Soluble Organic and Inorganic Nutrient Fluxes in Clearcut and Mature Deciduous Forests

R. G. Qualls,* B. L. Haines, W. T. Swank, and S. W. Tyler

ABSTRACT

The mechanisms by which forest ecosystems retain or lose soluble *inorganic* nutrients after disturbance are well known, but substantial amounts of soluble *organic* nutrients may also be released from cut vegetation. Our objective was to compare the leaching of dissolved organic and inorganic nutrients in cut and mature forest stands and to develop hypotheses about factors controlling the retention of soluble organic nutrients after disturbance. Solution chemistry was measured for 2 yr after clearcutting a small area in the surrounding undisturbed deciduous forest on a reference watershed at the Coweeta Hydrologic Laboratory in the Appalachian Mountains. Concentrations of dissolved organic C (DOC) and N (DON) in slash leachate were 2.6 to 3.2 times the concentrations in throughfall from undisturbed forest. Concentrations in forest floor, A horizon, and B horizon solutions from cut plots were 1.2 to 3.8 times those from undisturbed forest. Dissolved organic P (DOP) concentrations in cut plots were 3.1 and 3.6 times those of uncut plots in solutions from slash and forest floor, respectively, but did not differ in mineral soil. Fluxes of DOC, DON, and DOP in all strata were greater in cut plots than uncut plots. Fluxes of DON were greater than those of ammonium plus nitrate N in all strata of both cut and uncut plots. We hypothesize that the well-recognized retention mechanisms for inorganic nutrients combine with equilibrium adsorption of dissolved organic matter to efficiently buffer against leaching of both soluble inorganic and organic nutrients after clearcutting.

MUCH OF THE EMPHASIS on the cycling and leaching of nutrients after disturbance of forests has been focused on inorganic nutrients. Historically, this emphasis is partly a product of the cases of severe leaching of nitrate from some clearcut forests, such as the Hubbard Brook Experimental Forest (Bormann and Likens, 1979), and of concern for the eutrophication of downstream waters. Soluble organic nutrients are also released as vegetation grows, dies, and decomposes. For example, 27% of the C in freshly fallen autumn leaf litter in a deciduous forest was soluble in water (Qualls et al., 1991). Even such insoluble material as lignin in wood can generate substantial quantities of soluble organic matter as it is degraded by the white rot fungus *Phanaerochaete chrysosporium* (Reid et al., 1982).

The mechanisms by which inorganic nutrients are retained or lost after clear cutting are generally well known and illustrated in many studies. These include loss of root uptake (Bormann and Likens, 1979), or the rapid recovery of root uptake by stump sprouts (Boring et al., 1988), recovery of root uptake by seedling growth (Marks, 1974), delayed mineralization and subsequent nitrification due to a high C/N ratio in litter (Vitousek et al., 1979), temporary sorption on ion exchange sites (Vitousek et al., 1979) and in the case of P, fixation or sorption on soil (Wood et al., 1984; Walbridge et al., 1991). The increase in water flux from the root zone due to cutting and the concomitant reduction in evapotranspiration also plays an important role in controlling the leaching of nutrients (Likens and Bormann, 1995). The factors which control the leaching of organic nutrients after clearcutting or other disturbances, however, have not been extensively investigated.

Dissolved organic N is the major form of N in streamwater draining from many mature forest watersheds (Sollins and McCorison, 1981; Hedin et al., 1995). In a study of 31 watersheds with unpolluted old-growth forests in Chile representing an area without anthropogenic atmospheric N deposition, DON comprised about 95% of total N in streamwater (Hedin et al., 1995). Relatively high concentrations of DON drain from the forest floor, and this DON also generally comprises most of the total N draining from the forest floor of intact forests (Qualls et al., 1991; Johnson and Lindberg, 1992, Appendix; Northup et al., 1995; Currie et al., 1996). The importance of DON in solution transport in intact forests and the sudden inputs of potentially soluble nutrients in logging slash suggest that transport of soluble organic nutrients may be important in the retention or loss of nutrients after clearcutting. For example, Bormann and Likens (1979) estimated that a large amount of N lost from the forest floor after clearcutting could not be accounted for in either streamwater, inorganic N, or in vegetation regrowth and they hypothesized that it may have been translocated to deeper soil horizons and stored.

Our objectives in this study were to (i) compare fluxes of the dissolved organic nutrients DOC, DON, and DOP in a clearcut area and an adjacent, mature reference area, (ii) determine whether concentrations of dissolved organic nutrients or inorganic nutrients were greater in clearcut than in reference areas, and (iii) identify the strata where the greatest net leaching and deposition occur.

By examining concentrations and fluxes we can evaluate the relative importance of dissolved organic nutrients. Identifying the strata where most of the dissolved organic matter (DOM) originates or is removed from solution will help us develop hypotheses about the processes controlling the retention or loss of dissolved organics after disturbance. By comparing concentrations with fluxes in soil, we will evaluate the effects of increased leaching due to reduction in evapotranspiration.

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Abbreviations: DOC, dissolved organic carbon; DOM, dissolved organic matter; DON, dissolved organic nitrogen; DOP, dissolved organic phosphorus; ET, evapotranspiration; WS, Watershed [label].

Our emphasis is not just in demonstrating effects of clearcutting on nutrient cycling but in using this perturbation (in this case change in inputs, reductions of root uptake, and increase in hydrologic leaching) to gain insight into biogeochemical processes.

MATERIALS AND METHODS

Site Description

The study site was on, or adjacent to, Watershed 2 (WS 2) at the Coweeta Hydrologic Laboratory in the Nantahala Range of the Southern Appalachian mountains of North Carolina (83°26'W, 35°04'N) at an elevation of 840 m. Annual precipitation averages 177 cm for WS 2 but was 127.6 and 153.4 cm during the first and second years of the study, respectively. Snow comprises only 2 to 10% of precipitation.

The area was covered by a deciduous forest dominated by several species of oak (*Quercus* spp.), hickory (*Carya* spp.), red maple (*Acer rubrum* L.), and dogwood (*Cornus florida* L.). The forest had been undisturbed for at least 62 yr except for mortality due the chestnut blight (Monk and Day, 1988). Thickets of mountain laurel (*Kalmia latifolia* L.) and rosebay (*Rhododendron maximum* L.) cover portions of the study area. Soil in the study area was a Chandler loam, a coarse-loamy, micaceous, mesic Typic Dystrochrept. The dry mass of the forest floor on WS 2 averaged 1145 g m^{-2} (Ragsdale and Berish, 1988). Annual litterfall was 498 g m^{-2} (dry mass) and had a C/N ratio of 60 (W.T. Swank, unpublished data, 1991).

An experimental clearcutting was combined with installation of a weather station in an area on the perimeter of WS 2. An area of 890 m^2 was cut in November 1985 after leaf fall. Four 5 m by 5 m plots were randomly located within the area excluding the weather station. The perimeter of the clearcut area was trenched to ≈60-cm depth and the trench was lined with plastic to prevent root growth from the surrounding forest. We uniformly redistributed woody debris over the plots so that the dry weight equivalent of approximately 120 Mg ha^{-1} lay on each plot to mimic an experimental clearcut on an adjacent watershed. WS 7, in 1977 (Boring et al., 1988).

Experimental Design

The design was similar to a case-control design (Breslow, 1996) in which cut and uncut reference plots were paired based on similarity of the following criteria: (i) slope position (headslope), (ii) aspect (SSE to SSW), (iii) soil series, (iv) depth of A horizon (± 1 cm , 5–12 cm), and (v) matric water potential measured on three occasions prior to cutting (± 10% of value in MPa). After randomly locating four plots in the cut area, the area surrounding the cut within 50 m was mapped according to the above five criteria. Then an uncut reference plot was randomly located in the area, or areas, matching all five criteria for a given cut plot. Thus, each cut plot was paired with an uncut plot and treated as a block. The main effect of cutting on the dependent variable (concentration or flux) was tested by ANOVA as a randomized complete block design with four blocks (each pair) and repeated measures (over time) (SAS, 1996).

Sample Collection and Analysis

Solution was collected above the forest floor (throughfall or slash leachate), below the Oa horizon, in the mid A horizon, the mid AB horizon, the mid B, and 20 cm below the upper boundary of the C horizon. In the cut plots, slash leachate collectors were placed above the litter but beneath all woody logging debris. Throughfall collection troughs and zero tension lysimeters for forest floor solution are described in Qualls et al. (1991). Porous ceramic cup vacuum water samplers were installed in the mid A (8–12 cm depth), AB (18–22 cm depth), mid B (30–50 cm depth), and 20 cm below the upper boundary of the C horizon (90–120 cm depth) in each plot. Vacuum was manually maintained at 0.05 MPa continuously for the 7-d sampling period and samples withdrawn at 2- to 5-h intervals during storms to 2-d intervals depending on the changes in water potential. Porous cups were acid washed, which as shown by Grover and Lamborn (1970), eliminates phosphate sorption. Lab tests showed no adsorption of DOC, DON, or DOP from forest floor solution drawn through the ceramic cups. Samples were preserved, filtered (Whatman GF/F), and analyzed for ammonium, NO_3, PO_4, total dissolved N and P, and DOC as described in Qualls et al. (1991). Ammonium-N was measured by an automated phenol hypochlorite method (Technicon Industrial Systems, 1978). Phosphate-P was measured by an automated ascorbic acid molybdate blue method (Technicon Industrial Systems, 1973). Nitrate + nitrite N on undigested samples and persulfate digests was measured by automated hydrazine reduction followed by diazotization (Downes, 1978). Total dissolved N and P were determined using persulfate digestion followed by NO_3 and PO_4 analyses of the digests. The DON was calculated as total dissolved N minus NO_3 minus NH_4. The DOP was calculated as total dissolved P minus PO_4. Dissolved organic C was measured using an O.I. Analytical (College Station, TX) Model 700 TOC Analyzer.

Sampling Frequency

Throughfall, slash leachate and forest floor solution was collected continuously over a 2- yr period (3 Jan. 1986 to 3 Jan. 1988) while soil solution was collected during one intensive sampling week every 6 wk. Throughfall and forest floor sampling was described in Qualls et al. (1991). Samples of all strata were collected intensively for 7 d in every 6-wk period for 2 yr after cutting at intervals ranging from 2 to 5 h during, and shortly after storms, to 2 d between storms. Water potential readings were taken more frequently during periods of movement of wetting fronts in soil such that changes in water potential were generally <1 kPa. Consequently, for soil solution, one-sixth of the 2-yr period was sampled and the data are extrapolated to the 2-yr period to be presented in annual units (g m^{-2} yr^{-1}).

Estimation of Water Fluxes

Water fluxes in throughfall and from the bottom of the Oa horizon were measured as in Qualls et al. (1991). Interception by forest floor litter in the clearcut was assumed to be the same as in the reference plots. Error due to this assumption is probably very small, since litter interception was only 2% of throughfall. Precipitation and other meteorological data were measured at the weather station in the clearcut area.

We reasoned that the most accurate annual measure of the water flux from the bottom of the rooting zone of the uncut plots was the streamflow on the gauged watershed (WS 2). This, of course, assumes that the bedrock was tight and that all water leaves the watershed as either evapotranspiration or measured streamflow and that there was no net change in soil water storage over the 2-yr period. The most accurate measure of annual flux from the rooting zone of the cut plots was based on an empirical model that predicts the increase in streamflow due to cutting over that of a reference watershed at Coweeta (Douglas and Swank, 1975; Swank et al., 1988). This model

is based on the observed increases in streamflow derived from several cutting experiments on Coweeta watersheds and has proved to predict annual streamflow on clearcuts within a few cm. For example, the model predicted the increase in streamflow on the clearcut of the adjacent watershed, WS 7, within 1 cm the first year after clearcutting and within 3 cm the second year, which corresponded to about 1 and 2.5% of streamflow, respectively (Swank et al., 1988). Annual transpiration withdrawal from the soil was estimated from (precipitation–canopy interception–litter evaporation–estimated streamflow). The transpiration withdrawal from each depth increment was calculated by distributing the total transpiration among soil increments in proportion to the distribution of fine roots (McGinty, 1976; Vose and Swank, 1992). The annual flux from each depth increment was then estimated as flux from the bottom of the rooting zone plus the transpiration withdrawal from all lower soil increments.

To obtain the nutrient flux for the 2-yr period, these 2-yr water fluxes were then multiplied by a flux-weighted average nutrient concentration (described below). The rationale for this method of calculation was: (i) the water flux over the long term from the bottom of the root zone could be very accurately measured from streamflow on the gauged watershed, far more accurately than by a soil water balance, (ii) the empirical model of streamflow increases has been shown to accurately predict streamflow (and thus evapotranspiration [ET]) on entire clearcut watersheds at Coweeta, and (iii) short-term water fluxes were far more variable than chemical concentrations. The major assumptions in this estimate for soil horizon fluxes are: (a) that concentrations are flux weighted at least in proportion to the true flux, (b) that flux-weighted concentrations in soil over the 17 intensive sampling weeks are representative of the 2-yr period, (c) that the 2-yr streamflow from WS 2 equals drainage from the upper C horizon from the uncut plots, and (d) that transpiration withdrawals from each horizon are distributed by depth in proportion to the fine root distribution we used.

Short-Term Soil Water Fluxes

Our goal in measuring soil hydrologic properties was to estimate short-term downward water fluxes from the A, AB, B, and the upper 20 cm of the C horizon to use in flux weighting the measured concentrations. Matric water potential was measured using six tensiometers in each plot (Model 2310 Multiple Manometer, Soilmoisture Equipment, Santa Barbara, CA) that bracketed the depths at which water collectors had been placed (one in the A, one in the AB, two 20 cm apart in the B, and two 20 cm apart in the upper C horizons). To measure the water potential gradients in the vector parallel to the hill slope an additional set of tensiometers was located ≈10 m directly upslope from each plot that did not have another plot located within 20 m upslope. Readings of water potential were made at intervals of 3 to 36 h so that changes in water potential during the interval were generally <1 kPa. On occasions when individual tensiometers failed to work properly, matric potentials were interpolated from other surrounding tensiometers in the plot.

Two soil cores (6.12-cm diam. and 10-cm length) were collected in each horizon in two of the uncut plots. Cores were saturated and placed in a Tempe Pressure Cell (Soilmoisture Equipment) and curves of matric potential (ψ_m) vs. volumetric water content (θ) were measured. Cores were again saturated and the one-step outflow method of Passioura (1977), as used by Borcher et al. (1987), was used to estimate hydraulic conductivity vs. ψ_m from 0.5 kPa to 90 kPa using an applied pressure of 90 kPa. The program HYDRUS 1-D (Simanek and van Genuchten, 1996; Simunek et al. 1998) was then used to estimate the unsaturated hydraulic conductivity as a function of θ from the outflow data. Because data represent only desorption, hysteresis during water absorption is a likely source of error in water balance calculations. Then Darcy's Law was used as an accessory method to estimate fluxes based on the observed matric potential gradient between each pair of tensiometers, the volumetric water content inferred from the matric water potential, and the estimated hydraulic conductivity at the given volumetric water content. The Darcy's Law calculation generally gave overestimates of flux by an average factor of about 1.4 relative to the water balance method described below and was used to constrain fluxes and to aid in interpolation.

Table 1. Average hydrologic fluxes over the 2-yr sampling period (in annual units).

Stratum or horizon	Water fluxes	
	Uncut	Cut
	m yr^{-1}	
Precipitation	1.42	1.42
Throughfall or slash	1.25	1.36
Oa	1.22	1.32
A	0.89	1.07
AB	0.74	0.95
B	0.58	0.83
C	0.55	0.81

A water balance method was used as the primary method to estimate fluxes. The mineral soil was considered to be five layers: A, AB, upper B, lower B, and upper 20 cm of the C horizons. For each layer, water flux out of a layer (F_{out}) was calculated as

$$F_{out} = F_{in} - \text{evapotranspiration} - \Delta\theta \times \text{thickness}$$

where flux (F_{in}) into the A layer was the measured water flux out (F_{out}) of the O layer, or into other layers was the calculated F_{out} of the layer above; evapotranspiration was estimated with the PROSPER model (see below): $\Delta\theta$ was the change in volumetric water content over 3 to 36 h measurement intervals; thickness was layer thickness; and all terms had units of cm.

In some cases, the flux calculated from the water balance method was deemed to be unreasonable. Criteria for judging a flux as unreasonable were (a) it exceeded the precipitation which caused the last wetting front, (b) direction of flux did not match that indicated by Darcy's law, or (c) it exceeded by a factor of two that calculated by Darcy's Law. In those cases the flux was interpolated from the flux before ($t - 1$), and after ($t + 1$), the time interval according to the equation

$$F_{\text{water balance}(t)} = F_{\text{Darcy}(t)} \times \frac{1}{2}[(F_{\text{water balance}(t-1)}/F_{\text{Darcy}(t-1)}) + (F_{\text{water balance}(t+1)}/F_{\text{Darcy}(t+1)})]$$

Thus, the ratio of the flux calculated from the water balance to that calculated from Darcy's law was simply used to help interpolate. These cases usually occurred during the passage of a wetting front or in the horizon below a wetting front and consequently was probably caused by hysteresis or a wetting front which was not positioned at the boundary of the depth increment.

Evapotranspiration over the sampling intervals was estimated using PROSPER (Swift et al., 1975), an energy balance–aerodynamic method, which has been shown to closely predict measured annual streamflow on both mature and clearcut watersheds at Coweeta (Swift et al., 1975). Evapotranspiration data for WS 2 for the 2 yr of this study, representing the uncut

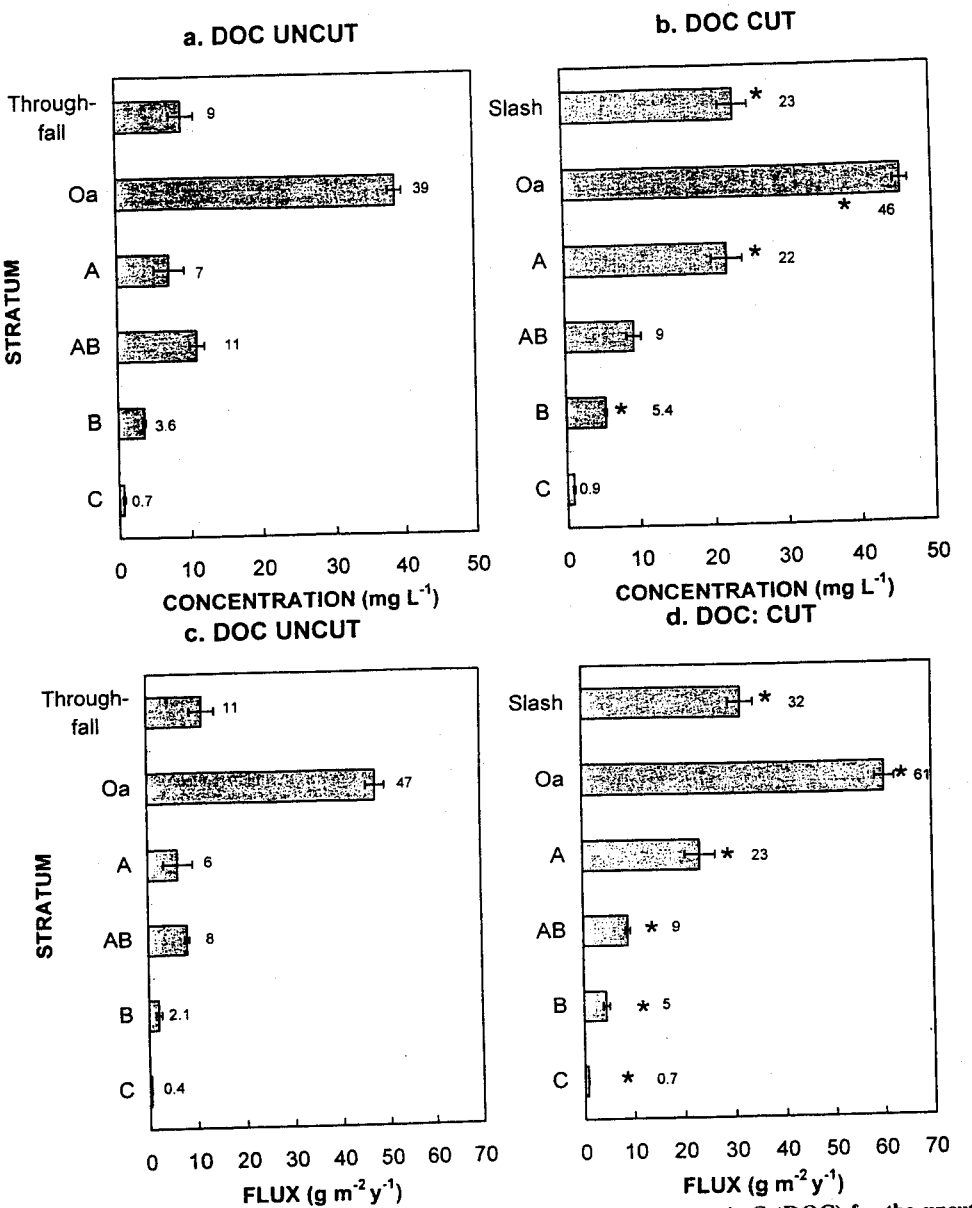

Fig. 1. Flux weighted average concentrations (a and b) and fluxes (c and d) of dissolved organic C (DOC) for the uncut and cut plots. Strata or soil horizons are indicated on the vertical axis. Asterisks indicate significant ($P < 0.05$) differences (a significant main effect of cutting treatment in the ANOVA) between cut vs. uncut plots and are placed on bar the which was greater. Error bars are standard error of the mean, indicated only for the organic form and reflect variability among plots, not temporal variability. Numbers beside the bars indicate values.

plots was shown in Vose and Swank (1992). The distribution of fine roots found by McGinty (1976) was also used in this model and PROSPER apportions withdrawals of transpired water from the depth increments according to this distribution as modified by the hydraulic conductivity of the depth increment at the simulated soil water content (Swift et al., 1975). PROSPER was also used to estimate ET in the cut area using leaf areas measured in plots by counting leaves and multiplying by an average leaf area for each species.

Calculation of Nutrient Fluxes

The flux-weighted average concentration for each soil horizon over the 2-yr period was calculated as follows. Concentration was multiplied by water flux for each collection interval, then this product was summed over all intervals, and finally divided by the sum of water fluxes. Then to calculate long-term nutrient fluxes, the flux weighted average concentration was multiplied by the long-term water fluxes. Nutrient fluxes in throughfall or slash leachate and Oa horizon water was also calculated similarly, but these were collected continuously.

RESULTS

Water fluxes for the 2-yr period (in annual units) are shown in Table 1. The estimated water flux from the bottom of the rooting zone was 1.47 times higher in the cut plots.

Dissolved organic C concentrations were significantly greater in the cut plots than in the uncut plots for all strata except the AB and C horizons (Fig. 1a vs. 1b). In particular, concentrations in slash leachate were 2.6 times higher than those in throughfall in the uncut plots. Differences were not as great in DOC concentration in water draining from the forest floor. The DON concen-

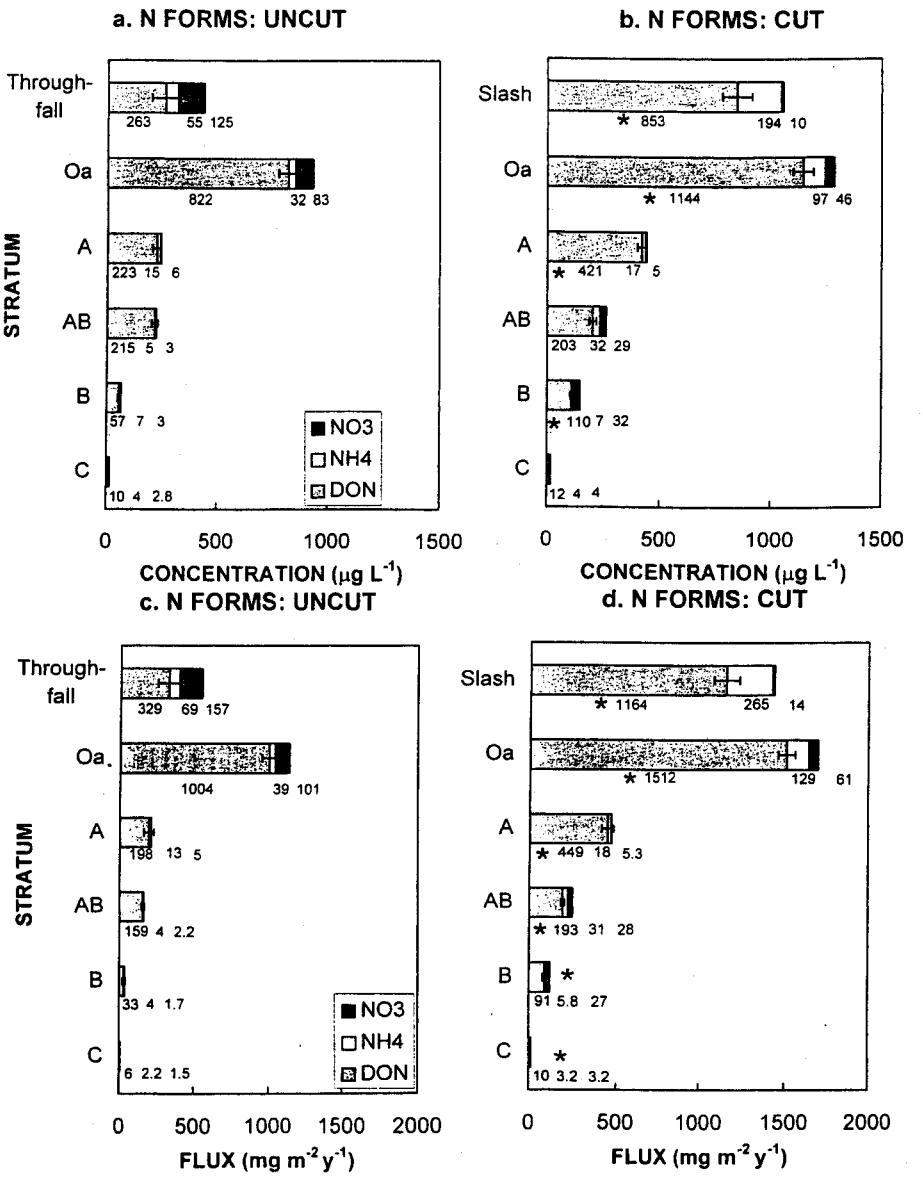

Fig. 2. Flux weighted average concentrations (a and b) and fluxes (c and d) of N forms for the uncut and cut plots. Asterisks indicate significant ($P < 0.05$) differences (a significant main effect of cutting treatment in the ANOVA) in dissolved organic N (DON) (not inorganic forms) between cut vs. uncut plots, and are placed on bar which was greater. Error bars are standard error of the mean, indicated only for the organic form and reflect variability among plots, not temporal variability. Numbers on or beside the bars indicate values and are in the same order as stacking of the bars.

trations were greater in the cut than in the uncut plots in all horizons except the AB and C horizons (Fig. 2a vs. 2b), and in fact the patterns mirrored those of DOC because of the close correlation between DOC and DON (Qualls and Haines, 1991). In contrast to DOC and DON, DOP was significantly higher in concentration only in slash leachate (vs. throughfall) and forest floor solution, not in soil solution (Fig. 3a vs. 3b).

On a net basis, more DOP was leached from the canopy of the uncut plots than from the forest floor (Fig. 3c and 3d). Slash and the forest floor were roughly equal sources of DOP in the cut plots but the fluxes were much higher in the cut plots. Nearly all of this DOP and the PO_4 percolating from the forest floor was removed in the A horizon.

Fluxes of DOC, DON, and DOP were significantly higher in cut than in uncut plots in all horizons (Fig. 1, 2, and 3, c vs. d). The higher fluxes were the result of higher water fluxes (Table 1) and generally higher concentrations.

Concentrations of DON were greater than those of inorganic N in both the uncut plots and the cut plots in all horizons (Fig. 2a and 2b). In the cut plots, DON comprised from 95% of total dissolved N in the A horizon to 60% in the C horizon. Concentrations of dissolved inorganic N were, nevertheless, higher in the cut plots in all horizons; 1.25 times higher in the Oa and 3.9 times higher in the B horizon (Fig. 2a vs. 2b).

As was generally the case with N forms, concentrations of DOP were greater than those of PO_4 in the uncut plots in all horizons except the AB and in throughfall (Fig. 3a). In the cut plots, however, PO_4 comprised 80% of the total dissolved P in the slash leachate and 58% in the Oa horizon solution due to a 10-fold increase in slash leachate PO_4 concentrations in the cut plots over the uncut plots (Fig. 3b). In the mineral

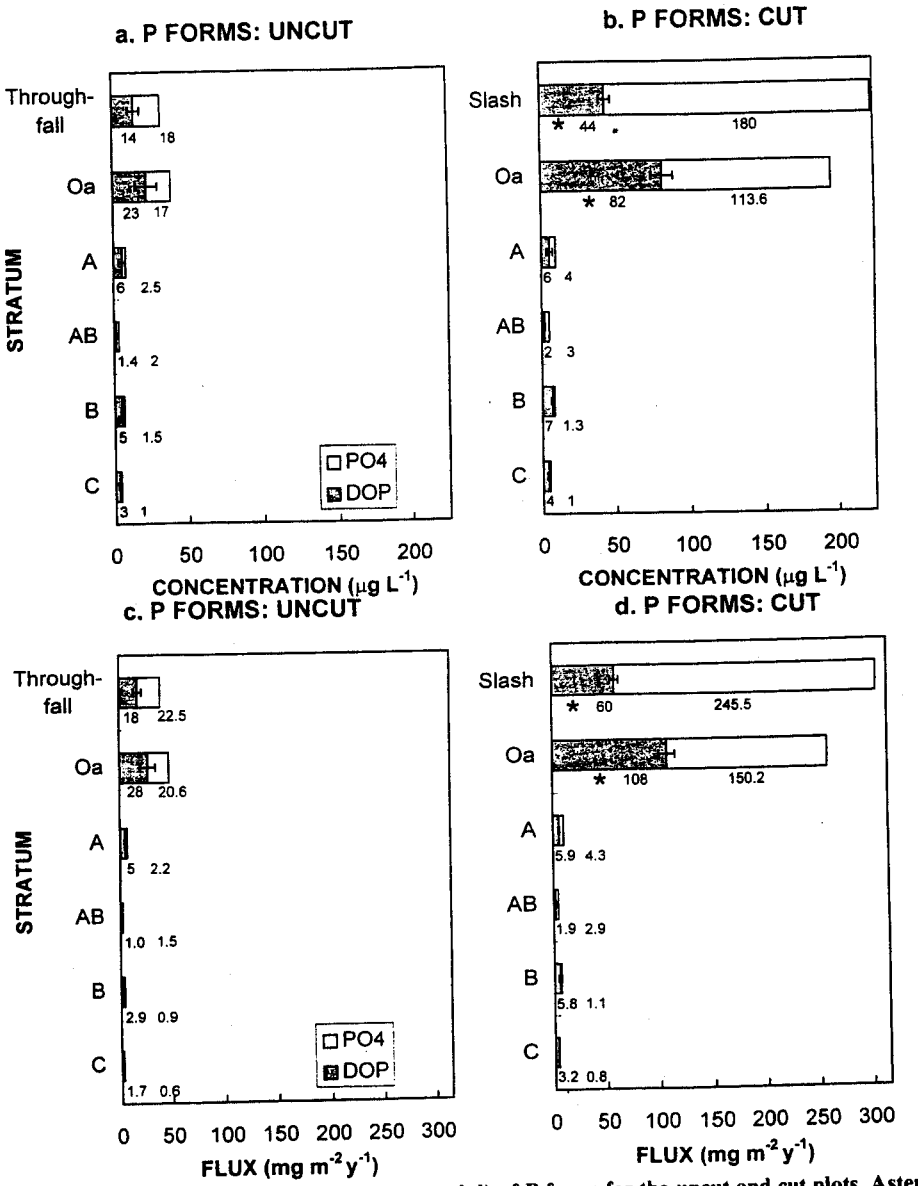

Fig. 3. Flux weighted average concentrations (a and b) and fluxes (c and d) of P forms for the uncut and cut plots. Asterisks indicate significant ($P < 0.05$) differences (a significant main effect of cutting treatment in the ANOVA) in dissolved organic P (DOP) (not PO_4) between cut vs. uncut plots , and are placed on bar which was greater. Error bars are standard error of the mean, indicated only for the organic form and reflect variability among plots, not temporal variability. Numbers on or beside the bars indicate values and are in the same order as stacking of the bars.

soil, however, concentrations remained below 7 μg L^{-1} in both the uncut and the cut plots, with DOP comprising 58 to 80% of the total dissolved P. Thus, the major contrast between N and P with respect to the importance of dissolved organic forms was that the DON dominated concentrations of total dissolved N in cut and uncut plots while concentrations of DOP were a smaller percentage of total dissolved P, especially in the throughfall or slash leachate and forest floor.

Net Addition and Removal in the Vertical Solution Profile

In the uncut plots, most DOC and DON originated in the forest floor with a smaller amount originating in slash leachate, and most DOC and DON was removed in the A horizon (Table 2). In the cut plots, however, more DOC and DON originated in the precipitation passing through the slash and there was a much smaller addition of DOC and DON as water passed through the forest floor of the cut plots compared to the uncut plots. In the cut plots more DOC and DON was removed from solution moving through the A horizon than from the rest of the soil profile together. Because of the increased fluxes, however, there was a greater net removal of DOC and DON in each soil horizon compared to the uncut plots and a greater translocation of organic C and N to lower depths. Nevertheless, more than 99% of DON draining from the forest floor of either cut or uncut plots was removed as water passed through the mineral soil into the upper C horizon.

DISCUSSION

The results demonstrated three major points: (i) DOC and DON concentrations were higher in the cut plots

Table 2. Net addition (indicated by a + sign) or removal (indicated by a − sign) of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), or dissolved organic phosphorus (DOP) from solution as it passed through each stratum or horizon. Calculated as: the flux through the stratum minus the flux through the stratum above.

	DOC		DON		DOP	
Stratum	uncut	cut	uncut	cut	uncut	cut
	— g m^{-2} yr^{-1} —		— mg m^{-2} yr^{-1} —			
Throughfall or slash†						
Oa	36	29	674	349	9.4	49
A	−41	−37	−806	−1060	−23	−102
AB	1.8	−15	−39	−255	−3.8	−4.0
Upper B	−6.0	−4.5	−126	−102	1.9	3.9
Lower B and upper 20 cm of C‡	−1.7	−3.7	−27	−82	−1.2	−2.6

† Net addition of DOC, DON, or DOP from the aboveground vegetation and logging slash was calculated by subtracting the small fluxes in precipitation which were 0.5 mg L^{-1} DOC, 20 μg L^{-1} DON, and 0 μg L^{-1} DOP from the throughfall–slash fluxes (Qualls et al., 1991).

‡ Net removal, as indicated by the negative sign, in the lower B and upper 20 cm of the C horizon was calculated using solution fluxes sampled in the middle of the B horizon and solution fluxes sampled 20 cm below the upper boundary of the C horizon.

in slash leachate (vs. throughfall), forest floor leachate, A horizon solution, and B horizon solution. In the case of DOP, concentrations were much higher in the cut plots in the slash leachate (vs. throughfall) and forest floor but not in the mineral soil. (ii) Greater water fluxes through the soil horizons of the cut plots combined with greater concentrations in some horizons to give greater fluxes of DOC, DON, and DOP in all strata. (iii) Fluxes of DON were greater than those of dissolved inorganic N, even in the cut plots. However in the case of P, fluxes of inorganic P exceeded those of DOP in the cut plots in slash and forest floor leachate.

Sources of Dissolved Organic Matter above the Mineral Soil

Sources of DOM in the cut plots were slash from cutting and other organic debris on the forest floor. On the other hand, leaching from live canopy leaves and soluble organics from litterfall during the first few years after cutting was greatly reduced. In the mature forest canopy, leaching was an important source of DOC, and, in particular, DOP (Qualls et al., 1991). Furthermore, much higher concentrations of dissolved organics during the growing season than in the dormant season in the mature forest suggested that canopy leaves leach more soluble organics than live bark. In the cut plots, however, sources may have included: (i) leaching of tannins from dead and fragmented bark, (ii) leaching of soluble organics from increasingly porous and fragmented wood, (iii) dissolution of lignin and other constituents by microbial enzymes, and (iv) leaching of microbial biomass such as that of shelf fungi.

The higher concentrations of dissolved organic nutrients in solution draining from the forest floor of the cut plots can largely be accounted for by the slash above the leaf litter of the forest floor. In fact, there appeared to be less net leaching of DOC from the forest floor in the cut plots compared to the uncut plots. This was likely to be due to the loss of most new leaf litter production after cutting.

Mattson et al. (1987) found that concentrations of DOC still averaged 76 mg L^{-1} in solution leaching from decaying logs 7 yr after clearcutting on the adjacent Watershed 7 at Coweeta. While one might assume that there would be little soluble organic matter in bole wood 7 yr after cutting, the loss by leaching of DOC amounted to 1/12 the loss as CO_2. This suggests that slash may remain a source of dissolved organic matter for several years.

In the case of P, the sequestration of P from wood and its concentration in fungal sporocarps in the cut plots may be particularly important in converting P to soluble forms subject to leaching. Exceptionally high concentrations of DOP and PO_4 occurred in collectors located below dying sporocarps of shelf fungi (*Polyporus versicolor*). Concentrations of PO_4 + DOP in these collectors averaged 437 μg L^{-1} for 120 d after appearance and decay of the sporocarps vs. 89 μg L^{-1} in these same collectors at other periods. Harmon et al. (1994) found that concentrations of P in sporocarps were about 9 to 100 times those in undecayed logs and they concluded that sporocarp formation was the main pathway of loss of N and P from logs during the first few years of decomposition.

Removal of Dissolved Organic Matter in Mineral Soil

Concentrations of DOC and DON declined with depth in the mineral soil and the greatest difference between the cut and uncut plots occurred in the A horizon. Physicochemical adsorption, largely by iron and aluminum oxyhydroxides can rapidly remove DOC from solution and can buffer differences in input concentration (Qualls and Haines, 1992a; McDowell and Wood, 1984; Jardine et al., 1989). The large differences in DOC concentration between the cut and uncut plots in the A horizon show little indication of the buffering of concentration by adsorption, but large inputs of dead root litter in the soil may also have greatly increased inputs of soluble organic C. It is unlikely that a large proportion of the DOC and DON was removed by decomposition in the dissolved phase, because DOC and DON from the uncut plots was very slow to mineralize (Qualls and Haines, 1992b).

In the case of DOP and PO_4, the relatively high concentrations draining from the forest floor of the cut plots were reduced to low levels abruptly in the A horizon, levels comparable to those of the uncut plots. This may reflect the strong tendency of PO_4 (Walbridge et al., 1991) and perhaps phosphate esters to adsorb in these Fe- and Al-rich soils. A large proportion of the dissolved organic P occurs in the hydrophilic acid fraction, one whose behavior may be dominated by phosphate monoester functional groups (Qualls and Haines, 1991), which are likely to adsorb strongly to Fe- and Al-rich mineral soils.

The increase in water fluxes through the soil was an important factor in causing greater fluxes of organic

nutrients from the lower soil horizon, more important, in fact, than differences in concentration. This close relationship between nutrient output and water flux is well known for inorganic ions at the watershed level such as Ca^{2+} and Na^{+} where concentration is relatively constant and flux is proportional to streamflow (Swank, 1988; Likens and Bormann, 1995). The estimated increases in annual water flux of 26 cm (a factor of 1.47) due to cutting our plots (Table 1) lies within the ranges found in several studies: increases of 34.6, 27.3, and 24 cm (factors of 1.4, 1.28, and 1.26) during the first 3 yr after cutting watershed 2 at Hubbard Brook Experimental Forest (Bormann and Likens, 1979), an increase by a factor of 1.4 in a cut Douglas fir watershed in the Oregon Cascades (Sollins and McCorison, 1981), an increase of 20.6 cm (a factor of 1.38) in a cut deciduous forest on Kentucky (Arthur et al., 1998), and an increase of 14.7 cm (a factor of 1.52) in a cut lodgepole pine stand in Utah (Burton, 1997).

While fluxes of DOC, DON, and DOP from the upper C horizon were greater in our cut plots than in our uncut plots, most of the DOC, DON, and DOP leaching from the slash and forest floor was retained in the upper horizons of the mineral soil. We interpret this retention as evidence that adsorption in the mineral soil efficiently retains the majority of the soluble organic nutrients released by clearcutting.

In calculating the short-term water fluxes, downslope movement of water may have caused errors in our nutrient flux calculations but we believe this error had little effect on our results. The nutrient fluxes were calculated from multiplying the flux-weighted concentration times the long-term water flux based on the more accurate watershed streamflow data. Thus, these fluxes were calculated from a vertical projection of the watershed area and consequently, are vertical fluxes averaged over the watershed. Downslope flow would have had the effect of skewing the weighting of concentrations but concentrations of DOC, DON, and DOP were not highly variable and were not correlated with calculated fluxes (not shown), so these errors are again believed to have little effect on our final fluxes.

A Comparison of Mechanisms Controlling Leaching of Dissolved Organic and Inorganic Nutrients

Numerous studies have demonstrated that leaching of inorganic N or P is greater in recently clearcut forests compared to mature reference stands (Bormann and Likens, 1979; Stevens and Hornung, 1990; Adamson et al., 1987; Ring, 1995; Sollins and McCorison, 1981). In this study we found that fluxes of dissolved organic nutrients were also greater in clearcut plots. Indeed fluxes of NO_3, NH_4, and PO_4 were elevated in our cut plots, but the average concentrations did not approach the mg L^{-1} levels found for nitrate, for example, in some cut forests (Bormann and Likens, 1979). In part because of this relatively small increase in NO_3 concentrations, the fluxes of DON typically remained greater than those of inorganic forms. The adjacent watershed (WS 7) was experimentally clearcut in 1977 and NO_3 export in streamwater during the first and second year was only about 0.3 and 1.1 kg ha^{-1}, respectively (Swank, 1988). In our cut plots the flux of NO_3 from the C horizon was much lower than that from the B horizon for unknown reasons, but the flux from the B horizon in our cut plots (0.27 kg ha^{-1}) was similar to export in streamwater during the first year after cutting WS 7. However, the export from WS 7 in streamwater the second year after cutting was considerably higher than that from the B horizon in our cut plots. This relatively low export of inorganic nutrients was due to a very rapid recovery of root uptake in stump sprouts and herbaceous plants which recovered to 93% of the precutting N uptake in aboveground NPP only 3 yr after cutting on mesic sites (Boring et al., 1988). A lag in nitrification may also have played a role in delaying nitrate loss (sensu Vitousek et al., 1979) in our cut plots. Output of N, especially NO_3, from clearcut forested watersheds varies by nearly two orders of magnitude (Vitousek et al., 1979; Emmett et al., 1990; Ring, 1995). Although the data on leaching of dissolved organic nutrients after clearcutting is extremely limited, we hypothesize that the range of increase in concentrations and fluxes of DON is much less than that observed for NO_3.

In a clearcut and control Douglas fir forested watershed in Oregon, Sollins and McCorison (1981) monitored DOC (second and third year after cutting only) and DON (third year after cutting only) in soil solution. They found that concentrations of DOC were higher in soil solution in the clearcut by factors ranging from 1.4- to 1.9-fold. The DON comprised from 41 to 58% of total N in soil solution in the third year after cutting. Like the Coweeta site, this clearcut forest exhibited a lag in nitrification and nitrate concentrations generally remained well below the 1 mg L^{-1} level.

We can classify the various mechanisms of retention as geochemical, hydrologic, and biological. The mechanisms controlling the loss of N in the form of nitrate are largely biological and hydrologic. Clearcutting is largely a biological and hydrologic disturbance in the sense that the soil remains intact if erosion is minor. In contrast, we propose that the loss of DON is controlled by geochemical and hydrologic mechanisms. The production of soluble organic nutrients by vegetation is, of course, biological but sorption and desorption are geochemical mechanisms.

The hydrologic control of DOC and DON flux was shown by the effect of increased water fluxes on nutrient flux in our cut plots and also in experiments on sorption/desorption equilibria during unsaturated flow through intact soil cores (Qualls and Haines, 1992a). Hydrologic controls are also likely to be important in the case of hydrologic flowpaths in the vicinity of streams which allow by-passing of strongly adsorbing soil horizons (see McDowell and Wood, 1984).

We hypothesize that the most important geochemical mechanisms leading to the retention of dissolved organic nutrients are: (i) the slow sustained release of potentially soluble DOM caused by slow dissolution, equilibrium controlled desorption from organic sur-

faces, and gradual exposure of surfaces to percolating water during fragmentation, and (ii) equilibrium adsorption to Fe and Al oxyhydroxides and clays. The slow gradual release of potentially soluble organics from detritus can be compared to factors tending to delay nitrification (sensu Vitousek et al., 1979). The well-recognized retention mechanisms for inorganic nutrients, most notably rapid recovery of net primary productivity, combined with geochemical mechanisms controlling leaching of DOM in these metal oxyhydroxide-rich soils to efficiently buffer the leaching of both soluble inorganic and organic nutrients after clearcutting.

CONCLUSIONS

1. Concentrations of DOC and DON were higher in the cut plots than in uncut plots in solutions from slash leachate (vs. throughfall), the forest floor, the A horizon, and the B horizon. DOP concentrations were higher in the cut plots than the uncut plots in solutions from slash leachate (vs. throughfall) and the forest floor but not in the mineral soil.

2. Fluxes of DOC, DON, and DOP in all strata were greater in cut plots than uncut plots, a product not only of concentration differences in some cases, but a 1.47-fold greater water flux from the C horizon of the cut plots.

3. Even in the cut plots, fluxes of the organic forms of nutrients exceeded those of the inorganic forms (except in the case of P in slash leachate and forest floor solution).

4. Despite greater fluxes of dissolved organic N from the cut plots, more than 99% of the DON draining from the forest floor on the cut plots was removed (presumably adsorbed) above the upper C horizon, demonstrating a remarkable degree of retention of this soluble form of N. We hypothesize that the well-recognized retention mechanisms for *inorganic* nutrients (e.g., uptake by roots of stump sprouts, adsorption of ions, and immobilization) combined with geochemical adsorption of dissolved organic matter to efficiently buffer against leaching of either soluble *inorganic* or *organic* nutrients after clearcutting.

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