing stock on an areal basis.

Finally the main channel of each stream was surveyed for accumulations of organic matter. Three categories of organic matter were recognized: 1) organic matter accumulations—accumulations of leaves and sticks supported by rocks and boulders, with no wood > 5-cm diameter, 2) logs—wood alone, with an average diameter > 5-cm diameter, 3) debris dams— sticks and leaves aggregated with supporting logs > 5-cm in diameter. Only accumulations that clearly affected stream morphology, i.e. created pools or stairstep patterns of flow, were included in the survey.

Unless otherwise noted, all statistical comparisons of sites were made using analysis of variance followed by multiple comparisons of means with a protected alpha level of 0.05.

Results and Discussion

Average Annual Benthic Organic Matter Levels

Mean annual LBOM averaged over the four sampling dates ranged from 124.24 to 255.21 g AFDW / m² (Table 8). Grady Branch (reference), Hugh White Creek (reference), and Carpenter Branch (intermediate successional) had significantly more LBOM than Big Hurricane Branch (recently disturbed) or Sawmill Branch (old field).

FBOM averaged 112.79 to 386.62 g AFDW / m² (Table 8). Carpenter Branch had significantly higher fine benthic organic matter than any of the other streams. The standing stock of FBOM in Hugh White Creek was significantly higher than in Big Hurricane Branch; Grady Branch and Sawmill Branch had intermediate levels of FBOM.

Seasonal Pattern of LBOM Standing Stock

Reference streams (Grady Branch and Hugh White Creek) exhibited a distinct seasonal pattern of LBOM abundance (Figure 5). LBOM in autumn and spring was significantly higher than observed during summer. Winter LBOM levels were intermediate. Of the disturbed streams, Big Hurricane Branch had an annual distribution of LBOM similar to the reference streams. In Big Hurricane Branch, autumn LBOM standing stocks were significantly higher than those observed in spring or summer. Winter LBOM levels were intermediate. In the other two streams there were no significant seasonal differences in LBOM standing stocks.

Seasonal Pattern of FBOM Standing Stock

In the reference streams, FBOM levels were highest in spring samples and lowest in summer (Figure 6). In Grady Branch FBOM levels observed during summer were significantly lower than those observed during any other season, and there were no significant differences in FBOM standing stocks measured on the other dates. In Hugh White Creek, FBOM standing stocks in autumn and spring were significantly higher than summer levels, winter levels were intermediate. In the disturbed streams there was no consistent pattern of FBOM distribution. In Sawmill Branch there were no significant differences in FBOM levels over the year. In Big Hurricane Branch, autumn FBOM levels were significantly higher than those observed at any other date. The FBOM standing stocks measured in winter and spring were significantly higher than those collected during summer. In Carpenter Branch, FBOM levels were significantly greater in summer compared to other seasons.

Distribution of Woody Debris

Woody debris was unevenly distributed in Coweeta streams and the amount of wood sampled in transects within each stream varied over several orders of magnitude. Thus, nonparametric estimates and tests were used to compare amounts of woody debris in the streams. Arithmetic means and confidence intervals based on the t-statistic are presented for purposes of comparison with other studies and with nonparametric procedures. However, these estimates are biased by the asymmetrical distribution of the data (distribution is skewed toward high wood standing stocks).

Standing stocks of small wood debris ranged from 11.1 to 341.6 g AFDW / m² (Table 9, median values are based on the Hodges-Lehman procedure, e.g. Hollander and Wolfe 1973). Sawmill Branch (old-field) had significantly lower standing stocks of small woody debris than

the other streams (Kruskal-Wallis Test, followed by a protected Wilcoxon Rank-Sum LSD, $\alpha=0.05$). There were no significant differences in the amount of small wood among the other streams.

Standing stocks of large woody debris in Coweeta streams ranged from 0.0 to 3955.5 g AFDW / m² (Table 10, median values based on Hodges-Lehman procedure). The reference streams, Grady Branch and Hugh White Creek, had significantly greater amounts of large wood than both Carpenter Branch (intermediate successional) and Sawmill Branch (old-field) (Kruskal-Wallis Test, followed by a protected Wilcoxon Rank-Sum LSD, $\alpha=0.05$). Big Hurricane Branch (clearcut) had intermediate levels of large wood.

Percent Composition of Organic Matter Standing Stocks

In reference streams total organic matter averaged 3125.9 g AFDW/m² (HWC) and 4346.6 g AFDW/m² (GB). The dominant fraction in both streams was large woody debris (78.8% in HWC and 91.0% in GB) (Figure 7). In Big Hurricane Branch, which drains the most recent clearcut (1977), total organic matter standing stocks averaged 1820.0 g AFDW/m², with 68.2% as large woody debris. Streams draining the old-field and intermediate successional forest had substantially lower total organic matter standing stocks than the other sites, averaging 297.2 g AFDW/m² in Sawmill Branch and 976.7 g AFDW/m² in Carpenter Branch. Large wood constituted only 14.2% of total organic matter in Carpenter Branch (intermediate successional) and was essentially absent in Sawmill Branch (old-field); the dominant form of organic matter in these two streams was FBOM (0.45 μ m-1mm). In Big Hurricane Branch (recent clearcut) the dominant form of organic matter was large wood, however its importance (as percent composition and absolute amount) was lower than in the reference streams. These findings suggest that watershed disturbance has resulted in decreases in the amount of large woody debris in stream channels.

The predominance of large woody debris is not unique to Coweeta streams. Naiman and Sedell (1979a) reported that greater than 90% of total organic matter in first and third order Oregon Cascade Mountain streams was large woody debris (> 10 cm diam.). Estimates of large wood standing stock in Cascade streams range from 15 to 45 kg/m² (Keller and Swanson 1979, Naiman and Sedell 1979a, Swanson et al. 1982), considerably higher than observed in Coweeta streams.

Aggregation and Distribution of Benthic Organic Matter

Debris dams (sticks and leaves aggregated with logs > 5 cm diam.) are not common in first and second order Coweeta streams due to the rarity of streamflows of sufficient magnitude to move and consolidate large woody debris, thus, logs generally remain in position where they fall into the stream. The reference streams had significantly more debris dams than Big Hurricane Branch, the recently disturbed stream; Carpenter Branch had an intermediate number (Table 11). Organic matter accumulations (accumulations of leaves and sticks with no wood > 5 cm diam.) are the most common morphological features in undisturbed Coweeta streams. Grady Branch had significantly more organic matter accumulations than any other stream, Hugh White Creek had a greater number of organic matter accumulations than Big Hurricane Branch, and Carpenter Branch had an intermediate number.

Solitary logs (> 5 cm diam.) are also common in Coweeta streams. Carpenter Branch, the stream draining intermediate successional forest, had significantly fewer logs than the other streams. There was no significant difference in the average diameter (20-cm) of logs in a comparison of all streams. Sawmill Branch was not surveyed for distribution of organic debris in the present study. However, a similar survey conducted in 1983 revealed an average of 2.17 organic matter accumulations, 0.33 logs, and no debris dams per 25-m reach.

A regression analysis of benthic organic matter standing stock versus distance upstream from the weir ponding basin indicated that organic matter was evenly distributed over the re-

aches studied for all streams. The finding that organic matter standing stocks were not substantially greater near the headwaters of either disturbed or reference streams has several implications. First, instream processing for most LBOM probably occurs near the site of introduction. If transport of LBOM represented a significant loss from these streams, one would expect a depletion of LBOM at downstream sites, where average discharge is greatest. Second, FBOM losses are balanced by processes generating particles. Were this not the case, downstream sites which have greatest fluctuations in discharge, would have less FBOM. A similar analysis for small (1-5 cm diam) and large (> 5 cm diam) woody debris showed no consistent upstream changes over the reaches studied.

The distribution pattern of benthic organic matter in Coweeta streams was further examined using a regression analysis on data from Hugh White Creek, a reference stream. Stream gradient, measured over 5-meter reaches upstream from each BOM sampling site, and stream distance were independent variables included in the regression model in an attempt to account for the variation in BOM distribution over the length of Hugh White Creek. Gradient alone was not a reliable predictor of either FBOM or LBOM standing stocks. This is an interesting conclusion because one might expect high gradient (erosional) reaches to have lower BOM standing stocks than low gradient (depositional) areas. When combined with stream distance in multiple regression analyses, gradient contributed slightly as a factor explaining variation in BOM standing stocks. Generally, multiple regressions indicated that LBOM levels increased slightly towards the stream source and were somewhat lower in high gradient areas. However, gradient and stream distance accounted for at best only 25% of the variation between LBOM samples. Including gradient as a factor in regression analyses of FBOM samples did not decrease the amount of unexplained variation. This analysis demonstrates that the factors affecting distributions of organic matter in small streams are at best, poorly understood.

Comparison of Standing Stock with Inputs of Organic Matter

The analysis of organic matter distribution versus stream distance and gradient suggests that geomorphic and hydrologic factors do not appear to strongly influence the distribution of organic material in first and second order Coweeta streams. However, differences within and between streams do occur on an annual basis. Possible sources of variation in the distribution of LBOM and FBOM include differences in the rate of input, seasonal pattern of input, and chemical quality of litter input. Because much of the LPOM in low-order streams tends to remain and be processed at points of entry, canopy density combined with retention characteristics of very short reaches may determine LPOM standing stocks. Certainly the input of wood is determined by the presence of trees adjacent to streams and the occurrence of stochastic events (wind, fire, ice storms, bank cutting, and debris avalanches) that fell trees into stream channels (Keller and Swanson 1979).

The relationship between litter input and standing stock was examined by calculating the daily litter input rate during ten periods of the year using total litter inputs (litterfall + blow-in) collected in 1983-1984 from Big Hurricane Branch, Hugh White Creek, Grady Branch, and Sawmill Branch (Webster, unpublished). Litter input rates were then used to estimate total litter inputs to the streams. Measurements of litterfall (1985-1986) on WS-13 were used to estimate litter input to Carpenter Branch (L. Risley, unpublished data).

In all streams, largest litter inputs to the stream channels occurred between July and November, with most of the input concentrated between September and November (Table 12). Greatest litter inputs were observed in reference streams and greatest differences in input occurred during autumn leaffall. During the remainder of the year, rates of litter input were about the same in all streams although Grady Branch and Big Hurricane Branch received minor pulses during late spring (April-July). Estimates of LBOM turnover were obtained by dividing total litterfall by mean annual LBOM standing stock. In the reference streams the turnover rate was 2.3 y^{-1} for Hugh White Creek and 2.6 y^{-1} for Grady Branch. In Sawmill

Branch (old-field) and Big Hurricane Branch (recent clearcut) turnover rates were 3.4 y^{-1} and 3.5 y^{-1} , respectively. In Carpenter Branch (intermediate successional) the turnover rate was either 1.5 y^{-1} for litterfall alone or 1.8 y^{-1} when a correction was applied to estimate blow-in (average 19.9% of total input to the other streams).

Several conclusions can be drawn from these findings. Reference streams receive greater litter inputs and retain a greater proportion. Disturbed streams receive lower litter inputs and process a greater proportion. Since travel distances for leaf material in streams are relatively short (Dance et al. 1979, Speaker et al. 1984, Webster et al. 1987), the differences between reference and disturbed streams probably cannot be attributed to differences in downstream transport. However, litter is processed faster in disturbed streams because early successional vegetation, which dominates the litterfall in recently disturbed streams, decays faster than litter from mature forests (Webster and Benfield 1986, Webster et al. 1987). Also, decay rates of all litter types appear to be accelerated in Coweeta streams following logging (Webster and Waide 1982, Golladay and Webster in press). Carpenter Branch (intermediate successional) receives less litter from its watershed and maintains relatively high LBOM standing stocks, which result in relatively low turnover compared to reference streams.

FBOM standing stocks were strongly influenced by litter input and the presence of LBOM. In general, reference streams had higher levels of FBOM than disturbed streams. In Sawmill Branch and Big Hurricane Branch (disturbed streams), FBOM standing stocks were highest in November, following a period during which litter inputs and subsequent particle generation rates were at annual maxima (e.g. Webster 1983). During winter and spring, FBOM standing stocks declined in disturbed streams corresponding a period when particle generation rates are at annual minima (e.g. Webster 1983). Also, disturbed streams are less retentive than reference streams and lose larger amounts of fine organic material during storms (Golladay et al. 1987). Reduced retentiveness probably accounts for the gradual decline in FBOM observed during winter in disturbed streams when large long-duration storms combined with low particle generation rates resulted in depletion of FBOM accumulated during late summer and autumn. In the reference streams, standing stocks of FBOM remained

high from autumn through the spring reflecting the slower processing rate of litter from mature forests. Reference streams were also more retentive than disturbed streams and thus less susceptible to large losses of FBOM during storms.

Carpenter Branch had anomalously high levels of FBOM and did not exhibit strong seasonal variation in FBOM standing stocks. The reasons are uncertain, however, WS-13 was once the site of a homestead (W.T. Swank personal communication). Sections of Carpenter Branch are deeply incised with steep dirt banks and fine sediment substrata typical of a pastureland stream. Also the middle portion (200-300 meters) of the stream is relatively low gradient. Perhaps the high FBOM levels are artifacts of soil erosion resulting from homesteading and unusual streambed morphology.

Changes in stream organic matter abundance following watershed disturbance

In many streams, distinct seasonal patterns of organic matter abundance can be linked to patterns of organic matter input from surrounding vegetation. LBOM standing stocks are highest in late autumn following the period of highest annual litterfall (e.g. Naiman and Sedell 1979a, Wakefield et al. 1980, Short and Ward 1981, Iversen et al. 1982, Minshall et al. 1982, Barlocher 1983). LBOM gradually declines throughout the rest of the year as coarse organic matter is processed into smaller particles. Generally, LPOM losses from streams are minimal and FPOM dominates the downstream transport of organic matter (e.g. Naiman and Sedell 1979b, Iversen et al. 1982). Annual rates of FPOM loss from streams are determined by patterns of litter input, rates of litter processing, retentiveness of stream channels, and annual hydrographs. In many areas substantial snowpack develops during winter, streams ice over, and discharge remains relatively constant (e.g. Likens et al. 1967). Under such conditions FBOM standing stocks may increase (Short and Ward 1981). With spring snowmelt,

streamflows increase and substantial scouring and downstream transport may occur, reducing FBOM standing stocks (Fisher and Likens 1973, Naiman and Sedell 1979b, Short and Ward 1981, Minshall et al. 1982). Extensive snowpacks seldom develop in the southern Appalachian Mountains, and streams at Coweeta are subject to scouring during large, relatively long duration storms occurring from late autumn through early spring. Resistance to downstream transport of material during the annual period of scouring is determined by the size and frequency of retention structures in stream channels. Even small debris dams and organic accumulations retain material during low flows, however, at some discharge any debris dam will erode, releasing material into the water column (Heede 1972, Fisher and Likens 1973).

Forest logging has decreased the resistance of Coweeta streams to organic matter export in several ways. The gradual decline in wood standing stocks following logging has resulted in a decrease in the size and frequency of retention structures in disturbed streams. Small infrequent retention structures are not efficient at retaining material during storms. The altered chemical quality of litter following forest logging has resulted in faster processing of litter and conversion of coarse to fine material earlier in the season. Increased processing combined with reduced litter inputs means that proportionally more organic material is in a readily transportable form, and less material is available to be incorporated into retention structures just prior to the season when export of organic matter is most likely to occur.

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Table 7. Physical characteristics of the study sites.

	Big Hurricane Branch	Sawmill Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Watershed #	7	6	13	14	18
Treatment	Clearcut	Old-field	Intermediate Successional	Reference	Reference
Area (ha)	58.7	8.9	16.1	61.1	12.5
Main Channel length (m)	1225	370	604	1125	345
Gradient (m/m)	0.19	0.24	0.19	0.15	0.20
Streambed Area (m ²)	3274	277	1330	8085	1116
Average Annual Discharge (L/sec) ¹	18.52	2.65	5.39	19.37	4.06

¹Based on Forest Service Records

Table 8. Fine and large benthic organic matter in Coweeta streams.

Values are means (g AFDW/m²) and in parentheses \pm 95% confidence limits and sample sizes.

	FBOM Annual Mean	LBOM Annual Mean
<u>Disturbed Streams</u>		
Sawmill Branch	157.0 (37.5,120)	129.1 (17.6,120)
Big Hurricane Branch	112.8 (15.0,240)	124.2 (18.5,239)
Carpenter Branch	386.6 (57.7,120)	255.2 (30.7,120)
<u>Reference Streams</u>		
Hugh White Creek	165.8 (20.0,240)	213.0 (23.5,240)
Grady Branch	147.1 (19.7,120)	244.0 (29.5,120)

Table 9. Estimates and confidence intervals for small woody debris in Coweeta streams.

Estimates were obtained using arithmetic means and confidence limits (95%) based on the t-statistic and nonparametrically using the Hodges-Lehman procedure. Values are g AFDW/m² of stream channel.

Site	Parametric mean	Parametric C.L.	Non-parametric median	Non-parametric C.L.	n	range
<u>Disturbed</u>						
Sawmill Branch	78.5	(0.0,228.9)	11.1	(1.1,337.5)	10	(0-674.9)
Big Hurricane Branch	383.2	(238.0,528.4)	341.6	(212.6,540.2)	20	(0-1080.4)
Carpenter Branch	261.4	(81.6,441.3)	196.5	(121.1,486.0)	10	(61.2-910.7)
<u>Reference</u>						
Hugh White Creek	311.8	(172.7,450.9)	284.4	(132.6,451.9)	20	(0-1048.2)
Grady Branch	300.0	(168.5,431.4)	270.3	(182.2,447.5)	10	(94.4-733.9)

Table 10. Estimates and confidence intervals for large woody debris in Coweeta streams.

Estimates were obtained using arithmetic means and confidence limits (95%) based on the t-statistic and nonparametrically using the Hodges-Lehman procedure. Values are g AFDW/m² of stream channel.

Site	Parametric mean	Parametric C.L.	Non-parametric median	Non-parametric C.L.	n	range
<u>Disturbed</u>						
Sawmill Branch	1457.4	(0.0,4608.0)	0.0	(0.0,6990.9)	10	(0-13,981)
Big Hurricane Branch	2832.9	(515.1,5150.7)	1241.4	(338.6,4144.8)	20	(0-20,370)
Carpenter Branch	231.6	(0.0,505.8)	138.4	(0.0,592.7)	10	(0-1,185)
<u>Reference</u>						
Hugh White Creek	5134.1	(930.3,9337.9)	2462.1	(184.3,7529.5)	20	(0-34,500)
Grady Branch	4577.9	(0.0,9209.3)	3955.5	(118.6,8279.6)	10	(0-15,527)

Table 11. Distribution of organic debris in Coweeta streams.

Values are means \pm 95% confidence limits.

	Disturbed			Reference	
	Big Hurricane Branch	Sawmill ¹ Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Organic Accumulations (# per 25 m)	1.1 (0.4)	2.2 (0.9)	1.9 (0.7)	2.7 (0.6)	5.1 (1.4)
Debris Dams (# per 25 m)	0.1 (0.1)	0.0 (0.0)	0.2 (0.2)	0.4 (0.2)	0.6 (0.5)
Logs (# per 25 m)	2.6 (0.5)	0.3 (0.5)	0.6 (0.4)	2.3 (0.6)	2.3 (0.8)
Log diameter (cm)	20.7 (2.1)	-	20.4 (13.5)	22.6 (2.4)	19.2 (3.0)

¹Data originally collected for 10 meter reaches, then converted to 25 meter reaches.

Table 12. Litter input to Coweeta streams.

Values are estimates (g AFDW/m² stream) for the 3 month interval preceeding the date. Rates of litter input were obtained from collections made in 1983-1984 and include litterfall and blow-in (Webster unpublished). Inputs to Carpenter Branch were estimates obtained during 1985-1986 and represent litterfall only (Risley unpublished).

	July 1985	November 1985	February 1986	April 1986	Total
<u>Disturbed Streams</u>					
Sawmill Branch	27.0	331.5	42.3	37.4	438.2
Big Hurricane Branch	57.4	310.8	41.3	26.6	436.1
Carpenter ¹ Branch	26.3	316.3	21.1	19.0	382.5
<u>Reference Streams</u>					
Hugh White Creek	35.8	388.9	36.2	30.5	491.4
Grady Branch	51.5	464.9	65.2	44.1	625.7

¹ Blow-in (ave. 19.9% of total input in other streams) not included.

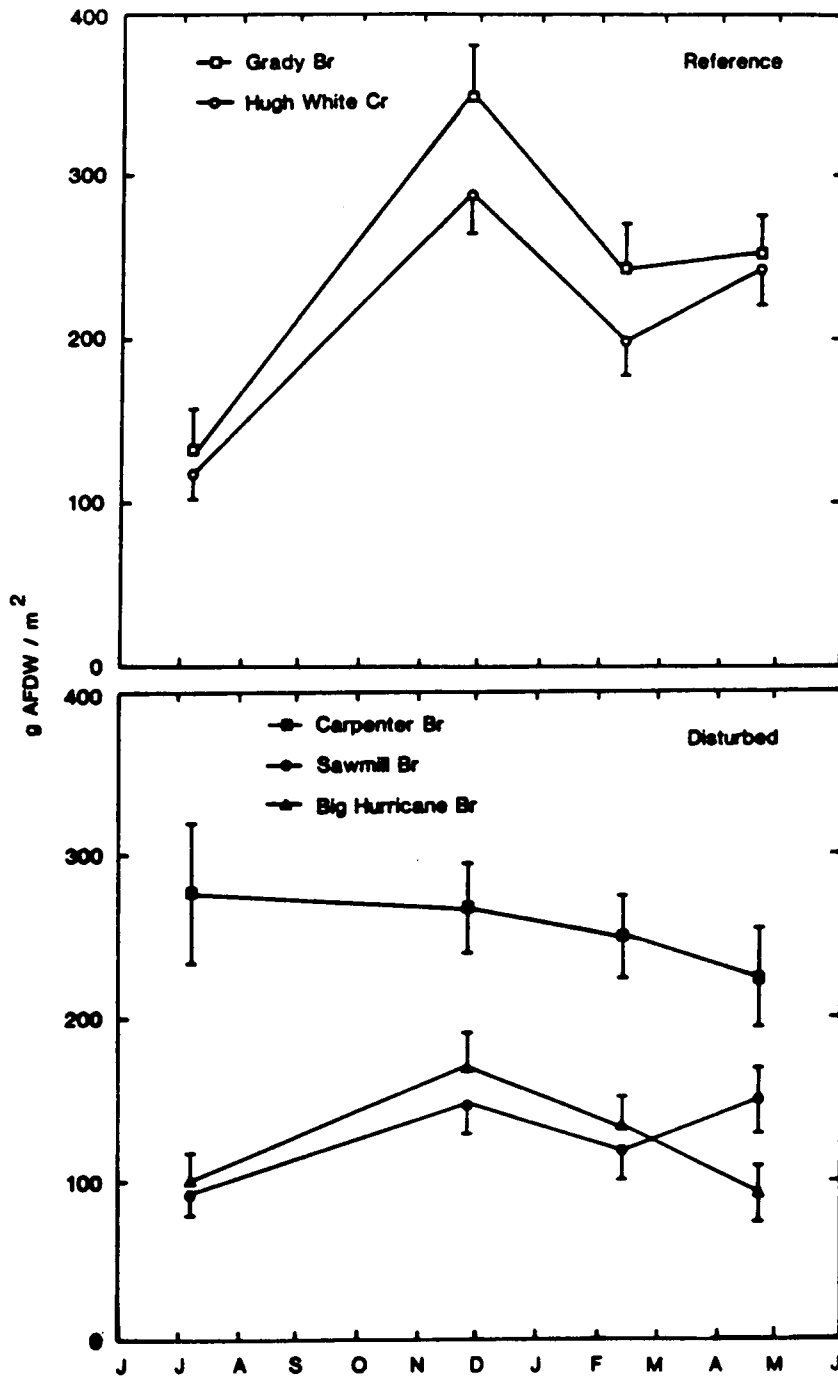


Figure 5. Large benthic organic matter in Coweeta streams: Values are means (g AFDW/m²) and standard errors.

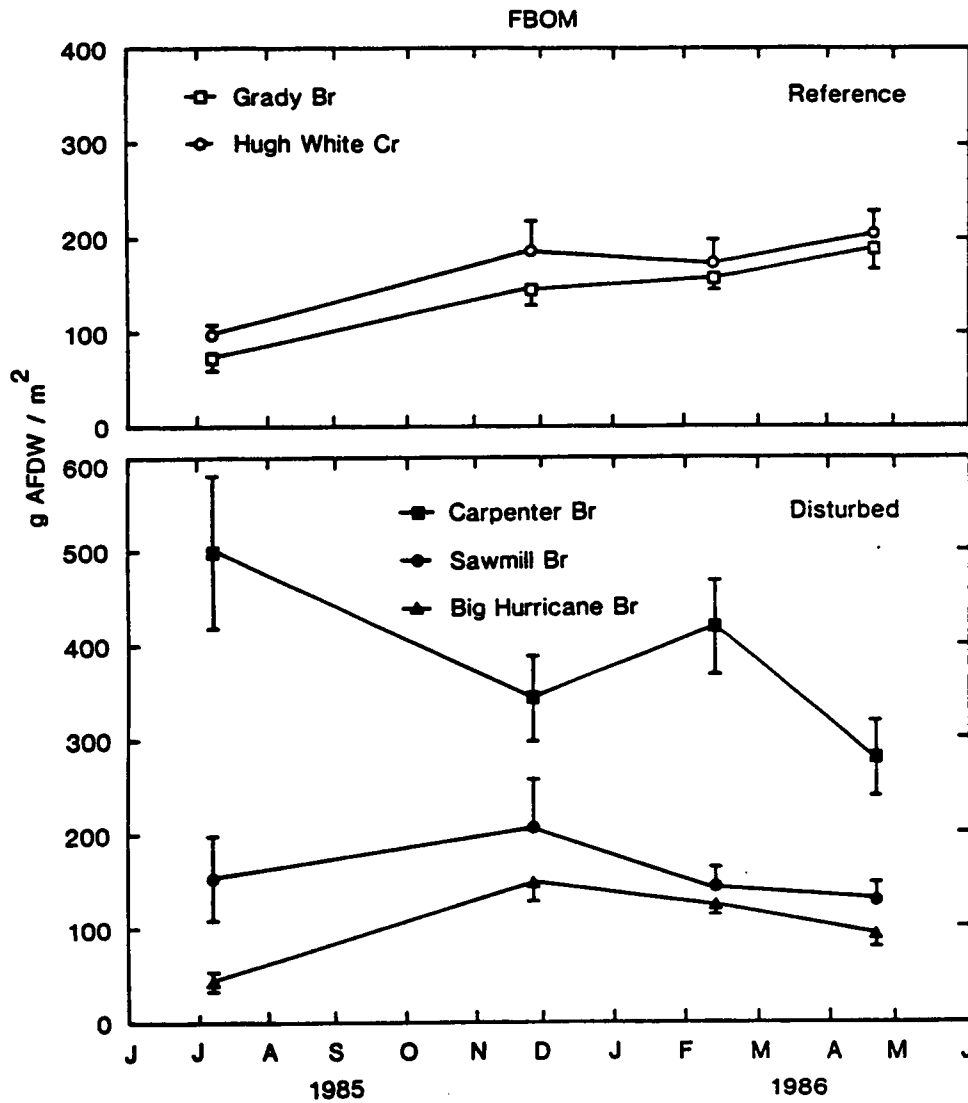


Figure 6. Fine benthic organic matter in Coweeta streams: Values are means (g AFDW/m²) and standard errors.

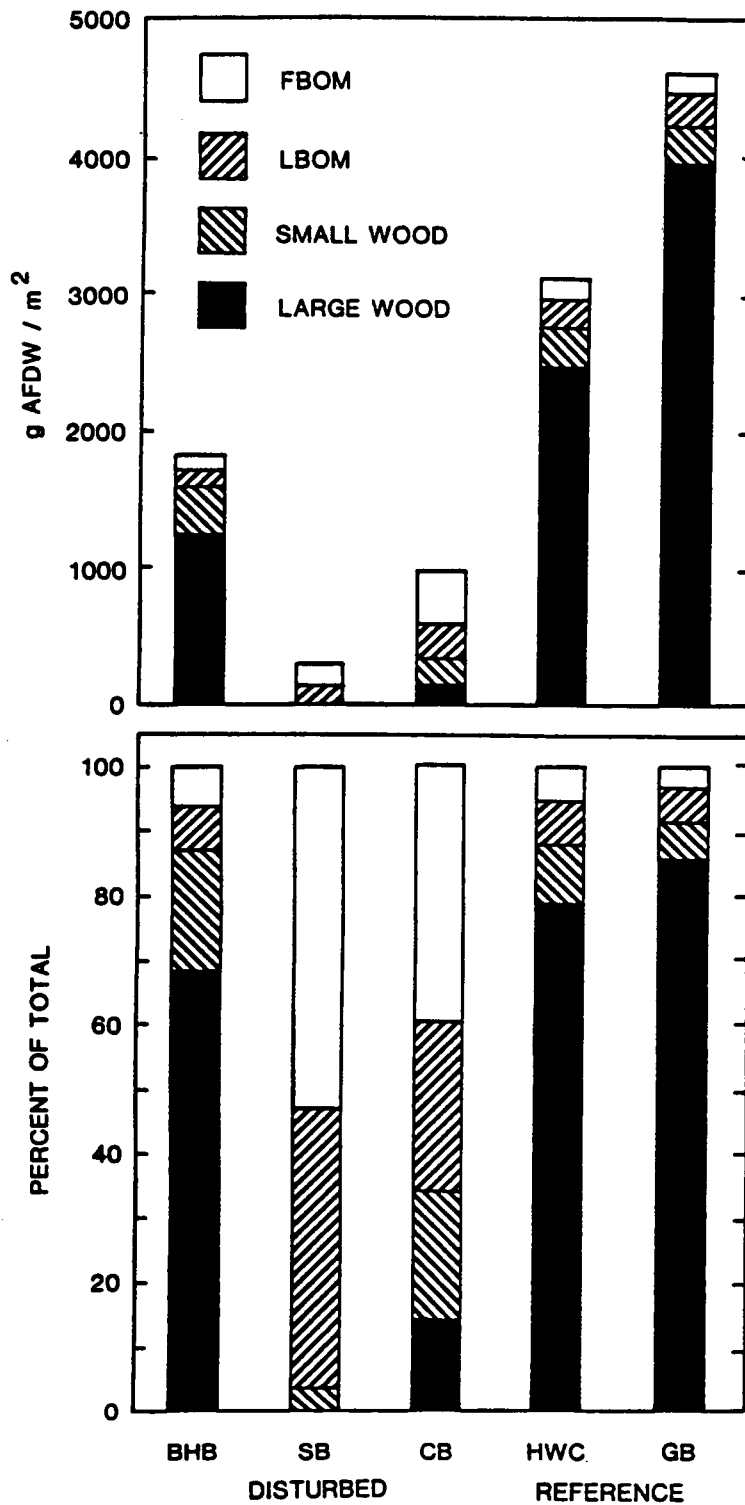


Figure 7. Composition of organic matter in Coweeta streams: Nonparametric estimates of wood standing stocks were used in calculations, but other values are means.

Chapter 3--Stream Ecosystem Stability

EFFECTS OF FOREST DISTURBANCE ON STREAM ECOSYSTEM STABILITY

Introduction

The responses of ecological systems to disturbance have been used to describe their ecological stability. Ecological stability has been defined in a variety of ways-- original studies defined stability as the persistence of identifiable communities through time (MacArthur 1955, Preston 1969) or the tendency of biological communities to return to their original state following disturbance (Margalef 1968, May 1973). More recent studies have linked stability to functional properties of ecosystems (e.g. energy flow, nutrient cycles) and defined stability as the tendency for ecosystems to return to original patterns of energy flow and nutrient cycling following disturbance (Webster et al. 1975, O'Neill 1976, Van Voris et al. 1980).

Webster et al. (1975) identified two components of functional stability which they referred to as resistance and resilience. Ecosystem resistance can be thought of as inertia, opposition to disturbance or displacement, or the magnitude of disturbance tolerated without degradation

of functional integrity (Waide 1987). Resistance is often linked to accumulated structure (e.g. biomass or pools of detritus). Resilience is the tendency of ecosystems to return to a reference state following displacement and is often linked to turnover rates of ecosystem components (Webster et al. 1975, O'Neill 1976). Resistance and resilience have been viewed as working in opposition, for characteristics that favor the accumulation of structure generally do not favor rapid turnover. Ecosystem characteristics are strongly influenced by the physical environment, and attempts have been made to classify ecosystems as either resilient or resistant based on interaction between ecosystem properties and environmental variability (Webster et al. 1975, O'Neill 1976). However, in a recent revision of functional stability concepts, Waide (1987) expressed the need for caution in classifying ecosystems as either resistant or resilient based on functional responses to exogenous disturbance. Since the degree of displacement and rate of recovery are determined by specific characteristics of a given system, responses to disturbance may be more a reflection of the scale at which ecosystem components operate than a measure of intrinsic differences in ecosystems. Waide (1987) suggested that a more useful application of functional stability may be to identify properties within an ecosystem that tend to resist potential disturbances and properties that will tend to restore ecosystem function following disturbance.

The effects of forest disturbance on watershed ecosystems have been intensively studied. Most of the studies treated streams and forests as integrated units (e.g. Likens et al. 1970, Bormann et al. 1974, Johnson and Swank 1973). While there is no question that streams and the areas they drain are closely linked, the study of unit-watersheds has resulted in the perception of streams as conduits and perhaps obscured unique properties of stream ecosystems. In this investigation streams and forests have been viewed as closely linked but independent ecosystems, and I have attempted to apply the concept of functional stability to evaluate the effects of forest disturbance on stream ecosystems.

The ability of forests to respond to disturbance (i.e. their stability) is linked to two primary components, living forest vegetation and dead organic matter stored in forest soils (Bormann et al. 1969, Vitousek and Reiners 1975). Vegetation is an important regulator of the

physical environment and nutrient cycling in forest soils (Bormann et al. 1969). Removal of forest vegetation results in decreased transpiration, increased soil temperature, and increased soil moisture, conditions that generally favor mineralization of stored soil organic matter (Bormann et al. 1969, Bormann et al. 1974). Decreased vegetative uptake in combination with increased mineralization rates often results in relatively open nutrient cycles and high rates of nutrient loss from forests following disturbance (Likens et al. 1970, Brown et al. 1973, Bormann et al. 1974, Neary 1977, Swank 1987). However, as vegetation regenerates, forest soil nutrient cycles return to predisturbance conditions within a few years of disturbance (Marks and Bormann 1972, Boring et al. 1981, Boring and Swank 1984). Soil organic matter, particularly the litter layer, is an important regulator of erodability in forest soils (Bormann et al. 1969). Accumulated litter protects soil from the erosive energy of raindrops, promotes soil particle adhesion, and encourages rainwater percolation instead of overland flow (Bormann et al. 1969). Dead organic matter is the primary factor minimizing erosion and loss of particulate material from forest soils following forest disturbance. In addition, soil organic matter acts as a longterm nutrient reservoir. Together vegetation and dead organic matter confer both resistance to disturbance and resilience following disturbance to forest ecosystems. Rapid regeneration of vegetation facilitates the recovery of ecosystem function (i.e., resilience) while the persistence of soil organic matter minimizes the effects of forest disturbance (i.e., resistance).

Vitousek and Reiners (1975) and Vitousek (1977) extended the concept of forest stability to include predictions about changes in stability that might occur over succession. According to their model, the rate of element accumulation (inputs minus outputs) is an index of the relative stability of forest ecosystems. The most important determinant of the rate of element accumulation is "net biomass increment" a measure of the change in storage of biomass (living + dead organic matter) through time (Vitousek and Reiners 1975, Vitousek 1977). Based on element accumulation rates, Vitousek and Reiners (1975) identified three stages that forest ecosystems pass through following disturbance. During the initial stage, or degradation phase, the net biomass increment of forest ecosystems is negative. The negative increment

results from reduced vegetative growth and conditions that favor decomposition in forest soils; net ecosystem production ($NEP = \text{gross primary production} - \text{community respiration}$) is negative and the storage pool of organic matter decreases. Forest stability, as measured by element accumulation rates, is minimal during the degradation phase because mineralization losses exceed nutrient uptake and accumulation in biomass. As forests regenerate, nutrient cycles become tighter. During the second (aggradation) phase, the net biomass increment becomes positive as production of rapidly growing vegetation exceeds ecosystem respiration ($NEP > 0$). Forest stability is maximal during the aggradation phase because nutrient uptake and accumulation in biomass exceeds mineralization losses. Finally, as forests mature, the net biomass increment becomes zero as vegetative production is balanced by ecosystem respiration ($NEP = 0$). Forest stability is intermediate during this "steady-state" phase because nutrient uptake is balanced by mineralization losses and nutrient cycles are not as tight as during the aggradation phase.

The model of forest stability presented by Vitousek and Reiners (1975) has several simplifying assumptions that are probably justified for many deciduous forest ecosystems. First, it assumes that nutrient inputs and outputs are closely linked to the hydrologic cycle and gaseous inputs and outputs are minimal (Woodmansee 1978). Also the model assumes that large scale disturbances (e.g. fire or grazing) are not frequent occurrences and that some approximate "steady-state" is eventually attained during ecosystem development. The model also assumes that forest ecosystems are neither net importers or exporters of "biomass" and that there is no net loss or gain of nutrients in an organic form.

Streams have traditionally been viewed as having the ability to respond rapidly to disturbance (Webster et al. 1975, O'Neill 1976). Some of the mechanisms of response include the short life cycles of stream invertebrates and rapid recolonization (drift, flying adults, hyporheic zone). The annual renewal of allochthonous organic matter (i.e. litterfall and blow-in of leaves and wood) insures a relatively constant energy base through time (Fisher and Likens 1973). Finally, the continual flushing by current can remove or at least displace the effects of disturbance downstream (Cairns and Dickson 1977, Webster and Patten 1979). However, the

continued downstream movement of current, especially during spates, can also be viewed as a source of instability for it displaces biologically important materials.

Streams are functionally unique in that the downstream movement of water prevents biologically important materials from cycling at any point in the system (Webster and Patten 1979). The tendency for material to be transported downstream is countered by mechanisms that tend to retard the rate of material loss (Webster and Patten 1979, Naiman and Sedell 1979a, 1979b, Minshall et al. 1983). As a result, materials tend to move downstream in a rolling (Leopold 1941) or spiralling (Webster 1975) motion as they pass through biotic and abiotic components of stream ecosystems. The efficiency of a stream is determined by the tightness of the spirals or the frequency with which material moves between various ecosystem components on its way downstream (Newbold et al. 1982b). The ability to retain material can be viewed as an ecosystem property or, in the case of storm transport, resistance to a natural disturbance.

Forest disturbance has a great impact on streams because of its longterm nature. Cutting or burning are short-term disturbances to forests and in the absence of further disturbance the forest undergoes succession or recovery. Forests recover rapidly because "biomass" is internally generated. In contrast, stream net ecosystem production is minimal and most "biomass" is derived from external sources (e.g. Fisher and Likens 1973). Being dependent on imported organic matter means that streams cannot fully recover from disturbance until predisturbance patterns of organic matter input are reestablished. This does not necessarily mean that streams fail to respond rapidly to forest disturbance. Inputs of organic matter to streams may be reduced following forest removal, but instream primary production and standing stocks of periphyton may increase due to increased insolation and increased nutrient levels (Hains 1981, Murphy and Hall 1981). Increases in primary production at least partially compensate for reductions in allochthonous inputs, restoring energy flow (resilience) following forest disturbance. Moss may be an important substrate following disturbance because it provides shelter from scour, traps organic particles, and has relatively high algal densities (Gurtz and Wallace 1984). Its persistence throughout stream recovery provides

habitat for stream consumers otherwise dependent on allochthonous leaf litter and minimizes the effects of forest disturbance (resistance) (Gurtz and Wallace 1984). Rapid regrowth of riparian vegetation restores detrital inputs to streams within a few years (Swanson et al. 1982, Webster et al. 1983), but the subtle effects of forest disturbance may be more persistent. The composition of detrital inputs may change considerably from mostly late successional decay resistant litter to rapidly decaying early successional litter (Webster et al. 1987). Changes in litter quality may alter the seasonal pattern of organic matter availability to stream consumers.

Complete forest recovery and the return of predisturbance quantity and quality of organic matter inputs to streams may take 100–400 years depending on the mature forest type of the region (Likens and Bilby 1982, Swanson and Lienkaemper 1978). During forest succession the most serious impact on stream ecosystems is probably a decline in the amount of large woody debris and numbers of debris dams in stream channels (Likens and Bilby 1982, Swanson and Lienkaemper 1978, Golladay et al. 1987). Debris dams have been reported to erode rapidly following watershed logging (Bilby 1981, Fisher and Likens 1973). Small twigs and leaves, which form the internal matrix of debris dams, decay relatively rapidly, and since allochthonous inputs are low, the matrix is not replaced. Even though large wood may remain, breakdown of the debris dam matrix may account for increases in organic matter transport observed following logging (Gurtz et al. 1980, Hobbie and Likens 1973, Webster and Golladay 1984). Large woody debris also gradually decays and is not replaced until the forest regenerates. For the stream, loss of wood during succession causes a gradual displacement of an ecosystem property, i.e. the ability to resist downstream export of material. The effect of displacement is most pronounced during storms or seasons of high discharge. Thus, forest disturbance ultimately reduces stream stability by reducing the ability of streams to resist shorter term natural disturbances.

Since net ecosystem production is probably never > 1 in forest stream ecosystems, the model presented by Vitousek and Reiners (1975) must be expanded to incorporate import and export of organic matter and associated nutrients in order to make predictions about the sta-

bility of streams draining successional forests. For a stream, net biomass increment or change in storage of biomass through time would equal $NEP + \text{organic import} - \text{organic export}$. Making predictions about nutrient retention in streams is complicated by the association of nutrients with organic matter and the import and export of nutrients in organic form must be incorporated into estimates of element accumulation rates. Immediately following forest disturbance streams are probably net exporters of organic matter. Removal of vegetation reduces litter inputs and instream conditions favor organic matter decomposition and erosion of organic accumulations and debris dams (Likens et al. 1970, Webster and Waide 1982, Golladay and Webster in press.). Organic matter breakdown causes conversion of large organic particles to more readily transportable fine particles, and mineralization results in release of nutrients into a readily transportable form (e.g. Newbold et al. 1982a). Increased inputs of inorganic nutrients from forest soils and increased autotrophic uptake from within streams may partially offset nutrient losses. However, moss and periphyton probably do not retain either organic matter or nutrients as efficiently as organic matter accumulations, especially during periods of high discharge. During the degradation phase of forest succession, streams also exhibit net losses of nutrients and organic matter.

As forests aggrade, inputs of leaf litter to streams return to predisturbance levels (Webster and Waide 1982). During this period breakdown of large wood releases nutrients directly through mineralization and production of easily transportable fine particles, and indirectly through decreased retention efficiency of stream channels (Golladay et al. 1987). Nutrient inputs to streams from forest soils are very low due to nutrient uptake by rapidly regenerating forest vegetation (Vitousek and Reiners 1975). Thus as forests recover, streams continue to degrade mainly due to decreased retention efficiencies and nutrient losses associated with the loss of large woody debris from stream channels. As forests recover and reach steady-state the predisturbance patterns of nutrient input and wood input to streams become reestablished. Stream ecosystems aggrade (i.e. accumulate biomass and nutrients) as large wood accumulates in stream channels and retention efficiencies are restored. In the absence of further disturbance, stream ecosystems may reach a form of steady-state where

processes of biomass and nutrient accumulation (import and uptake) are balanced by processes of loss (mineralization and export). However, in streams where geomorphic processes (i.e. landslides and debris torrents) are important influences on longterm patterns of biomass storage (e.g. Keller and Swanson 1979), steady-state may never be attained.

Stream ecosystems provide an interesting contrast to forest ecosystems. Due to their dependence on imported organic matter and associated nutrients, stream succession probably occurs more slowly than forest succession. Stream stability is probably reduced until forests regenerate and restore predisturbance patterns of organic matter and nutrient inputs. In this investigation, I examined the effects of forest disturbance nutrient retention in streams during storms by measuring nutrient inputs (soil water, throughfall) and outputs (streamwater) in streams draining early, intermediate, and late successional watersheds.

Study Site

This work was conducted at Coweeta Hydrologic Laboratory, Macon County, North Carolina, USA. Four sites were selected for study; two streams draining disturbed watersheds were matched with two streams draining reference watersheds of similar size. Big Hurricane Branch (BHB) drains WS (Watershed)-7, a 58.7-ha experimental watershed, which was grazed by cattle from 1941-1952 and cable logged during the winter of 1976-1977. Regrowth is dominated by hardwood sprouts, herbs, vines, and seedlings (Boring et al. 1981). Carpenter Branch (CB) drains WS-13, a 16.1-ha experimental watershed. Originally mixed hardwoods, all trees and shrubs were cut in 1939-1940 and again in 1962 (Swank and Douglass 1977). No wood was removed from the site and soil disturbance was minimal (Swank and Douglass 1977). The watershed is now covered by a young hardwood forest dominated by yellow poplar (*Liriodendron tulipifera*) at lower elevations and mixed oaks (*Quercus spp.*) at higher elevations (Leopold and Parker 1985). Hugh White Creek (HWC) drains WS-14, a 61.1-ha

watershed, and Grady Branch (GB) drains WS-18, a 12.5-ha watershed. Watersheds 14 and 18 are mixed hardwood forests and are longterm reference watersheds at Coweeta (Swank and Douglass 1977). Both sites were selectively logged before 1925 and, except for the chestnut blight, have been undisturbed for 60 years.

Undisturbed Coweeta streams are densely shaded by streamside vegetation, autochthonous primary production is low, and autumnal leaffall provides a majority of the annual energy input (Webster et al. 1983). Coweeta streams support a diverse invertebrate fauna dominated by detritivores (Woodall and Wallace 1972, Haefner and Wallace 1981). Since many of the measurements made are influenced by stream size, streams were paired based on similarities in average annual discharge and watershed area (Table 13). Hugh White Creek was selected as a reference stream for Big Hurricane Branch, and Grady Branch was selected as a reference stream for for Carpenter Branch. All streams are located within two kilometers of each other. They are equipped with V-notch weirs, and continuous records of streamflow are maintained by the Forest Service. Further characteristics of the study sites are presented in Table 13.

Methods

From June 1984-May 1985, water samples were collected during 8 storms at a single site on each stream just upstream of the weir ponding basin. Stream water samples (ca. 500 ml) were collected by ISCO Model 2100 automated water samplers. Intake hoses were positioned above the streambed in well-mixed riffles. Samplers were manually turned on when there appeared to be a possibility of rain. All samplers were placed near the stream gaging stations and streams were sampled during storms at a frequency that varied depending on how fast streamflow was changing. Sampling frequency was greatest during rising flows and continued less frequently following storms until streamflow returned to within 5-10% of original baseflow.

Sampling frequency varied from 5 minutes during intense thunderstorms to several hours during less intense steady rains. Fifteen to 25 samples were collected from each stream during each storm. Baseflow stream water samples were collected quarterly so baseline nutrient concentrations could be determined.

Following collection, water samples were taken to the laboratory, refrigerated, and subsamples were filtered (Gelman type A/E glass fiber filters) within 48 hr of collection. An additional subsample was taken from the filtered fractions and acidified to pH 2, then the three fractions (unfiltered, filtered, filtered and acidified) from each original water sample were frozen. Samples were subsequently analyzed for the following: acidified— ammonia (NH_4); filtered— total Kjeldahl nitrogen (TKN), nitrate (NO_3), total phosphorus (TP), dissolved inorganic phosphorus (DIP), sulfate (SO_4), K, Ca; unfiltered— TKN, TP, K, Ca. All chemical analyses were performed at Coweeta Hydrologic Laboratory using a water chemistry protocol described in detail by Reynolds and Deal (1987). Phosphorus, nitrogen and sulfate were analyzed using a Technicon Autoanalyzer-II system. Samples used in TKN determinations were digested in H_2SO_4 , then the cyanurate-salicylate reaction was used to determine TKN as NH_4 . NO_3 concentrations were determined using Cd/Cu reduction to NH_4 followed by a sulfanilamide color reaction. At Coweeta NO_2 concentrations are undetectable (McSwain and Beale 1980), so no separate analyses for NO_2 were performed. NH_4 analyses were performed using the colorimetric Berthelot reaction. Potassium-sodium tartrate was added to NH_4 samples to prevent metal hydroxide interferences. A H_2SO_4 digestion was used in TP determinations with TP determined as O- PO_4 . DIP concentrations were measured using the ammonium-molybdate reaction. Samples were digested in H_2SO_4 to hydrolyze condensed phosphates to DIP. SO_4 analysis was performed using barium chloride and methylthymol blue reactions. Cation interference was eliminated by passing samples through an ion exchange column (Dowex-50W-8X). Cation concentrations were determined using a Perkin Elmer Model 372 atomic absorption spectrophotometer.

Five throughfall collectors (10 X 400 cm pvc troughs draining into 20-L buckets) were placed over each stream to estimate inputs of nutrients during storms. Immediately following

storms, throughfall volumes were recorded and subsamples (ca. 250 ml) were taken to the laboratory for processing as described for stream water.

Porous cup lysimeters were placed on each watershed to measure nutrient concentrations in soil water entering each stream. Lysimeters, 200 X 5 cm diameter PVC pipe with a ceramic cup on the bottom, were installed to a depth of 30-50 cm in the soil adjacent to the stream bank. Lysimeters were emptied once weekly for six months prior to being sampled during storms. When storms seemed likely, lysimeters were emptied, set at 0.1 bar vacuum, and allowed to fill over the duration of the storm. Following the storm, water was collected from each lysimeter (ca. 250 ml), taken to the laboratory, and analyzed as described above for filtered stream water samples (particulate materials in lysimeter samples were negligible). Lysimeter samples were also collected quarterly between storms so baseline nutrient concentrations in soil water could be determined.

This sampling program permitted the estimation of nutrient inputs and outputs during storms. The total loss of nutrients was calculated by multiplying stream nutrient concentration times the volume of streamflow represented by each sample and summing over the duration of the storm. Major inputs to Coweeta streams during storms are channel interception and soil water. Soils at Coweeta are highly permeable, with infiltration rates often exceeding 125 cm/hr, thus overland flow is negligible (Douglass and Swank 1975). Channel interception was estimated from the volume of water in throughfall collectors and channel area. Soil water inputs were estimated as the difference between streamflow and water entering as stream channel interception. The total amounts of dissolved and particulate nutrients entering the stream during each storm were calculated as the product of concentration and volume for each input. The net loss or gain of a nutrient during a storm was the difference between nutrient transport in streamflow and inputs as channel interception and soil water.

Rainfall during the 8 storms sampled ranged from 0.5 to 7.0 cm and average rainfall intensities ranged from 0.5 to 1.05 cm/hr (Table 14). Late autumn and winter storms were long duration (up to 40 hours) and moderate intensity. Spring and summer storms were generally shorter (1-6 hrs) and more variable in intensity but often characterized by periods of relatively

intense rainfall. Rainfall amounts and intensities were very similar between watersheds. Based on Forest Service records, there was 149.6 cm of precipitation during the period from May 1984-April 1985. The 52-year average for Coweeta is 180.3 cm (range 122.9-224.5), and the period sampled was the 6th driest year on record (W.T. Swank, personal communication)

Using stream flow records provided by the Forest Service, annual water budgets were constructed for the study sites (Table 13). Storm flows and baseflows were calculated by a computer program that defined storms as any period where the increase in discharge exceeded 0.055 L/sec/ha per hour with a quickflow volume greater than 0.00254 cm (Hewlett and Hibbert 1967). Annual volumes of throughfall and soil water were estimated using the average percent contribution of each to total storm volume for the 8 storms sampled at each site. Annual water budgets were used to calculate annual nutrient budgets by multiplying average nutrient concentrations by the appropriate volume of water. The annual net loss or gain of a nutrient was the difference between total inputs (channel interception, soil water during baseflows and storm flows) minus total outputs (stream flow during baseflows and storm flows).

Results

Nitrogen

Sources of nitrogen during storms

In a comparison of the larger streams, Big Hurricane Branch (disturbed) received significantly greater amounts of soil nitrogen than Hugh White Creek (paired t-test, $P=0.05$), and differences were greatest during winter storms (Table 15). There was no significant difference

in the inputs of nitrogen in throughfall (paired t-test, $P=0.61$). In a comparison of the smaller streams, a similar pattern of inputs emerged. Carpenter Branch (disturbed) received significantly greater amounts of soil nitrogen than Grady Branch (reference) (paired t-test, $P=0.05$), and differences were most pronounced during winter storms. There were no significant differences in throughfall inputs to Carpenter Branch (disturbed) compared to Grady Branch (reference) (paired t-test, $P=0.55$). Averaged over all storms, soil water inputs represented 66.7% and 61.2% of the nitrogen entering the disturbed streams (Big Hurricane Branch and Carpenter Branch respectively). In the reference streams nitrogen inputs were dominated by throughfall with an average of 36.0% and 38.8% of the nitrogen entering from the soil (Hugh White Creek and Grady Branch, respectively). This analysis indicates that a primary difference among streams is a larger amount of nitrogen entering disturbed streams from forest soils, especially during winter storms. Soil nitrogen dominates inputs to disturbed streams while throughfall nitrogen dominates inputs to reference streams.

Concentration of nitrogen species in throughfall, soil water, and streamwater

The pattern of nitrogen inputs to disturbed and reference streams was strongly influenced by concentrations of nitrogen species in throughfall and soil water. Concentrations of all nitrogen species ($\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, dissolved organic nitrogen—DON, and particulate organic nitrogen—PON) in throughfall generally highest during late spring and summer storms and lowest during winter storms (Figure 8). Through fall $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations were similar among sites. Throughfall PON and DON concentrations were somewhat higher in reference than in disturbed streams (Table 16). At all sites throughfall DON and PON concentrations were sometimes extremely high, especially during low intensity or short duration storms during the forest growing season (e.g. 15 Jun 1984, 2 May 1985), indicating that substantial amounts of nitrogen can be transferred from forest canopies to streams.

Nitrogen concentrations in soil water were uniformly low, often an order of magnitude or more lower than in throughfall (Table 16). There was no obvious seasonal pattern of soil water nitrogen concentration for any nitrogen species at any site. When averaged across all storms, soil water $\text{NO}_3\text{-N}$ concentrations entering Carpenter Branch (disturbed) were significantly higher than at any other site (ANOVA-followed by multiple comparisons, $P < 0.05$). Soil water $\text{NO}_3\text{-N}$ concentration entering Big Hurricane Branch (disturbed) was significantly lower than Carpenter Branch, but significantly higher than the reference sites (ANOVA, followed by multiple comparisons, $P < 0.05$). There were no significant differences among sites in the concentrations of the other nitrogen species ($\text{NH}_4\text{-N}$ or DON) in soil water (ANOVA, $P > 0.05$). In the reference streams (Grady Branch, Hugh White Creek), DON tended to be the dominant nitrogen species in soil water and $\text{NH}_4\text{-N}$ concentrations were higher than $\text{NO}_3\text{-N}$ concentrations. In the disturbed streams (Big Hurricane Branch, Carpenter Branch) $\text{NO}_3\text{-N}$ was the dominant inorganic nitrogen species. The dominance of soil water as a source of nitrogen to disturbed streams during storms is largely due to the relatively high concentrations of $\text{NO}_3\text{-N}$ in the soil water. Concentrations of all nitrogen species were lower in soil water than throughfall, however, the volume of water entering streams as soil water was often much greater than throughfall, resulting in large inputs of nitrogen from forest soils to streams.

Concentrations of dissolved $\text{NO}_3\text{-N}$ in stream water, when averaged over all storms, were significantly greater in Big Hurricane Branch than any other stream (ANOVA, followed by multiple comparisons, $P < 0.05$) (Table 16). $\text{NO}_3\text{-N}$ concentrations in Carpenter Branch were significantly greater than those observed in either of the reference streams. There were no significant differences in average concentrations of either $\text{NH}_4\text{-N}$ or DON among the four streams. Although occasional high concentrations of dissolved nitrogen species were observed for individual storms, there were no consistent seasonal patterns of concentration for any nitrogen species. Particulate organic nitrogen was the dominant nitrogen species in stream water at all sites. When averaged over all storms, concentrations of PON measured in Big Hurricane Branch were significantly greater than those observed in the other streams (ANOVA, followed by multiple comparisons, $P < 0.05$). Storms sampled during summer and

autumn (15 Jun 1985, 20 Jun 1985, 10 Nov 1984) had relatively high PON concentrations (Figure 9). Storms sampled during winter had relatively low PON concentrations, and during late spring storms (2 May 1985, 7 May 1985) intermediate concentrations were measured.

Species composition of nitrogen inputs and outputs

Nitrogen inputs and outputs were calculated using 3 nitrogen species, dissolved inorganic nitrogen ($\text{DIN} = \text{NH}_4\text{-N} + \text{NO}_3\text{-N}$), DON, and PON. DIN was a substantial contributor to all streams, averaging 54% of total N-inputs to disturbed streams and 41% of N-inputs to reference streams. PON was generally the smallest fraction of inputs averaging 12% of inputs to disturbed and 27% of inputs to reference streams.

In a comparison of sites, Big Hurricane Branch (disturbed) received significantly more DIN from the surrounding watershed than Hugh White Creek (paired t-test, $P=0.04$) (Table 17). There is some evidence to suggest that Carpenter Branch (disturbed) also received greater DIN from its watershed than Grady Branch (paired t-test, $P=0.09$). Differences in DIN inputs to paired streams were most pronounced during winter storms when disturbed streams received relatively large amounts of $\text{NO}_3\text{-N}$ in soil water. Big Hurricane Branch (disturbed) received significantly greater amounts of DON than Hugh White Creek (paired t-test, $P=0.03$) reflecting the relatively high concentrations of DON in soil water. There was no significant difference in DON inputs to Carpenter Branch and Grady Branch (paired t-test, $P=0.34$). The only source of PON to the streams was in throughfall. There was no significant difference in PON inputs to the stream pairs (paired t-tests, $P>0.15$).

PON was the dominant form of nitrogen loss from all streams during storms averaging 46% of the total in disturbed streams and 52% in reference streams. DIN was the second most important form of nitrogen loss averaging 42% of the total in disturbed and 31% in the reference streams. DON losses averaged less than 20% in all streams.

In a comparison of sites, outputs of DIN were significantly greater from Big Hurricane Branch than Hugh White Creek (paired t-test, $P=0.05$) and Carpenter Branch lost significantly more DIN than Grady Branch (paired t-test, $P=0.008$). DIN outputs were generally highest during winter storms for all streams, although the tendency was not very pronounced for Hugh White Creek (Table 17). Outputs of DON were significantly higher in Big Hurricane Branch compared to Hugh White Creek (paired t-test, $P=0.03$). There was no significant difference in DON outputs from Carpenter Branch and Grady Branch (paired t-test, $P=0.42$), and there were no strong seasonal tendencies in DON output from any of the streams. PON outputs were significantly higher from Big Hurricane Branch (disturbed) compared to Hugh White Creek (reference) (paired t-test, $P=0.01$) and may have been greater from Carpenter Branch (disturbed) compared to Grady Branch (reference) (paired t-test, $P=0.08$). There was no strong seasonal pattern of PON export from any of the streams.

Comparison of inputs and outputs of each N-species

For DIN and DON there was generally no significant difference in inputs and outputs of nitrogen. This analysis indicates that for these N-species no net transformations occurred during storms (Table 17). One exception to this pattern was Hugh White Creek (reference), which accumulated DIN during storms. For PON, all streams exhibited significant net losses during storms. In general disturbed streams exhibited greater net losses of PON than reference streams.

Storm nitrogen budgets

Both disturbed and reference streams generally exhibited net losses of nitrogen during storms, however during several storms (15 Jun 1984, 21 Mar 1985, 2 May 1985) net gains of nitrogen occurred (Table 18). Net gains of nitrogen occurred most frequently in the reference

streams (Hugh White Creek or Grady Branch) and were larger than those observed in Carpenter Branch (disturbed). Net gains of nitrogen were never observed in Big Hurricane Branch. When pooled by treatment, disturbed streams (Big Hurricane Branch and Carpenter Branch) exhibited significantly greater net nitrogen losses than reference streams (Hugh White Creek and Grady Branch) (ANOVA followed by Duncan's Multiple Range Test, $P < 0.05$). Net nitrogen loss from disturbed streams averaged 57.12 mg/m^2 streambed/storm and from reference streams averaged 15.92 mg/m^2 streambed/storm. When comparisons were made between streams of similar size, Big Hurricane Branch lost significantly more nitrogen than Hugh White Creek (paired t-test, $P = 0.004$). There was no difference in nitrogen loss from Carpenter Branch and Grady Branch (paired t-test, $P = 0.16$).

Phosphorus

Sources of phosphorus during storms

Throughfall inputs were greatest at all sites during spring and summer storms (Table 19). There was no apparent seasonal pattern of soil water phosphorus input to the streams. In comparisons of the paired streams (Big Hurricane Branch vs Hugh White Creek, Carpenter Branch vs Grady Branch), there were no significant differences in the amounts of phosphorus entering the streams during storms from either throughfall or soil water (paired t-tests, $P > 0.1$). When averaged over all storms, the dominant phosphorus input to Carpenter Branch (disturbed), Hugh White Creek (reference), and Grady Branch (reference) was in throughfall (70.0%, 78.7%, and 59.4% respectively). Soil water was the major phosphorus input to Big Hurricane Branch, (recent clearcut) averaging 56.1% of total.

Concentration of phosphorus species in throughfall, soil water, and stream water

Concentrations of phosphorus species in throughfall were generally highest during late spring and summer storms and lowest during winter storms (Figure 10). When averaged over the year, there were no significant differences among streams in concentrations of any throughfall phosphorus species (ANOVA, $P > 0.05$) (Table 20). The dominant phosphorus species in throughfall at all sites was POP. Concentrations of POP and DOP in throughfall were occasionally high, especially during low intensity or short duration storms early in the forest growing season (e.g. 15 Jun 1984, 2 May 1985).

Concentrations of phosphorus species in soil water were roughly an order-of-magnitude lower than those observed in throughfall (Table 20). There was no strong seasonal pattern of DIP or DOP concentration at any of the sites. When averaged across all storms, DIP concentrations in soil water entering Big Hurricane Branch were significantly greater than soil water DIP concentrations entering either of the reference sites (ANOVA, followed by multiple comparisons, $P < 0.05$). Soil water DIP concentrations entering Carpenter Branch were intermediate. There were no significant differences among sites in the concentrations of DOP in soil water (ANOVA, followed by multiple comparisons, $P > 0.05$).

Concentrations of dissolved phosphorus species in stream water were similar to concentrations in soil water entering streams during storms (Table 20). When averaged across all storms there were no significant differences among streams in either DIP or DOP concentrations in stream water (ANOVA, $P > 0.05$). Concentrations of DIP and DOP in stream water were almost always near analytical detection limits, and there was no seasonal pattern of concentration evident for either species in any stream. POP was the dominant phosphorus species in stream water during storms at all sites. When averaged over all storms, concentrations of POP observed in Big Hurricane Branch were significantly greater than those observed in the other streams (ANOVA, followed by multiple comparisons, $P < 0.05$). There was also a distinct seasonal pattern of POP concentration observed at all sites. During summer

and autumn storms, stream water concentrations of POP were higher than those sampled at other times of the year (Figure 11).

Species composition of phosphorus inputs and outputs

When phosphorus inputs from throughfall and soil water were combined and averaged over all storms, POP was the dominant phosphorus input to reference streams, averaging 48.6% of inputs, DIP and DOP averaged 27.1% and 24.3% of total inputs respectively. In the disturbed streams, DIP was the dominant phosphorus input, averaging 40.5% of total. POP and DOP averaged 35.0% and 24.5% of total inputs respectively.

In comparisons of the paired streams (Big Hurricane Branch vs Hugh White Creek, Carpenter Branch vs Grady Branch) there were no significant differences in the inputs of either DIP, DOP, or POP (paired t-tests, $P > 0.1$). No seasonal patterns of inputs were observed for either DIP or DOP, although both disturbed streams received relatively large inputs of DIP during a storm sampled on 11 Feb 1985 (Table 21). POP inputs were greatest to all streams during late spring, summer, and autumn.

POP was the dominant form of phosphorus loss from all streams during storms, averaging 83% of total output in reference and disturbed streams. The other phosphorus species were a minor component of total transport. DOP averaged 10% of total output and DIP averaged 7% of total output in both disturbed and reference streams. In a comparison of sites, outputs of DIP were significantly greater from Big Hurricane Branch than Hugh White Creek (paired t-test, $P = 0.007$), and there was no significant difference in DIP outputs in a comparison of Carpenter Branch and Grady Branch (paired t-test, $P > 0.1$). DIP outputs were generally greatest for all streams during winter or early spring storms (Table 21). Outputs of DOP were significantly greater from Big Hurricane Branch compared to Hugh White Creek (paired t-test, $P = 0.05$), but there was no significant difference in DOP outputs in a comparison of Carpenter Branch and Grady Branch (paired t-test, $P > 0.1$). DOP outputs were often low, especially in

the reference streams, and there was no strong seasonal pattern of output. Outputs of POP were significantly greater from disturbed streams in comparisons of both Big Hurricane Branch and Hugh White Creek (paired t-test, $P=0.02$) and Carpenter Branch versus Grady Branch (paired t-test, $P=0.03$). Outputs of POP from all streams were greatest for storms sampled during late winter or early spring (11 Feb 1985, 21 Mar 1985).

Comparisons of inputs and outputs for each phosphorus species

For DIP and DOP there was generally no significant difference among inputs and outputs for any of the streams (Table 21). One possible exception might be Grady Branch, which appears to have a tendency to accumulate DIP during storms. This analysis indicates that no net transformations of dissolved phosphorus are occurring in Coweeta streams during storms. Both of the disturbed streams and Grady Branch exhibited significant net losses of POP during storms. Hugh White Creek, the other reference stream, also tended to lose POP during storms. In general the disturbed streams exhibited greater net losses of POP than the reference streams. Forest disturbance appears to reduce the ability of Coweeta streams to retain phosphorus associated with particles during storms.

Storm phosphorus budgets

Both disturbed and reference streams generally lost phosphorus during storms; however, during several storms (15 Jun 1984, 2 May 1984) net gains of phosphorus occurred (Table 22). Net gains of phosphorus occurred most frequently in the reference streams (Hugh White Creek or Grady Branch) and were larger than the one storm where a gain of phosphorus was observed in Carpenter Branch (disturbed). Net gains of phosphorus were never observed in Big Hurricane Branch. When pooled by treatment, disturbed streams exhibited significantly greater net phosphorus losses than reference streams (ANOVA followed by Duncan's Multiple

Range Test, $P < 0.05$). Net phosphorus loss from the disturbed streams averaged 34.02 mg/m^2 streambed/storm and from the reference streams averaged 8.59 mg/m^2 streambed/storm.

Potassium

Sources of potassium during storms

Throughfall potassium inputs to the streams were greatest during storms sampled in spring and summer (e.g. 15 Jun 1984, 20 Jun 1984, 2 May 1984, 7 May 1984) while soil water inputs to the streams were greatest during winter storms (e.g. 4 Dec 1984, 11 Feb 1985, 21 Mar 1985) (Table 23). Big Hurricane Branch (disturbed) received significantly more potassium in soil water than Hugh White Creek (reference) (paired t-test, $P = 0.01$) and Carpenter Branch (disturbed) received significantly more potassium in soil water than Grady Branch (paired t-test, $P = 0.03$). There were no significant differences in throughfall inputs in comparisons of disturbed and reference streams (paired t-test, $P > 0.1$). When averaged over all storms, the primary input of potassium was in soil water, averaging 69% of total input to reference streams and 85% of total input to disturbed streams.

Concentrations of potassium species in throughfall, soil water, and stream water

Throughfall DIK and POK concentrations were generally highest during storms sampled in late spring and summer and lowest in concentration during winter storms (Figure 12). Concentrations of both DIK and POK were often higher in throughfall entering reference streams compared to disturbed sites, and differences in concentration were most pronounced for late spring and summer storms. However, there was no significant difference between

streams in concentrations of either throughfall DIK or POK when concentrations were averaged over the entire year (ANOVA, $P > 0.1$) (Table 24).

Concentrations of DIK in soil water were generally lower than those observed in throughfall. There was no seasonal pattern of soil water DIK evident at any of the sites. When averaged over all storms, DIK concentrations in soil water entering Big Hurricane Branch were significantly greater than those measured at the other sites (ANOVA, followed by multiple comparisons, $P < 0.05$) (Table 24). There was no strong seasonal pattern of stream water DIK or POK concentration evident at any of the sites. When averaged over the year, DIK concentrations in Big Hurricane Branch were significantly higher than the other streams (ANOVA, followed by multiple comparisons, $P < 0.05$), and all comparisons among the other three streams indicated that average DIK concentrations were significantly different. Concentrations of POK in all streams were somewhat lower than DIK concentrations. In all streams, highest average POK concentrations were measured during a short-duration, relatively intense storm sampled on 20 Jun 1984, however average storm concentrations of POK were relatively constant throughout the rest of the year (Figure 13). When averaged over all storms, concentrations of POK in Big Hurricane Branch were significantly greater than the other streams (ANOVA, followed by multiple comparisons, $P < 0.05$). POK concentrations in Carpenter Branch were significantly higher than the reference sites ($P < 0.05$), and there was no significant difference between POK concentrations in the reference sites (ANOVA, followed by multiple comparisons, $P < 0.05$).

Species composition of potassium inputs and outputs

When potassium inputs from throughfall and soil water were combined, DIK was the dominant form of potassium input to the streams during storms averaging 96.6% of total inputs to reference streams and 98.3% of total inputs to disturbed streams.

In comparisons of paired streams, Big Hurricane Branch received significantly more DIK during storms than Hugh White Creek (paired t-test, $P=0.01$), and Carpenter Branch received significantly more DIK than Grady Branch (paired t-test, $P>0.05$). There were no significant differences in inputs of POK to the paired streams (paired t-test, $P>0.1$). DIK input to all streams was greatest during winter or early spring storms (e.g. 04 Dec 1984, 11 Feb 1985, 21 Mar 1986, Table 25). Storm inputs of POK to all streams were relatively constant throughout the year.

Dissolved DIK was the dominant form of potassium loss from all sites averaging 79.7% of total outputs from disturbed streams. Comparing sites, Big Hurricane Branch lost significantly more DIK during storms than Hugh White Creek (paired t-test, $P=0.009$); however, there was no significant difference in DIK loss from Carpenter Branch and Grady Branch (paired t-test, $P>0.1$). Outputs of DIK from all streams were greatest during winter or early spring storms (Table 25). POK was a minor component of potassium loss averaging 20.3% of total from reference streams and 27.8% of total from disturbed streams. Outputs of POK were significantly greater from disturbed streams in comparisons of both Big Hurricane Branch versus Hugh White Creek (paired t-test, $P=0.01$), and Carpenter Branch versus Grady Branch (paired t-test, $P=0.02$). At all sites POK losses were greatest during winter and early spring storms.

Comparison of inputs and outputs of each potassium species

DIK dynamics were different in reference and disturbed streams. DIK inputs and outputs from Hugh White Creek (reference) were approximately balanced (Table 25). Grady Branch (reference) had a tendency to lose DIK during storms (paired t-test, $P=0.07$). Big Hurricane Branch (disturbed) gained significant amounts of DIK during storms (paired t-test, $P=0.006$), and a tendency to accumulate DIK was also observed in Carpenter Branch (paired t-test, $P=0.08$). For POK all streams exhibited significant net losses during storms (paired t-tests,

$P < 0.05$). In general the disturbed streams exhibited larger net losses of POK than the reference streams.

Storm potassium budgets

Disturbed and reference streams generally lost potassium during storms. Losses of potassium from all streams tended to be greatest during storms sampled in winter or early spring (Table 26). Net gains of potassium were observed in all streams and were most common during late spring or summer storms. When pooled by treatment, there was no significant difference in net potassium loss between disturbed and reference streams (ANOVA, $P > 0.10$). When streams of similar size were compared (Big Hurricane Branch vs Hugh White Creek, Carpenter Branch vs Grady Branch) there were no significant differences between streams in the average net loss of potassium (paired t-tests, $P > 0.1$).

Calcium

Sources of calcium during storms

Inputs of calcium in soil water were generally greatest during winter or early spring storms (e.g. 4 Dec 1984, 11 Feb 1985, 21 Mar 1985) (Table 27). Inputs of calcium in throughfall did not vary with season. Comparing paired streams, Big Hurricane Branch (disturbed) received significantly greater quantities of calcium in soil water than Hugh White Creek (reference) (paired t-test, $P = 0.006$) and Carpenter Branch (disturbed) received significantly greater inputs of soil water calcium than Grady Branch (reference) (paired t-test, $P = 0.05$). There was no significant difference in throughfall inputs to the streams (Big Hurricane Branch vs Hugh White Creek, Carpenter Branch vs Grady Branch; paired t-test, $P > 0.10$). Soil water was the

primary source of calcium to all streams and when averaged over all storms contributed 91.8% of total inputs to disturbed streams and 85.4% of total inputs to reference streams.

Concentrations of calcium species in throughfall, soil water, and stream water

Throughfall DICa concentrations entering all streams were generally highest during late spring and summer storms and lowest during winter storms (Figure 14). Concentrations of throughfall POCa were lower than DICa at all sites and were relatively constant throughout the year. Concentrations of both DICa and POCa in throughfall entering reference streams were slightly higher than disturbed streams; however, there were no significant differences among sites for either DICa or POCa averaged for all storms (ANOVA, $P > 0.05$) (Table 28).

Concentrations of DICa in soil water were lower than throughfall DICa concentrations entering Carpenter Branch (disturbed), Hugh White Creek (reference), and Grady Branch (reference). In Big Hurricane Branch (recently disturbed), soil water DICa concentrations were often higher than throughfall DICa concentrations. At all sites lowest soil water DICa concentrations were measured during winter storms (4 Dec 1984, 11 Feb 1985). When averaged over all storms, soil water DICa concentrations entering Big Hurricane Branch were significantly higher than those measured at any other site, and there were no significant differences among soil water DICa concentrations at the other sites (ANOVA, followed by multiple comparisons, $P < 0.05$) (Table 28).

Stream water DICa concentrations were slightly higher than soil water DICa concentrations in Carpenter Branch (disturbed), Hugh White Creek (reference), and Grady Branch (reference) (Table 28). In Big Hurricane Branch (recently disturbed) stream water DICa concentrations were slightly lower than soil water DICa concentrations. Stream water DICa concentrations were lowest at all sites during winter storms (4 Dec 1984, 11 Feb 1985) (Figure 15). When averaged over the year, DICa concentrations in Big Hurricane Branch were significantly

higher than any other stream, and all comparisons between the remaining streams indicated that average DICa concentrations were significantly different (ANOVA, followed by multiple comparisons, $P < 0.05$). Concentrations of POCa in stream water were lower than DICa concentrations at all sites (Table 28). Concentrations of POCa in stream water during storms did not vary with either season or storm intensity. When averaged over all storms, concentrations of POCa measured in Big Hurricane Branch (recently disturbed) were significantly higher than those in Carpenter Branch (disturbed) or Hugh White Creek (reference), POCa concentrations in Grady Branch were intermediate (ANOVA, followed by multiple comparisons, $P < 0.05$).

Species composition of calcium inputs and outputs

When calcium inputs to streams from throughfall and soil water were combined and averaged over all storms, DICa was the dominant form of calcium entering streams during storms averaging 97.8% of inputs to reference sites and 98.6% of inputs to disturbed sites.

Comparing the paired streams Big Hurricane Branch (disturbed) received an average of 470.8 mg/m² more DICa during storms than Hugh White Creek (paired t-test, $P = 0.006$), Carpenter Branch (disturbed) received an average of 34.2 mg/m² more DICa than Grady Branch (paired t-test, $P = 0.045$). There was no significant difference in inputs of POCa to the paired streams (Big Hurricane Branch vs Hugh White Creek, Carpenter Branch vs Grady Branch, paired t-test, $P > 0.1$). Inputs of DICa to the streams were greatest during winter or early spring storms (e.g. 4 Dec 1984, 11 Feb 1985, 21 Mar 1985). Inputs of POCa were relatively constant throughout the year (Table 29).

DICa was the primary form of calcium loss from all sites averaging 79.7% of total outputs from reference sites and 84.2% of total outputs from disturbed streams. Comparing sites, Big Hurricane Branch (disturbed) lost significantly (average 448.51 mg/m²) more DICa during storms than Hugh White Creek (reference) (paired t-test, $P = 0.006$); however, there was no significant difference in DICa loss during storms in a comparison of Carpenter Branch and

Grady Branch (paired t-test, $P > 0.1$). Outputs of DICa from all streams were greatest during winter storms (Table 29). POCa was a minor component of calcium loss during storms, averaging 20.3% of total in reference streams and 15.8% of total in disturbed streams. Storm outputs of POCa from Big Hurricane Branch (disturbed) were generally greater than from Hugh White Creek (reference) (paired t-test, $P = 0.06$). There was no significant difference in storm outputs from Carpenter Branch or Grady Branch (paired t-test, $P > 0.10$). POCa outputs from all sites were generally greatest during winter or early spring storms.

Comparison of inputs and outputs of each calcium species

Both reference streams (Hugh White Creek and Grady Branch) exhibited net losses of DICa during storms (paired t-tests $P = 0.007$ and $P = 0.004$ respectively) and Carpenter Branch (disturbed) also tended to lose Ca during storms (paired t-test, $P = 0.065$) (Table 29). There was no significant difference between storm inputs and outputs of DICa in Big Hurricane Branch, the most recently disturbed stream. Big Hurricane Branch, Carpenter Branch, and Hugh White Creek lost significant amounts of POCa during storms (paired t-tests, $P < 0.05$), and Grady Branch also tended to lose POCa during storms (paired t-test, $P = 0.08$). The largest average net losses of POCa during storms were measured in Big Hurricane Branch, the most recently disturbed stream.

Storm calcium budgets

Disturbed and reference streams generally lost calcium during storms (Table 30). Calcium losses from all streams were greatest for storms sampled during the winter. Net gains of calcium were observed in all streams and were greatest during later spring or early summer storms. When pooled by treatment, there was no significant difference in net calcium loss between disturbed and reference streams (ANOVA, $P > 0.1$). When streams of similar size

were compared there was no significant difference in net calcium loss between Big Hurricane Branch and Hugh White Creek; however Grady Branch (reference) lost more calcium than Carpenter Branch (disturbed) (paired t-test, $P=0.03$).

Sulfate

Sources of SO_4 during storms

Storm inputs of SO_4 in soil water to all streams were greatest during winter or early spring storms (Table 31), and relatively large inputs of throughfall SO_4 were measured at all sites during winter and early spring storms. Comparing paired streams, Big Hurricane Branch (disturbed) received significantly more SO_4 in soil water than Hugh White Creek (paired t-test, $P=0.02$); however, there was no significant difference in soil water SO_4 inputs to Carpenter Branch and Grady Branch (paired t-test, $P>0.1$). There were no significant differences in throughfall inputs to the paired streams (paired t-test, $P>0.01$). Soil water was the primary source of SO_4 to all streams averaging 71.9% of total inputs to reference and 82.8% of total inputs to disturbed sites.

Concentrations of SO_4 in throughfall, soil water, and stream water

Throughfall SO_4 concentrations were highest during spring and summer storms and lowest during winter storms at all sites (Figure 16). When averaged over all storms, throughfall SO_4 concentrations entering the reference streams were significantly greater than those entering the disturbed streams (ANOVA, followed by multiple comparisons, $P<0.05$) (Table 32).

Sulfate concentrations in soil water were lower than throughfall concentrations at all sites. No strong seasonal pattern of SO_4 concentration in soil water was observed at any of the sites. When averaged over the year soil water SO_4 concentrations entering Big Hurricane Branch (disturbed) were significantly higher than those entering either Hugh White Creek (reference) or Carpenter Branch (disturbed), with concentrations entering Grady Branch being intermediate (ANOVA, followed by multiple comparisons, $P < 0.05$) (Table 32). Concentrations of SO_4 in stream water averaged over all storms were lower than soil water concentrations in three streams, Big Hurricane Branch (disturbed), Carpenter Branch (disturbed), and Grady Branch (reference) (Table 32). In Hugh White Creek (reference) stream water SO_4 concentrations were higher than soil water concentrations. When averaged over the year, stream water concentrations of SO_4 in Carpenter Branch (disturbed) were significantly lower than the other sites and there were no significant differences in stream water SO_4 concentrations among the other sites (ANOVA, followed by multiple comparisons, $P < 0.05$). No strong seasonal pattern of SO_4 concentration in stream water was observed at any of the sites.

Comparison of outputs and inputs of SO_4 during storms

Sulfate outputs from all streams were greatest during winter or spring storms (Table 33). In a comparison of sites Big Hurricane Branch (disturbed) lost an average of 281.99 mg/m^2 more SO_4 than Hugh White Creek (reference) (paired t-test, $P = 0.03$), there was no significant difference in sulfate outputs from Carpenter Branch and Grady Branch. Big Hurricane Branch (disturbed) gained an average of 282.0 mg/m^2 SO_4 during storms (paired t-test, $P = 0.003$), and Grady Branch (reference) also exhibited net accumulations of SO_4 during storms (average 135.03 mg/m^2 , paired t-test, $P = 0.02$) (Table 34). There was no significant difference in inputs and outputs in either Carpenter Branch or Hugh White Creek.

Sulfate budgets

Disturbed and reference streams generally gained sulfate during storms (Table 34). However, in Carpenter Branch (disturbed) and Hugh White Creek (reference), net losses of SO_4 were measured during late autumn or winter storms. When pooled by treatment there were no significant differences in net sulfate gains between disturbed and reference streams ($P > 0.1$). When streams of similar size were compared, Big Hurricane Branch (disturbed) retained an average of 285.34 mg/m^2 more SO_4 than Hugh White Creek (reference) (paired t-test, $P = 0.008$). There was no significant difference in SO_4 retention between Carpenter Branch (disturbed) and Grady Branch (reference) (paired t-test, $P > 0.1$).

Baseflow nutrient concentrations

Nutrient concentrations entering streams in soil water and leaving in streamwater were measured on 4 occasions during stable baseflows (10 June 1984, 8 November 1984, 8 February 1985, 1 May 1985). Assuming volumes of water entering in soil water are equal to discharge during baseflows, nutrient concentrations provide an indication of nutrient loss or accumulation. However, estimates of nutrient loss or gain based on baseflow concentrations only reflect hydrologic transport. Nutrient budgets for elements with atmospheric cycles (i.e. nitrogen, sulfur) assume losses and gains to the atmosphere are balanced. There is evidence that significant amounts of nitrogen may be lost from Coweeta streams to the atmosphere during the first years following forest clearing (e.g. Swank and Caskey 1982). Unfortunately sufficient information is not available for Coweeta streams to include rates of gaseous loss or gain of nitrogen and sulfur in budget calculations.

Based on total nitrogen concentrations, Big Hurricane Branch (disturbed), Hugh White Creek (reference), and Grady Branch (reference) appeared to be net exporters of nitrogen during baseflows (Table 35). Total nitrogen concentrations leaving those streams were sig-

nificantly higher than concentrations entering in soil water (ANOVA, $P < 0.05$). Stream water total nitrogen concentration in Carpenter Branch (disturbed) also tended to be greater than soil water but the difference was not significant (ANOVA, $P > 0.05$). Baseflow export of nitrogen was due primarily to net losses of $\text{NO}_3\text{-N}$ and PON. In Big Hurricane Branch, Hugh White Creek, and Grady Branch $\text{NO}_3\text{-N}$ concentrations in streamwater were significantly greater than concentrations in soil water (ANOVA, $P < 0.05$). Since particulate inputs to streams in soil water are negligible, all of the streams were net exporters of PON during baseflows.

Big Hurricane Branch (disturbed), Carpenter Branch (disturbed), and Grady Branch (reference) were net exporters of phosphorus, i.e. baseflow concentrations of total P in streamwater were significantly higher than in soil water (ANOVA, $P < 0.05$) (Table 35). There was no difference in soil water and stream water total P concentration in Hugh White Creek (reference) (ANOVA, $P > 0.05$). Phosphorus losses were due to net export of POP in all streams, there was no significant difference in concentrations of DIP and DOP in soil water and streamwater (ANOVA, $P > 0.05$).

Concentrations of total potassium in stream water were significantly higher than soil water concentrations entering Carpenter Branch (disturbed), Hugh White Creek (reference), and Grady Branch (reference) (ANOVA, $p < 0.06$) (Table 35). There was no significant difference between soil water and stream water total K concentration in Big Hurricane Branch (disturbed) (ANOVA, $P > 0.05$). Net export of potassium was due to net export of POK, and in the reference streams net export of DIK. Total calcium inputs and outputs were approximately balanced in all streams. There was a tendency to accumulate DICa in all streams (i.e. stream DICa concentration $<$ soil water concentration), but all of the streams were net exporters of POCa. Sulfate appeared to accumulate in all streams; however, there were no significant differences between soil water and streamwater SO_4 concentrations at any site (ANOVA, $P > 0.05$).

Annual Nutrient Budgets

Annual nutrient budgets were constructed using average nutrient concentrations and volumes of water (Table 13) entering and leaving streams during stormflows (Tables 16,20,24,28,32) and baseflows (Table 35). On an annual basis DIN was the primary form of nitrogen entering disturbed streams (61.2% of total) with most DIN entering during baseflows (Tables 36 and 37). DON was the primary form of nitrogen input to reference streams (49.4% of total). DIN input to reference streams averaged 37.2% of total nitrogen inputs, and for both DON and DIN most of the annual input occurred during baseflows. Storm input accounted for 41.9% of total nitrogen entering reference streams and 19.9% of total nitrogen input to disturbed streams. DIN was the major form of nitrogen output from disturbed streams accounting for 45.8% of annual output. PON accounted for 30.3% of annual nitrogen output. In the reference streams PON was the primary form of nitrogen output averaging 40.1% of total annual output. Most of the nitrogen output from disturbed and reference streams occurred during baseflows. Storms accounted for 23.7% of total nitrogen output from disturbed streams and 26.0% of nitrogen output from reference streams.

Disturbed and reference streams were net exporters of nitrogen, annual net losses ranged from 2640 mg/m² streambed/year from Hugh White Creek (reference) to 8420 mg/m² streambed/year from Big Hurricane Branch (disturbed). In comparisons of similar sized streams, Big Hurricane Branch (disturbed) lost more nitrogen than Hugh White Creek (reference) during both baseflows and stormflows. Greater nitrogen losses from Big Hurricane Branch were due to greater net losses of PON during baseflows and stormflows and to relatively large net loss of DIN during baseflows. In comparisons of the smaller streams, Carpenter Branch (disturbed) lost 3010 mg/m² streambed/year total nitrogen while Grady Branch (reference) lost 3140 mg/m² streambed/year total nitrogen. The largest contributor to net nitrogen loss from Carpenter Branch and Grady Branch was PON. Carpenter Branch lost more PON than Grady Branch during both baseflows and stormflows; however, Carpenter Branch

exhibited lower net nitrogen losses than Grady Branch because of an apparent large net accumulation of DIN during baseflows. There was no significant difference between concentrations of $\text{NO}_3\text{-N}$ or $\text{NH}_4\text{-N}$ in soil water entering Carpenter Branch and stream water (Table 35), thus the magnitude of DIN accumulation during baseflows is uncertain. It appears that forest disturbance affected annual stream nitrogen budgets in two ways. First, forest disturbance resulted in a decreased ability of streams to retain PON. Although PON represented a substantial portion of net nitrogen losses in both disturbed and reference streams, losses from disturbed streams were much higher than reference. Since PON is a relatively small component of nitrogen inputs, most of the PON exported by streams during baseflows and stormflows must originate within stream channels. The second effect of forest disturbance was substantially more nitrogen moving through disturbed streams compared to reference streams. Greater nitrogen flux in disturbed streams was largely due to greater inputs and outputs of DIN during baseflows and stormflows probably resulting from increased $\text{NO}_3\text{-N}$ availability in disturbed forest soils (Likens et al. 1970, Vitousek and Reiners 1975).

In reference streams DIP and DOP were the most important inputs of phosphorus averaging 37.3% and 40.6% of total annual inputs respectively (Tables 38 and 39). DOP was the dominant species of phosphorus entering disturbed streams averaging 67.6% of total inputs. Storms accounted for 49.8% of total phosphorus inputs to reference streams and 23.8% of phosphorus inputs to disturbed streams. POP was the predominant form of phosphorus output averaging 63.0% of total annual output from the reference streams and 78.5% of total output from disturbed streams. Most of the POP output from reference streams occurred during storms while in disturbed streams most of the POP output occurred during baseflows. For all species combined, storms accounted for 52.0% of annual phosphorus output from reference streams and 33.8% of annual phosphorus output from disturbed streams.

On an annual basis, disturbed and reference streams were net exporters of phosphorus. In a comparison of similar sized streams, net phosphorus export averaged 3260 mg/m^2 streambed/year from Big Hurricane Branch (disturbed) and 750 mg/m^2 streambed/year from Hugh White Creek (reference). A majority of the net phosphorus loss from both streams was

attributable to net POP loss, other phosphorus species exhibited net gains or only modest net losses. The difference in phosphorus net export from Big Hurricane Branch and Hugh White Creek was largely due to much larger net POP losses from Big Hurricane Branch compared to Hugh White Creek. Net phosphorus loss from Carpenter Branch (disturbed) averaged 2310 mg/m² streambed/year and from Grady Branch (reference) averaged 930 mg/m² streambed/year. Net phosphorus losses from both streams were due primarily to net POP export, with much greater net POP loss observed from Carpenter Branch. It seems clear that the greatest impact of forest disturbance on stream phosphorus dynamics is a reduced ability to retain POP during both baseflows and stormflows.

Potassium and calcium inputs and outputs in both disturbed and reference streams were dominated by the movement of cations. For potassium, DIK represented > 95% of total inputs and 80-90% of total outputs from all sites (Tables 40 and 41). Storms were a small component of total potassium inputs averaging 14.4% of total inputs to disturbed and 25.1% of total input to reference streams. Storm outputs of potassium were also small ranging from 14 to 20% of total annual output from the streams. On an annual basis Carpenter Branch (disturbed), Grady Branch (reference), and Hugh White Creek (reference) exhibited net losses of potassium due largely to net losses of POK during baseflows and stormflows. Big Hurricane Branch (disturbed) exhibited a net gain of potassium due to relatively large, but not statistically significant net accumulation of DIK during baseflows. Like the other streams, Big Hurricane Branch exhibited relatively large net losses of POK during both baseflows and stormflows. Forest disturbance appears to have reduced the ability of streams to retain POK as reflected by substantially greater net POK losses from disturbed streams compared to reference sites. It is interesting that POK is a relatively minor component of net potassium inputs and outputs, but a major contributor to net potassium loss from all sites. It would appear that most of the DIK moving through the streams is undergoing little net transformation. The relatively large net accumulation of DIK in Big Hurricane Branch during baseflows is puzzling; however, since the difference in soil water DIK concentration entering Big Hurricane

Branch and stream water DIK concentration was not statistically significant (Table 35), some uncertainty must be attached to that calculation.

Inputs and outputs of calcium were primarily DICa, which represented 99% of total inputs and > 80% of total calcium outputs from all streams (Tables 42 and 43). Storms were a relatively minor contributor to budget calculations accounting for 10-16% of total calcium outputs. On an annual basis, Big Hurricane Branch (disturbed), Carpenter Branch (disturbed), and Grady Branch (reference) exhibited net losses of calcium. Hugh White Creek (reference) appeared to accumulate calcium because of apparent large net accumulation of DICa during baseflows. Two of the other streams (Big Hurricane Branch, Carpenter Branch) also appeared to accumulate DICa during baseflows; however, since there were no statistically significant differences in baseflow soil water and streamwater DICa concentration (Table 35) in any of the sites some degree of uncertainty must be attached to apparent DICa accumulations. POCa was a minor component of total calcium inputs and outputs but like POK was a major form of calcium net loss from all streams. In a comparison of the paired streams, Big Hurricane Branch (disturbed) lost substantially more POCa than Hugh White Creek (reference) during both baseflows and stormflows. However, in a comparison of the other sites the reference stream (Grady Branch) lost more POCa than the disturbed stream (Carpenter Branch).

On an annual basis most of the inputs and outputs of SO₄ occurred during baseflows (Tables 44 and 45). Baseflow inputs of SO₄ accounted for 86.6% of total in disturbed and 79.9% of total in reference streams. Baseflow SO₄ outputs accounted for 85.3% of total in disturbed and 78.8% of total in reference streams. Both disturbed and reference streams accumulated SO₄, and most of the apparent uptake occurred during baseflows. Although differences in soil water SO₄ concentration and baseflow SO₄ concentration in streams were not significant, differences between means were large suggesting that some net accumulation was occurring. Forest disturbance did not appear to have great impact on SO₄ retention in streams. Big Hurricane Branch (recently disturbed) accumulated substantially more SO₄ than any of the other sites. However, Grady Branch (reference) also accumulated more SO₄ than

Carpenter Branch (disturbed) or Hugh White Creek (reference). Thus, differences in SO_4 retention do not appear to be related to forest disturbance.

Discussion

Effects of forest disturbance on nutrient inputs to streams

Changes in nutrient inputs to streams following forest clearing reflect disruptions of nutrient cycling in forest canopies and soils. In this study, nitrogen availability in forest soils was very sensitive to forest disturbance. Concentrations of DIN in soil water entering reference streams were relatively low ($\text{NO}_3\text{-N} < 0.005$ mg/L, $\text{NH}_4\text{-N} < 0.013$ mg/L) and the dominant form of DIN was $\text{NH}_4\text{-N}$ (Tables 16,35). In disturbed sites soil water concentrations of $\text{NO}_3\text{-N}$ were elevated above reference levels ($\text{NO}_3\text{-N} > 0.020$ mg/l). Changes in nitrogen cycling were also reflected in the greater movement of DIN through disturbed streams (Tables 36 and 37) and seasonal patterns of nitrogen input during storms (Table 15). Differences in DIN inputs to disturbed and reference streams were greatest during large, long duration storms when substantial quantities of $\text{NO}_3\text{-N}$ were flushed from forest soils and into streams.

Inputs of inorganic nitrogen to streams are determined by the availability of nitrogen in forest soils. Nitrogen availability results from a balance between processes favoring mineralization and immobilization. Undisturbed forests are characterized by a relatively closed nitrogen cycle where the amount of DIN cycling internally greatly exceeds losses in soil solution (Bormann et al. 1977). Forest clearing and associated increases in soil moisture and temperature result in an imbalance between mineralization and immobilization. Soil conditions favor decomposition of organic matter releasing $\text{NH}_4\text{-N}$, and in the absence of plant uptake, the subsequent oxidation of $\text{NH}_4\text{-N}$ by nitrifying bacteria to $\text{NO}_3\text{-N}$ (Likens et al. 1970,

Vitousek and Melillo 1979). $\text{NO}_3\text{-N}$ is a relatively mobile nitrogen species that can be flushed from soils and readily transported in streamwater (Likens et al. 1970, Vitousek and Melillo 1979). Elevated concentrations of $\text{NO}_3\text{-N}$ in soil solution and stream water following forest disturbance have been widely reported (e.g. Likens et al. 1970, Brown et al. 1973, Neary 1977, Swank 1987). It is interesting to note that most studies have observed peaks in $\text{NO}_3\text{-N}$ concentration within 5 years of disturbance and a return to near reference levels with the re-growth of vegetation. Clearly, this study demonstrates that even slight increases in DIN availability in forest soils can cause substantial increases in nitrogen inputs to streams.

Phosphorus inputs to Coweeta streams appeared to be relatively insensitive to forest disturbance. Slight but significant increases in DIP concentration entering Big Hurricane Branch (recently disturbed) were observed during storms, but there were no significant differences in inputs to disturbed and reference sites. DIP is immobilized by a variety of physical and biological processes (e.g. Wood et al. 1984) and does not appear to be readily flushed from forest soils to streams following disturbance.

Cycling of cations (DIK and DICa) was moderately affected by forest disturbance. The predominant source of DIK and DICa in soil solution at Coweeta is weathering of bedrock (Velbel 1985a, 1985b). Cation availability is determined by the weatherability of bedrock and the rate at which water moves through forest soils (Velbel 1985a, 1985b). However, DIK and DICa are also required for plant growth, and thus a portion of the total cation pool is tied up in living and dead forest biomass (Likens et al. 1970, Covington 1981, Boring et al. 1981). The yield of cations to streams is determined not only by weathering rates but also by immobilization and mineralization. In this study soil water entering reference streams averaged 0.40-0.55 mg/L DICa and 0.25-0.35 mg/L DIK (Tables 24,28,35). Soil water entering Carpenter Branch had concentrations of DIK slightly higher (0.37 mg/L during storms, 0.36 mg/L during baseflows) and concentrations of DICa slightly lower (0.39 mg/L during storms, 0.43 mg/L during baseflows) than reference sites. Concentrations of DIK and DICa entering Big Hurricane Branch (recently disturbed) were much higher than reference levels (DIK 0.62 mg/L baseflows, 0.64 mg/L stormflows; DICa 0.95 mg/L baseflows, 0.92 mg/L stormflows). These

differences in concentration were reflected in the patterns of cation inputs to streams during storms. Streams draining disturbed sites received more DIK and DICa from soils than reference sites (Tables 23,27). At all sites largest cation inputs were observed during large long duration storms when substantial quantities of water entered streams from soil solution.

Similarly elevated concentrations of cations in soil solution and in streams draining disturbed sites have been widely reported (e.g. Likens et al. 1970, Brown et al. 1973, Neary 1977, Swank 1987). Increased cation concentrations can be linked to increased mineralization in excess of vegetative uptake following forest clearing (Likens et al. 1970). Increased nitrification, typical of disturbed soils, produces hydrogen ions that may displace cations on exchange sites and result in elevated cation concentrations in soil solution and stream water (Likens et al. 1970). Both increased mineralization and nitrification could be occurring on disturbed sites at Coweeta, accounting, in part, for increased cations concentrations entering streams during storms. It is not clear whether weathering rates are affected by forest disturbance and contribute to increased concentrations of cations in soil solution. However, at Coweeta total flux of cations from watersheds to streams is determined not only by concentrations in soil solution but also by the volume of water moving through soils (Velbel 1985a, 1985b). Rainwater does not rapidly move through soils and enter streams but instead displaces stored water from the bottom of the soil profile (Hewlett et al. 1977). Increased water storage in disturbed sites due to decreased interception and transpiration may result in greater inputs of cations simply because a greater volume of water enters streams during storms (Hewlett and Helvey 1970). At Coweeta, water yields to streams may remain elevated for 30-40 years following disturbance (Swift and Swank 1981).

A final factor complicating the pattern of cation inputs observed in this study is differences in the weatherability of the bedrock beneath the watersheds. There are two principal lithostratigraphic units underlying Coweeta Hydrologic Laboratory, the Tallulah Falls formation and the Coweeta Group (Velbel 1985a, 1985b). Of these formations the Tallulah Falls group is more weatherable meaning the yield of cations per unit volume of water moving through the basin (or average concentration in soil water) is higher. Big Hurricane Branch (disturbed) and

Grady Branch (reference) drain watersheds entirely on the Tallulah Falls formation. Hugh White Creek (reference) drains a watershed with upper slopes on the relatively resistant Coweeta group and lower areas on Tallulah Falls formation. Carpenter Branch (disturbed) drains an area entirely on Coweeta Group (Velbel 1985a, 1985b). Concentrations of soil water cations entering Hugh White Creek (Coweeta Group) are lower than those entering the other reference stream and reflect the relatively lower weatherability of the bedrock beneath a portion of the basin (Tables 24,28). Cation concentrations entering Carpenter Branch (disturbed) whose basin is entirely underlain by the relatively resistant Coweeta group are similar to reference levels, being slightly higher in DIK and lower in DICa concentration. Big Hurricane Branch (disturbed) receives the highest concentrations of cations but drains an area underlain by weatherable bedrock. Thus the effects of disturbance may be partially obscured by geological differences between the basins. This study indicates that forest disturbance alters cation inputs to streams but the actual effect is the result of combined biological, hydrological, and geochemical processes.

Information on the effects of forest disturbance on sulfur inputs to streams gained by this study is obviously incomplete since SO_4 was the only sulfur species measured. However, SO_4 inputs may be increased for a time following disturbance as indicated by the elevated concentration of SO_4 entering Big Hurricane Branch (recently disturbed) during baseflows and stormflows (Tables 32,35). The primary input of sulfur to forests is as SO_4 in precipitation (Likens et al. 1970, Swank 1986). SO_4 entering forest soils appears to be rapidly immobilized by chemical adsorption on Fe and Al oxides and by microbially mediated incorporation into organic matter (Fitzgerald et al. 1983, Swank et al. 1984, Swank 1986). In general, immobilization exceeds mineralization and net accumulations of SO_4 have been observed in both reference and disturbed forests (Likens et al. 1970, Swank 1986). However, increased SO_4 loss has been observed from recently cleared watersheds suggesting increased mineralization or decreased immobilization of SO_4 in disturbed soils (Swank 1987).

Nutrient concentrations in throughfall are determined primarily by background concentrations in precipitation but are modified by any net uptake or release of material as rainwater

penetrates the forest canopy. Generally nutrient concentrations increase as water travels through forest canopies, increased concentrations result from foliar leaching and rainfall scavenging of material deposited between storms (Swank 1984). Complete removal of the forest canopy should reduce nutrient inputs to streams since foliar leaching and rainfall scavenging would be eliminated. However rapid regrowth of vegetation (e.g. Marks and Bormann 1972, Boring et al. 1981, Boring and Swank 1984) should restore canopy contributions to throughfall within a few years. Data from this study show that there were no differences in throughfall inputs to disturbed and reference streams suggesting a rapid recovery of canopy contributions following disturbance (Tables 15,19,23,27,31). It is interesting to note that forest disturbance does appear to have a subtle effect on contributions of throughfall nutrients to streams during storms. In this study concentrations of many nutrient species (especially PON, DIK, POK, DICa, POCA, SO₄) were substantially higher entering reference sites than disturbed sites (Tables 16,20,24,28,32). Throughfall volumes were generally lower in reference sites compared to disturbed sites (Golladay personal observation) suggesting greater interception of rainfall in reference sites. Throughfall contributions to reference sites were a smaller volume, more concentrated solution than that entering disturbed sites. Throughfall does represent a substantial source of nitrogen and phosphorus averaging 62.6% of total nitrogen inputs and 69.1% of total phosphorus inputs to reference streams during storms. The relative contribution of throughfall to total nitrogen and phosphorus inputs is reduced following disturbance (36.1% of total nitrogen input to disturbed streams, 43.9% of total phosphorus input to Big Hurricane Branch), but reductions are largely an artifact of increased inputs of nitrogen and phosphorus from disturbed soils and do not reflect changes in absolute amounts of either nutrient entering streams in throughfall. Throughfall was a minor contributor to total potassium, calcium, and sulfate inputs to disturbed and reference streams. Lower relative contributions of throughfall potassium, calcium, and sulfate to disturbed streams also result from increased inputs of each nutrient from disturbed forest soils. Overall, it appears that forest disturbance has a relatively short term impact on throughfall nutrient contributions to streams during storms.

The results of this study indicate that forest clearing has a long term impact on forest nutrient cycles and thus nutrient inputs to streams. The availability of nutrients in forest soils is increased following forest disturbance resulting in greater nutrient inputs to streams. Throughfall inputs to streams appear to be relatively unaffected by forest disturbance, or the effects of disturbance, if any, are short-lived. Nutrients that undergo a number of biological transformations (e.g. nitrogen) appear to be most affected by forest clearing, resulting in large relatively long term changes in inputs to streams. Nutrients with substantial geological and biological pools (e.g. calcium and potassium) appear to be less strongly affected by forest clearing, and the resulting changes in nutrient inputs to streams are relatively modest. Finally, elements that are normally strongly retained in forest soils by both chemical and biological processes (e.g. phosphorus and sulfate) appear to be little affected by forest clearing and inputs of these nutrients to streams are not altered following disturbance.

Effects of forest disturbance on nutrient retention in streams

Changes in nutrient outputs from streams following forest clearing reflect disruptions of forest nutrient cycling and also disruption of instream mechanisms of nutrient retention. Changes in nutrient retention following forest removal are most apparent during storms, a frequently occurring natural disturbance. The storm nutrient budgets for Coweeta streams suggest that mechanisms of nitrogen and phosphorus retention in streams may be very sensitive to forest disturbance since net losses of both elements were generally greater from disturbed streams than reference sites (Tables 18,22).

The primary output of nitrogen during storms was PON averaging 52% of output from reference streams and 42% of output from disturbed sites. PON is a relatively minor component of total inputs (27% to reference, 12% to disturbed), suggesting that most PON originates within stream channels. Forest clearing appears to have reduced the ability of streams to retain PON, as indicated by generally greater concentrations of PON in stream water (Table

16), greater total outputs (Table 17), and greater net losses (Table 17) from disturbed sites compared to reference sites. Outputs of DIN were also greater from disturbed sites compared to reference sites (Table 17) and this is reflected in greater average streamwater DIN concentrations in disturbed streams during storms (Table 16). However, balanced net budgets for DIN during storms (Table 17) suggest that large losses of DIN from disturbed sites are an artifact of the large $\text{NO}_3\text{-N}$ inputs from disturbed soils. Although forest disturbance greatly affects the availability of DIN in soils, this material appears to flush through stream ecosystems during storms without undergoing any net transformations.

Storm outputs of phosphorus were dominated by POP, averaging greater than 80% of total outputs in disturbed and reference sites. Although inputs of POP were an important component of phosphorus budgets (average 48.6% reference, 35.0 % disturbed), species budgets (Table 22) showed net losses of POP for disturbed and reference streams during storms. The imbalance of species budgets for POP strongly suggests an instream origin for this material. Forest disturbance reduces the ability of streams to retain POP, as reflected in greater outputs and net losses of POP from disturbed sites during storms. Forest disturbance appeared to have little impact on the ability of streams to retain either DIP or DOP. Although losses of DIP and DOP were greater from Big Hurricane Branch (recently disturbed) compared to the other streams, they probably reflect somewhat greater availability of phosphorus in recently disturbed soils. Concentrations of DIP and DOP were near detection limits in both soil solution and stream water suggesting that there were seldom substantial quantities available in either form.

Potassium and calcium budgets suggest that forest clearing has had little impact on the ability of streams to retain these elements during storms. The primary output of potassium and calcium during storms was inorganic (DIP and DIK) representing 80% of total outputs from disturbed and reference streams. Big Hurricane Branch (recently disturbed) had higher concentrations and greater outputs of DIK and DIP but also received more of each element from soil solution than the other sites. Big Hurricane Branch lost more cations during storms than the other sites due to the combined effects of greater weatherability of the bedrock be-

neath its watershed and increased cation yield from disturbed forest soil. Thus, elevated cation loss from Big Hurricane Branch was probably not caused by a reduction in instream mechanisms of cation retention. Species budgets for cations (Tables 25 and 29) suggest that even though more material may have moved through Big Hurricane Branch, this stream appears to have accumulated more DIK and lost less DICa than the other sites. Although a small component of total outputs, net losses of POK and POCa were generally observed from both disturbed and reference sites (Tables 25 and 29). For POK, net losses were greatest from disturbed sites, and for POCa, Big Hurricane Branch (recently disturbed) had greater net losses than the other streams. It appears that the greatest impact of forest disturbance on calcium and potassium retention in streams is a decreased ability to retain POK and POCa.

Sulfate budgets suggest that forest disturbance has had little impact on SO_4 retention in streams during storms. Sulfate enters streams primarily from forest soils, and both disturbed and reference streams often showed net accumulations of SO_4 during storms (Table 34). Big Hurricane Branch (recently disturbed) and Grady Branch (reference) showed significant net accumulations of SO_4 averaged over all storms, while Carpenter Branch (disturbed) and Hugh White Creek (reference) showed approximate balances when averaged over storms (Table 34). Differences in inputs to the two groups of streams (BHB, GB and CB, HWC) were greatest during winter and early spring storms when large quantities of SO_4 enter Big Hurricane Branch and Grady Branch from forest soils. It appears that Big Hurricane Branch and Grady Branch retained more SO_4 than the other sites because they received more from their watersheds. The effects of forest disturbance, if any, are obscured by some unknown factor affecting the availability of SO_4 in forest soils. In forest soils SO_4 is immobilized by chemical adsorption and microbial uptake (e.g. Fitzgerald et al. 1983, Swank et al. 1984, Swank 1986), little information is available on mechanisms of SO_4 uptake in Coweeta streams although both chemical and biological uptake are probably important.

Changes in nutrient outputs from streams following forest disturbance are also reflected in annual nutrient budgets. PON was the primary form of nitrogen output from reference streams, averaging 40.1% of total annual output. In disturbed streams DIN was the primary

form of nitrogen output, averaging 45.0% of total. PON averaged 30.3% of total outputs from disturbed streams. PON was a relatively minor component of nitrogen input in both disturbed and reference sites. Forest clearing appears to have reduced the ability of streams to retain PON, and this is reflected in the large PON outputs and net losses from disturbed sites during both baseflows and stormflows. Outputs of DIN from disturbed streams were also relatively large, reflecting the increased availability of DIN in disturbed soils.

Annual phosphorus outputs were dominated by POP which represented 63.0% of total output from reference and 78.5% of total output from disturbed sites. As with PON, inputs of POP were a minor component of total annual input. POP was the primary form of net phosphorus loss from both disturbed and reference sites. POP outputs and net losses were much greater from disturbed streams compared to reference streams during both baseflows and stormflows.

Annual potassium and calcium outputs, primarily DIK and DICa, accounted for > 80% of the total loss of each element from all of the streams. Greatest cation inputs and outputs were observed from Big Hurricane Branch during both baseflows and stormflows, reflecting recent disturbance and relatively weatherable bedrock beneath its basin. Cation inputs and outputs in Hugh White Creek (reference) were lower than Grady Branch (reference) reflecting differences in bedrock mineralogy. Carpenter Branch (disturbed) had potassium inputs and outputs greater than reference levels while calcium inputs and outputs were lower than reference levels suggesting that the effects of disturbance may be partially obscured by geologic differences between sites. Although a minor component of total annual inputs and outputs, POK and POCa were major contributors to net potassium and calcium losses from all streams during both baseflows and stormflows. POK outputs and net losses were much greater from disturbed streams compared to reference streams, and for POCa, outputs and net losses from Big Hurricane Branch (recently disturbed) were much greater than from the other streams. Thus, forest disturbance appears to have a greater impact on the ability of streams to retain potassium and calcium associated with organic particles than on the ability of streams to retain cations.

Annual SO_4 budgets support the conclusions drawn from storm SO_4 budgets, i.e. forest disturbance has had little impact on SO_4 retention in streams. All streams accumulated SO_4 during both baseflows and stormflows. Movement of SO_4 and SO_4 accumulation was greatest in Big Hurricane Branch (recently disturbed), but there were no obvious effects of disturbance on SO_4 outputs or net accumulation in the other streams.

Changes in stream stability following forest disturbance

This study indicates that forest disturbance has a longterm impact on the ability of streams to retain nutrients. Unlike forests, where disturbance appears to primarily interfere with biological uptake and accumulation of nutrients, stream disturbance results in a reduction in the ability to retain nutrients already incorporated into organic matter. As a result, disturbed streams lose substantial quantities of nutrient containing particles during both baseflows and stormflows. Elements with annual budgets or annual rates of nutrient loss containing a substantial particulate fraction (i.e. nitrogen and phosphorus) appear to be most affected by forest clearing. However, even elements with budgets dominated by inputs and outputs of dissolved species may be strongly affected by disturbance, especially where dissolved species are moving through stream ecosystems without undergoing any net transformation.

Annual budgets indicate that both disturbed and reference streams are net exporters of particulate nutrients without suggesting a possible origin for that material. The origins of particles in headwater streams are somewhat obscure although Wotton (1984) discussed mechanisms that result in the generation of microfine particles ($0.5\mu\text{m}$ - $10\mu\text{m}$) in aquatic systems and can probably be applied to larger particles as well. There are two categories of particles, primary particles result from the comminution of larger organic matter (Wotton 1984). The ultimate origin of primary particles is the sequential processing of allochthonous inputs by stream biota (Cummins 1974, Boling et al. 1975). The second category, secondary

particles result from a combination of physical and biological processes including: ingestion, aggregation, and subsequent egestion of primary particles by scavenging organisms; flocculation of dissolved organic matter; and bubble scavenging of dissolved and particulate organic matter (Bowen 1984, Wotton 1984).

Inputs of large organic matter to streams were not measured as a part of this study; however, estimates of litter input to disturbed and reference streams are available. Annual leaf litter inputs to Coweeta streams range from 436.1 to 625.7 g AFDW/m²/year (Golladay, Chapter 2, this volume). Small wood (< 5 cm diam.) inputs range from 70.1 to 266.5 g AFDW/m²/year (Webster unpublished). In general disturbed streams appear to receive somewhat lower allochthonous inputs than the reference sites. Using estimates of the percent nutrient composition of leaf material and wood in the litterfall of an undisturbed hardwood forest (WS-18 at Coweeta, Cromack 1973), minimum estimates of annual nutrient inputs in litterfall entering the study sites were obtained. This permitted the recalculation of annual budgets with the contributions of nutrients entering streams in litterfall included.

Litterfall nitrogen inputs ranged from 4100 mg/m² streambed/year in Big Hurricane Branch to 6790 mg/m² streambed/year in Grady Branch (Tables 46 and 47) representing a substantial source of nitrogen to all streams. When annual budgets were recalculated, both reference streams appeared to have accumulated substantial quantities of nitrogen. Carpenter Branch (disturbed) also appeared to have accumulated nitrogen but at lower than reference rates. However, the nitrogen budget for Carpenter Branch was strongly influenced by a large, but not statistically significant net accumulation of DIN during baseflows (Table 37). The nitrogen budget for Carpenter Branch is approximately balanced if that accumulation is ignored. Big Hurricane Branch (recently disturbed) exhibited substantial net losses of nitrogen.

Litterfall was also an important source of phosphorus and litterfall inputs ranged from 610 mg/m² streambed/year in Big Hurricane Branch to 1010 mg/m² streambed/year in Grady Branch. With litterfall phosphorus included in the budget calculations, inputs and outputs of phosphorus to the reference streams were approximately balanced. Disturbed streams lost

substantial quantities of phosphorus--Big Hurricane Branch lost 2650 mg/m² streambed/year and Carpenter Branch lost 1680 mg/m² streambed/year.

Inputs of litterfall potassium and calcium were small compared to the inputs of DIK and DICa to the streams. As previously discussed, annual budgets of calcium and potassium were strongly influenced by inputs and outputs of DIK and DICa, thus the addition of litterfall potassium and calcium did not change the variable pattern of net losses or gains observed between sites. However, net losses of POK and POCa were substantial from all sites, and inclusion of litterfall potassium and calcium resulted in approximately balanced inputs and outputs of organic potassium and net accumulations of organic calcium in the reference streams. For Big Hurricane Branch (recently disturbed) inputs of litterfall potassium and calcium did not balance outputs of POK or POCa, thus net losses (11,050 and 9,600 mg/m² streambed/yr for POK and POCa respectively) were observed for the organic pool of each element. In Carpenter Branch litterfall inputs of potassium did not balance outputs of POK, thus a net loss (4,280 mg/m² streambed/year) of organic potassium was observed. Calcium litterfall inputs to Carpenter Branch were slightly larger than POCa outputs resulting in a net accumulation (140 mg/m² streambed/year) of organic calcium.

After being revised to include litterfall, budget calculations indicate that litterfall represents an important source of nutrients to both disturbed and reference streams. Annually, if most of this material is processed into small, readily transportable, fine particles, litterfall inputs can account for much of the particulate nutrient export observed in both disturbed and reference streams. However, budget calculations are based on a number of other assumptions. The year sampled (June 1984-May 1985) was a drier than normal year, in an average year one might expect greater nutrient export from disturbed and reference streams. In addition, budgets based on one year cannot identify the role of geomorphic processes (i.e. landslides and debris torrents) in the long term accumulation or loss of organic matter and associated nutrients from streams. The percent composition of nutrients in successional vegetation may be higher than that collected from mature hardwood forest. Higher nutrient concentrations in early successional litterfall could result from greater nutrient availability in

disturbed soils and thus greater plant uptake. The presence of nitrogen fixing species could result in elevated nitrogen content of early successional litter. On WS-7 at Coweeta the relative density and biomass of black locust (Robinia pseudo-acacia), a nitrogen-fixing species, increased following forest cutting (Boring et al. 1981). Thus, the annual budgets may underestimate the litterfall nutrient contribution to disturbed streams. The annual budgets do not include any atmospheric nutrient losses or gains. Gaseous inputs or outputs could be important in annual stream nitrogen budgets since nitrogen has the potential to undergo a number of gaseous transformations (i.e. volatilization, denitrification, nitrogen fixation). Unfortunately sufficient information is not available on the rates of gaseous nitrogen transformation or on the effects of disturbance on those rates to include gaseous losses or gains in budget calculations. Finally, no information is available on the rate of secondary particle formation in Coweeta streams or if particle formation contributes to annual budgets. Clearly, this study indicates that nutrient budgets for Coweeta streams are linked to the import and export of nutrients associated with organic matter. It also appears that nutrients are undergoing a net transformation in headwater channels, i.e. being converted from a readily retained form (leaves and woody debris) to a readily transformed form (fine organic particles).

Since net losses of particulate nutrients are elevated in disturbed streams, forest clearing must have some effect on the rate at which nutrient containing particles are generated or the efficiency with which they are retained or both. Particle generation rates in streams are determined by the availability of organic matter to be processed, the presence of consumer organisms, and the physical-chemical environment (i.e. nutrient levels, temperature). Following forest disturbance increased stream temperature and nutrient levels, conditions favoring accelerated organic matter processing, have been widely reported (e.g. Likens et al. 1970, Swift and Messer 1971, Swank 1987). Leaf litter inputs may be greatly reduced initially following forest disturbance. However, the rapid regeneration of forests generally restores a portion of litter inputs within a few years (Swanson et al. 1982, Webster et al. 1983), although data from Coweeta streams indicate that total litter inputs may be somewhat reduced for 10-20 years following disturbance (Golladay, chapter 2, this volume). The composition of litter inputs

may change considerably following forest disturbance from relatively slow decaying, late successional species (e.g. oaks) to rapidly decaying early successional species (e.g. dogwood and birch) (Webster et al. 1987). Stream detritivores appear to be relatively unaffected by forest disturbance. In the absence of leaf litter, their preferred substrate, they colonize alternate habitats (e.g. Rounick et al. 1982, Gurtz and Wallace 1984). However, if leaf litter becomes available they rapidly process it (e.g. Webster and Waide 1982). Thus particle generation rates in streams may be reduced immediately following disturbance but should recover rapidly and may even exceed predisturbance rates as forests regenerate and litter inputs are restored.

Woody debris is also an important component of stream ecosystems that may be adversely affected by forest disturbance. The structural role of wood debris in streams has been well documented. Organic matter tends to accumulate into debris dams behind logs large enough to span stream channels and not be displaced by stream flow (Bormann et al. 1969, Swanson and Lienkaemper 1978, Likens and Bilby 1982). Aggregation conserves allochthonous inputs by promoting instream processing and retention of organic matter (Bilby and Likens 1980, Triska and Cromack 1980, Bilby 1981). Debris dams also cause a stepped pattern of streambed morphology, reducing stream power, erosiveness, and particle transport (Heede 1972, Fisher and Likens 1973, Keller and Swanson 1979). During the early stages of disturbance, wood debris may be an important site of nutrient immobilization and retention. Covington (1981) reported that logging slash is important to nutrient uptake and retention in terrestrial systems during the early stages of forest recovery. Following forest disturbance, similar mechanisms could operate in streams as wood decomposition in aquatic systems has been reported to immobilize and accumulate nitrogen (Buckley and Triska 1978, Aumen et al. 1983, 1985a, 1985b, Baker et al. 1983, Melillo et al. 1983). As wood decays it becomes increasingly susceptible to abrasion, resulting in production of nutrient containing fine particles. Ward and Aumen (1986) estimated that abrasion of decomposing wood may contribute 100 g fine organic particles / m² / yr to western Cascade Mountain streams, a value exceeding mean annual FBOM standing stock tenfold. It seems clear that wood debris has the potential to be

an important source of fine, nutrient containing particles as well as being an important structural element of streams. Also, over the course of decay, breakdown of wood debris and associated nutrient uptake may represent a net conversion of nutrients from dissolved to particulate form.

No information is available on the rates of particle generation from wood in Coweeta streams. However, wood breakdown rates appear to be accelerated following logging (Golladay and Webster in press) and the abundance of wood in Coweeta streams appears to decrease following forest clearing (Golladay, Chapter 2, this volume). The abundance of wood debris is determined by the rate of input from watersheds and the breakdown rate in streams. In the case of disturbances such as logging, wood standing stocks may increase due to inputs of logging slash (Likens and Bilby 1982, Gurtz and Wallace 1984, Duncan and Brusven 1985). However, during forest regrowth wood litterfall is reduced until predisturbance patterns of vegetation are restored (Swanson and Lienkaemper 1978, Likens and Bilby 1982). The decreased abundance of wood debris in disturbed Coweeta streams can probably be attributed to reduced wood inputs and accelerated breakdown rates. Similar declines in wood standing stocks have been observed in streams draining other disturbed areas (e.g. Likens and Bilby 1982, Swanson and Lienkaemper 1978).

It appears that watershed disturbance results in rapid changes in inputs and abundance of organic matter (leaf litter and wood debris) to streams which in turn reduces stream stability. Decreased litter inputs and altered litter quality results in rapid organic matter processing. Thus, in disturbed streams annual litter inputs are rapidly converted from a form that is efficiently retained (CPOM) to FPOM which is readily transported. In Coweeta streams this transformation occurs in late autumn, and substantial quantities of nutrient containing particles are lost from disturbed streams during winter storms. Decreased wood abundance also decreases stream stability. Accelerated wood breakdown in disturbed streams represents conversion of organic matter and associated nutrients from an efficiently retained form to relatively transportable form. Decreased wood input to disturbed streams and associated decreases in wood abundance result in a reduction of stream obstructions that promote re-

tention of biologically important material. In the disturbed Coweeta streams average velocities are greater and channel roughness (Manning's n) is lower than reference sites, differences that can be attributed to decreased frequency of retention structures (debris dams, logs, and organic matter accumulations) (Golladay et al. 1987). Thus, stream recovery provides an interesting contrast to forest recovery. Forest recovery is characterized by a brief period of degradation (relatively high net nutrient loss) followed by a period of rapid recovery (nutrient accumulation). The reestablishment of tight nutrient cycles is largely regulated by the regrowth of forest biomass. In contrast, the degradation of stream ecosystems is prolonged and the recovery period more gradual. The length of the recovery period is determined by the rate at which the predisturbance patterns of allochthonous inputs (especially large woody debris) are restored, and varies depending on the nutrient. Of the elements measured in this study, nitrogen cycling appears to recover most rapidly. Within 25 years of forest clearing, the nitrogen budget for Carpenter Branch, a disturbed stream, appears to be balanced or showing net accumulation. Phosphorus cycling appears to require a longer recovery period, with phosphorus budgets showing net losses in disturbed streams for at least 25 years following forest clearing. For potassium, net losses from the organic pool occur for at least 25 years following disturbance, while for calcium inputs and outputs from the organic pool appear to balance within 25 years of disturbance. Differences in nutrient retention between disturbed and reference streams are greatest during storms. For all streams stormflows account for 10-20% of total annual discharge, but a substantial quantity of the annual net nutrient loss occurs during those brief periods. Thus during the recovery period following forest clearing, stream stability is reduced, reflected in a decreased ability to respond to a frequently occurring natural phenomenon, i.e. the ability to retain nutrients during storms.

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Table 13. Physical features of the study sites.Values with parentheses are means and 95% (\pm) confidence intervals.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Watershed #	7	13	14	18
Treatment	Disturbed	Disturbed	Reference	Reference
Area (ha)	58.7	16.1	61.1	12.5
Main Channel length (m)	1225	604	1125	345
Gradient (m/m)	0.19	0.19	0.15	0.20
Streambed Area (m ²)	3274	1330	8085	1116
Average Annual Discharge (L/sec) ¹	18.52 (1.85)	5.39 (0.32)	19.37 (1.45)	4.06 (0.31)
Baseflow (m ³) May 1984-May 1985	382,200	101,400	361,100	73,000
Storm flow (m ³) May 1984-May 1985	45,800	16,300	71,200	12,300
Channel Interception (m ³) May 1984-May 1985	1,600	900	4,300	700
Soilwater storm input (m ³) May 1984-May 1985	44,200	15,400	66,900	11,600
Total Flow (m ³)	428,000	117,700	432,000	85,300

¹Based on a minimum of 35 years of Forest Service Records

Table 14. Total rainfall and average intensity of storms.

Intensity was calculated by dividing total rainfall amount by the duration of a storm. Values represent averages of all sites.

Storm Date	Total Rainfall (cm)	Intensity (cm/hr)
15 Jun 84	0.50	0.15
20 Jun 84	1.57	1.05
10 Nov 84	3.27	0.55
4 Dec 84	4.04	0.23
11 Feb 85	6.30	0.48
21 Mar 85	2.10	0.06
1 May 85	1.24	0.08
7 May 85	4.19	0.10

Table 15. Sources of nitrogen during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall
15 Jun 1984	24.09	10.82	17.09	12.61	5.47	7.71	4.01	6.99
20 Jun 1984	13.01	29.58	7.16	14.73	4.19	9.30	8.15	13.16
10 Nov 1984	19.53	9.76	9.69	21.13	8.33	12.42	3.68	23.27
4 Dec 1984	20.97	4.84	52.56	7.37	11.71	5.29	17.64	9.13
11 Feb 1985	157.65	17.92	130.86	24.43	11.86	20.41	39.62	26.87
21 Mar 1985	70.53	14.54	16.29	15.34	4.49	21.83	6.55	27.36
2 May 1985	18.37	25.23	17.26	28.86	3.50	28.19	5.32	34.39
7 May 1985	55.31	22.67	68.64	21.05	5.23	28.19	40.25	24.56

Table 16. Concentrations of nitrogen species in throughfall, soil water, and stream water.

Values are means (mg/L averaged across all storms) with 95% confidence intervals and sample sizes in parentheses.

		Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Throughfall	NO ₃	0.250 (0.048,40)	0.235 (0.053,37)	0.208 (0.048,39)	0.330 (0.135,40)
	NH ₄	0.112 (0.030,40)	0.134 (0.032,37)	0.068 (0.018,39)	0.123 (0.036,40)
	DON	0.449 (0.228,40)	0.438 (0.230,37)	0.599 (0.236,39)	0.589 (0.273,40)
	PON	0.541 (0.244,40)	0.468 (0.176,39)	0.815 (0.426,39)	0.741 (0.275,40)
Soil Water	NO ₃	0.023 (0.008,58)	0.049 (0.016,31)	0.005 (0.001,59)	0.004 (0.001,34)
	NH ₄	0.011 (0.004,58)	0.009 (0.002,31)	0.012 (0.005,59)	0.011 (0.004,34)
	DON	0.043 (0.014,58)	0.026 (0.014,31)	0.026 (0.010,59)	0.026 (0.016,34)
Stream Water	NO ₃	0.059 (0.003,173)	0.053 (0.004,174)	0.012 (0.001,166)	0.025 (0.005,168)
	NH ₄	0.011 (0.001,173)	0.013 (0.001,174)	0.013 (0.002,166)	0.012 (0.001,168)
	DON	0.040 (0.006,173)	0.040 (0.005,174)	0.038 (0.005,166)	0.035 (0.005,168)
	PON	0.190 (0.045,173)	0.123 (0.024,174)	0.097 (0.018,166)	0.103 (0.018,170)

Table 17. Inputs and outputs of DIN, DON, and PON during storms.

Values are mg/m²/storm. Net difference is the difference between inputs and outputs of a particular species averaged over all storms. Positive values indicate a net accumulation of a nitrogen species, negative values indicate a net loss. P-values (in parentheses) indicate the probabilities that net differences are significantly different from zero.

	Big Hurricane Branch			Carpenter Branch			Hugh White Creek			Grady Branch		
	DIN	DON	PON	DIN	DON	PON	DIN	DON	PON	DIN	DON	PON
<u>Inputs</u>												
15 Jun 1984	14.53	17.34	3.03	9.67	16.38	3.64	1.25	8.65	3.28	2.25	6.44	2.32
20 Jun 1984	16.57	9.93	16.10	8.38	5.94	7.56	5.01	3.35	5.06	1.40	11.36	8.64
10 Nov 1984	9.77	15.74	3.79	21.06	1.16	8.60	9.57	4.97	6.21	19.25	0.74	6.98
4 Dec 1984	12.98	9.97	2.87	54.63	1.97	3.33	13.24	2.93	0.82	22.37	1.41	2.99
11 Feb 1985	94.49	77.87	3.21	148.30	0.00	6.99	20.84	3.51	7.92	26.59	29.40	8.72
21 Mar 1985	53.27	29.54	2.26	24.72	4.53	2.38	13.60	7.12	5.61	23.39	5.66	4.85
2 May 1985	16.66	11.64	15.29	24.32	7.95	13.85	5.94	5.86	19.88	9.99	10.81	18.91
7 May 1985	33.23	35.06	9.70	45.70	32.24	9.73	7.57	11.19	14.67	10.43	37.08	17.31
<u>Outputs</u>												
15 Jun 1984	22.09	0.35	67.41	3.45	2.63	29.72	0.92	3.42	6.62	2.43	2.58	18.67
20 Jun 1984	14.62	22.37	107.21	3.90	7.01	44.12	1.31	2.94	12.52	1.56	7.83	21.47
10 Nov 1984	11.04	19.69	80.87	13.95	1.70	35.24	4.93	8.28	33.86	3.72	2.51	38.77
4 Dec 1984	37.88	36.22	18.59	46.48	11.06	18.53	10.47	17.01	9.61	16.27	17.91	16.27
11 Feb 1985	205.47	6.22	169.10	159.91	20.82	98.43	17.88	1.14	46.95	135.45	16.43	45.70
21 Mar 1985	61.33	31.90	31.75	50.25	22.43	9.32	11.30	14.97	3.64	14.06	12.16	7.53
2 May 1985	31.19	15.42	8.41	14.75	0.00	21.99	3.16	0.00	18.48	5.19	7.02	13.21
7 May 1985	58.11	0.00	102.43	42.50	29.42	48.64	5.99	5.32	34.92	9.05	0.00	42.23
Net Difference	-23.79 (0.11)	11.33 (0.32)	-66.19 (0.01)	0.20 (0.96)	-3.11 (0.49)	-31.24 (0.01)	2.63 (0.001)	-0.69 (0.79)	-12.89 (0.04)	-9.01 (0.55)	4.56 (0.44)	-16.66 (0.01)

Table 18. Net loss (< 0) or gain (> 0) of nitrogen during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	-54.95	-6.11	2.22	-12.68
20 Jun 1984	-101.60	-33.15	-3.34	-9.56
10 Nov 1984	-79.01	-20.07	-26.33	-16.26
4 Dec 1984	-66.87	-16.13	-20.09	-23.68
11 Feb 1985	-205.22	-123.88	-33.69	-132.88
21 Mar 1985	-39.91	-50.37	-3.59	0.16
2 May 1985	-11.42	9.38	10.05	14.30
7 May 1985	-82.56	-31.99	-12.81	13.53

Table 19. Sources of phosphorus during storms.Values are mg/m² streambed/storm.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall
15 Jun 1984	1.40	6.32	3.11	3.27	2.70	3.09	1.07	2.37
20 Jun 1984	0.88	12.08	0.09	3.22	0.28	3.81	2.03	3.18
10 Nov 1984	7.05	2.17	1.94	2.44	4.68	1.75	4.67	3.41
4 Dec 1984	4.84	1.25	0.00	1.44	0.00	1.86	1.56	1.55
11 Feb 1985	53.18	2.14	9.24	2.71	0.00	3.10	5.22	3.12
21 Mar 1985	6.97	1.84	0.00	1.94	0.37	2.89	0.55	3.78
2 May 1985	2.52	6.60	7.06	7.29	4.29	8.69	4.84	9.68
7 May 1985	10.75	5.72	1.08	4.88	0.00	7.87	3.61	6.08

Table 20. Concentrations of phosphorus species in throughfall, soil water, and stream water.

Values are means (mg/L as PO₄ averaged across all storms) and in parentheses 95% confidence intervals and sample sizes.

		Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Throughfall	DIP	0.095 (0.046,40)	0.051 (0.051,39)	0.096 (0.048,39)	0.077 (0.048,40)
	DOP	0.079 (0.034,40)	0.073 (0.038,39)	0.131 (0.077,39)	0.100 (0.046,40)
	POP	0.343 (0.099,40)	0.158 (0.069,39)	0.300 (0.158,39)	0.278 (0.103,40)
Soil Water	DIP	0.008 (0.002,59)	0.006 (0.003,32)	0.004 (0.001,59)	0.005 (0.001,36)
	DOP	0.008 (0.004,59)	0.007 (0.005,32)	0.012 (0.005,59)	0.012 (0.005,36)
Stream Water	DIP	0.005 (0.009,173)	0.005 (0.001,174)	0.005 (0.003,166)	0.004 (0.001,169)
	DOP	0.008 (0.002,173)	0.011 (0.003,174)	0.009 (0.002,166)	0.008 (0.002,169)
	POP	0.122 (0.024,173)	0.083 (0.012,174)	0.082 (0.022,166)	0.083 (0.018,170)

Table 21. Inputs and outputs of phosphorus species to streams during storms.

Values are mg/m² streambed/storm. Net difference is the average net difference between inputs and outputs of a particular species over all storms. Positive values indicate a net accumulation of a phosphorus species, negative values indicate a net loss. P-values (in parentheses) indicate the probabilities that net differences are significantly different from zero.

	Big Hurricane Branch			Carpenter Branch			Hugh White Creek			Grady Branch		
	DIP	DOP	POP	DIP	DOP	POP	DIP	DOP	POP	DIP	DOP	POP
<u>Inputs</u>												
15 Jun 1984	2.48	0.47	4.78	3.16	1.92	1.29	0.95	3.51	1.33	1.40	1.01	0.97
20 Jun 1984	4.80	0.45	7.71	0.35	0.56	2.41	1.51	0.14	2.43	0.37	2.20	2.64
10 Nov 1984	2.14	5.43	1.67	1.48	0.77	2.11	1.01	3.95	1.47	1.68	4.50	1.90
4 Dec 1984	4.32	1.13	0.64	0.35	0.42	0.67	0.55	0.47	0.85	1.77	0.04	1.30
11 Feb 1985	40.90	13.27	1.12	8.53	1.71	1.71	0.59	0.00	2.51	5.80	0.91	1.63
21 Mar 1985	8.04	0.17	0.59	1.14	0.19	0.62	1.10	0.00	2.17	1.19	0.00	3.15
2 May 1985	1.71	2.88	4.53	0.57	9.02	4.77	1.15	4.78	7.05	0.67	6.36	7.48
7 May 1985	3.70	8.51	4.26	1.54	0.92	3.49	0.58	0.34	6.94	3.78	1.23	4.68
<u>Outputs</u>												
15 Jun 1984	1.69	1.28	26.47	0.98	3.32	9.99	0.35	0.04	3.77	0.41	0.00	3.98
20 Jun 1984	1.04	0.80	56.33	0.79	1.50	17.75	0.73	1.27	6.46	0.35	3.14	9.81
10 Nov 1984	1.67	1.42	54.51	0.35	0.00	21.08	0.43	0.00	26.03	1.38	0.00	19.09
4 Dec 1984	4.96	7.97	24.66	0.86	3.99	11.13	1.23	0.00	5.80	0.23	0.00	6.51
11 Feb 1985	6.83	14.18	164.17	3.92	7.70	56.57	1.72	0.25	34.36	3.38	5.99	29.78
21 Mar 1985	3.30	7.67	35.14	2.08	8.14	24.50	0.86	6.92	4.99	1.55	4.75	14.86
2 May 1985	1.38	1.45	18.13	1.82	0.00	15.22	0.56	0.54	4.46	1.14	0.00	6.85
7 May 1985	2.52	12.72	36.48	1.11	0.00	47.02	0.16	0.00	8.23	0.75	3.06	15.04
Net Difference	5.59 (0.22)	-1.90 (0.22)	-48.81 (0.02)	0.65 (0.38)	-1.14 (0.50)	-23.27 (0.01)	0.18 (0.50)	0.52 (0.50)	-8.67 (0.09)	0.93 (0.08)	0.20 (0.50)	-8.77 (0.04)

Table 22. Net loss (< 0) or gain (> 0) of phosphorus during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	-21.72	-7.91	1.63	-1.02
20 Jun 1984	-45.90	-16.74	-4.37	-7.73
10 Nov 1984	-48.54	-17.08	-20.03	-11.02
4 Dec 1984	-31.50	-14.55	-5.16	-3.64
11 Feb 1985	-129.86	-56.26	-33.23	-30.81
21 Mar 1985	-34.00	-32.98	-9.50	-16.84
2 May 1985	-11.84	0.86	7.43	6.53
7 May 1985	-35.23	-41.07	-0.53	-9.18

Table 23. Sources of potassium during storms.Values are mg/m² streambed/storm.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall
15 Jun 1984	180.95	27.40	66.61	40.32	17.08	32.82	34.48	28.41
20 Jun 1984	116.22	46.73	35.61	25.80	36.78	14.70	29.23	26.42
10 Nov 1984	174.72	25.61	64.74	35.32	35.66	26.74	48.91	31.48
4 Dec 1984	492.13	16.70	232.58	19.52	104.14	22.63	161.92	13.03
11 Feb 1985	1101.62	16.64	534.20	20.60	175.74	34.27	382.24	13.99
21 Mar 1985	559.01	15.92	211.14	17.26	89.81	38.19	160.91	17.80
2 May 1985	209.01	18.38	104.32	23.30	51.54	36.84	91.94	36.80
7 May 1985	433.25	39.40	217.11	36.50	102.81	85.47	188.37	54.39

Table 24. Concentrations of potassium species in throughfall, soil water, and stream water.

Values are means (mg/L as K averaged across all storms) and in parentheses 95% confidence intervals and sample sizes.

		Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Throughfall	DIK	2.028 (0.935,40)	1.888 (0.931,39)	4.085 (2.028,39)	3.211 (1.566,40)
	POK	0.137 (0.059,40)	0.203 (0.131,39)	0.517 (0.279,39)	0.335 (0.188,40)
Soil Water	DIK	0.621 (0.098,59)	0.377 (0.020,33)	0.262 (0.018,59)	0.322 (0.026,36)
Stream Water	DIK	0.536 (0.012,173)	0.384 (0.008,174)	0.358 (0.008,166)	0.439 (0.012,169)
	POK	0.278 (0.057,173)	0.187 (0.033,174)	0.119 (0.016,166)	0.122 (0.018,170)

Table 25. Inputs and outputs of potassium species to streams during storms.

Values are mg/m² streambed/storm. Net difference is the average net difference between inputs and outputs of a particular species over all storms. Positive values indicate a net accumulation of a potassium species, negative values indicate a net loss. P-values (in parentheses) indicate the probabilities that net differences are significantly different from zero.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	DIK	POK	DIK	POK	DIK	POK	DIK	POK
<u>Inputs</u>								
15 Jun 1984	207.34	1.01	102.34	4.59	46.70	3.20	60.71	2.20
20 Jun 1984	158.22	4.73	59.29	2.14	49.99	1.49	53.79	1.86
10 Nov 1984	198.12	2.20	90.90	8.39	57.65	4.76	77.33	3.05
4 Dec 1984	504.13	4.70	248.69	3.41	123.78	2.99	172.17	2.78
11 Feb 1985	1118.21	0.05	554.74	0.05	209.42	0.59	395.51	0.72
21 Mar 1985	572.45	2.47	225.32	3.08	124.36	3.64	175.41	3.30
2 May 1985	226.74	1.29	126.24	1.38	83.29	5.09	121.88	6.86
7 May 1985	472.33	0.32	253.61	0.00	174.58	13.70	242.54	0.22
<u>Outputs</u>								
15 Jun 1984	135.51	57.08	60.06	29.46	29.00	6.48	60.08	14.37
20 Jun 1984	118.37	137.64	39.99	25.44	23.95	9.90	54.83	21.67
10 Nov 1984	179.06	101.18	108.89	49.97	73.95	30.35	92.21	37.71
4 Dec 1984	432.62	132.78	253.47	52.31	150.17	37.64	245.27	42.68
11 Feb 1985	941.78	357.40	530.95	145.54	255.64	55.19	450.47	141.31
21 Mar 1985	415.21	106.70	223.22	98.05	124.25	27.65	202.84	45.53
2 May 1985	201.56	38.81	107.59	25.48	62.63	16.24	122.72	8.15
7 May 1985	398.07	126.03	205.81	56.83	119.64	34.87	243.23	24.11
Net Difference	79.42 (0.01)	-130.11 (0.01)	16.39 (0.08)	-57.51 (0.01)	3.82 (0.75)	-22.86 (0.01)	-21.55 (0.07)	-39.31 (0.04)

Table 26. Net loss (< 0) or gain (> 0) of potassium during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	15.76	17.41	14.40	-11.55
20 Jun 1984	-93.06	-4.02	17.62	-20.86
10 Nov 1984	-79.92	-59.58	-41.90	-49.53
4 Dec 1984	-56.58	-53.68	-61.04	-80.74
11 Feb 1985	-180.82	-121.75	-100.82	-195.55
21 Mar 1985	53.02	-92.87	-23.90	-69.66
2 May 1985	-12.34	-5.44	9.51	2.12
7 May 1985	-51.45	-9.04	33.77	-24.60

Table 27. Sources of calcium during storms.Values are mg/m² streambed/storm.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall
15 Jun 1984	321.84	10.09	74.22	10.74	49.60	6.29	23.69	6.09
20 Jun 1984	215.21	22.62	43.74	14.79	8.10	7.11	64.58	10.83
10 Nov 1984	223.82	12.15	68.05	21.90	73.51	12.28	63.71	16.85
4 Dec 1984	553.44	7.51	203.02	7.76	104.56	8.11	143.23	7.37
11 Feb 1985	1302.95	13.11	491.09	16.25	150.52	19.40	382.25	14.13
21 Mar 1985	864.63	21.73	223.52	17.08	95.42	37.91	190.37	31.51
2 May 1985	309.07	9.72	89.94	17.55	41.84	14.15	73.07	16.85
7 May 1985	679.84	18.48	210.13	22.44	103.50	25.60	191.98	19.83

Table 28. Concentrations of calcium species in throughfall, soil water, and stream water.

Values are means (mg/L as Ca averaged over all storms) and in parentheses 95% confidence intervals and sample sizes.

		Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Throughfall	DICa	0.869 (0.303,40)	0.916 (0.295,39)	1.239 (0.378,39)	1.138 (0.378,40)
	POCa	0.149 (0.042,40)	0.130 (0.049,39)	0.190 (0.065,39)	0.161 (0.065,40)
Soil Water	DICa	0.950 (0.202,59)	0.390 (0.049,33)	0.427 (0.114,59)	0.466 (0.110,38)
Stream Water	DICa	0.879 (0.013,173)	0.441 (0.006,174)	0.438 (0.009,166)	0.566 (0.015,169)
	POCa	0.153 (0.033,173)	0.106 (0.014,174)	0.102 (0.012,166)	0.137 (0.018,170)

Table 29. Inputs of calcium species to streams during storms.

Values are mg/m² streambed/storm. Net difference is the average net difference between inputs and outputs of a particular species over all storms. Positive values indicate a net accumulation of a calcium species, negative values indicate a net loss. P-values (in parentheses) indicate the probabilities that net differences are significantly different from zero.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	DICa	POCa	DICa	POCa	DICa	POCa	DICa	POCa
<u>Inputs</u>								
15 Jun 1984	331.36	0.57	83.83	1.12	55.40	0.49	29.63	0.14
20 Jun 1984	233.10	4.73	57.07	1.44	73.73	1.49	74.16	1.25
10 Nov 1984	233.00	2.97	82.65	7.30	81.65	4.14	78.92	2.54
4 Dec 1984	559.13	1.83	209.23	1.54	111.54	1.12	149.37	1.23
11 Feb 1985	1315.38	0.70	505.89	1.45	168.92	1.01	395.37	1.00
21 Mar 1985	878.98	7.38	232.81	7.78	124.79	8.54	214.80	7.06
2 May 1985	317.80	0.99	107.08	0.41	54.29	1.69	87.22	2.70
7 May 1985	694.88	3.43	231.20	1.36	126.64	2.47	206.94	4.87
<u>Outputs</u>								
15 Jun 1984	221.16	36.04	66.35	14.99	34.76	3.34	79.53	10.01
20 Jun 1984	187.99	81.05	39.17	17.77	29.10	22.38	66.14	36.25
10 Nov 1984	265.02	58.74	110.49	20.93	79.61	28.56	111.04	35.26
4 Dec 1984	712.96	80.12	315.51	44.74	156.19	37.06	248.13	83.90
11 Feb 1985	1426.41	277.69	624.55	134.76	296.48	68.38	530.50	287.28
21 Mar 1985	719.22	85.98	299.17	81.51	170.45	39.94	314.49	44.96
2 May 1985	336.86	38.25	118.18	12.73	76.15	12.04	155.45	16.20
7 May 1985	738.21	6.40	258.50	49.30	177.00	28.10	354.59	38.33
Net Difference	-5.53 (0.88)	-80.21 (0.03)	-40.27 (0.06)	-44.29 (0.02)	-27.85 (0.02)	-27.36 (0.01)	-78.18 (0.01)	-66.42 (0.08)

Table 30. Net loss (< 0) or gain (> 0) of calcium during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	74.73	3.61	17.78	-4.93
20 Jun 1984	-31.41	1.56	23.73	-28.97
10 Nov 1984	-87.78	-41.46	-22.38	-65.73
4 Dec 1984	-232.13	-149.48	-80.59	-181.42
11 Feb 1985	-388.04	-251.96	-194.94	-421.41
21 Mar 1985	81.16	-140.09	-78.30	-137.58
2 May 1985	-56.32	-23.42	-32.21	-81.73
7 May 1985	-46.30	-75.24	-75.99	-181.12

Table 31. Sources of sulfate during storms.Values are mg/m² streambed/storm.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall	Soil	Throughfall
15 Jun 1984	288.78	31.28	99.83	27.14	46.75	27.04	109.87	25.83
20 Jun 1984	329.85	100.22	61.68	59.25	104.38	31.51	78.40	41.31
10 Nov 1984	335.60	37.32	164.22	60.41	102.89	47.20	153.32	68.10
4 Dec 1984	852.75	22.68	439.53	28.68	257.62	28.77	505.99	29.06
11 Feb 1985	2205.14	73.30	606.56	102.83	477.52	89.88	1115.42	122.57
21 Mar 1985	1034.43	130.70	308.23	137.86	174.00	198.81	392.73	144.18
2 May 1985	366.71	35.15	188.51	53.85	97.03	71.60	212.20	75.88
7 May 1985	671.39	85.00	300.95	97.92	184.00	125.55	455.17	112.90

Table 32. Concentrations of sulfate in throughfall, soil water, and stream water.

Values are means (mg/L as SO₄, averaged over all storms) and in parentheses 95% confidence intervals and sample sizes.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
Throughfall	3.965 (1.053,40)	3.818 (0.814,39)	6.800 (1.875,40)	6.252 (1.514,40)
Soil Water	1.214 (0.286,58)	0.647 (0.131,33)	0.670 (0.122,59)	0.894 (0.282,36)
Stream Water	0.765 (0.030,175)	0.616 (0.020,174)	0.813 (0.033,166)	0.790 (0.031,169)

Table 33. Outputs of sulfate from streams during storms.

Values are mg/m² streambed/storm.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	161.38	80.98	44.00	62.81
20 Jun 1984	170.44	71.92	52.59	103.38
10 Nov 1984	233.68	165.60	173.60	191.18
4 Dec 1984	666.88	418.68	351.76	417.16
11 Feb 1985	1828.38	1041.71	826.97	882.02
21 Mar 1985	510.04	356.35	266.36	382.07
2 May 1985	239.49	117.71	97.58	187.59
7 May 1985	534.07	333.08	278.42	396.48

Table 34. Net loss (< 0) or gain (> 0) of sulfate during storms.

Values are mg/m² streambed/storm. Net difference is the average net difference between inputs and outputs over all storms. Positive values indicate a net accumulation of SO₄, negative values indicate a net loss. P-values (in parentheses) indicate the probabilities that net differences are significantly different from zero.

	Big Hurricane Branch	Carpenter Branch	Hugh White Creek	Grady Branch
15 Jun 1984	158.68	46.00	29.79	72.89
20 Jun 1984	259.62	49.01	83.31	16.33
10 Nov 1984	139.24	59.02	-23.51	30.23
4 Dec 1984	208.55	49.54	-65.37	117.89
11 Feb 1985	450.06	-331.79	-259.65	355.99
21 Mar 1985	655.08	89.75	106.45	154.85
2 May 1985	162.36	124.65	71.06	100.14
7 May 1985	222.31	65.79	31.14	171.60
Net Difference	281.99 (0.01)	-3.34 (0.98)	18.99 (0.72)	135.03 (0.02)

Table 35. Concentrations of nutrient species in soil water and streamwater during baseflows.

Values are means with 95% confidence intervals and sample sizes in parentheses. Symbols indicate significant differences in nutrient concentration between soil water and streamwater.

	Big Hurricane Branch		Carpenter Branch		Hugh White Creek		Grady Branch	
	Soil	Stream	Soil	Stream	Soil	Stream	Soil	Stream
NO ₃	0.026 * (0.012,24)	0.053 (0.018,10)	0.059 (0.030,15)	0.040 (0.018,10)	0.005 * (0.002,26)	0.013 (0.005,10)	0.004 * (0.002,15)	0.013 (0.002,10)
NH ₄	0.011 (0.006,25)	0.011 (0.002,10)	0.009 (0.004,15)	0.015 (0.009,10)	0.013 (0.010,26)	0.012 (0.005,10)	0.010 (0.004,15)	0.014 (0.005,10)
DON	0.026 (0.012,25)	0.032 (0.009,10)	0.026 (0.015,15)	0.033 (0.023,10)	0.018 * (0.010,26)	0.043 (0.032,10)	0.020 (0.015,15)	0.018 (0.014,10)
PON	- -	0.018 (0.018,10)	- -	0.033 (0.034,10)	- -	0.024 (0.023,10)	- -	0.030 (0.025,10)
Total N	0.062 * (0.017,24)	0.114 (0.029,10)	0.094 (0.034,15)	0.121 (0.038,10)	0.036 * (0.014,26)	0.092 (0.032,10)	0.034 * (0.015,15)	0.074 (0.023,10)
DIP	0.004 (0.002,25)	0.002 (0.002,10)	0.002 (0.001,15)	0.003 (0.002,10)	0.006 (0.004,26)	0.002 (0.002,10)	0.005 (0.004,15)	0.004 (0.002,10)
DOP	0.009 (0.008,25)	0.006 (0.005,10)	0.013 (0.011,15)	0.005 (0.005,10)	0.016 (0.010,26)	0.002 (0.002,10)	0.004 (0.004,15)	0.006 (0.007,10)
POP	- -	0.021 (0.016,10)	- -	0.026 (0.023,10)	- -	0.016 (0.009,10)	- -	0.006 (0.007,10)
Total P	0.013 * (0.008,25)	0.029 (0.014,10)	0.015 § (0.011,15)	0.033 (0.020,10)	0.022 (0.010,26)	0.021 (0.009,10)	0.009 * (0.004,15)	0.017 (0.007,10)
DIK	0.639 (0.151,25)	0.497 (0.038,10)	0.357 (0.034,15)	0.346 (0.027,10)	0.250 * (0.029,25)	0.338 (0.034,10)	0.315 * (0.051,15)	0.413 (0.041,10)
POK	- -	0.080 (0.045,10)	- -	0.057 (0.018,10)	- -	0.028 (0.020,10)	- -	0.034 (0.027,10)
Total K	0.639 (0.151,25)	0.577 (0.050,10)	0.357 § (0.034,15)	0.403 (0.032,10)	0.250 * (0.029,25)	0.366 (0.023,10)	0.315 * (0.051,15)	0.447 (0.029,10)
DICa	0.919 (0.369,25)	0.835 (0.061,10)	0.432 (0.090,15)	0.379 (0.025,10)	0.502 (0.272,25)	0.386 (0.032,10)	0.539 (0.236,15)	0.535 (0.054,10)
POCa	- -	0.111 (0.059,10)	- -	0.047 (0.023,10)	- -	0.059 (0.027,10)	- -	0.093 (0.048,10)
Total Ca	0.919 (0.369,25)	0.946 (0.050,10)	0.432 (0.090,15)	0.426 (0.009,10)	0.502 (0.272,25)	0.446 (0.036,10)	0.539 (0.236,15)	0.628 (0.041,10)
SO ₄	1.289 (0.543,25)	0.592 (0.050,10)	0.711 (0.277,15)	0.514 (0.075,10)	0.732 (0.233,26)	0.551 (0.050,10)	0.934 (0.478,15)	0.532 (0.070,10)

* P < 0.05
§ P < 0.06

Table 36. Annual nitrogen budgets for Coweeta streams.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Big Hurricane Branch			Hugh White Creek		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DIN	4,320 (47.5)	7,470 (42.7)	-3,150	800 (28.0)	1,120 (20.2)	-320
DON	3,040 (33.4)	3,740 (21.3)	-700	800 (28.0)	1,920 (34.8)	-1,120
PON	- -	2,100 (12.0)	-2,100	- -	1,070 (19.4)	-1,070
Total	7,360 (80.9)	13,310 (76.0)	-5,950	1,600 (56.0)	4,110 (74.5)	-2,510
<u>Storm flows</u>						
DIN	640 (7.1)	990 (5.6)	-340	290 (10.1)	220 (4.0)	70
DON	810 (8.9)	560 (3.2)	250	540 (18.7)	330 (6.1)	210
PON	280 (3.1)	2,660 (15.2)	-2,380	440 (15.3)	850 (15.5)	-410
Total	1,730 (19.1)	4,200 (24.0)	-2,470	1,270 (44.0)	1,400 (25.5)	-130
Annual Total	9,090	17,510	-8,420	2,870	5,510	-2,640

Table 37. Annual nitrogen budgets for Coweeta streams continued.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Carpenter Branch			Grady Branch		
	input	output	difference	input	output	difference
Baseflows						
DIN	5,190 (57.4)	4,200 (34.9)	990	920 (24.8)	1,770 (25.9)	-850
DON	1,980 (21.9)	2,520 (20.9)	-540	1,310 (35.5)	1,180 (17.2)	130
PON	- -	2,520 (20.9)	-2,520	- -	1,960 (28.7)	-1,960
Total	7,170 (79.3)	9,240 (76.7)	-2,070	2,230 (60.3)	4,910 (71.9)	-2,680
Storm flows						
DIN	930 (10.3)	810 (6.7)	120	420 (11.4)	410 (6.0)	10
DON	610 (6.7)	490 (4.1)	120	610 (16.6)	380 (5.6)	230
PON	330 (3.7)	1,510 (12.5)	-1,180	430 (11.7)	1,130 (16.6)	-700
Total	1,870 (20.7)	2,810 (23.3)	-940	1,460 (39.7)	1,920 (28.1)	-460
Annual Total	9,040	12,050	-3,010	3,690	6,830	-3,140

Table 38. Annual phosphorus budgets for Coweeta streams.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Big Hurricane Branch			Hugh White Creek		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DIP	470 (23.4)	230 (4.4)	240	220 (27.3)	180 (11.5)	40
DOP	1,050 (52.5)	700 (13.3)	350	180 (21.8)	270 (17.2)	-90
POP	- -	2,450 (45.8)	-2,450	- -	270 (17.2)	-270
Total	1,520 (75.9)	3,380 (64.2)	-1,860	400 (49.2)	720 (45.8)	-320
<u>Storm flows</u>						
DIP	160 (7.8)	70 (1.3)	90	80 (10.4)	40 (2.8)	40
DOP	150 (7.4)	110 (2.1)	40	170 (20.7)	80 (5.1)	90
POP	180 (8.8)	1,710 (32.4)	-1,530	160 (19.7)	720 (46.3)	-560
Total	490 (24.1)	1,890 (35.8)	-1,400	410 (50.8)	840 (54.2)	-430
Annual Total	2,010	5,270	-3,260	810	1,560	-750

Table 39. Annual phosphorus budgets for Coweeta streams continued.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Carpenter Branch			Grady Branch		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DIP	150 (10.2)	230 (6.0)	-80	330 (32.1)	260 (12.5)	70
DOP	990 (66.4)	380 (10.0)	610	260 (25.2)	390 (18.8)	-130
POP	- -	1,980 (52.1)	-1,980	- -	390 (18.8)	-390
Total	1,140 (76.8)	2,590 (68.2)	-1,450	590 (57.3)	1,040 (50.1)	-450
<u>Storm flows</u>						
DIP	110 (7.1)	60 (1.6)	50	100 (9.7)	40 (2.1)	60
DOP	130 (8.9)	130 (3.5)	0	180 (17.5)	90 (4.2)	90
POP	110 (7.5)	1,020 (26.7)	-910	160 (15.5)	910 (43.6)	-750
Total	350 (23.4)	1,210 (31.8)	-860	440 (42.7)	1,040 (49.9)	-600
Annual Total	1,490	3,800	-2,310	1,130	2,080	-1,051

Table 40. Annual potassium budgets for Coweeta streams.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Big Hurricane Branch			Hugh White Creek		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DIK	74,590 (88.7)	58,020 (73.7)	16,570	11,160 (70.6)	15,090 (73.5)	-3,930
POK	- -	9,340 (11.9)	-9,340	- -	1,250 (6.1)	-1,250
Total	74,590 (88.7)	67,360 (85.6)	7,230	11,160 (70.6)	16,340 (79.6)	-5,180
<u>Storm flows</u>						
DIK	9,420 (11.2)	7,510 (9.5)	1,910	4,360 (27.6)	3,150 (15.3)	1,210
POK	70 (0.1)	3,890 (4.9)	-3,820	280 (1.8)	1,050 (5.1)	-770
Total	9,490 (11.3)	11,400 (14.4)	-1,910	4,640 (29.4)	4,200 (20.4)	440
Annual Total	84,080	78,760	5,320	15,800	20,540	-4,740

Table 41. Annual potassium budgets for Coweeta streams continued.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Carpenter Branch			Grady Branch		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DIK	27,230 (82.4)	26,390 (70.0)	840	20,580 (79.2)	27,020 (76.3)	-6,440
POK	- -	4,350 (11.5)	-4,350	- -	2,220 (6.3)	-2,220
Total	27,230 (82.4)	30,740 (81.5)	-3,510	20,580 (79.2)	29,240 (82.6)	-8,660
<u>Storm flows</u>						
DIK	5,680 (17.2)	4,700 (12.4)	980	5,220 (20.0)	4,820 (13.6)	400
POK	140 (0.4)	2,290 (6.1)	-2,150	190 (0.4)	1,340 (3.8)	-1,150
Total	5,820 (17.6)	6,990 (18.5)	-1,170	5,410 (20.8)	6,160 (17.4)	-750
Annual Total	33,050	37,730	-4,680	25,990	35,400	-9,410

Table 42. Annual calcium budgets for Coweeta streams.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Big Hurricane Branch			Hugh White Creek		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DICa	107,280 (88.9)	97,470 (78.0)	9,810	22,420 (83.9)	17,240 (70.0)	5,180
POCa	- -	12,960 (10.4)	-12,960	- -	2,630 (10.7)	-2,630
Total	107,280 (88.9)	110,430 (88.4)	-3,150	22,420 (83.9)	19,870 (80.7)	2,550
<u>Storm flows</u>						
DICa	13,260 (11.0)	12,310 (9.9)	950	4,200 (15.7)	3,860 (15.7)	340
POCa	80 (0.1)	2,140 (1.7)	-2,060	100 (0.4)	900 (3.6)	-800
Total	13,340 (11.1)	14,450 (11.6)	-1,110	4,300 (16.1)	4,760 (19.3)	-460
Annual Total	120,620	124,880	-4,260	26,720	24,630	2,090

Table 43. Annual calcium budgets for Coweeta streams continued.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Carpenter Branch			Grady Branch		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
DiCa	32,950 (86.3)	28,910 (72.4)	4,040	35,260 (86.3)	35,000 (71.7)	260
POCa	-	4,350 (10.9)	-4,350	-	6,080 (12.5)	-6,080
Total	32,950 (86.3)	33,260 (83.3)	-310	35,260 (86.3)	41,080 (84.2)	-5,820
<u>Storm flows</u>						
DiCa	5,140 (13.5)	5,400 (13.5)	-260	5,510 (13.5)	6,220 (12.7)	-710
POCa	90 (0.2)	1,300 (3.2)	-1,210	90 (0.2)	1,500 (3.1)	-1,410
Total	5,230 (12.5)	6,700 (16.7)	-1,470	5,600 (13.7)	7,720 (15.8)	-2,120
Annual Total	38,180	39,960	-1,780	40,860	48,800	-7,940

Table 44. Annual sulfate budgets for Coweeta streams.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Big Hurricane Branch			Hugh White Creek		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
SO ₄	150,470 (89.1)	69,110 (86.6)	81,360	32,690 (78.0)	24,610 (77.5)	8,080
<u>Storm flows</u>						
SO ₄	18,420 (10.1)	10,710 (13.4)	7,710	9,190 (22.0)	7,160 (22.5)	2,030
Annual Total	168,890	79,820	89,070	41,880	31,770	10,110

Table 45. Annual sulfate budgets for Coweeta streams continued.

Values are mg/m² streambed/year with the percent of total annual inputs or outputs listed in parentheses.

	Carpenter Branch			Grady Branch		
	input	output	difference	input	output	difference
<u>Baseflows</u>						
SO ₄	54,240 (84.2)	39,210 (83.9)	15,030	61,100 (81.9)	34,800 (80.0)	26,300
<u>Storm flows</u>						
SO ₄	10,160 (15.8)	7,540 (16.1)	2,620	13,460 (18.1)	8,680 (20.0)	4,780
Annual Total	64,400	46,750	17,650	74,560	43,480	31,080

Table 46. Annual budgets including litterfall nutrient contributions.

Nitrogen, phosphorus, potassium, and calcium content of hardwood litter 0.85%, 0.125%, 0.47%, and 1.23%; nitrogen, phosphorus, potassium, and calcium content of wood litter 0.55%, 0.088%, 0.081%, and 0.079% respectively. Nutrient data collected from undisturbed hardwood forest at Coweeta (WS-18) (Cromack 1973). Nutrient contributions are mg/m² streambed/year.

		Litter Input g AFDW/m ²	Nitrogen	Phosphorus	Potassium	Calcium
BHB	baseflow soil	-	7,360	1,520	74,590	107,280
	stormflow soil	-	1,040	220	8,380	12,810
	throughfall	-	700	270	1,120	520
	leaves	436	3,710	550	2,050	5,360
	wood	70	390	60	60	60
	total inputs	-	13,200	2,620	86,200	126,030
	total outputs	-	17,510	5,270	78,760	124,880
	net	-	-4,310	-2,650	7,440	1,150
CB	baseflow soil	-	7,170	1,140	27,230	32,950
	stormflow soil	-	970	150	4,350	4,500
	throughfall	-	900	200	1,480	740
	leaves	459	3,900	570	2,160	5,640
	wood	70	390	60	60	60
	total inputs	-	13,330	2,120	35,280	43,890
	total outputs	-	12,050	3,800	37,730	39,960
	net	-	1,280	-1,680	-2,450	3,930

Table 47. Annual budgets including litterfall nutrient contributions, continued.

Nitrogen, phosphorus, potassium, and calcium content of hardwood litter 0.85%, 0.125%, 0.47%, and 1.23%; nitrogen, phosphorus, potassium, and calcium content of wood litter 0.55%, 0.088%, 0.081%, and 0.079% respectively. Nutrient data collected from undisturbed hardwood forest at Coweeta (WS-18) (Cromack 1973). Nutrient contributions are mg/m² streambed/year.

		Litter Input g AFDW/m ²	Nitrogen	Phosphorus	Potassium	Calcium
HWC	baseflow soil	-	1,600	400	11,160	22,420
	stormflow soil	-	360	130	2,170	3,530
	throughfall	-	910	280	2,480	770
	leaves	491	4,180	610	2,310	6,040
	wood	98	540	90	80	80
	total inputs	-	7,590	1,510	18,200	32,840
	total outputs	-	5,510	1,560	20,540	24,630
	net	-	-2,080	-50	-2,340	8,210
GB	baseflow soil	-	2,230	590	20,580	35,260
	stormflow soil	-	430	180	3,350	4,850
	throughfall	-	1,040	260	2,060	760
	leaves	626	5,320	780	2,940	7,700
	wood	266	1,470	230	220	210
	total inputs	-	10,490	2,040	29,150	48,780
	total outputs	-	6,830	2,080	35,400	48,800
	net	-	3,660	-40	-6,250	-20

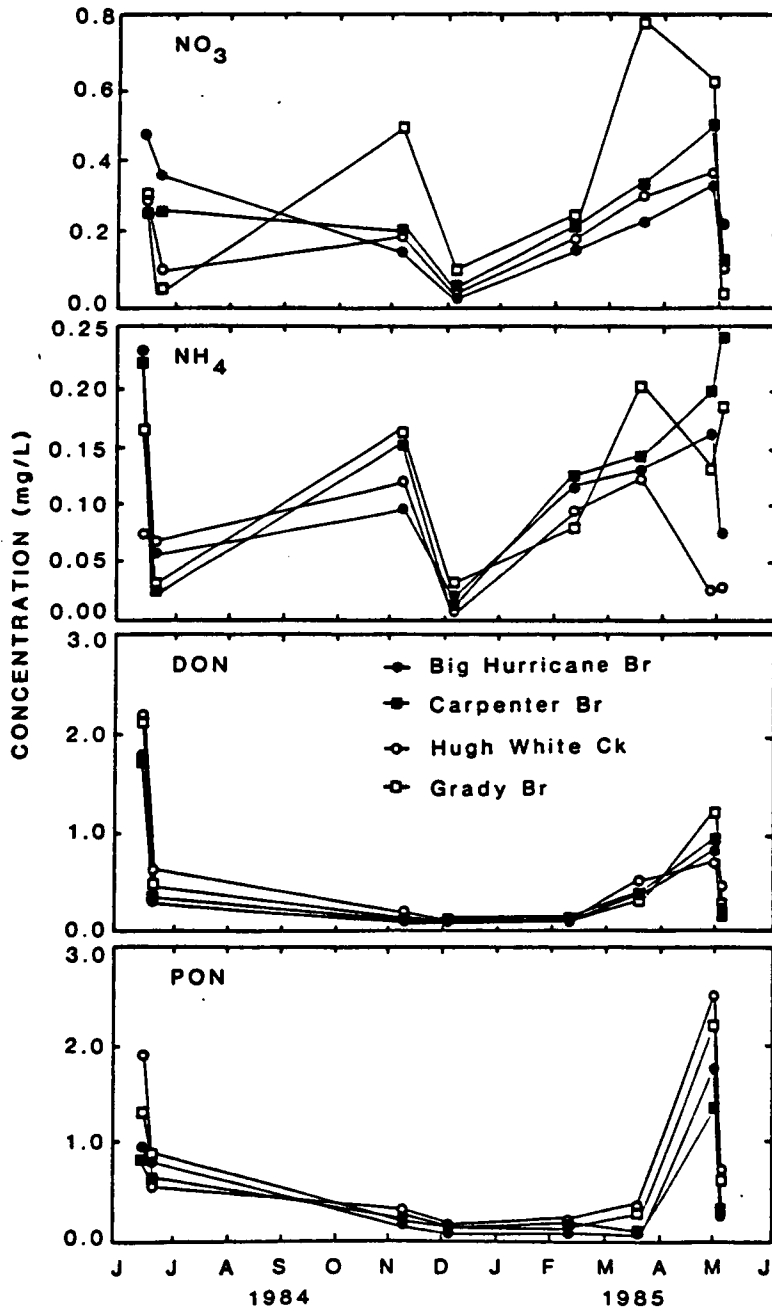


Figure 8. Throughfall nitrogen species: Values are mean concentration in mg/L.

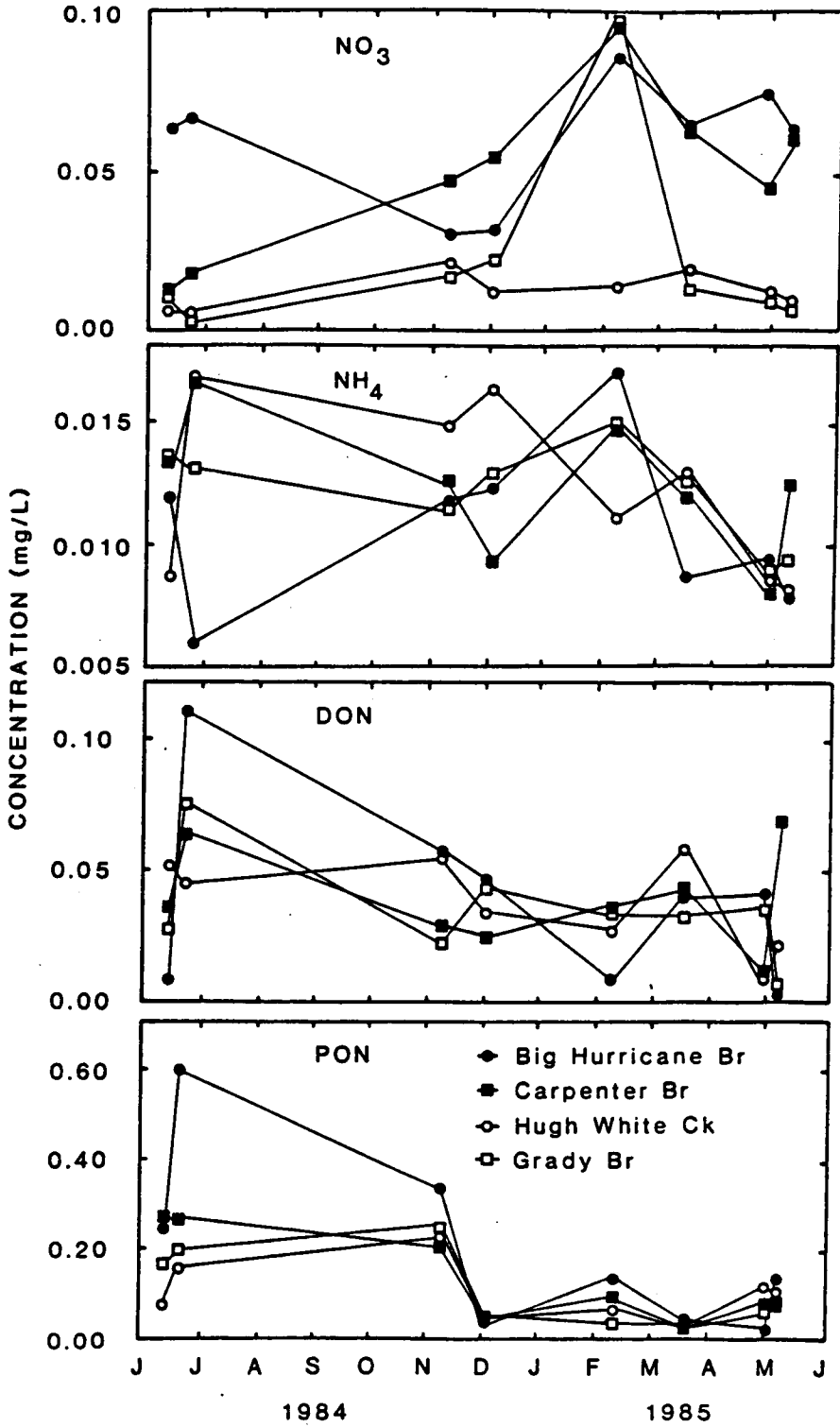


Figure 9. Stream water nitrogen species: Values are mean concentration in mg/L.

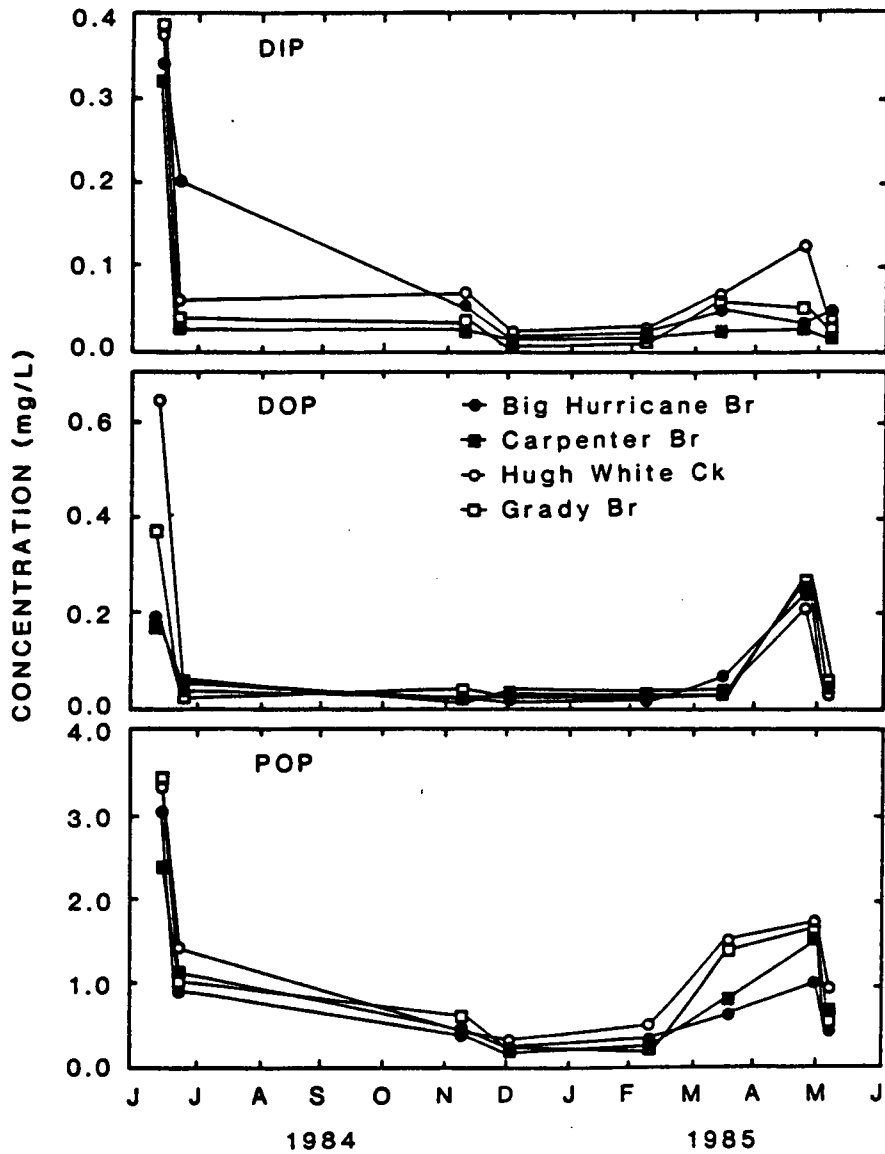


Figure 10. Throughfall phosphorus species: Values are mean concentration in mg/L.

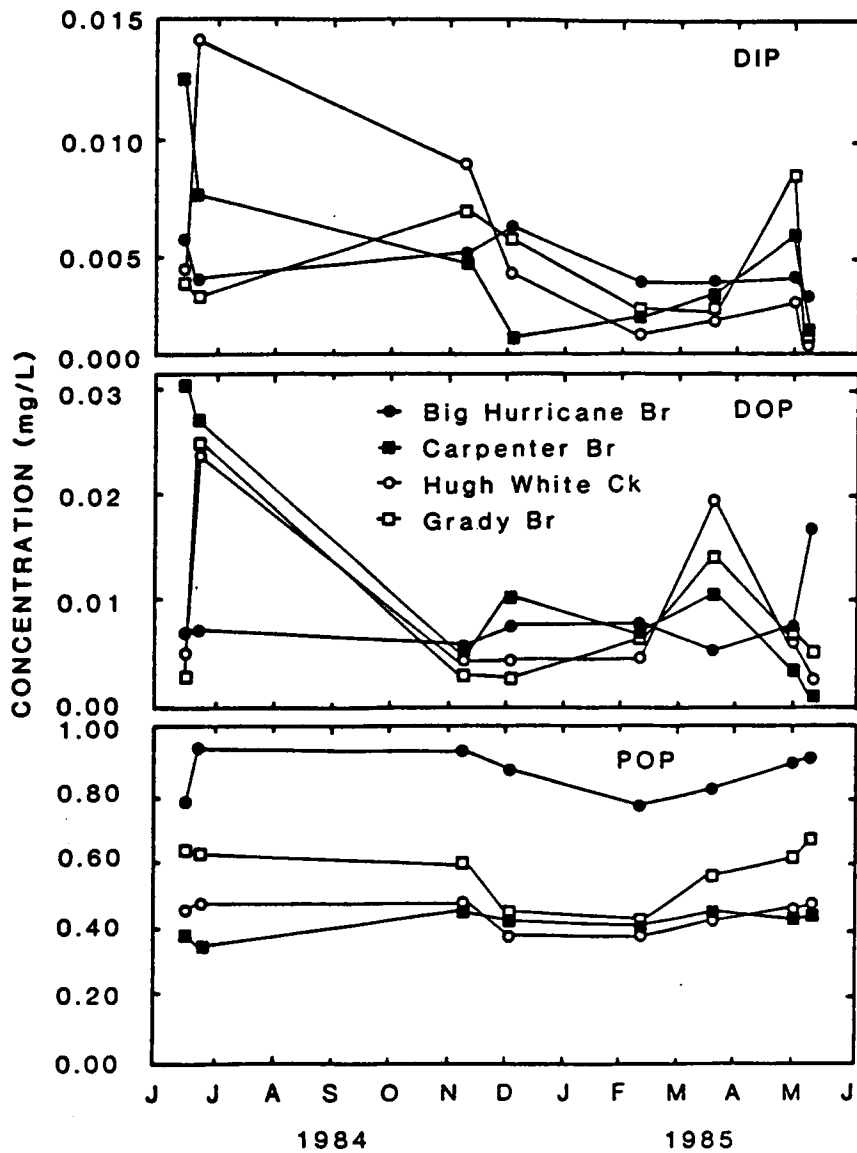


Figure 11. Stream water phosphorus species: Values are mean concentration in mg/L.

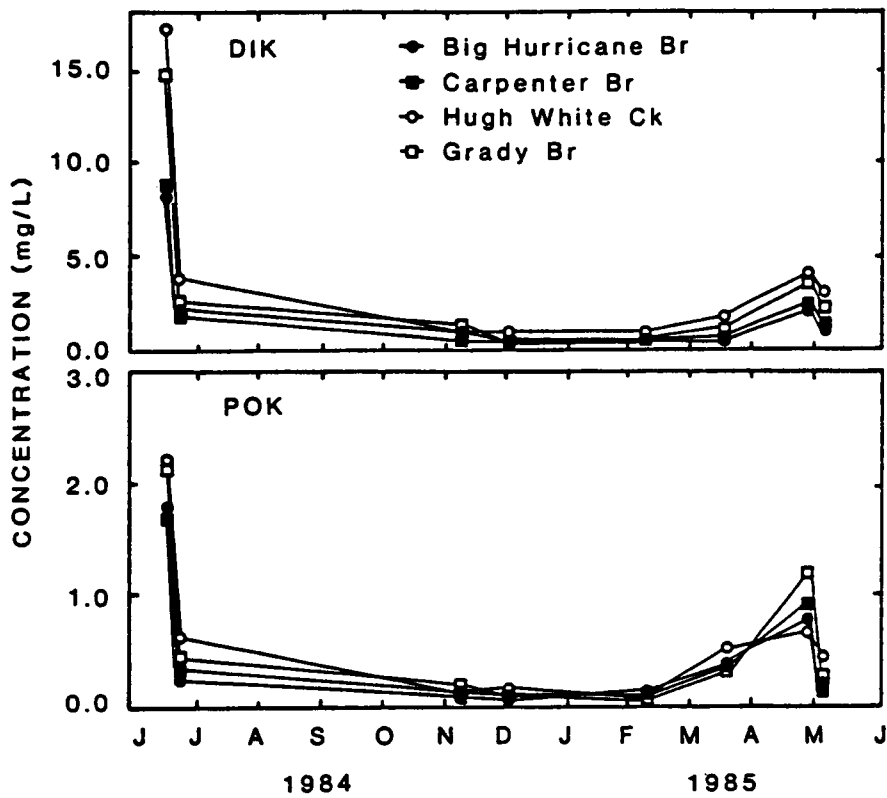


Figure 12. Throughfall potassium species: Values are mean concentration in mg/L.

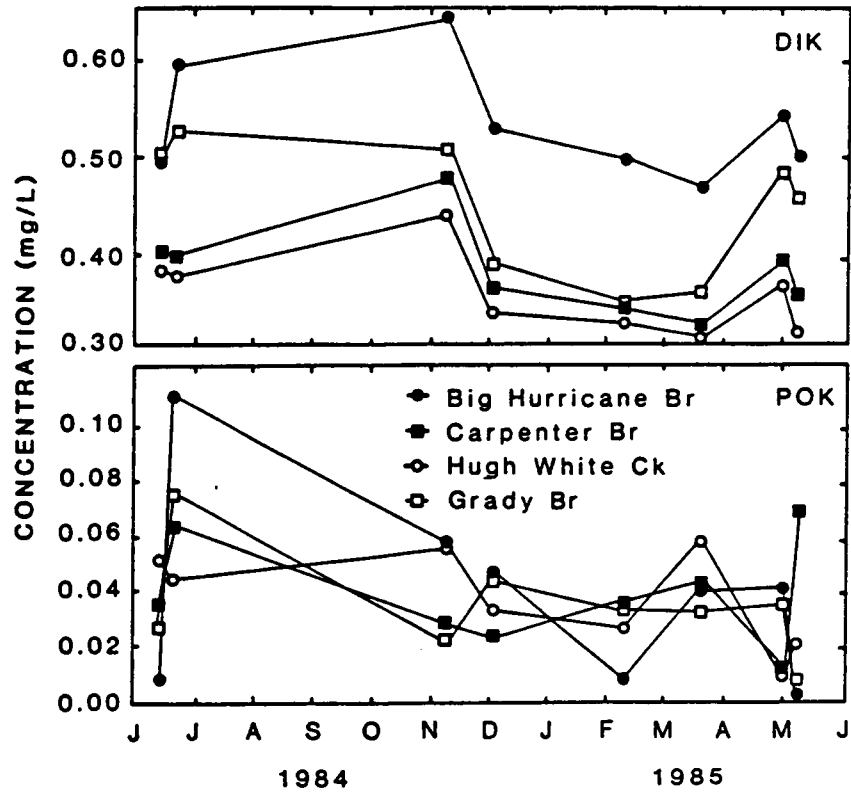


Figure 13. Stream water potassium species: Values are mean concentration in mg/L.

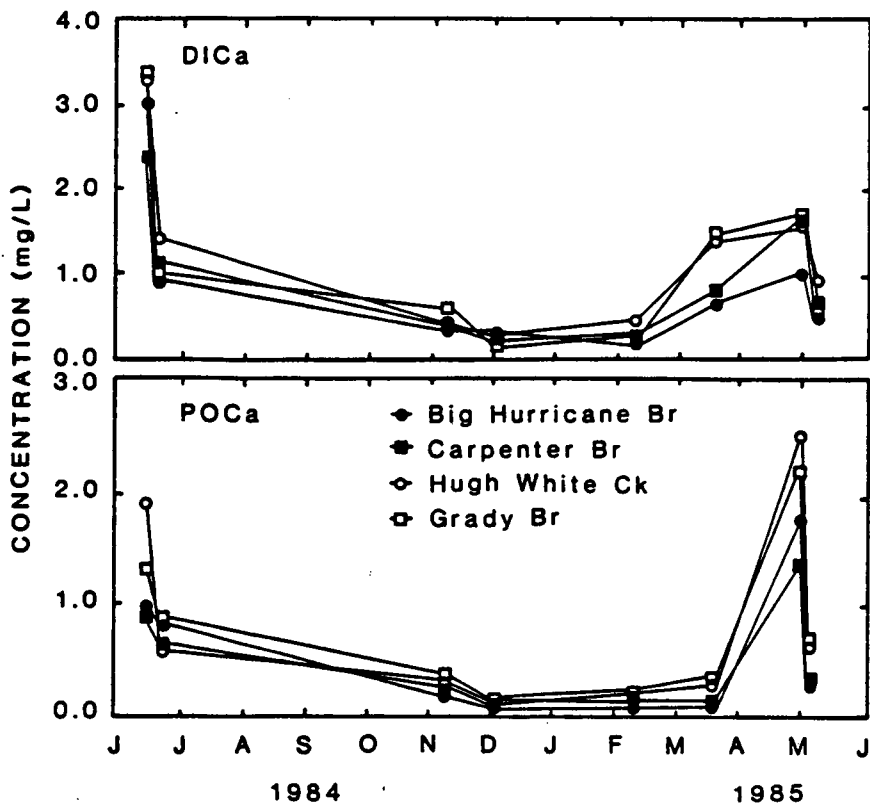


Figure 14. Throughfall calcium species: Values are mean concentration in mg/L.

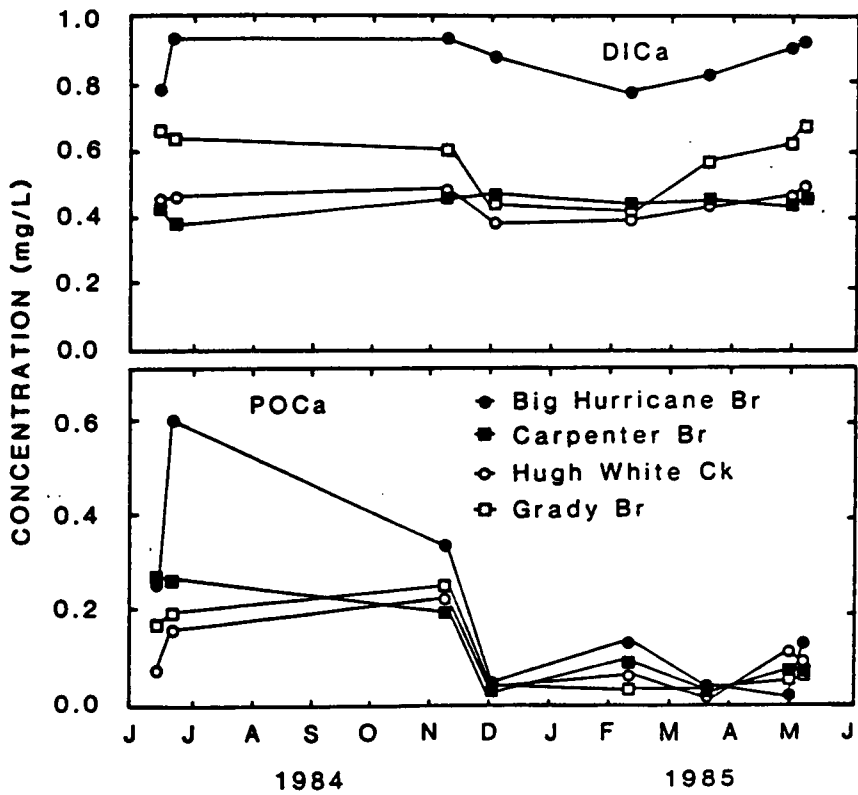


Figure 15. Stream water calcium species: Values are mean concentration in mg/L.

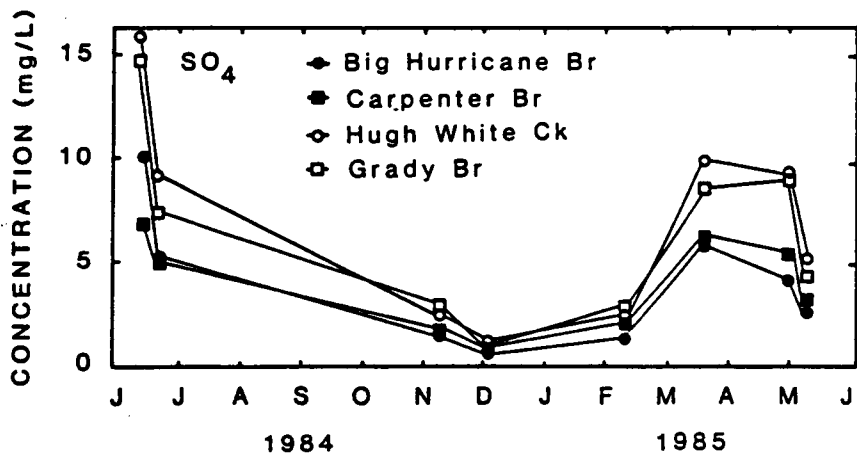


Figure 16. Throughfall sulfate: Values are mean concentration in mg/L.

Summary

Chapter 1--1. Surveys of stream morphology and measurements of particulate organic matter (seston) transport were made in four streams to examine response to forest disturbance. Seston was sampled during baseflows and stormflows in streams draining an 8-year-old clearcut, a 25-year-old clearcut, and two reference watersheds at Coweeta Hydrologic Laboratory in the southern Appalachian Mountains of North Carolina.

2. Surveys of stream morphology indicated that there were fewer debris dams and organic matter accumulations in disturbed streams.

3. Baseflow seston concentrations varied seasonally, ranging from 0.5 to 1.0 mg/L in winter and from 3.0 to 7.0 mg/L during summer. Baseflow seston concentrations did not differ consistently between streams.

4. In all streams, seston concentration increased with increasing discharge during storms and was positively correlated with the rate of change of discharge during rising flows. Seston concentrations decreased during peak flows and gradually declined as discharge returned to baseflow.

5. Average seston concentrations during storms were generally highest in streams draining disturbed watersheds, and export (g AFDW transported/m² stream channel) was sig-

nificantly higher in streams draining disturbed watersheds. Storm transport varied with season, storm intensity, and storm duration.

6. These results show that baseflow seston concentrations in streams draining disturbed areas may return to normal levels within a few years following disturbance; however, concentrations during storms may remain elevated for many years.

Chapter 2--1. Benthic organic matter was collected quarterly from streams draining a 9-year-old clearcut, an 18-year-old "old-field", a 25-year-old successional forest, and 2 reference watersheds. Samples were separated into large benthic organic matter (LBOM > 1 mm) and fine benthic organic matter (FBOM < 1 mm). An additional survey of large (> 5 cm diam.) and small (1-5 cm diam.) wood was conducted.

2. LBOM ranged from 124.2 to 255.2 g AFDW/m² and was significantly higher in streams draining reference watersheds and the intermediate successional forest than in either the recent clearcut or old-field. Reference sites exhibited LBOM peaks in late autumn and spring. There were no distinct seasonal patterns in disturbed streams.

3. FBOM averaged 112.8 to 386.6 g AFDW/m², and the stream draining the intermediate successional forest had significantly higher FBOM levels than the other sites. In reference streams, FBOM abundance peaked in spring. In disturbed streams, FBOM standing stocks were highest in summer or late autumn.

4. Large wood ranged from 0.0 to 3955.5 g AFDW/m² and was significantly higher in the reference streams than in streams draining the old-field or successional forest. The stream draining the recent clearcut was intermediate. Small wood averaged from 11.06 to 341.6 g AFDW/m² and was significantly lower in the stream draining the old-field than at the other sites.

5. Comparisons of organic matter inputs with standing stocks indicated that disturbed streams at Coweeta receive less material and process it faster than reference streams. Disturbed streams also appear to be less retentive than reference streams and exhibit a gradual decline in FBOM during the winter when large, long duration storms combined with low particle generation rates deplete accumulated FBOM.

Chapter 3–1. Stream stability, defined as the ability to retain biologically important nutrients was determined for streams draining 9- and 25-year-old clearcuts and 2 reference watersheds. Inputs and outputs of organic and inorganic forms of nitrogen, phosphorus, calcium, and potassium were measured during baseflows and stormflows. Inputs and outputs of sulfate were also measured. Sources of nutrients measured were soil water and throughfall; nutrient loss was as downstream transport.

2. Storm nutrient budgets indicated that streams draining early and intermediate successional forest were less retentive of nitrogen and phosphorus than reference sites. Nitrogen loss from disturbed streams averaged 58.04 mg/m² streambed/storm and from reference streams averaged 16.52 mg/m² streambed/storm. Phosphorus loss from disturbed streams averaged 32.52 mg/m² streambed/storm and from reference streams averaged 7.14 mg/m² streambed/storm. A majority of the nitrogen and phosphorus loss in all streams was in association with organic particles. There was no difference between disturbed and reference streams in potassium, calcium, or sulfate retention during storms. However, disturbed streams tended to lose more particulate organic potassium and calcium than disturbed sites.

3. Annual budgets indicated that all streams were net exporters of nitrogen and phosphorus. Nitrogen losses were 8420, 2990, and 2890 mg/m² streambed/year from streams draining 9-, 25-year-old clearcuts, and undisturbed forest respectively. Net losses of phosphorus were 3280 and 2310 mg/m² streambed/year in streams draining 9- and 25-year-old clearcuts, respectively, and 842 mg/m² streambed/year from reference streams. Nitrogen and phosphorus loss was largely accounted for by net export of PON and POP: disturbed streams lost substantially more PON and POP than reference streams during both base- and stormflows.

4. Annual potassium and calcium budgets were dominated by the movement of cations. Forest clearing appeared to have little impact on instream mechanisms of cation retention. Differences in potassium and calcium retention between streams were due to the combined effects of soil disturbance and differences in watershed geology.

5. Annual sulfate budgets indicate that forest disturbance has had little impact on SO₄ retention in streams. All streams accumulated SO₄ during baseflows and stormflows.

6. These results indicate that forest disturbance has a long term impact on stream ecosystems by reducing their stability for many years following forest clearing. Unlike forests, where disturbance appears to primarily interfere with biological uptake and accumulation of nutrients, stream disturbance results in a reduction in the ability to retain nutrients already incorporated into organic matter. As a result, disturbed streams lose substantial quantities of nutrient containing particles during baseflows and stormflows.

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