

Effects of Forest Harvest on Stream-Water Quality and Nitrogen Cycling in the Caspar Creek Watershed¹

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Abstract: The effects of forest harvest on stream-water quality and nitrogen cycling were examined for a redwood/Douglas-fir ecosystem in the North Fork, Caspar Creek experimental watershed in northern California. Stream-water samples were collected from treated (e.g., clearcut) and reference (e.g., noncut) watersheds, and from various locations downstream from the treated watersheds to determine how far the impacts of these practices extended. Additionally, a detailed nutrient cycling study was performed in a clearcut and reference watershed to gain insights into changes in nitrogen cycling after harvesting activities.

Stream-water nitrate concentrations were higher in clearcut watersheds, especially during high stream discharge associated with storm events. Elevated concentrations of nitrate were due to increased leaching from the soil as mineralization (i.e., release of nutrients from organic matter) was enhanced and nutrient uptake by vegetation was greatly reduced after harvest. The elevated nitrate concentration in stream water from clearcut watersheds decreased in the higher-order downstream segments. This decrease is believed to be primarily due to dilution, although in-stream immobilization may also be important. Although elevated nitrate concentrations in stream water from the clearcut watershed might suggest a large nitrogen loss after clearcutting, conversion to a flux indicates a maximum loss of only $1.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; fluxes decreased to $<0.4 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ 3 years after the harvest. Nitrogen fluxes from the reference watershed over the same period were $<0.1 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. The increased nitrogen flux was due to both higher nitrate concentrations and an increased water flux from the clearcut watershed.

In contrast to many forest ecosystems that show large nutrient losses in stream water after harvest, this redwood/Douglas-fir ecosystem shows relatively small losses. The rapid regrowth of redwood stump sprouts, which use the vast rooting system from the previous tree, is capable of immobilizing nutrients in its biomass, thereby attenuating nutrient losses by leaching. Rapid regeneration also provides soil cover that appreciably reduces the erosion potential after harvest. Removal of nitrogen, primarily in the harvested biomass, results in an appreciable loss of nitrogen from the ecosystem. These data suggest that nitrogen fixation by *Ceanothus* may be an important nitrogen input that is necessary to maintain the long-term productivity and sustainability of these ecosystems.

The effects of forest harvest and postharvest practices on nutrient cycling were examined for a redwood/Douglas-fir ecosystem in the North Fork, Caspar Creek experimental watershed in northern California. This ecotype is intensively used for commercial timber production, and streams draining these ecosystems are an important salmon-spawning habitat. Although the effects of forest

harvest practices on stream flow and sediment generation have been intensively studied (e.g., Keppeler and Ziemer 1990, Rice and others 1979, Thomas 1990, Wright and others 1990, Ziemer 1981, and papers contained in these proceedings), the impacts of harvest practices on nutrient cycling processes have not been rigorously examined for the coastal region of northern California.

Water quality and long-term nutrient sustainability are major components addressed within the ecosystem approach to forest management (Swanson and Franklin 1992). Forest harvest practices are often considered to have adverse impacts on water quality and sensitive aquatic communities owing to enhanced sediment and nutrient losses due to erosion and leaching (Hornbeck and others 1987, Likens and others, 1970, Martin and others 1986). The loss of plant nutrients in drainage waters, suspended sediments, and biomass removed by harvesting may further affect nutrient sustainability of forest ecosystems (Hornbeck and others 1987, Johnson and others 1982, 1988). Sustainable forestry is based on the premise of removing essential nutrients at a rate less than or equal to that which can be replenished by natural processes. As forest ecosystems become more intensively managed, it is imperative that best-management practices be developed and used to minimize environmental impacts and assure long-term ecosystem sustainability.

This paper specifically examines the effects of forest harvest and postharvest management practices on the nitrogen cycle because nitrogen is the mineral nutrient required in the largest amount by the vegetation and it is believed to be the most limiting nutrient in this ecosystem. In addition, results for 10 additional nutrients are available in the final project report (Dahlgren 1998). This research uses a biogeochemistry approach to nutrient cycling that examines processes and interactions occurring within and between the atmosphere, hydrosphere, biosphere, and geosphere (fig. 1). The process-level information obtained can be used to decipher the complex interactions that occur in nutrient cycling processes at the ecosystem scale. Results from this research can be applied to the development of best-management practices to maintain long-term forest productivity while minimizing adverse environmental impacts from forest management.

Methods

Study Site Characteristics

Headwater catchments in the North Fork of Caspar Creek were selected for this study (fig. 2). The watersheds are located in the Jackson Demonstration State Forest, 11 km southeast of Fort Bragg, California, and approximately 7 km from the Pacific Ocean. The North Fork of Caspar Creek has a drainage area of 473 ha and

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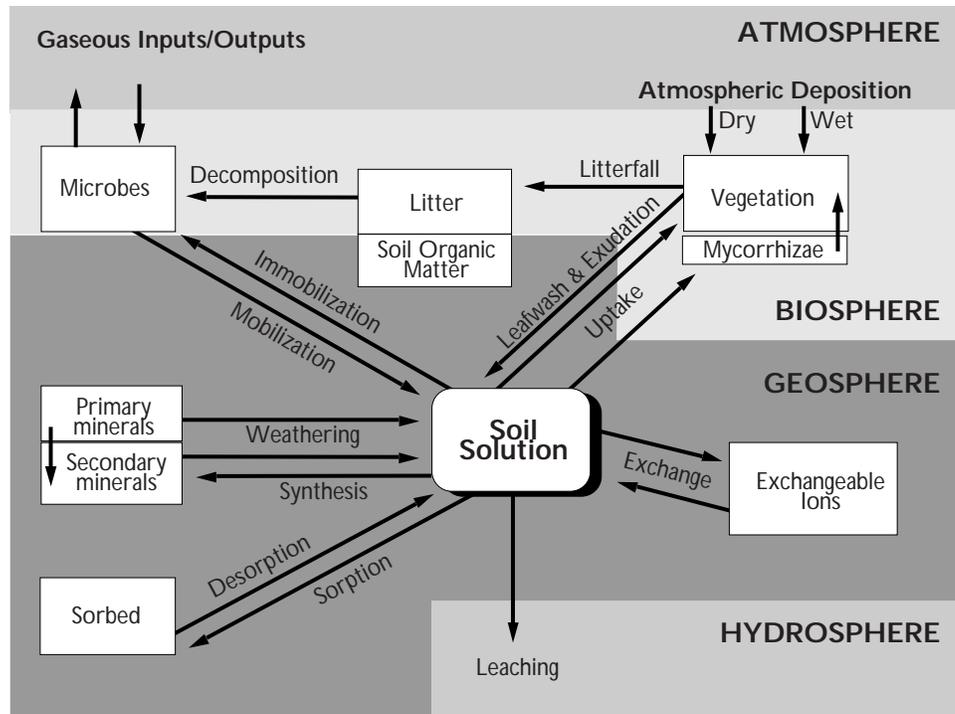


Figure 1—Nutrient cycles consist of a series of interrelated processes occurring within and between the atmosphere, hydrosphere, biosphere, and geosphere. Each nutrient is linked through a set of specific interconnected steps that ultimately lead to a series of cyclic pathways.

ranges in elevation from 37 to 320 m. The topography of the North Fork watersheds ranges from broad, rounded ridgetops to steep inner gorges. Slopes within the watershed are <30 percent (35 percent of the area), 30-70 percent (58 percent of area), and >70 percent (7 percent of the area) (Wright and others 1990).

The climate is Mediterranean, having dry summers with coastal fog and mild temperatures ranging from 10 to 25 °C. Winters are mild and wet, with temperatures ranging between 5 and 14 °C. The average annual rainfall is about 1,200 mm with no appreciable snowfall (Ziemer 1981). Soils are dominated by well-drained Ultic Hapludalfs and Typic Haplohumults formed in residuum derived predominately from sandstone and weathered coarse-grained shale of Cretaceous Age.

The North Fork of Caspar Creek was originally clearcut logged and burned in approximately 1910 (Tilley and Rice 1977). Current vegetation is dominated by second-growth redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with minor associated western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and grand fir (*Abies grandis* (Dougl.) Lindl.). The mean stand density based on cruise data from three watersheds was 207 redwood stems ha⁻¹ (mean DBH = 56 cm) and 86 Douglas-fir stems ha⁻¹ (mean DBH = 66 cm). Timber volume at the onset of this study before logging was estimated at about 700 m³ ha⁻¹ (Krammes and Burns 1973).

Solid-Phase Soil Analyses

Sites for six soil pits were randomly selected within a clearcut (KJE) and reference (MUN) watershed (fig. 2). Soil pits (1.5 by 0.5 by 1-1.2 m; L × W × D) were excavated to a depth corresponding to the limit of the major rooting zone (BC horizon; 100-120 cm). Each pedon was described, and soil samples for chemical analyses and clods for bulk density measurements were collected from across the entire pit face for each morphological horizon. All soil samples were collected during September 1992, the month during which the soil is driest.

Soil samples were air-dried, gently crushed, and passed through a 2-mm sieve; roots passing through the sieve were removed with a forceps. Bulk density was determined by the paraffin-coated clod method using three replicate clods per horizon (Soil Survey Staff 1984). Total carbon and nitrogen were determined on ground samples (<250 μm) by dry combustion with a C/N analyzer. Soil carbon and nitrogen pools (kg ha⁻¹) were calculated for each soil profile (n = 6) by summing the nutrient content of all horizons within the major rooting zone. Nutrient pools for each horizon were determined from the nutrient concentration in the <2 mm fraction, mean horizon thickness, and bulk density of each horizon with a correction for the coarse fragment (>2 mm) volume.

Collection and Analysis of Ecosystem Waterflows

The chemistry of ecosystem waterflows along the hydrologic cycle (e.g., precipitation, canopy throughfall, soil solution, and streamflow) was used to compare nutrient cycling processes in the clearcut (KJE) and reference (MUN) watersheds for 3 water years commencing 1 October 1993 and ending 30 September 1996. Samples were collected on a monthly basis during the rainy season (November-May) and on an event basis as necessary outside of the rainy season. Bulk precipitation was collected from duplicate sites within the clearcut watershed (KJE). Bulk precipitation collectors are effective in capturing the wetfall component but have been shown to only partially capture the dryfall (particulate and gases) relative to the collection efficiency of a forest canopy (Lindberg and others 1986). Thus, bulk precipitation fluxes probably underestimate the total atmospheric deposition to a forest ecosystem. Canopy throughfall was collected in triplicate from beneath the canopy of redwood and Douglas-fir in the area adjacent to the soil solution collection sites in the reference watershed (MUN). Precipitation and throughfall collectors consisted of a 4-L polyethylene bottle containing a 15-cm diameter funnel with Teflon wool inserted in the neck to act as a coarse filter.

In situ soil solutions were collected from three sites in the clearcut (KJE) and reference (MUN) watersheds using zero-tension lysimeters. Lysimeters consisted of open-topped polyethylene containers (15 by 10 by 4 cm; L × W × D) filled with acid-washed

quartz sand (Driscoll and others 1988). Lysimeters were placed in duplicate at the 20- and 40-cm depths along with a single collector at the 60-cm depth. Lysimeters were installed by tunneling from below and from the side of the excavated soil pit to the desired depth. This installation technique minimizes disturbance to the soil fabric and rooting system overlying the lysimeter. Lysimeters were installed one year before soil solutions were collected for chemical analysis. This equilibration period minimizes the potential for artifacts due to disturbance from lysimeter installation (Johnson and others 1995).

Concentrations of stream-water nutrients from watersheds receiving various combinations of forest harvest practices (e.g., clearcutting and burning) were compared to reference watersheds having no disturbance (fig. 2). Additionally, samples were collected along the main channel of the North Fork to determine the magnitude and persistence of the cumulative effects of timber harvest practices within the larger watershed. Grab samples were collected biweekly (rainy season) to monthly (nonrainy season) at 13 sites commencing in March 1991 and continuing through June 1996. In addition to the regular grab-sampling protocol, automatic pumping samplers were used to intensively collect water samples during storm events from the clearcut (KJE) and reference (MUN) watersheds. The autosamplers were programmed to collect storm samples using a variable probability (SALT) random sampling procedure (Thomas 1985, 1989). All stream-water samples were

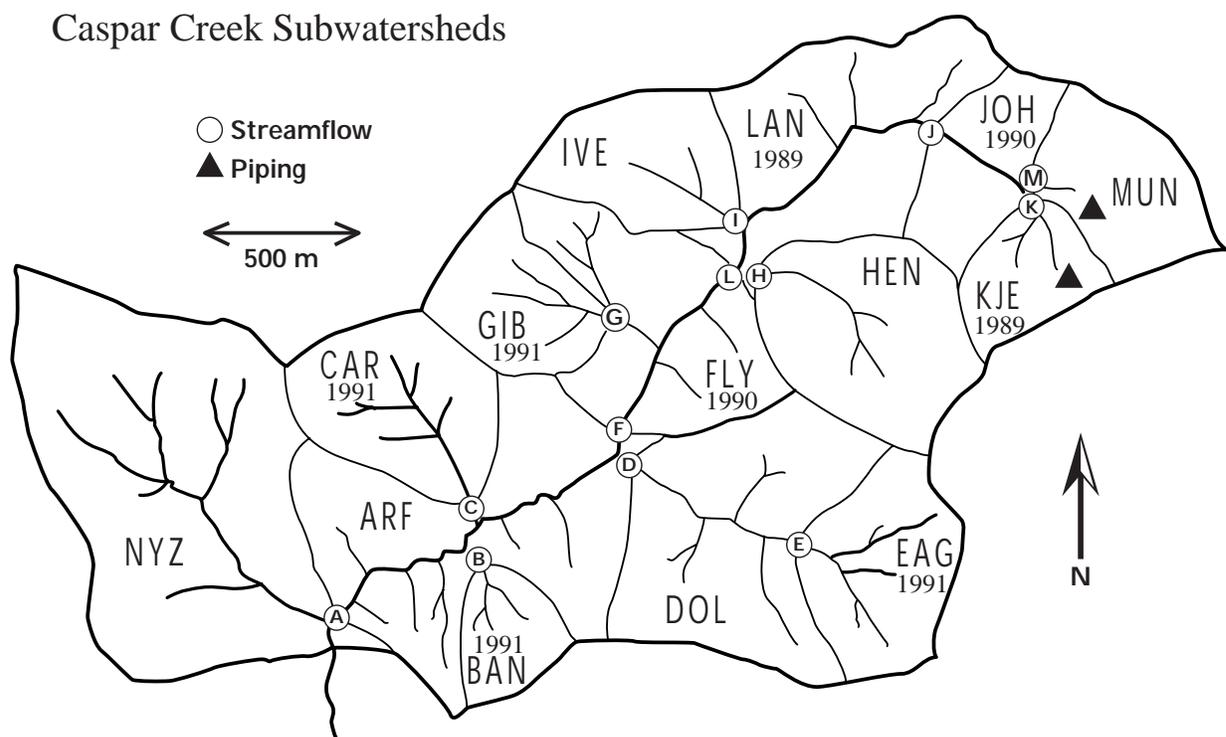


Figure 2—Site map indicating the location of the individual subwatersheds within the North Fork of Caspar Creek watershed. Letters indicate location of stream-water sampling sites; triangles, the location of piping water samples; and years, the year in which felling activity was completed in clearcut watersheds.

collected by the USDA Forest Service Caspar Creek Research Team. Before chemical analyses, all solutions were filtered through a 0.2- μm membrane filter. Ammonium and nitrate were determined by ion chromatography. Data for 10 additional solutes are given in the final report (Dahlgren 1998). During the 1994-1995 water year, water samples from three storm events were bulked to provide approximately a 20-L sample for isolation of the suspended sediment fraction ($>0.4 \mu\text{m}$). Carbon and nitrogen concentrations were determined by dry combustion using a C/N analyzer.

Nutrient Analysis in Biomass

Nutrient pools in biomass were determined for the regenerating redwood spouts in the clearcut watershed (KJE) and for the second-growth redwood/Douglas-fir stand in the reference watershed (MUN). Ten randomly selected 10-m by 10-m plots were sampled within the clearcut watershed in November 1995 to quantify total aboveground biomass production 6 years after completion of harvest. All shoots and their diameters were recorded within each plot for the stump-sprouting redwoods. To develop allometric relationships for the redwood sprouts, 10 individual stems spanning the range of diameter classes (0.76–7.6 cm) were destructively sampled. Biomass from each sprout was divided into foliage, twigs ($<2 \text{ mm}$), and branches/stems ($>2 \text{ mm}$). The mass of each category was recorded after drying at 70 °C.

Nutrient pools in the second-growth stand of the reference watershed (MUN) were estimated by sampling various biomass components from four replicates each of redwood and Douglas-fir. Foliage and branch samples were obtained from the mid-point of the upper, middle and lower one-third portions of each tree canopy by climbing the tree. For each tree, all branch and foliage samples at each canopy position were separately processed and chemically analyzed. Individual root samples from each tree were obtained by excavating at the base of each tree; samples were collected one meter away from the base of the tree in the Oi/Oe and A horizons. Stemwood and bark were collected by coring individual trees at breast height (1.4 m).

Carbon and nitrogen concentrations were determined on ground samples ($<250 \mu\text{m}$) by dry combustion using a C/N analyzer. Nitrogen recovery was 95.2 ± 2.3 percent based on analysis of National Bureau of Standard's reference materials. Nutrient pools in biomass of the redwood/Douglas-fir forest were determined from stand density, allometric relationships obtained from Gholz and others (1979), and nutrient concentrations determined from the preceding analyses. Because no allometric relationships were available for aboveground biomass in redwood, we estimated the redwood biomass amounts using the Douglas-fir allometric relationships. This extrapolation introduces a potential error into the estimate for the redwood aboveground nutrients; however, this error will most likely be on the order of <20 percent. Root biomass for the second-growth forest and stump sprouts was estimated from the data of Ziemer and Lewis³ obtained from comparable forest stands in northern California.

³ Unpublished data from Ziemer and Lewis on file at USDA Forest Service, Redwood Sciences Laboratory, Arcata, CA 95521.

Results and Discussion

Soils

Soils provide ecosystem resiliency after perturbations owing, in large part, to their capacity to provide stored nutrients for regenerating vegetation. The effects of clearcut harvesting on the quantity and distribution of organic carbon and nitrogen in soils were examined by comparing soils in the reference watershed (MUN) to those in the clearcut watershed (KJE) 3 years after the harvest. An important difference between soils in the two watersheds was the loss of the majority of the litter layer (Oi/Oe horizon) from the clearcut watershed. An Oi/Oe layer with a thickness of 1-3 cm was found on all soils within the reference watershed. The loss of the litter layer after harvest was due to microbial decomposition and mixing of the litter layer with the mineral soil during logging operations. The litter layer plays an important role in forest ecosystems by protecting the mineral soil from erosion, storing nutrients and water, and acting as mulch to reduce temperature fluctuations and evaporative water loss.

Nutrient pools contained within the primary rooting zone (upper 100-120 cm) were determined as a function of soil horizon for the reference and clearcut watersheds (*fig. 3*). In spite of the loss of the litter layer from soils in the clearcut watershed, there were no statistical differences ($p < 0.05$) in organic carbon or nitrogen pools between the clearcut and reference watersheds. The soils store a very large pool of organic carbon ($\sim 170 \text{ Mg ha}^{-1}$), primarily in the A and AB horizons (the upper 30 cm). The loss of the Oi/Oe horizon from the clearcut watershed appears to be compensated for by an increase in organic carbon in the A horizon. This may reflect the mixing of the litter layer with the mineral soil during harvesting operations. The soils similarly store large concentrations of nitrogen ($>9 \text{ Mg ha}^{-1}$); however, this nitrogen pool is not readily available to the vegetation until mineralization releases the nitrogen from the soil organic matter (*fig. 1*). Because the soil N pool is so large ($10,000 \text{ kg ha}^{-1}$), even an appreciable decrease, such as 100 kg ha^{-1} , after harvest cannot be accurately determined by standard solid-phase analysis, especially given the high spatial variability. Therefore, analysis of solid-phase soil properties is not a sensitive method for determining changes in nutrient cycling processes due to disturbance.

Ecosystem Waterflows

Analysis of ecosystem waterflows is a far more powerful approach than solid-phase soil analysis for detecting treatment effects after ecosystem disturbance because aqueous transport is a primary mechanism for the redistribution of nutrients within an ecosystem. Because ecosystem waterflows provide information about current-day nutrient transport processes, their composition is very sensitive to changes due to disturbance. The nutrient concentrations were examined along the hydrologic cycle within the second-growth redwood/Douglas-fir and clearcut ecosystems to examine changes in nutrient cycling (*fig. 4*). The precipitation had trace inputs of N ($\text{NH}_4 = 0.8 \mu\text{M}$ and $\text{NO}_3 = 1.0 \mu\text{M}$) that were not appreciably altered by canopy processes. Concentrations of NH_4 in soil solutions were

very low (<3 μM) and showed no difference between the reference and clearcut soils. Nitrate concentrations were also low; however, nitrate concentrations were significantly greater throughout the entire soil profile of the clearcut watershed. Enhanced nitrogen mineralization rates coupled with reduced uptake were responsible for the increased nitrate mobility after the harvest (fig. 1). Soil solution nitrate concentrations in this study were very low compared to values commonly exceeding 200 μM after clearcutting of northern hardwood forests in the Hubbard Brook Ecological Forest in New Hampshire (Dahlgren and Driscoll 1994). Within the soil profile from the clearcut, the concentration of nitrate decreases appreciably with depth because of nitrogen uptake by the stump-

sprouting redwoods. In the absence of this nitrogen uptake, nitrogen losses to stream water would probably be much higher. Concentrations of nitrate were higher in the stream water than at the 60-cm depth in the soil profile in both watersheds. The higher nitrate concentrations in the stream water most likely result from changes in the hydrologic flowpath during storm events. Our data suggest that water from the upper soil horizons (0- to 30-cm depth) is preferentially routed to the streams during storm events owing to the low saturated hydraulic conductivities associated with the clay-rich B horizons that begin at a depth of about 30 cm. Mean concentrations of nitrate in stream water were very similar to those occurring in soil solutions at the 20- and 40-cm depth (fig. 4).

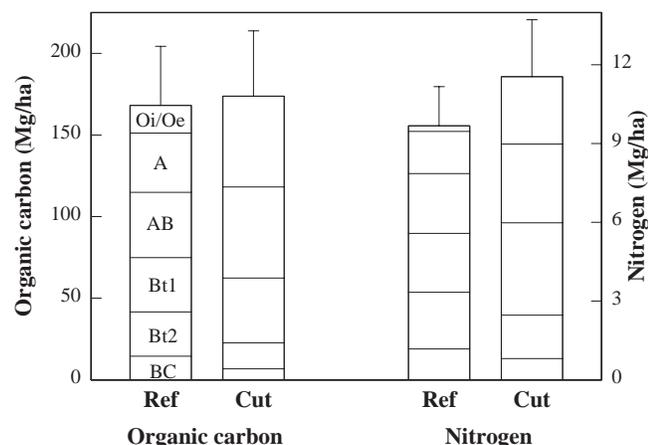


Figure 3—Carbon and nitrogen pools in reference watershed (MUN) and clearcut watershed (KJE) 3 years after the harvest. The individual segments of each bar indicate the nutrient amount contained within that individual soil horizon (no Oi/Oe in clearcut). Error bar indicates the standard error of the mean.

Stream-Water Nitrate

Watershed-scale manipulations are a powerful approach for studying the cumulative effects of forest management practices on nutrient cycling processes. Watershed manipulation studies use a paired watershed approach in which two watersheds with similar characteristics are employed. In this study, stream-water chemistry from the reference watershed (MUN) is compared to that from clearcut (KJE) and clearcut/burned (EAG) watersheds to examine the effects of harvesting practices on nutrient cycling (fig. 2). The export of nutrients in stream water is often one of the primary processes responsible for nutrient losses from forested ecosystems. Monitoring of stream-water chemistry began in the KJE watershed approximately 1.25 years (in March 1991) after completion of felling operations and in the EAG watershed immediately after harvest and burning activities.

Nitrate concentrations in stream water from the reference watershed were generally less than our detection limits of 0.4 μM ; however, concentrations exceeding 10 μM were measured during two storm events in the 1995-1996 water year (fig. 5). In contrast, nitrate concentrations in the harvested watersheds ranged between 10 and 70 μM during storm events. Baseflow nitrate concentrations in the clearcut watershed were also low, often below detection limits (0.4 μM). It appears that nitrate concentrations showed a progressive decrease in peak concentrations after the clearcut (1991 to 1994), with the exception of increased concentrations during storm events in the 1995-1996 water year. The increased nitrate concentrations during the 1995-1996 water year were observed in both the clearcut and reference watersheds, suggesting that the increase was not solely due to the disturbance associated with harvest practices.

Increased nitrate concentration in stream water after clearcutting is a common observation; however, the magnitude of nitrate leaching varies appreciably between ecosystems. For example, maximum nitrate concentrations in stream water after clearcutting of northern hardwood forests in the White Mountains of New Hampshire were 500 μM (Dahlgren and Driscoll 1994), nearly an order of magnitude greater than those observed in this study. We believe that the rapid immobilization of nitrogen by the stump sprouting redwood biomass is an important factor limiting the leaching losses of nitrate in this redwood/Douglas-fir ecosystem.

The maximum concentrations of nitrate often occur in the

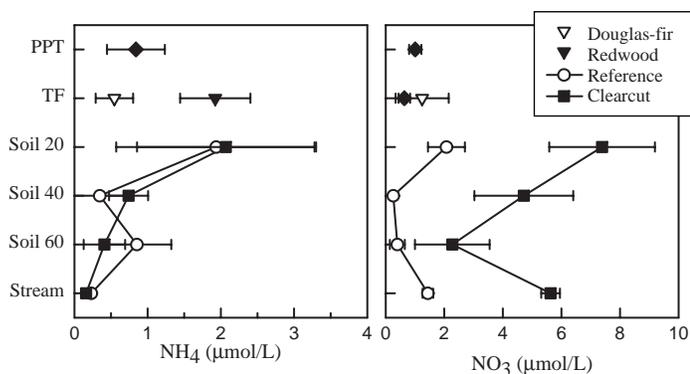


Figure 4—Mean \pm standard deviation for ammonium and nitrate in precipitation (PPT); canopy throughfall (TF); soil solutions at 20-, 40-, and 60-cm depths; and stream water for the period October 1993 to June 1996 in the clearcut (KJE) and reference (MUN) watersheds.

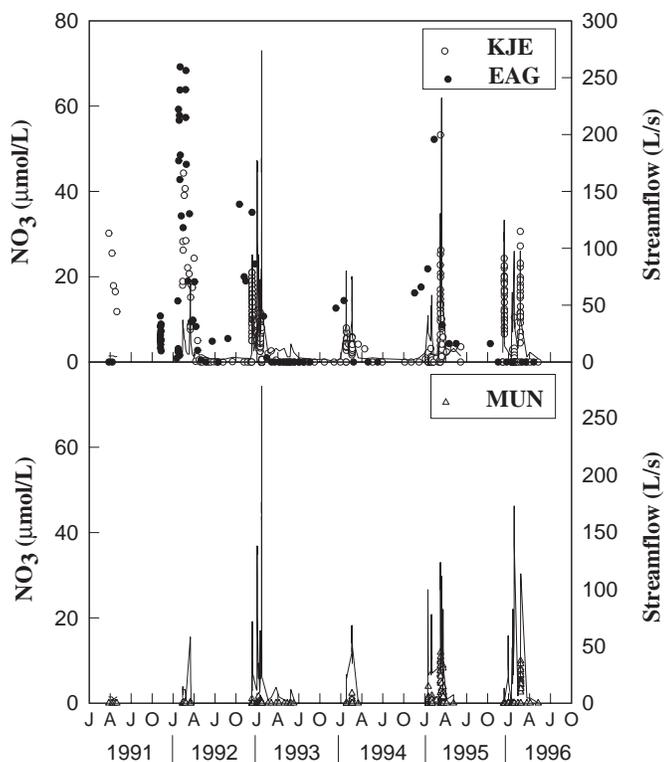


Figure 5—Stream-water nitrate concentrations and stream flow in the clearcut (KJE), clearcut and burned (EAG; no stream flow shown), and reference (MUN) watersheds of the North Fork, Caspar Creek.

second year after clearcutting (Martin and others 1986). This results from enhanced immobilization of nitrogen during the first year as microorganisms begin to decompose woody litter, with high C/N ratios, that was added to the soil organic matter pool as slash during the harvest. Because we missed the January 1990 to March 1991 monitoring period in the KJE watershed, we cannot specifically determine the timing of peak nitrate concentrations after harvest in this watershed. However, nitrate concentrations in stream water peaked in the EAG watershed in the water year immediately after harvest and burning. Removal of woody biomass by burning may result in less microbial immobilization and a more rapid release of mineral nitrogen in this watershed.

Maximum nitrate concentrations occur during high-discharge storm events and drop to low levels during baseflow (fig. 5). We interpret these data to indicate that changing hydrologic flowpaths during storm events result in the delivery of high-nitrate waters to the stream during peak discharge. Data on soil solution indicate that the highest nitrate concentrations occur within the upper soil horizons (fig. 4). The soils within the watershed have a thick, clay-enriched horizon beginning at a depth of approximately 30 cm. This horizon contains >40 percent clay, substantially reducing the hydraulic conductivity that results in temporary saturation above this layer. Given the steep slopes within the watershed, this

saturated layer may move laterally downslope, transporting nutrients from within the nutrient-rich rooting zone (upper 30 cm). This water enters the stream as subsurface lateral flow (Keppeler and Brown, these proceedings) contributing to maximum stream-water nitrate concentrations during peak discharge. The lateral flow of water above the clay-rich horizon and through macropores (e.g., root channels and soil pipes) was observed repeatedly on roadcuts within the Caspar Creek drainage supporting this mechanism.

Nutrient Input/Output Budgets

Although nutrient concentrations in ecosystem waterflows provide information on processes regulating nutrient concentrations in stream water, the most important consideration from an ecosystem sustainability perspective is the nutrient flux ($\text{kg ha}^{-1} \text{yr}^{-1}$) associated with atmospheric deposition and streamflow. Fluxes in stream-water nutrients were calculated by combining stream discharge (L s^{-1}) with nutrient concentrations (mg L^{-1}). Because the water yields of clearcut and reference watersheds differ appreciably (Keppeler, these proceedings; Ziemer, these proceedings), what appear to be small differences in stream-water nutrient concentrations result in much larger differences in nutrient fluxes.

Nitrogen fluxes in precipitation are shown for the 5 water years of the study in table 1. The precipitation fluxes are regulated to a large degree by the precipitation amount for a given year. Precipitation amounts from nearby Fort Bragg during the study period ranged from a low of 78 cm during the 1993-1994 water year to a high of 148 cm during the 1994-1995 water year. Nitrogen fluxes in bulk precipitation were very low, ranging between 0.1 and 0.4 $\text{kg N ha}^{-1} \text{yr}^{-1}$ during the study period. Actual nitrogen inputs to this ecosystem may be somewhat higher because the forest canopy has a much higher efficiency of capturing atmospheric gases, aerosols, and particulate matter than the funnel used to collect the bulk precipitation. In contrast, the capture efficiency of the clearcut watershed would be greatly attenuated by the removal of the canopy.

Nitrogen fluxes in stream water were substantially higher for the clearcut watershed than for the reference watershed (table 1). The maximum nitrogen flux in the clearcut watershed was 1.85 $\text{kg N ha}^{-1} \text{yr}^{-1}$ in the 1991-1992 water year. Nitrogen fluxes decreased over time to 0.15 $\text{kg N ha}^{-1} \text{yr}^{-1}$ in the 1995-1996 water year (the 7th water year following harvest). In contrast, nitrogen fluxes were low (<0.10 $\text{kg N ha}^{-1} \text{yr}^{-1}$) in the reference watershed. The increased

Table 1—Nitrogen fluxes contained in precipitation and stream water from the reference (MUN) and clearcut (KJE) watersheds for the 5-year study period.

Water year	Precipitation	Stream water	
		Reference	Clearcut
		----- kg ha^{-1} -----	
1991-92	0.22	<0.01	1.85
1992-93	0.40	<0.01	1.08
1993-94	0.36	<0.01	0.19
1994-95	0.15	0.08	0.37
1995-96	0.10	0.04	0.15

nitrogen flux in stream water after harvest results from the combination of increased stream-water nitrate concentrations and an increase in water yield due to reduced evapotranspiration and interception of water by the canopy. Nitrogen fluxes return to background levels when the immobilization capacity of the regenerating vegetation approaches the rate of nitrogen mineralization. The recovery period of 5-7 years is consistent with the findings of other studies examining the effects of clearcutting on stream-water nutrient fluxes (Dahlgren and Driscoll 1994, Hornbeck and others 1987, Martin and others 1986).

Cumulative Effects in Stream-Water Nitrate Concentrations

The cumulative effects of timber harvest operations (i.e., the distance to which a harvesting effect is observed downstream from the harvested watershed) is a very important attribute of watershed biogeochemistry. Some impacts may be observed far downstream of the actual disturbance, whereas other impacts may not be detectable downstream of a disturbance. *Figure 6* shows mean stream-water nitrate concentrations in nondisturbed reference watersheds (HEN, IVE, and MUN), harvested watersheds (BAN, CAR, EAG, GIB, and KJE), sampling points along the main stem that combine water from reference and harvested watersheds (DOL, FLY, LAN, and JOH), and the main stem just before it exits the experimental watershed (ARF).

The reference watersheds showed very low concentrations of nitrate with a relatively low standard deviation. Nitrate concentrations in stream water draining the clearcut watersheds showed elevated nitrate concentrations with a mean of about 4 μM

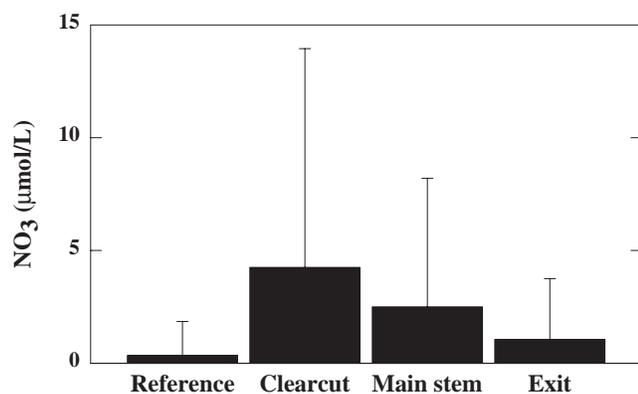


Figure 6—Cumulative effects of nitrate concentrations (mean±standard deviation) in stream waters of the North Fork, Caspar Creek experimental watershed. Data shown are for reference watersheds (HEN, IVE, and MUN), harvested watersheds (BAN, CAR, EAG, GIB, and KJE), locations downstream from harvested watersheds (Main stem: DOL, FLY, LAN, and JOH), and at the exit point (Exit; ARF) of the stream from the experimental watershed.

over the 5-year study period. The high standard deviation associated with harvested watersheds reflects the temporal variability that occurs in nitrate leaching after the harvest. Maximum concentrations of about 70 μM were measured from clearcut watersheds. Also contributing to the large standard deviations are the large fluctuations that occur in nitrate concentrations during storm events because of changing hydrologic flowpaths. Nitrate concentrations decreased at sampling points downstream from the harvested watersheds and reached a mean value of about 1 μM as the stream water exited the experimental watershed. The decrease in nitrate concentrations as the water enters higher-order streams appears to be largely due to dilution with low-nitrate waters entering from nondisturbed portions of the watershed. There may be some attenuation of nitrate concentrations by in-stream immobilization of nitrate by biota; however, the short residence time of water in the watershed provides very little time for biological processes to affect water quality.

Nutrient Pools in Biomass

An inventory of the number and size distribution of stump-sprouting redwoods in watershed KJE was made 6 years after clearcut harvesting. This inventory showed 5020 ± 1970 stems ha⁻¹ (mean ± std. dev.; range = 2600 - 8300) having a DBH of 2.59 ± 0.71 cm (mean ± std. dev.). The DBH of the stump sprouts ranged from <1 to 10 cm. The diameter distribution indicates that the majority (76 percent) of the stems have DBH values ≤ 3 cm with far fewer stems in the larger diameter classes (Dahlgren 1998). Within a cluster of stems surrounding a stump, there were generally 1 to 4 dominant stems with DBH values greater than about 6 cm.

Total carbon storage in the aboveground biomass of the 6-year-old redwood stand was 7.8 Mg ha⁻¹ (*table 2*). On the basis of an average carbon content of about 50 percent for the biomass, there was more than 15 Mg ha⁻¹ of aboveground biomass within the redwood sprouts 6 years after harvest. This rapid accumulation of biomass after harvest is the result of the rapid regrowth associated with regeneration from stump sprouting versus establishment from seed. The large intact rooting system can acquire an abundance of nutrients to support regrowth. Also important in this rapid regrowth is the immobilization of potentially mobile nutrients, such as nitrate, into the aboveground biomass. The accumulation of 70 kg N ha⁻¹ in the aboveground biomass and the retention of 16 kg N ha⁻¹ in the living rooting system greatly attenuate leaching of nitrogen after harvest (*table 1*). Warmer and moister soil conditions combined with higher organic matter concentrations from logging slash after clearcutting result in higher decomposition, mineralization, and leaching (*fig. 1*). Thus, rapid immobilization of nutrients by the aggrading redwood forest will have a strong influence on nutrient dynamics and leaching after harvest in these ecosystems.

Nutrient pools calculated for the second-growth redwood/Douglas-fir stand showed 644 Mg C ha⁻¹ (~1288 Mg ha⁻¹ of biomass) stored in this forest ecosystem that is more than 80 years old (*table 2*). The wood and bark components contain about 86 percent (555.5 Mg ha⁻¹) of the biomass carbon, and only 6.4 percent (41 Mg ha⁻¹) of the biomass carbon pool is found in the belowground root biomass.

Table 2—Carbon and nitrogen pools contained in stump-sprouting redwood 6 years after clearcutting (KJE) and in the second-growth redwood/Douglas-fir stand (MUN).

Biomass component	Carbon		Nitrogen	
	Clearcut	Second-growth	Clearcut	Second-growth
	----- kg ha ⁻¹ -----			
Foliage	1,914	12,400	42.6	269
Branches/redwood stems	5,915	34,900	27.5	95
Wood		488,000		735
Bark		67,500		214
Roots	2,660	41,000	15.6	166
Total	10,489	643,800	85.7	1,479

The biomass contains nearly four times the amount of organic carbon stored in the soil profile (~170 Mg ha⁻¹). There was a total of 1480 kg ha⁻¹ of nitrogen in the redwood and Douglas-fir biomass in this ecosystem (table 2). Only 10 percent (166 kg ha⁻¹) of the nitrogen pool is found in the belowground root biomass. Approximately 64 percent (949 kg ha⁻¹) of the total nitrogen in the biomass is contained within the wood and bark components. Because conventional clearcutting removes only the wood and bark components, it is this 949 kg ha⁻¹ of nitrogen that will be removed from the ecosystem by traditional clearcut harvesting.

Nutrients in Suspended Sediments

The transport of nutrients in suspended sediments can be substantial if steps are not taken to minimize erosion after harvest. We determined the nutrient concentrations of suspended sediment collected from both the clearcut (KJE) and reference (MUN) watersheds in order to provide an estimate of the amount of nitrogen lost from these watersheds as suspended sediment. The nitrogen content of suspended sediment in the reference watershed (4.4 ± 1.9 g N kg⁻¹) was 2.7 times higher than in the clearcut watershed (1.6 ± 0.5 g N kg⁻¹). This difference possibly reflects the origin of the suspended sediment. The soil surface of the reference watershed is covered by a litter layer that would produce a relatively organic-rich sediment. In contrast, the loss of the litter layer from the clearcut watershed results in a soil surface with a lower organic matter concentration. Thus, the difference in the nitrogen content of suspended sediments between the two watersheds probably reflects the contrasting nature of the soil surface in the two watersheds, or different source areas. The source of much of the sediment in KJE was likely from sediments stored in the channel (Lewis, these proceedings).

The suspended sediment load predicted for an unlogged condition in water years 1990-1996 for the entire North Fork Caspar Creek experimental watershed was about 385 kg ha⁻¹ yr⁻¹ before harvest activities (Lewis, personal communication). If the nitrogen content (4.4 g N kg⁻¹) of the suspended sediments from the reference watershed (MUN) is representative of that for the entire watershed

before harvest, 1.7 kg ha⁻¹ yr⁻¹ of nitrogen would be lost from the watershed as suspended sediment. Harvest activities within the entire North Fork experimental watershed resulted in an increase of 345 kg ha⁻¹ yr⁻¹ of suspended sediment (Lewis, personal communication). However, the total nitrogen lost from the clearcut watershed would actually be somewhat lower than that lost from the reference watershed because of the lower nitrogen content associated with suspended sediment from the clearcut watershed (1.6 g N kg⁻¹). Because of the limited data collected in this study and the large temporal variability associated with suspended sediment fluxes over the course of a harvest rotation, it is very difficult to estimate the long-term nitrogen fluxes from these watersheds.

Ecosystem Nitrogen Sustainability

Sustainable forestry is based on the premise of removing essential nutrients at a rate less than or equal to that which can be replenished by natural processes. As shown in the preceding discussion, nitrogen is lost from the ecosystem primarily by biomass removal, suspended sediment, and leaching. Denitrification may also result in nitrogen loss; however, we have no estimates of how much nitrogen may be lost by this mechanism. The primary inputs of nitrogen into the ecosystem are atmospheric deposition and nitrogen fixation, primarily by *Ceanothus*. A nitrogen mass balance was calculated on the basis of estimated nitrogen inputs and outputs over the course of an 80-year harvest rotation (table 3). Regardless of the amount of nitrogen lost in the suspended sediment fraction, there is a net loss of nitrogen from this ecosystem. Nitrogen losses are dominated by biomass removal (~950 kg ha⁻¹), which removes about 60 percent of the nitrogen contained in the biomass. Although the nitrogen loss in the suspended sediment fraction cannot be precisely estimated, it appears to be on the order of 1.0 - 2.0 kg N ha⁻¹ yr⁻¹. These losses greatly exceed the only measured input of about 20 kg N ha⁻¹ in the bulk precipitation. This input/output balance suggests a nonsustainable forest management practice over the long term; however, nitrogen fixers such as *Ceanothus* can contribute appreciable nitrogen inputs into these ecosystems. *Ceanothus thyrsiflorus* (blue-blossom ceanothus) is an aggressive invader after clearcutting, and it has the potential to fix large quantities of nitrogen to replenish the nitrogen deficit imposed by harvesting. Nitrogen fixation rates for *Ceanothus velutinus* in the Oregon Cascades range from 70 to 100 kg N ha⁻¹ yr⁻¹

Table 3—Nitrogen mass balance for clearcut harvest management based on an 80-year harvest rotation. The suspended sediment flux is estimated based on limited data from this study.

Nutrient component	Nitrogen pools and fluxes	
	----- kg ha ⁻¹ -----	
Soil pool	9,500	
Biomass pool	1,480	
Atmospheric deposition flux		+20
Nitrogen fixation flux		+?
Harvest removal flux		-950
Stream-water flux		-10
Suspended sediment flux		-80 to -160

(Binkley and others 1982, Youngberg and Wollum 1976). These data, as well as data reported in the literature (e.g., Swanson and Franklin 1992), suggest that nitrogen fixation by *Ceanothus* may be necessary to maintain the long-term productivity and sustainability of these ecosystems. Additional research appears warranted to determine the importance of *Ceanothus* in the postharvest recovery of the nitrogen budget in this ecosystem.

Conclusions

Clearcut harvesting of this redwood/Douglas-fir ecosystem did not result in any short-term detectable decrease in soil carbon and nitrogen pools. Stream-water nitrate concentrations were increased after clearcutting, especially during storm events with high stream-discharge volumes; however, fluxes in stream water were relatively low compared to results from other forest ecosystems. Immobilization of nutrients by the rapid regrowth of redwood stump sprouts appears to make this ecosystem relatively resilient to nutrient loss by leaching after harvest. The elevated nitrate concentration in streams draining clearcut watersheds was substantially decreased at downstream sampling points. By the time the stream left the experimental watershed, nitrate concentrations were near those of the nonperturbed reference watersheds. Removal of nitrogen in the harvested biomass results in an appreciable loss of nitrogen from the ecosystem. These data suggest that nitrogen fixation by *Ceanothus* may be an important nitrogen input that is necessary to maintain the long-term productivity and sustainability of these ecosystems.

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References

- Binkley, D.; Cromack K.; Fredriksen, R.L. 1982. **Nitrogen accretion and availability in some snowbrush ecosystems.** *Forest Science* 28: 720-724.
- Dahlgren, R.A. 1998. **Effects of forest harvest on biogeochemical processes in the Caspar Creek Watershed.** Unpublished Draft Final Report prepared for the California Department of Forestry and Fire Protection. Contract No. 8CA17039. Sacramento, CA; 151 p.
- Dahlgren, R.A.; Driscoll, C.T. 1994. **The effects of whole-tree clearcutting on soil processes at the Hubbard Brook Experimental Forest, New Hampshire, USA.** *Plant and Soil* 158: 239-262.
- Driscoll, C.T.; Fuller, R.D.; Simone, D.M. 1988. **Longitudinal variations in trace metal concentrations in a northern forested ecosystem.** *Journal of Environmental Quality* 17: 101-107.
- Gholz, H.L.; Grier, C.C.; Campbell, A.G.; Brown, A.T. 1979. **Equations for estimating biomass and leaf area of plants in the Pacific Northwest.** Research Paper 41. Corvallis, OR: Forest Research Laboratory, Oregon State University; 37 p.
- Hornbeck, J.W.; Martin, C.W.; Pierce, R.S.; Bormann, F.H.; Likens, G.E.; Eaton, J.S. 1987. **The northern hardwood forest ecosystem: ten years of recovery from clearcutting.** Res. Paper NE-RP-596. Broomall, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 30 p.
- Johnson, D.W.; West, D.C.; Todd, D.E.; Mann, L.K. 1982. **Effects of sawlog vs. whole-tree harvesting on the nitrogen, phosphorus, potassium, and calcium budgets of an upland mixed oak forest.** *Soil Science Society of America Journal* 46: 1304-1309.
- Johnson, D.W.; Kelly, J.M.; Swank, W.T.; Cole, D.W.; Van Miegroet, H.; Hornbeck, J.W.; Pierce, R.S.; Van Lear, D. 1988. **The effects of leaching and whole-tree harvesting on cation budgets of several forests.** *Journal of Environmental Quality* 17: 418-424.
- Johnson, D.W.; Walker, R.F.; Ball, J.T. 1995. **Lessons from lysimeters – soil N release from disturbance compromises controlled environment study.** *Ecological Applications* 5: 395-400.
- Keppeler, E.T.; Ziemer, R.R. 1990. **Logging effects on streamflow: water yield and summer low flows at Caspar Creek in Northwestern California.** *Water Resources Research* 26: 1669-1679.
- Krammes, J.S.; Burns, D.M. 1973. **Road construction on Caspar Creek watersheds ... a 10-year progress report.** Res. Paper PSW-93. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 10 p.
- Likens, G.E.; Bormann, F.H.; Johnson, N.M.; Fisher, D.W.; Pierce, R.S. 1970. **Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem.** *Ecological Monographs* 40: 23-47.
- Lindberg, S.E.; Lovett, G.M.; Richter, D.D.; Johnson, D.W. 1986. **Atmospheric deposition and canopy interactions of major ions in a forest.** *Science* 231: 141-145.
- Martin, C.W.; Pierce, R.S.; Likens, G.E.; Bormann, F.H. 1986. **Clearcutting affects stream chemistry in the White Mountains of New Hampshire.** Res. Pap. NE-579. Broomall, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 12 p.
- Rice, R.M.; Tilley, F.B.; Datzman, P.A. 1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976.** Res. Paper PSW-146. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 12 p.
- Soil Survey Staff. 1984. **Procedures for collecting soil samples and methods of analysis for soil survey.** Soil Survey Investigations Report No. 1. Washington, DC: Soil Conservation Service, U.S. Department of Agriculture.
- Swanson, F.J.; Franklin, J.F. 1992. **New forestry principles from ecosystem analysis of Pacific Northwest forests.** *Ecological Applications* 2: 262-274.
- Thomas, R.B. 1985. **Estimating total suspended sediment yield with probability sampling.** *Water Resources Research* 21: 1381-1388.
- Thomas, R.B. 1989. **Piecewise SALT sampling for estimating suspended sediment yields.** Gen. Tech. Rep. PSW-83. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 11 p.
- Thomas, R.B. 1990. **Problems in determining the return of a watershed to pretreatment conditions: techniques applied to a study at Caspar Creek, California.** *Water Resources Research* 26: 2079-2087.
- Tilley, F.B.; Rice, R.M. 1977. **Caspar Creek watershed study—a current status report.** State Forest Notes 66. Sacramento, CA: State of California Department of Forestry; 15 p.
- Wright, K.A.; Sendek, K.H.; Rice, R.M.; Thomas, R.B. 1990. **Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California.** *Water Resources Research* 26: 1657-1667.
- Youngberg, C.T.; Wollum, A.G. 1976. **Nitrogen accretion in developing *Ceanothus velutinus* stands.** *Soil Science Society of America Journal* 40: 109-112.
- Ziemer, R.R. 1981. **Storm flow response to road building and partial cutting in small streams of northern California.** *Water Resources Research* 17: 907-917.