NUTRIENT UPTAKE AND COMMUNITY METABOLISM IN STREAMS DRAINING HARVESTED AND OLD-GROWTH WATERSHEDS: A PRELIMINARY ASSESSMENT

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Abstract—The effect of timber harvesting on streams is assessed using two measures of ecosystem function: nutrient spiraling and community metabolism. This research is being conducted in streams of the southern Appalachian Mountains of North Carolina, the Ouachita Mountains of Arkansas, the Cascade Mountains of Oregon, and the redwood forests of northern California, in order to understand similarities and differences among stream ecosystem responses to timber harvesting across diverse geographic regions. Data from Cedar and Peacock Creeks in the redwood forest are used to illustrate the principles and usefulness of measuring stream ecosystem function for assessing watershed disturbances. Streams draining logged watersheds had smaller dominant substrate size and more sand and fine sediments in the channel. Nutrient uptake (NH_4^{+1}, PO_4^{-3}) and community metabolism (primary productivity, respiration, P:R, net daily metabolism) were measured in streams draining old-growth (Cedar Creek) and harvested (Peacock Creek) watersheds. Phosphate uptake length was significantly shorter in Cedar Creek (212 m) than in Peacock Creek (1020 m). Ammonium uptake length was not significantly different in these streams (111 m vs. 109 m, respectively). Preliminary analyses of stream metabolism suggest that primary productivity is greater in streams draining logged watersheds, but community respiration is greater in stream draining old-growth watersheds, resulting in sustantial differences in P:R and NDM.

INTRODUCTION

The Frontier Forest Initiative of the World Resources Institute reported that north temperate regions contain more than 50 percent of the world's healthy, intact "frontier" forests (World Resources Institute 1997). The United States has about 12 percent of the world's temperate forest and is harvesting these forests at a rate of more than 500,000 ha/y (World Resources Institute 1997).

The regenerated forests of temperate regions are often quite different from the original forests. Studies of the reforested areas of the northeastern United States have shown changes in tree species composition and smaller tree sizes compared with historical forests. Forest plantations may compensate for the loss of forest resources, but there is little evidence suggesting that they maintain pre-harvest levels of ecosystem function (Franklin 1988, Swank and Crossley 1988).

Timber harvests affected streams in most forested areas of the United States (Cummins 1980, Webster and Swank 1985, Webster and others 1992). van der Leeden and others (1990) reported that 7.5 percent of the total U.S. stream length has been impacted by logging and silvicultural practices.

Ecosystems are complex, self-regulating, functional units. Unlike communities and populations which are structurally defined, ecosystems are defined by rates and processes, such as energy flow or material cycling. These processes are mediated by the trophic structure of the ecosystem. Functional indicators are those metrics that directly or indirectly measure energy flow and material cycling within ecosystems. Functional indicators (such as ecosystem metabolism or nutrient cycling) are less likely to be constrained by regionally restricted biota. Thus, functional approaches lead to a more global view of stream ecosystems, a view that is much less variable than one based only on taxa inhabiting stream communities (Cummins 1988). Hunsaker and others (1990) stated that for regional ecological risk assessments to be effective, the system must be functionally defined, with the spatio-temporal boundaries of the system set by functional attributes of the communities inhabiting the system. Assessments that are functionally based are likely to have greater applicability across regions (Hunsaker and others 1990).

The most commonly measured functional attributes of ecosystems are primary productivity, or photosynthesis, (P) and community respiration (R). These two metrics are termed community metabolism when considered together. Two additional metrics are calculated from P and R: the ratio of P to and daily P-R which yields an estimate of net daily metabolism (NDM). These four metrics have been shown to be sensitive indicators of ecosystem stress (Bott and others 1985, Hill and others 1997). Metabolism is expected to be stimulated by nutrients and some organic substances and suppressed by some pesticides and organic substances, decreased pH, metals, and habitat degradation stress (Bott and others 1985, Hill and others 1997).

Many of the transformations which nutrients undergo while being transported into, through, and out of a stream segment are determined by difference between input and output. The actual pathway an atom of nutrient takes through this system, usually inferred from movements of radioactive tracers from one ecosystem component to another, is described as spiraling (Webster and Patten 1979).

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Elwood and others (1983) listed three aspects of the spiraling concept that make it useful for the analysis of stream ecosystems. First, it is a simple means of measuring nutrient (including carbon) flow through streams. Second, this concept emphasizes the interaction of hydrologic transport and ecological processes governing nutrient cycling. Third, the interaction of both spatial and temporal dynamics of streams is emphasized. Additionally, spiral length may be indicative of increases in nutrient turnover, transport, and loss from streams as predicted for stressed ecosystems.

Newbold and others (1981) developed an index of nutrient spiraling known as spiraling length, defined as the average downstream distance associated with one complete cycle of a nutrient atom. In developing this index, they assumed that a nutrient atom passes through water, particulate, and consumer compartments while being transported. These components of the spiral can be quantified and the sum of their average distances is the spiraling length.

Investigations of factors controlling spiral length have shown a greater role by the biotic component (e.g., Elwood and others 1981; Newbold and others 1982, 1983; Mulholland and others 1985b, 1985a) than by abiotic factors. Spiral length is decreased by those organisms that retain organic matter and nutrients within a stream (e.g., sessile microorganisms, filter-feeding insects, and grazers), and increased by organisms which promote particle transport (e.g., shredders). Elwood and others (1981) found that 91 percent of exchangeable phosphorus uptake by fine particulate organic matter (FPOM) was due to microorganisms. Similarly, about 80 percent of the exchangeable phosphorus uptake by stream sediments was due to microorganisms. These findings are in agreement with those of Gregory (1978) who reported less than 20 percent of the phosphorus uptake by stream sediments and organic matter was abiotic.

Newbold and others (1983) reported that uptake length accounted for nearly 90 percent of the total spiral length. Mulholland and others (1985b) found uptake length to be as much as 98 percent of spiral length. If spiral length can be estimated accurately (± 10 percent) from uptake length, then pulse additions of non-radioactive phosphorus and ensuing downstream depletion of this phosphorus should serve as a measure of phosphorus spiraling in those streams where the use of radioactive tracers would be undesirable (Stream Solute Workshop 1990, Mulholland and others 1990, Webster and others 1991). Uptake length is expected to increase with most stressors, though some organic substances may result in uptake length shortening.

The goal of this research is to evaluate stream ecosystem function in response to different timer harvesting intensities and time since harvesting. The research is being conducted in streams of the southern Appalachian Mountains of North Carolina, the Ouachita Mountains of Arkansas, the Cascade Mountains of Oregon, and the redwood forests of northern California. A secondary objective will be the assessment of intra- and inter-annual variability in measures of stream ecosystem function. We predict that any amount of watershed disturbance by logging will affect ecosystem function by depressing community metabolism and increasing nutrient uptake lengths.

METHODS

Study Sites

The study is being conducted at 24 sites grouped by different levels of watershed degradation due to the intensity of forestry management practice. Sites have been selected at National Science Foundation Long-Term Ecological Research (LTER) sites and US Forest Service (USFS) research units at the Southern Research Station and Redwood Sciences Laboratory. Sites are of comparable watershed size. The LTER sites have extensive historical databases on hydrology, chemistry and aquatic community structure and managed impact programs. The USFS sites have historical data on hydrology, physical habitat, aquatic community structure and timber harvest.

Coweeta Hydrologic Laboratory—The Coweeta Hydrologic Laboratory is a 2,185 ha experimental facility in North Carolina administered by the USFS. It has been dedicated to forest hydrology research since its establishment in 1933. Stream sampling has been conducted on eight mixed hardwood control areas and 13 catchments where forest management prescriptions have been applied.

Ouachita National Forest—The Ouachita National Forest is an 800,000 ha mixed hardwood-conifer forest in central Arkansas. Research sponsored by the USFS Southern Research Station has been conducted on streams in the unit since 1988. In 1990, clear-cutting was eliminated and a research program initiated to examine the effects of new forest management strategies on stream ecosystems.

H. J. Andrews Experimental Forest (LTER)—The H.J. Andrews Experimental Forest, located in the Cascade Range of Oregon, is a 6,400 ha drainage basin administered by the USFS Pacific Northwest Research Laboratory. When it was established in 1948, the basin was covered with virgin forest. Old-growth forest stands with dominant trees over 400 years old still cover about 40 percent of the total area. Mature stands (100 to 140 years old) originating from wildfire cover about 20 percent. About 30 percent of the Andrews Forest has been harvested, creating young plantation forests varying in composition and age.

Redwood Sciences Laboratory—Unlike the other study units, which have their experimental watersheds located in close proximity, the redwood forest study unit has widely dispersed experimental watersheds. These study watersheds are an aggregation of management units of the Six Rivers National Forest and the Redwoods State and National Park and are scattered over a large portion of California's northwestern coastal mountains. Research has been conducted for several years in these units by the USFS Redwood Sciences Laboratory and the U.S. Geological Survey.

At present, only data from the redwood forest study unit has been analyzed. For the purpose of demonstrating the potential use of community metabolism and nutrient spiraling, Cedar and Peacock Creeks in the Smith River drainage basin east of Crescent City were selected.

Nutrient Uptake/Spiraling

Phosphate and ammonium uptake lengths were determined using the method described by the Stream Solute Workshop (1990), Mulholland and others (1990) and Webster and others (1991). A solution containing known concentrations of K_2HPO_4, NH_4Cl, and NaCl tracer was added to the stream and downstream changes in concentration measured. The solution, containing 5-10 times background concentrations of NH_4^{+1} and PO_4^{-3}, was added at a uniform rate until a plateau in tracer concentration was detected at the most downstream station (fig. 1). Once plateau concentration was achieved, triplicate samples were collected from stations located every 10 m along the 100 m stream reach. Samples were refrigerated until analyzed for NH_4^{+1} and PO_4^{-3} (APHA 1998).

The rise, plateau and decline of solute added to the stream was monitored by recording Cl^- concentration and specific conductivity every 30 seconds for the duration of the nutrient addition. Data logging continued until the specific conductivity returned to pre-release levels. Transient storage (A_s), the temporary storage of solutes in water that is moving more slowly than the main stream flow, was estimated as the difference between plots of the actual and predicted rise and fall of the tracer solution and adjusted for total streambed area (Stream Solute Workshop 1990).

Measured concentrations of nutrients and tracer were corrected for background levels and adjusted for hydrologic dilution (based on reduction in chloride concentration). Downstream concentrations were divided by the most upstream concentration, and the log of these concentrations regressed against distance (Webster and others 1991). The slope of the regression yields an uptake rate per unit stream length and the inverse of this is uptake length (Newbold and others 1981).

Stream metabolism—Total stream metabolism was measured *in situ* using continuously recording dissolved oxygen meters deployed at a single, downstream point in each study reach (Owens 1974; Young and Huryn 1996, 1999). The meters recorded dissolved oxygen (DO), percent DO saturation, and temperature every 15 minutes for 24 hours. Reaeration was determined by regressing the rate of change in DO concentration against the oxygen deficit (saturation DO concentration less actual DO concentration) (Owens 1974). Daily primary productivity and respiration were estimated by plotting the reaeration adjusted DO concentrations against time. Mean night-time respiration was extrapolated to estimate day-time respiration. Primary productivity is the area above the respiration line, and respiration is the area below the line (Bott 1996).

RESULTS

Physico-Chemical Characteristics

The two redwood forest study streams were similar in many of their physical characteristics, with the exception of wetted width, riffle to pool ratio, dominant substrate, and the amount of sand in the channel. Cedar Creek had lower background PO_4^{-3} and NH_4^{+1}(14.6 ± 0.030 and 29.5 ± 2.4µg/L) than Peacock Creek (18.9 ± 0.106 and 63.0 ± 8.5µg/L) (table 1).

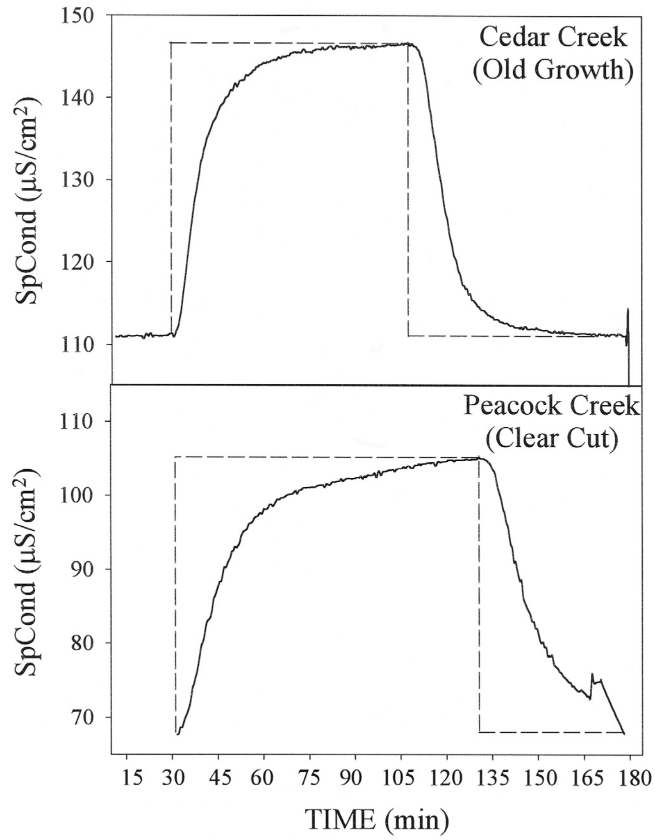

Figure 1—Actual (solid line) and predicted (dotted line) tracer concentration for solute releases in Cedar Creek (top) and Peacock Creek (bottom). The area differences between the two curves is an estimate of transient storage.

Nutrient Uptake/Spiraling

Three measures related to nutrient uptake and spiraling were considered in this preliminary study: transient storage, nutrient uptake rate, and nutrient uptake length. Transient storage in Cedar Creek (old growth) was 25 m^2 compared to 42 m^2 Peacock Creek (clear-cut) (table 2, fig. 1).

Phosphate uptake rate in Cedar Creek was 0.0066 µg/m compared to 0.0010 mg/m in Peacock Creek. These uptake rates translate into uptake lengths of 212 m and 1020 m, respectively (table 2, fig. 2).

Ammonium uptake rates in Cedar and Peacock Creeks were 0.0167 mg/m and 0.0138 mg/m, resulting in uptake lengths of 111 m and 109 m, respectively (table 2, fig. 3).

Community Metabolism

Four measures of community metabolism were measured in each of the study streams: gross primary productivity, respiration, P/R, and NDM. Gross primary productivity was 450 mg O_2/d in Cedar Creek (old growth) and 600 mg O_2/d in Peacock Creek. Respiration in these two streams was 690 mg O_2/d and 528 mg O_2/d. Net daily metabolism in Cedar Creek was -240 mg O_2/d compared to 72 mg O_2/d for Peacock Creek. The ratio of primary productivity to respiration (P:R) was 0.65 and 1.13 for Cedar and Peacock Creeks (table 2, fig. 4).

Table 1—Physico-chemical descriptions of Cedar Creek (old growth) and Peacock Creek (clearcut)

	Cedar Creek	Peacock Creek
Mean (± SE) channel width (m)	2.9 (0.3)	2.9 (0.2)
Mean (± SE) wetted width (m)	2.1 (0.2)	2.9 (0.3)
Streambed area (m^2)	286	291
Wetted width:channel width	0.73	1.00
Mean (± SE) depth (cm)	16 (3)	14 (2)
Maximum depth (cm)	67	46
Mean (± SE) canopy cover (%)	95 (1)	96 (1)
Mean (± SE) channel slope (°)	1.9 (0.4)	1.4 (0.4)
Riffle:pool	2.3	1.5
Dominant substrate	Cobble	Coarse gravel
Sand and fine sediments (%)	0	8
Mean temperature (°C)	13.2	12.9
Temperature range (°C)	12.6–13.5	12.8–13.1
Weather conditions	Foggy	Foggy
24-h antecedent precipitation (mm)	0	0
Background NH_4^{+1} (± SE) (µg/L)	29.5 ± 2.4	63.0 ± 8.5
Background PO_4^{-3} (± SE) (µg/L)	14.6 ± 0.03	18.9 ± 0.11
Harvest history	Never logged	2–3 clearcuts
Fire history	Unknown	Common
Watershed geology	Franciscan ultramafic	Franciscan ultramafic

Table 2—Measurements related to nutrient spiraling (transient storage, uptake rates, uptake lengths) and community metabolism (net primary productivity, community respiration) in Cedar Creek (old growth) and Peacock Creek (clearcut)

	Cedar Creek	Peacock Creek
Transient storage (m^2)	25	42
NH_4^{+1} uptake rate (mg m^{-1})	0.0167	0.0138
PO_4^{-3} uptake rate (mg m^{-1})	0.0066	0.0010
NH_4^{+1} uptake length (m)	111	109
PO_4^{-3} uptake length (m)	212	1020
Gross primary productivity (P)(mg O_2 d^{-1})	450	600
Community respiration (R) (mg O_2 d^{-1})	690	528
P:R	0.65	1.13
Net daily metabolism (NDM) (mg O_2 d^{-1})	-240	72

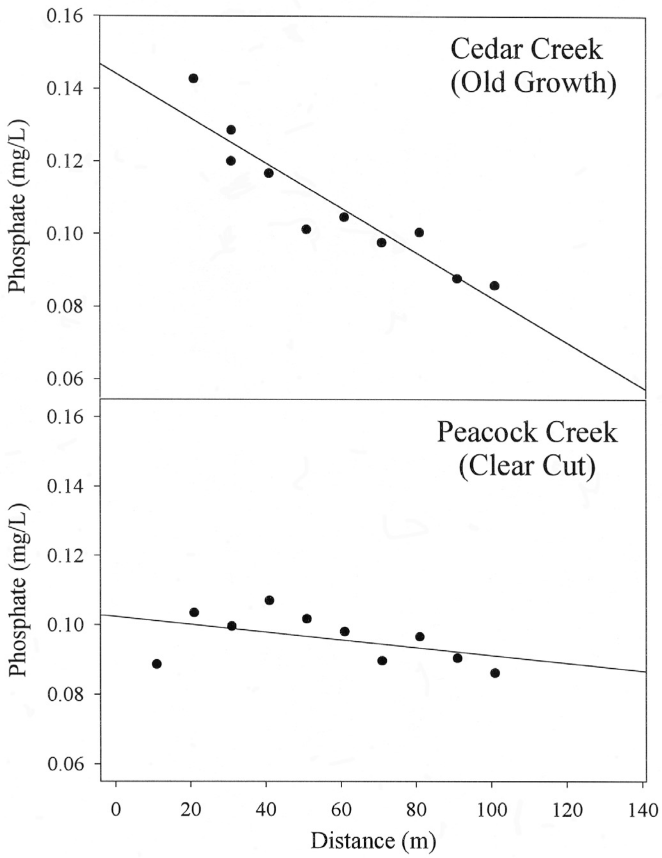

Figure 2—Regression of PO_4 concentration against downstream distance for Cedar Creek (top) and Peacock Creek (bottom). The slope of the regression line is the PO_4 uptake rate.

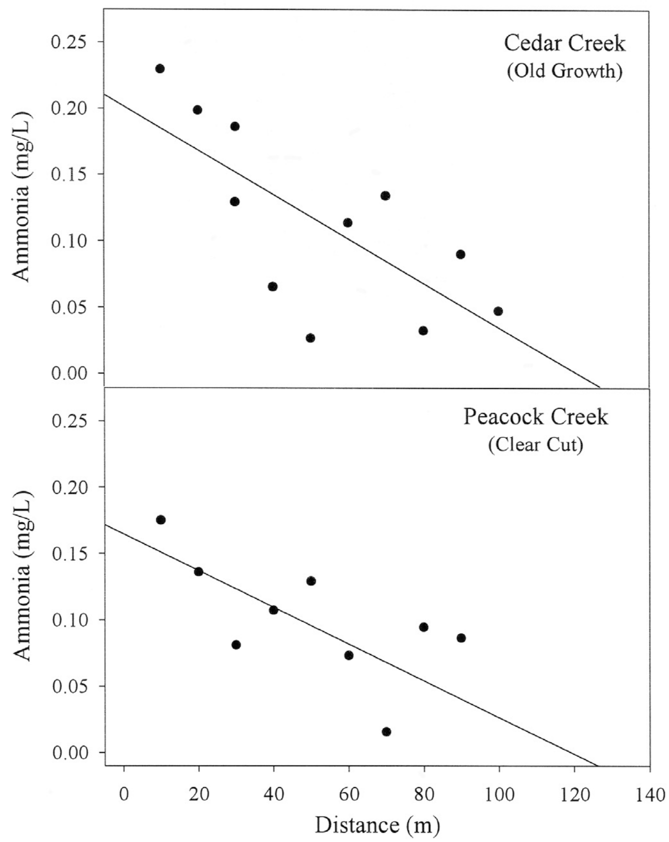

Figure 3—Regression of NH_4 concentration against downstream distance for Cedar Creek (top) and Peacock Creek (bottom). The slope of the regression line is the NH_4 uptake rate.

DISCUSSION

Logging activities, such as trail and road building, skidding, and slash removal, result in increased sedimentation in streams draining those watersheds (Lieberman and Hoover 1948, Golladay and others 1987, Webster and others 1992). Sediment influx to streams following logging is initially high, decreases slightly as the watershed begins revegetation, rises again during the transition from pioneer to later successional vegetation, then declines as the forest matures (Vitousek and Reiners 1975, Webster and others 1992).

Subtle differences in physical characteristics of Cedar and Peacock Creeks are probably a result of timber harvesting. Three measures, the ratio of wetted width to channel width, dominant in-stream substrate, and percent of the streambed as sand and fine material, were used as indicators of stream sedimentation. Wetted width:channel width in the clear-cut stream (Peacock Creek) is 1.00 indicating a lack of channel braiding and complexity. Substrate in Peacock Creek is dominated by smaller material (coarse gravel, 16-64 mm diameter) than that dominating in Cedar Creek (cobble, 64-250 mm diameter). Likewise, Peacock Creek had more sand and fine sediments in the channel than did Cedar Creek.

Increased nutrient export from logged watersheds has been demonstrated in several studies (Bormann and others 1974, Vitousek and Reiners 1975, Campbell and Doeg 1989, Webster and others 1992). Peacock Creek was exporting more nutrients than Cedar Creek, especially PO_4^{-3}.

The physico-chemical similarities between these two streams suggests that differences in nutrient uptake and community metabolism are likely due to differences in harvest histories.

Timber harvesting has been shown to affect nutrient processing in streams draining logged watersheds. Webster and others (1991, 1992) reported decreased PO_4^{-3} retention in logged streams, resulting in longer uptake lengths, and attributed this to biotic and abiotic changes in the stream. We found no differences between our two study streams in transient storage or NH_4^{+1} uptake, but PO_4^{-3} uptake in Peacock Creek was much lower, resulting in much longer uptake lengths.

Community metabolism in small streams draining forested watersheds tends to be dominated by processing of organic carbon derived from the watershed rather than generated *in situ* (Webster and others 1995), resulting in a P:R < 1 and a NDM < 0. As the riparian canopy opens as a result of logging, primary productivity increases (Webster and others 1983) and P:R approaches 1. Even with no difference in riparian canopy between Cedar and Peacock Creeks, net

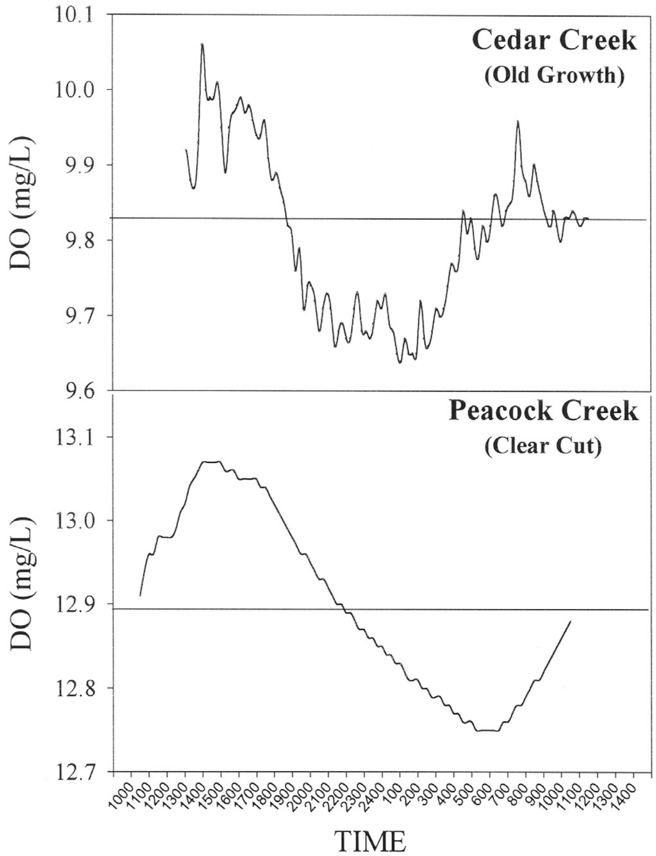

Figure 4—Diel dissolved oxygen curves for Cedar Creek (top) and Peacock Creek (bottom). Net primary productivity is the area under the curve and above the reference line. Community respiration is the area under the curve and below the reference line; DO = dissolved oxygen.

primary productivity was higher in Peacock Creek. This may be related to the higher nutrient levels in this stream. Community respiration, however, was lower in Peacock Creek, suggesting that the microbial community may have been carbon limited. Carbon limitation in streams draining logged watersheds is related to decreases in particulate organic carbon inputs, the depletion of organic carbon storage, and decreased dissolved organic carbon influx (Meyer and Tate 1983, Golladay and others 1989). Our results are consistent with the suggestion that disturbed watersheds are less efficient at processing organic carbon, as indicated by the lower respiration in Peacock Creek, which results in a positive NDM and a P:R > 1.

The preliminary results of our study of nutrient spiraling and community metabolism in paired old-growth and clear-cut watersheds demonstrates the potential use of these measures to assess the impacts of watershed disturbances on stream ecosystem function. While the patterns are clear, we must temper our interpretations of the data with the knowledge that our data at present are limited in number, unreplicated, and in every sense preliminary. Over the three-year term of this study, we will achieve the experimental replication and refinement of measurements of hyporheic storage and release of nutrients, stream physical characteristics, stream reaeration, and light regime, to achieve statistically robust inter-regional comparisons of the impacts of logging on stream ecosystem function.

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