

LAND, AIR AND WATER RESOURCES PAPER

EFFECTS OF FOREST HARVEST ON BIOGEOCHEMICAL PROCESSES IN THE CASPAR CREEK WATERSHED

FINAL REPORT TO: CALIFORNIA DEPARTMENT OF FORESTRY & FIRE PROTECTION
AGREEMENT NUMBER 8CA17039

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Randy A. Dahlgren

EXECUTIVE SUMMARY

Water quality and long-term sustainability are major components addressed within the ecosystem approach to forest management. Forest harvest practices are often implicated as having adverse impacts on sensitive aquatic communities and on the long-term sustainability of forest ecosystems. While careless harvest practices can certainly cause adverse impacts, proper forest management practices can minimize or even eliminate these adverse effects. As forest ecosystems become more intensively managed, it is imperative that management practices be developed and utilized to minimize environmental impacts and assure long-term ecosystem sustainability. This research examined the effects of forest harvest and post-harvest management practices on biogeochemical processes. The biogeochemistry approach examines processes and interactions occurring within and between the atmosphere, hydrosphere, biosphere and geosphere. Results from this research provide information to help us understand the complex interactions that occur in nutrient cycling processes at the ecosystem scale: This information can be further applied to the development of management practices to maintain long-term forest productivity and to minimize adverse environmental impacts from forest management activities.

The primary objective of this study was to examine the cumulative effects of forest management practices on stream water solute concentrations and on nutrient cycling in a coastal redwood/Doug fir ecosystem. Specific objectives were to:

1. Examine changes in stream water solute concentrations and nutrient fluxes following various harvest and post-harvest forest management practices,
2. Examine the magnitude and spatial pattern of downstream impacts associated with disturbance in headwater catchments,
3. Examine the relationship, between stream water and pipeflow solute concentrations and their relationship to stream discharge, and
4. Compare nutrient cycling within clearcut and non-undisturbed (reference) catchments.

Major findings of research

Soils. There were minimal changes in soil properties and soil nutrient pools three years after clearcut harvesting. The 1-3 cm thick litter layer (Oi/Oa) was largely lost from the clearcut watershed due to mixing and decomposition following harvest. This may lead to a greater erosion potential in the short-term following harvest. Soil pH in the A and AB horizons of the clearcut watershed was decreased by 0.2 to 0.5 units following harvest. This pH depression will have little impact on ecosystem processes. There were no significant changes to soil nutrient pools following clearcutting. Thus, clearcutting had no major effect on soil properties and nutrient pools in the three years following harvest.

Biomass Nutrients. Rapid regrowth of redwood stump sprouts immobilized large concentrations of nutrients, thereby attenuating their loss by leaching from the watershed. A mean of 5020 redwood stem/ha having an above-ground biomass of 15 Mg/ha was measured six years following the clearcut. The above-ground biomass of the regenerating redwood contained 70, 56, 12, 80, 14 and 7 kg/ha of N, Ca, Mg, K, P and S, respectively. This rapid regrowth of redwoods also provides soil cover which appreciably reduces the erosion potential following harvest. Based on foliar nutrient concentrations in the redwood sprouts, there are no apparent nutrient deficiencies limiting their regrowth. Harvesting of the 80-year-old redwood/Doug fir forest resulted in removal (in wood and bark) of 949, 65, 405, 401 and 75 kg/ha of N, P, K, Ca and Mg, respectively. A comparison of nutrients removed in biomass with soil nutrient pools indicates that N, P and S are the most critical nutrients with respect to long-term forest productivity. The data suggest that nitrogen fixation by *Ceanothus* species may be necessary to replace nitrogen lost to harvesting in order to maintain the long-term productivity and sustainability of these ecosystems. We conclude that the stump sprouting ability of redwood makes these ecosystems comparatively resilient to the adverse effects of nutrient loss by leaching and erosion.

Ecosystem Waterflows. In the period 4-6 years following clearcutting, concentrations of most solutes in soil solutions were significantly lower in the clearcut watershed. The only solute to show an increase in the clearcut watershed was NO_3 . This is due to increased mineralization from organic matter (due to warmer and moister soil conditions) and decreased uptake due to removal of vegetation. We believe the lower concentrations for most solutes in the clearcut results from dilution. Canopy interception (10-16%) and higher evapotranspiration in the pre-harvest, second growth forest substantially decrease the amount of water leaching from the reference watershed. This is also reflected in the lack of streamflow in the reference watershed following cessation of rainfall, which is in contrast to the clearcut watershed that has water flow throughout the dry summer months.

Stream water solute concentrations were similar between the reference and clearcut watersheds, except for NO_3 and SO_4 which had higher concentrations in the clearcut watershed. Elevated concentrations of NO_3 and SO_4 are most likely due to increased leaching from the soil as mineralization is enhanced and uptake by vegetation is greatly reduced. With the exception of NO_3 , all solute concentrations display a large decrease due to dilution during high-discharge, storm events.

In contrast, NO₃ concentrations increase at peak discharge, probably reflecting a change in the hydrologic flowpath and source of the water. We speculate that subsurface lateral flow above clay rich, argillic horizons and macropore flow through root channels deliver NO₃-enriched waters from the upper soil horizons during storm events. Much of this water may reach the stream channel as pipeflow. Solute concentrations in pipeflow can explain many of the changes in stream water solute concentrations during storm events. The elevated concentration of NO₃ in stream water from the clearcut watersheds was rapidly decreased in the higher-order downstream segments. This decrease in NO₃ concentration is believed to result from a dilution effect, although in-stream immobilization and denitrification in the riparian zone may also have an effect. Thus, the impacts of elevated NO₃ concentrations on the aquatic community are primarily restricted to the stream segment draining the clearcut watershed with little effect on the higher-order downstream segments.

Nutrient fluxes from the clearcut watershed were generally 2 to 2.5 times greater than from the adjacent reference watershed. Since stream water solute concentrations were similar in both watersheds, the increased fluxes must be primarily due to an increased water flux from the clearcut watershed. While elevated NO₃ concentrations in stream water from the clearcut watershed might suggest a large loss of nitrogen due to clearcutting, conversion to a flux (kg/ha/yr) indicates maximum loss of only 1.85 kg/ha/yr, and fluxes decreased to <0.4 kg/ha/yr in the three years following harvest. Thus, stream water loss of nitrogen following clearcutting is not a major environmental concern in this redwood/Doug fir ecosystem.

Suspended Sediment. Nutrient concentrations in suspended sediment (>0.4 μ m) indicating a mixture of inorganic and organic components. Suspended sediments in the reference watershed had a much larger organic matter component compared to the clearcut watershed. Concentrations of N (1.2 - 6.5 g/kg) and P (1.1 - 1.5 g/kg) are relatively high in the suspended sediments indicating that enhanced erosion could lead to appreciable nutrient loss following forest harvest. An estimate of nitrogen loss by suspended sediment transport indicates losses on the order of 1 to 2 kg N/ha/yr in both reference and clearcut watersheds. The greater fluxes of suspended sediment in the clearcut watershed were offset by the lower nitrogen concentration of the suspended sediment in the clearcut watershed.

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Introduction

This study examines the cumulative effects of timber harvest and post-harvest practices on stream water solute concentrations and nutrient cycling processes in a coastal redwood/Doug fir ecosystem in northern California. Timber harvest practices are often implicated as having adverse environmental impacts on sensitive aquatic communities and on the long-term sustainability of forest ecosystems. Previous studies examining the impacts of timber harvest often provide conflicting results suggesting that site conditions, specific harvesting techniques, and post-harvest practices have a strong effect on the resulting impacts. Thus, harvest impacts are highly site specific and can not be directly extrapolated from other sites and/or ecosystems. While the effects of forest harvest practices on streamflow and sediment generation have been intensively studied (*e.g.*, Rice et al., 1979; Ziemer, 1981; Keppeler and Ziemer, 1990; Thomas, 1990; Wright et al., 1990), the impacts of harvesting practices on stream water solute concentrations and nutrient cycling processes have not been fully evaluated for the coastal region of northern California. This type of research is becoming increasingly important as forested watersheds become more intensively managed and attempts are made to minimize adverse management impacts.

Stream water solute concentrations and ecosystem-scale nutrient cycling are regulated by complex interactions occurring within and between the atmosphere, hydrosphere, biosphere and geosphere (Fig. 1). To gain insights into the important processes regulating stream water solute concentrations and ecosystem nutrient cycling, an integrated study incorporating both watershed-scale and plot-scale investigations was performed.

Watershed-scale studies are based on input-output budgets for nutrients and water (Fig. 2). Watershed manipulations are a powerful approach for studying the effects of forest management practices (*e.g.*, clearcutting, burning) on nutrient cycling processes. Manipulation studies commonly utilize the paired watershed approach in which two watersheds with similar characteristics are employed. One watershed of the pair is maintained in its original state to serve as a reference while the other watershed undergoes a particular experimental treatment. Studies on the watershed scale integrate all processes occurring within the boundaries of a given watershed. This may include several plant species, several soil types, contrasting microclimates, and complex hydrologic flow paths. Watershed studies provide ecosystem level data that incorporate all ecosystem processes, but do not distinguish between individual processes or their relative importance.

To gain a greater understanding of how specific processes affect stream water solute concentrations and nutrient cycling, a plot-scale investigation was integrated within the paired watersheds of this study. Plot-scale studies employ a combination of biomass, litter, and solid-phase soil sampling to determine nutrient pools, and collection and quantification of ecosystem waterflows (*e.g.*, precipitation, canopy throughfall, soil solutions, and stream water) to determine nutrient fluxes. These measurements were integrated with hydrologic investigations by the USDA Forest Service/Jackson State Forest, Caspar Creek Research Team, lead by R. Ziemer and E. Keppeler, which examined storm runoff characteristics, suspended sediment concentrations, and hillslope hydrology including macropore flow. These integrated plot-scale studies provide a much greater

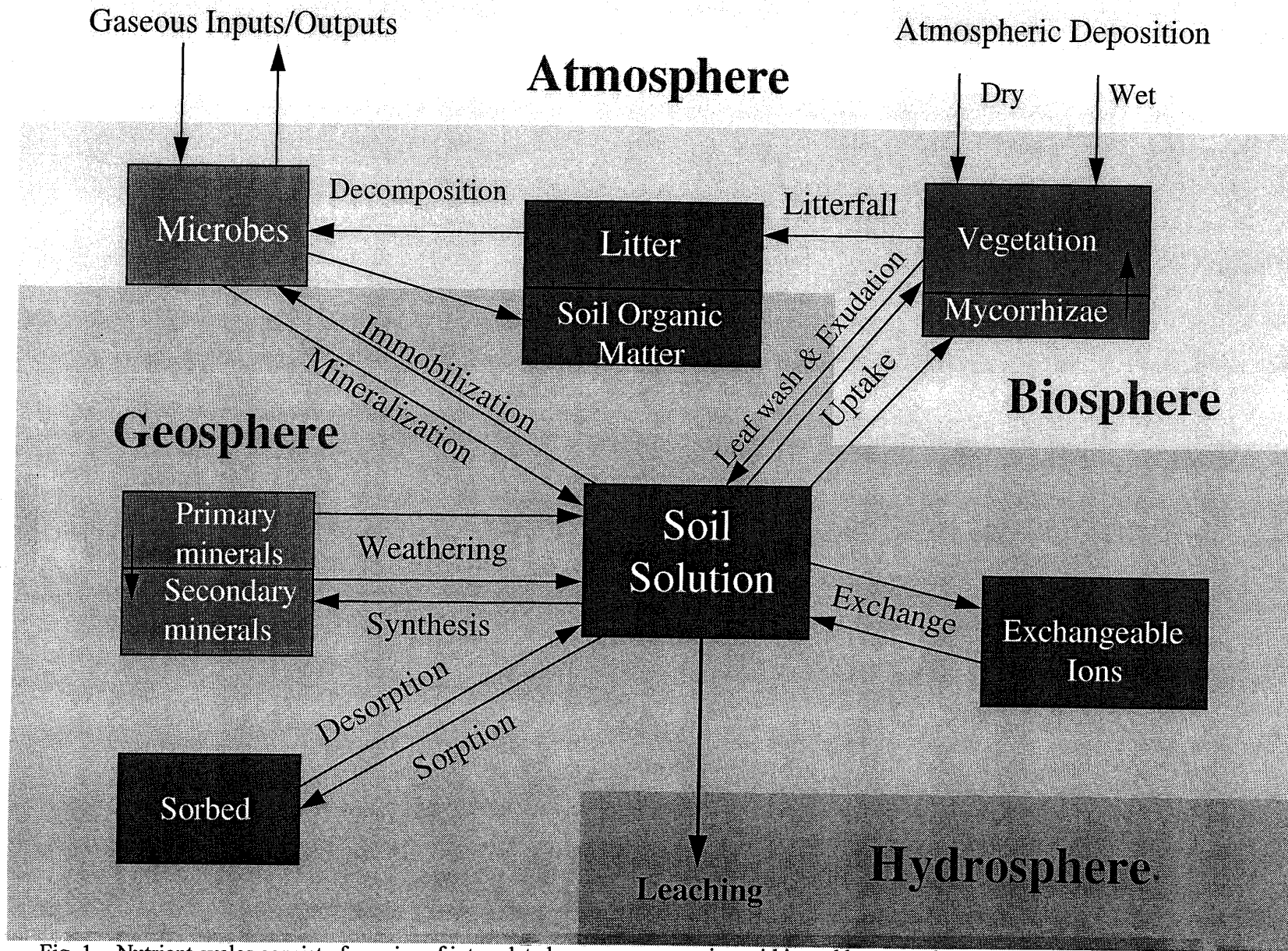


Fig. 1. Nutrient cycles consist of a series of interrelated processes occurring within and between the atmosphere, hydrosphere, biosphere and geosphere. Each nutrient is linked through a set interconnected steps that ultimately lead to a series of cyclic pathways.

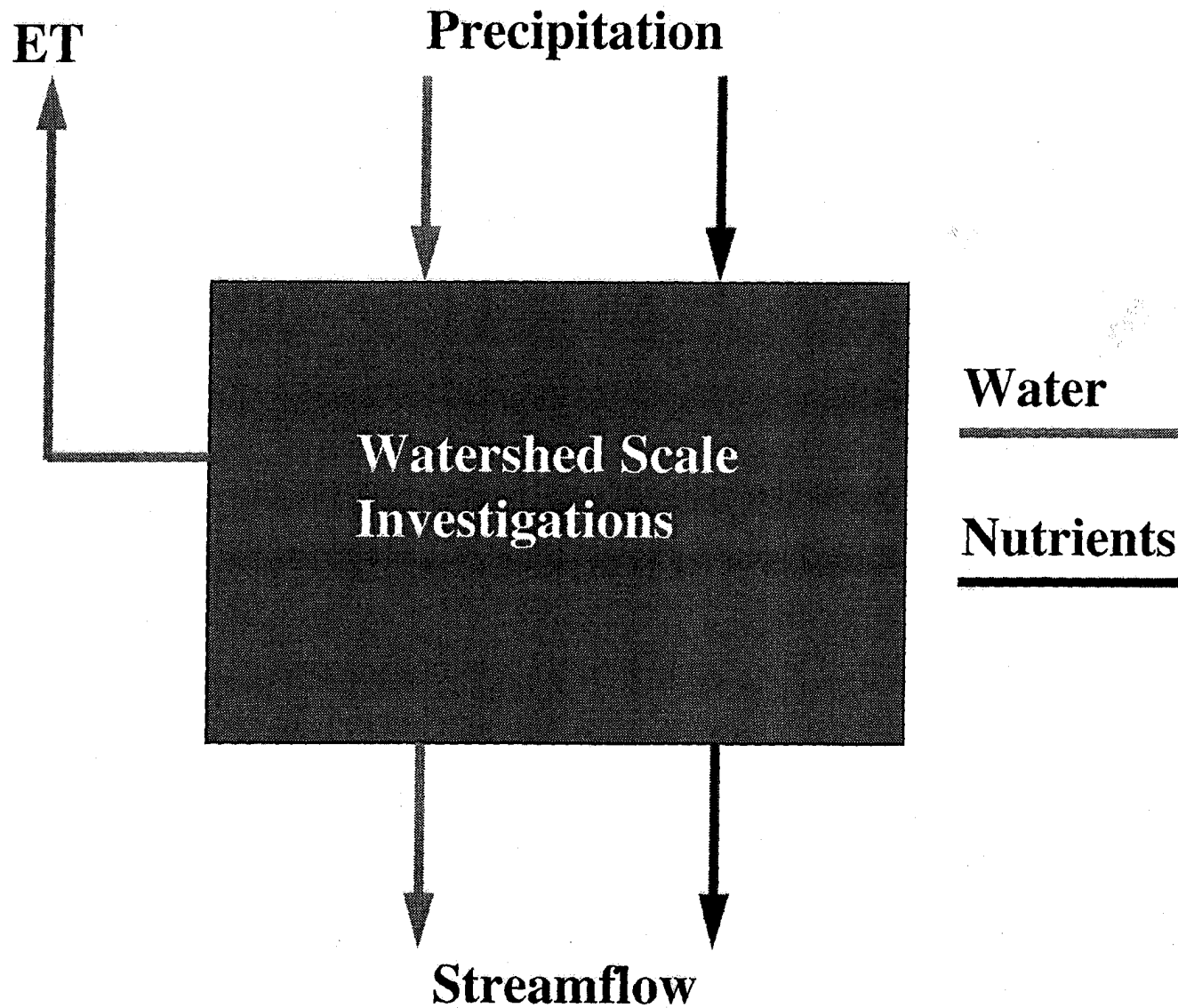


Fig. 2. Watershed-scale investigations are based on input/output budgets for both water and nutrients. The difference between the volume of water input as precipitation and lost as stream water can be assigned to evapotranspiration if the bedrock is relatively impermeable. The difference between nutrient inputs and outputs is a measure of the net nutrient balance associated with all pools and fluxes within the watershed.

understanding of the importance of individual processes. The trade-off for greater understanding of individual processes is that plot-scale studies are much more labor intensive and costly than simply measuring inputs and outputs from a watershed. Because a single watershed may contain several contrasting stands, soils, hydrologic flowpaths, and distinct microclimates, it is not always possible to predict watershed scale response from plot-scale investigations. Thus, the most powerful approach is to couple watershed-scale investigations that integrate all processes and all spatial variability within a watershed with plot-scale studies to ascertain details on the importance of individual processes.

Research Objectives

The primary objective of this study was to examine the cumulative effects of forest management practices on stream water solute concentrations and nutrient cycling in a coastal redwood/Doug fir ecosystem. Specific objectives were to:

1. Examine changes in stream water solute concentrations and nutrient fluxes following various harvest and post-harvest forest management practices,
2. Examine the magnitude and spatial pattern of downstream impacts associated with disturbance in headwater catchments,
3. Examine the relationship between stream water and pipeflow solute concentrations and their relationship to stream discharge, and
4. Compare nutrient cycling within clearcut and non-disturbed (reference) catchments.

Five subwatersheds within the North Fork of Caspar Creek experimental watershed were subjected to typical timber harvest practices, including various combinations of felling, yarding, road construction, broadcast burning, and herbicide treatment. Three additional subwatersheds remained undisturbed and were monitored as controls. To investigate the effects of these practices on water quality, stream water samples were collected from headwater catchments of treated and reference watersheds, and from various locations downstream from the disturbances to determine how far the impacts of these practices persisted. In addition, a detailed (*i.e.*, plot-scale) nutrient cycling study was performed in a clearcut and in a reference watershed to gain insights into changes in nutrient cycling following forest harvest.

Materials and Methods

Study Site Characteristics

Headwater catchments in the North Fork of Caspar Creek were selected for this study (Fig. 3). 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 483 ha and ranges in elevation from 37 to 320 m. The topography of the North Fork watersheds ranges from broad, rounded ridge tops to steep inner gorges. Slopes within the watershed are: 35% of the area with slopes <30%, 58% of the area with slopes 30-70%, and 7% of the area with slopes >70% (Wright et al., 1990).

The climate is Mediterranean, having dry summers with coastal fog. Summer temperatures are mild, 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 1200 mm with no appreciable snowfall (Ziemer, 1981). Soils are dominated by Alfisols and Ultisols formed in residuum derived predominately from sandstone and weathered coarse-grained shale of Cretaceous Age. The soils are well drained and have relatively high saturated and unsaturated hydraulic conductivities (Wosika, 1981).

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 some associated western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and grand fir (*Abies grandis* (Dougl.) Lindl.). The mean stand density based on cruise data from subwatersheds JOH, KJE and LAN was 321 stems/ha having a mean DBH of 61 cm. The distribution between species was: redwood 207 stems/ha, 56 cm DBH; Doug fir 86 stems/ha, 66 cm DBH; and grand fir/western hemlock 27 stems/ha, 56 cm DBH. Precut timber volume at the onset of this study was estimated at about 700 m³/ha (Krammes and Burns, 1973).

Solid-Phase Soil Analyses

Sites for six soil pits were randomly selected within a clearcut (KJE) and reference (MUN) watershed using a quadrant map of the study area. Soil pits (1.5 x 0.5 x 1-1.2 m; L x W x D) were excavated by hand to a depth corresponding to the limit of the major rooting zone (BC horizon; 100-120 cm). The saprolitic parent material below this depth was unconsolidated, and a few roots were observed to penetrate several meters into this material as revealed in nearby roadcuts. Each pedon was described and bulk soil samples and clods for bulk density measurements were collected from across the entire 1.5-m pit face for each morphological horizon. All soil samples were collected during the month of September (1992) when the soil was at its driest moisture content of the year.

Soil samples were air-dried, gently crushed, and passed through a 2-mm sieve; roots passing through the sieve were removed with a forceps. The air-dried, <2mm soil was used for the analyses which

The clay-size fraction ($<2\mu\text{m}$) was isolated by sedimentation after organic matter removal with follow, unless otherwise noted. Soil pH was measured potentiometrically in water (1:2, soil:water) following a 15 min equilibration period. Canon exchange capacity and exchangeable cations were measured using 1 M NH_4OAc (pH=7) (Soil Survey Staff, 1984). Bulk density was determined by the paraffin-coated clod method using three replicate clods per horizon (Soil Survey Staff, 1984). Organic carbon and nitrogen were determined on ground samples ($<250\mu\text{m}$) by dry combustion with a C/N analyzer. Total digestible phosphorus was measured using a modified Kjeldahl digestion with phosphorus quantification by ICP (Parkinson and Allen, 1975). An index of plant-available phosphorus was determined using the Bray No. 2 extraction (Olsen and Sommers, 1982). sodium hypochlorite, free iron oxide removal with citrate-dithionite, and dispersion by sonication treatment for 5 min. The clay fraction was collected by sedimentation and desalted by rinsing with distilled water. X-ray diffraction was performed on oriented clays using the methods outlined by Whittig and Allardice (1986). Diffractograms were made on a Diano 8000 X-ray diffractometer using Cu Ka radiation generated with 50 kV accelerating potential and 15 mA tube current. Samples were step scanned for 1 s at a 0.04 degree 2θ step. Soil nutrient pools were calculated for each soil profile (n=6) by summing the nutrient content of all horizons within the major rooting zone. Nutrient concentrations 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, pipeflow (macropore flow), and streamflow) was used to compare nutrient cycling in clearcut (KJE) and reference (MUN) watersheds. Precipitation, canopy throughfall, and soil solutions were analyzed for three water years commencing October 1, 1993 and ending September 30, 1996. Precipitation, canopy throughfall, and soil solutions were collected and analyzed on an approximately 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. Thus, bulk precipitation fluxes probably underestimate the total atmospheric deposition to a forest ecosystem. Throughfall was collected in triplicate from beneath the canopy of redwood and Doug 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 of the six soil pits excavated in the clearcut and reference watersheds using zero-tension lysimeters. Lysimeters consisted of open-topped polyethylene containers (15 x 10 x 4 cm; L x W x D) filled with acid-washed quartz sand (Driscoll et al., 1988). This container was connected to a buried 2 L polyethylene bottle which was evacuated

using a vacuum pump and flask. Zero-tension 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.

Stream water samples were collected from a series of subwatersheds and from selected sites along the main channel of the North Fork of Caspar Creek. Samples from individual headwater catchments were examined to evaluate the effects of specific timber harvest practices on stream water solute concentrations. Solute concentrations from subwatersheds receiving various combinations of forest harvest practices (e.g., clearcutting, burning, and herbicide treatment) were compared to reference watersheds having no disturbance. Figure 3 shows the sampling locations within the North Fork Caspar Creek watershed and the completion date of felling activities within each watershed. For more detailed information on harvest and post-harvest management activities, contact the USDA Forest Service, Redwood Sciences Laboratory, Arcata, CA. 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 (non-rainy season) from eight subwatersheds (BAN,CAR,EAG,GIB,HEN,IVE,KJE,MUN) and five sites (ARF,DOL,FLY,JOH, LAN) along higher order segments of the North Fork (Fig. 3). All stream water samples were collected at stream gauging stations and stream stage (discharge) was recorded for each water sample. Water sampling commenced in March 1991 and continued through June 1996. In addition to the regular grab sample protocol, automatic pumping samplers were used to intensively collect water samples during storm events from selected headwater catchments. In particular, the clearcut catchment (KJE) and the reference catchment (MUN) were sampled intensively during storm events for five water years (1991-96). The autosamplers were programmed to collect storm samples using a stage-activated, even-interval timed sampling (1 hour interval). Pipeflow was also collected in the clearcut (KJE) and reference (MUN) subwatersheds (see Fig. 3) using a stage-activated, even-interval timed sampling protocol for the 1991-96 water years. All stream water and pipeflow samples were collected by the U.S.D.A. Forest Service/Jackson State Forest, Caspar Creek Research Team.

Prior to chemical analyses, all ecosystem waterflows were filtered through a 0.2 μm membrane filter. The pH was measured potentiometrically using a combination electrode. Cations (Ca, Mg, K, Na, NH_4) and anions (Cl, NO_3 , ortho- PO_4 , SO_4) were determined by ion chromatography (Dionex). Dissolved organic and inorganic carbon were determined on selected samples using a Dohrmann carbon analyzer. Alkalinity was determined on selected samples by titration to an endpoint of pH=4.5 to estimate concentrations of bicarbonate. The dissolved inorganic carbon concentrations and HCO_3 concentrations determined from alkalinity titrations verified that we could acceptably estimate HCO_3 concentrations as the difference between the sum of cation and anion charge (<5% error). Silicon concentrations were measured using ICP spectroscopy.

Caspar Creek Subwatersheds

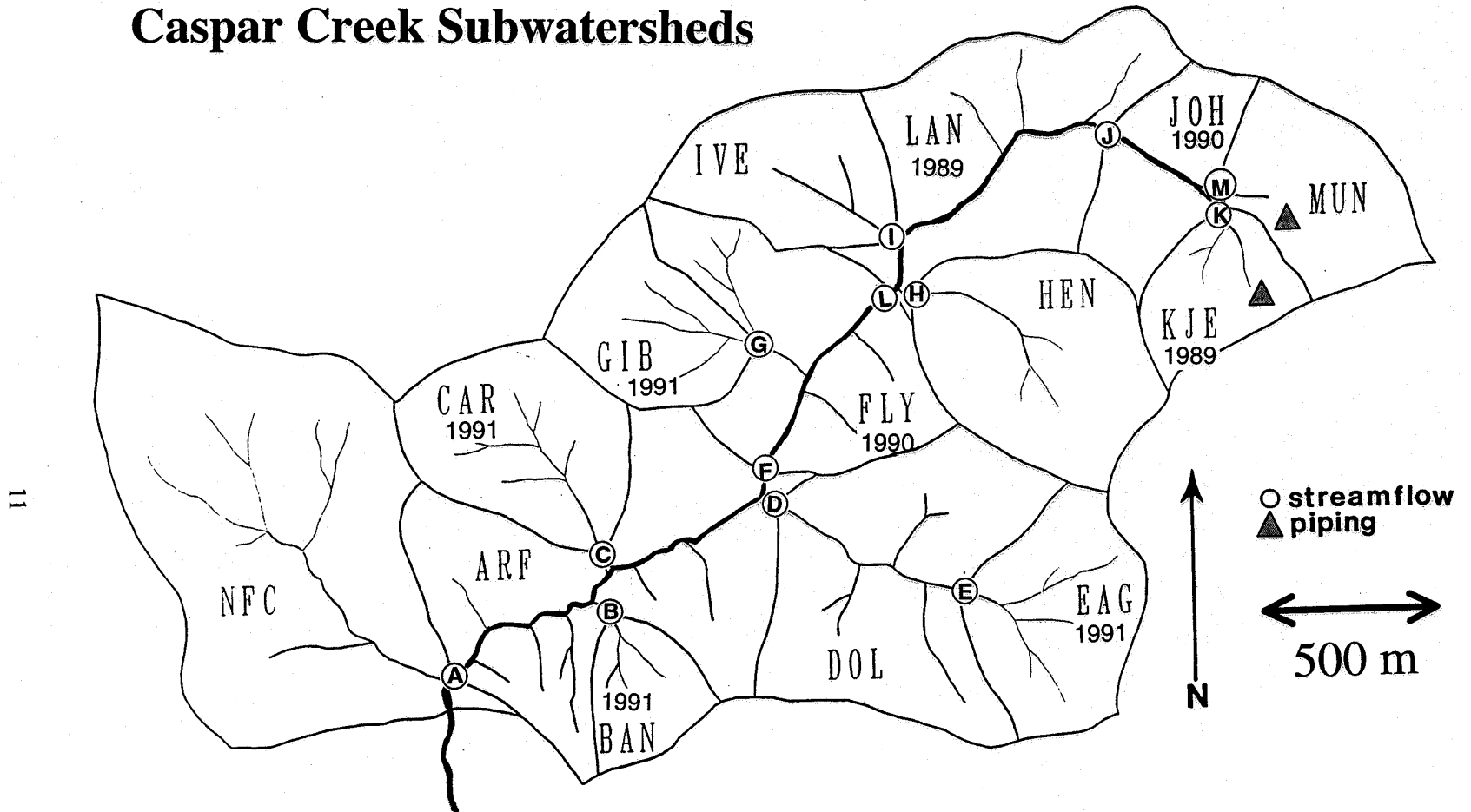


Fig. 3. Watershed map indicating the location of the individual subwatersheds within the North Fork of Caspar Creek. Letters indicate location of stream water sampling sites, triangles the location of piping water samples, and years indicate the year in which the felling activity was completed in the clearcut watersheds. For more detailed information on harvest and post harvest management activities, contact the USDA Forest Service, Redwood Sciences Laboratory, Arcata, CA.

During the 1994-95 water year, water samples from three storm events were bulked to provide approximately a 20 L sample for isolation of the suspended fraction ($>0.4 \mu\text{m}$). Sufficient suspended sediment was obtained for complete chemical analysis from all three events in the clearcut watershed (KJE), but from only one storm event (January) in the reference catchment (MUN). Carbon and nitrogen concentrations were determined by dry combustion using a C/N analyzer. Concentrations of Al, Si, Fe, Ca, Mg, K, Na and P were quantified as follows: fusion with lithium metaborate, dissolution in nitric acid, and quantification using ICP spectroscopy.

Nutrient Analysis in Biomass

Nutrient pools in biomass were determined for the regenerating redwood spouts in the clearcut watershed (KJE) and for the redwood/Doug fir stand in the reference watershed (MUN). A total of ten randomly selected 10 x 10 m plots were selected within the clearcut watershed to quantify total above-ground biomass production six years following harvest (November, 1995). 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 sample was divided into eight categories: foliage, twigs (<2 mm), and five branch size classes (2-5 mm, 5-10 mm, 10-20 mm, 20-50 mm, 50-100 mm, and >100 mm). The weight of each category was recorded following drying at 70°C . Biomass from the individual categories of each tree was then ground (<2 -mm) and digested for nutrient analysis.

Nutrient pools in the second growth forest of the reference watershed were estimated by sampling various biomass components from four replicates each of redwood and Doug 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. Foliage and associated foliage bearing branches were further separated into age classes (current, 1, 2, and 3 year old foliage). Larger branch segments were separated by diameter classes as follows: <0.5 , 0.5-1, 1-2, 2-5 and >5 cm. Individual root samples from each tree were obtained by excavating at the base of each tree, with sample collection occurring one meter away from the tree base in the Oi/Oa and A horizons. Root samples from three excavated lateral roots were composited by diameter class: <1 , 1-2, 2-5, 5-10 and >10 mm. Stemwood and bark were collected by coring individual trees at breast height (1.4 m).

Chemical analyses of biomass samples were conducted on dried (70°C) and ground (<2 mm) tissue samples. Carbon and nitrogen concentrations were determined by dry combustion using a C/N analyzer. Other nutrient concentrations were determined following digestion of 0.4 g of tissue in 5 mL of concentrated nitric acid. Samples were heated at 150°C for a minimum of 3 h, after which time the temperature was reduced to 100°C and samples were taken to dryness. Subsequently, samples were brought up to a 50 mL volume with 1 M nitric acid. Concentrations of Ca, Mg, K, Fe, P, Zn, S, Mn, Cu and Al were determined in extracts by ICP spectroscopy. Percent element recovery was determined from analysis of National Bureau of Standard's reference materials. Mean recovery and standard deviations ($n=8$) were: C = $96.4 \pm 1.6\%$, N = $95.2 \pm 2.3\%$, P = $89.2 \pm 3.7\%$, K = 97.8 ± 5.8 , Ca = $87.6 \pm 4.7\%$, Fe = $86.7 \pm 6.6\%$, Mn = $80.5 \pm 3.8\%$, and Cu = $83 \pm 8.6\%$.

Nutrient pools in biomass of the second growth redwood/Doug fir forest were determined from stand density, allometric relationships obtained from Gholz et al. (1979), and nutrient concentrations determined from the preceding analyses. Root biomass in the reference watershed and following harvest in the clearcut watershed was estimated from the data of Ziemer and Lewis (unpublished data) obtained from a comparable forest stand in northern California. Due to several assumptions that are required for these calculations, it must be stressed that the biomass nutrient pools are our best estimates rather than a precisely measured value.

Statistical Analyses

Differences between solid-phase soil properties, soil solution solute concentrations and biomass nutrient concentrations were tested using appropriate statistical methods (*e.g.*, t-test, ANOVA). All statistical analyses were performed using SYSTAT for Windows, Version 5 (SYSTAT Inc., Evanston, IL).

Results and Discussion

Soils and Soil Properties

The USDA-SCS soil mapping of the watersheds in the North Fork of Caspar Creek showed the following soil distribution:

Upper slopes of the watershed (about 49% of watershed)

Vandamme loam: fine, mixed, isomesic Typic Haplohumults

Lower and middle slopes of the watershed (about 48% of watershed)

Irmulco loam: fine-loamy, mixed, isomesic Ultic Hapludalfs

Tramway loam: fine-loamy, mixed, isomesic Ultic Hapludalfs

Adjacent to stream channel in lower portions of the watershed (about 3% of watershed)

Dehaven-Hotel loam complex: loamy-skeletal, mixed, isomesic Mollic/Ultic Hapludalfs

A typical pedon description for a soil in the reference watershed (MUN) is shown in Table 1. These soils contain a thick argillic horizon (Bt1, Bt2, Bt3) that contains 30 - 45% clay. Roots were concentrated in the A and AB horizons with a lower abundance of roots in the dense argillic horizon. Road cut exposures showed that some roots extend to a depth of several meters into the saprolitic parent material. Bulk density for the Oi/Oa, A, AB, and Bt horizons were 0.19, 0.75, 1.32 and 1.57 g/cm³, respectively. Clay mineralogy was dominated by randomly interstratified chlorite-vermiculite in the A, AB and Bt1 horizons and randomly interstratified chlorite-vermiculite/smectite at depth. The abundance of smectite in the randomly interstratified complex increased with increasing depth. A minor component of kaolinite was found throughout the entire soil profile.

A comparison of selected solid-phase soil properties between the reference and clearcut watersheds is shown in Table 2. The soils in the reference watershed were moderately acid (pH range 5.4 to 6.3) and displayed a general pH decrease with increasing depth (Table 2). Organic C and total N concentrations were highest in the A and AB horizons and decreased with depth. The C/N molar ratio in the Oi/Oa litter layer was 91 compared to a range of 26 to 14 in the mineral soil horizons. Acid digestible P concentrations showed a similar distribution to that of organic C and total N while available P concentrations showed a large decrease in the B horizons (<3.3 mg/kg). The cation exchange capacity of the mineral soil horizons fell within the range 14 to 27 cmol_c/kg with base saturation values in the range 50 to 63%. The abundance of exchangeable cations followed: Ca > Mg » K ≈ Na.

The effects of clearcutting on solid-phase soil properties are most readily observed in the upper soil horizons where biological influences and physical disturbance factors are greatest. There were only a few statistically significant differences (p<0.05) between soil properties in the reference and clearcut watersheds (Table 2). One important difference between the two watersheds was the loss of the litter layer (Oi/Oa) from the clearcut watershed within three years of the harvest. An Oi/Oa

Table 1. Soil profile description for a representative soil profile in the clearcut (KJE) and reference (MUN) catchments of the North Fork, Caspar Creek watershed:

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Consistence	Roots	Boundary	>2 mm (%)
Oi	3-O [†]							
A	0-12	10YR 3/3	l	2 f-m sbk	sh fr so po	3vf, 3f, 2m, lco	cw	<5
AB	12-29	7.5YR 3/4	cl	2 m sbk	h fr ss ps	2vf, 3f, 2m, 2co	cs	<5
Btl	29-60	7.5YR 4/6	c	2 m sbk	vh fr s p	2vf, 2f, 2m, 2co	cs	<5
Bt2	60-85	7.5YR 5/6	cl	2 co sbk	vh fr s p	2vf, lf, lm, l co	gs	<5
BO	85-121	7.5YR 5/6	cl	2 co sbk	vh fr ss ps	lvf, lf, lm, lco	dw	<5
BC	>121	7.5YR 5/8	scl	M		1f, 1m, 1co		

[†]No O horizons are found in the clearcut catchment.

Abbreviations:

Texture: scl-sandy clay loam; l-loam; cl-clay loam; c-clay

Structure: 2-moderate; f-fine; m-medium; c-coarse; sbk-subangular blocky; M-massive

Boundary: c-clear; g-gradual; d-diffuse; s-smooth; w-wavy

Consistence: (Dry) sh-slightly hard; h-hard; vh-very hard; (Moist) fr-friable; (Wet) so-nonsticky; ss-slightly sticky; s-sticky; po-nonplastic; ps-slightly plastic; p-plastic

Roots: 1-few; 2-common; 3-many; vf-very fine; f-fine; m-medium; co-coarse

Table 2. Selected soil characterization data from the reference (Ref) watershed (MUN) and the clearcut (CC) watershed (KJE). Values represent the mean with the standard deviation in parenthesis.

Parameter	Oi/Oa	A		AB		Bt1		Bt2		Bt3	
	Ref	Ref	CC	Ref	CC	Ref	CC	Ref	CC	Ref	CC
pH	5.51 (.18)	6.25* (.12)	6.07* (.14)	6.30* (.10)	5.82* (.37)	6.08 (.17)	5.91 (.26)	5.77 (.26)	5.67 (.31)	5.32 (.16)	5.36 (.36)
Organic carbon (mg/kg)	441 (21)	42.3 (10.8)	47.7 (19.2)	21.9 (4.8)	18.0 (7.3)	7.9 (2.3)	7.4 (1.6)	6.0 (.7)	5.3 (1.5)	4.6 (1.8)	4.2 (2.7)
Nitrogen (mg/kg)	5.67 (.45)	1.90 (.28)	2.14 (.80)	1.25 (.26)	0.96 (.37)	0.53* (.17)	0.69* (.12)	0.47 (.05)	0.55 (.16)	0.39 (.11)	0.49 (.25)
C/N (molar ratio)	91.4 10.1	25.9 4.7	26.0 5.2	20.5 1.4	21.9 5.1	17.5* .7	12.9* 3.9	14.9 1.5	11.6 3.6	118 4.0	11.8 5.8
Total P (mg/kg)	1207 134	517 94	534 135	362 54	333 60	266* 21	207* (39)	189* 24	149* 28	138* 21	112* 7
Available P (mg/kg)	127.0 35.6	24.2 14.5	12.7 9.1	7.3 8.6	4.5 6.7	3.3 3.5	1.5 .8	2.0 1.5	1.2 .4	1.0 .1	1.0 .1
CEC (cmol _c /kg)	144.7 5.5	27.1 3.1	26.6 7.6	20.6* 2.4	13.9* 4.3	14.3 2.8	10.9 (3.0)	19.1 5.2	12.7 6.7	21.6 5.1	14.4 6.9
Exch. Ca (cmol _c /kg)	30.9 2.3	12.5 2.0	15.4 6.2	7.5 1.6	8.3 3.3	6.0 .8	5.0 1.4	7.0* (2.8)	3.8* 1.0	6.3* 2.5	3.3* 1.5
Exch. Mg (cmol _c /kg)	10.2 1.2	2.9 .7	3.2 .8	1.8 .4	2.7* .8	2.1* .5)	2.5 .6	3.1 (1.3)	3.3 .9	4.2 1.3	3.6 .9
Exch. K (cmol _c /kg)	2.27 .38	0.77* .22	1.33* .48	0.50 .19	0.65 .27	0.50 .09	0.50 .18	0.47 .12	0.43 .18	0.40 .11	0.40 .13
Exch. Na (cmol _c /kg)	1.13 (.26)	0.40* (.09)	0.22* (.04)	0.42* (.08)	0.22* (.04)	0.45* (.08)	0.23* (.05)	0.45* (.11)	0.30* (.06)	0.50* (.09)	0.28* (.12)
Base saturation (percent)	30.8 (2.6)	61.2* (7.5)	74.1* (6.9)	48.9* (6.4)	84.8* (9.5)	65.5 (15.6)	77.7 (14.4)	56.5 (8.7)	74.4 29.1	52.9 13.3	63.9 29.6

*Means are significantly different between reference and clearcut watershed at p<0.05.

layer with a thickness of 1-3 cm is found on all soils within the reference watershed. The loss of this layer in the clearcut watershed is due primarily to decomposition, but also results from mixing with the mineral soil and redistribution during logging. Another possible factor was enhanced erosion of the litter layer due to removal of the forest canopy and decreased infiltration related to soil compaction.

Soil pH was lower in the A and AB horizons of the clearcut watershed. This acidification may result from enhanced decomposition, mineralization and nitrification in the surface soil horizons following harvest (Dahlgren and Driscoll, 1994). Organic carbon and nitrogen concentrations were slightly higher (but not significantly different) in the A horizon of the clearcut watershed possibly indicating a mixing with the former litter layer. Total P concentrations were higher in the B horizons of the reference watershed which is most likely associated with spatial variability of soils on the landscape rather than differences associated with clearcutting. Exchangeable sodium concentrations were consistently higher in all mineral soil horizons of the reference watershed suggesting enhanced inputs of sea salts associated with canopy capture of dry deposition (aerosols and particulate matter) and fog/cloud deposition (Parfitt et al., 1997).

Nutrient pools contained within the primary rooting zone (upper 100-120 cm) are shown as a function of soil horizon for the reference (MUN) and clearcut (KJE) watersheds in Figure 4. The only significant difference between the reference and clearcut watershed was a larger pool of exchangeable Na in the reference watershed. The soils store a very large pool of organic carbon (~ 170 Mg/ha), primarily in the A and AB horizons. The loss of the Oi/Oa horizon from the clearcut watershed appears to be compensated for by an increase in organic C in the A horizon. This could reflect the mixing of the litter layer with the mineral soil during harvest activities. The soils similarly store large concentrations of total N (>9 Mg/ha); however, this N 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 kg/ha), even an appreciable decrease of say 100 kg/ha following clearcutting can not be detected by solid-phase analysis. However, the leaching loss of even a few kg/ha can be easily detected in stream water chemistry. Thus, the analysis of ecosystem waterflows is a far more powerful approach for detecting treatment effects due to ecosystem disturbance. The pool of total P is distributed relatively uniformly throughout the soil profile while the available P pool is located primarily in the upper soil horizons. The pool of available P is on the order of 1-2% of the total P pool. Mycorrhizae fungi associated with the rooting system of the vegetation may be able to liberate P in excess of that held in the available P pool. The pool size associated with the exchangeable cations follows: Ca (18 Mg/ha) > Mg (5 Mg/ha) > K (3 Mg/ha) > Na (1 Mg/ha). This distribution is dictated by the competitive affinity of each cation for the cation exchange sites.

In summary, the only consistent trends in solid-phase soil properties that may be attributed to clearcutting are moderate soil acidification in the A and AB horizons, a decrease in exchangeable Na concentrations, and the loss of the Oi/Oa litter layer in the clearcut watershed.

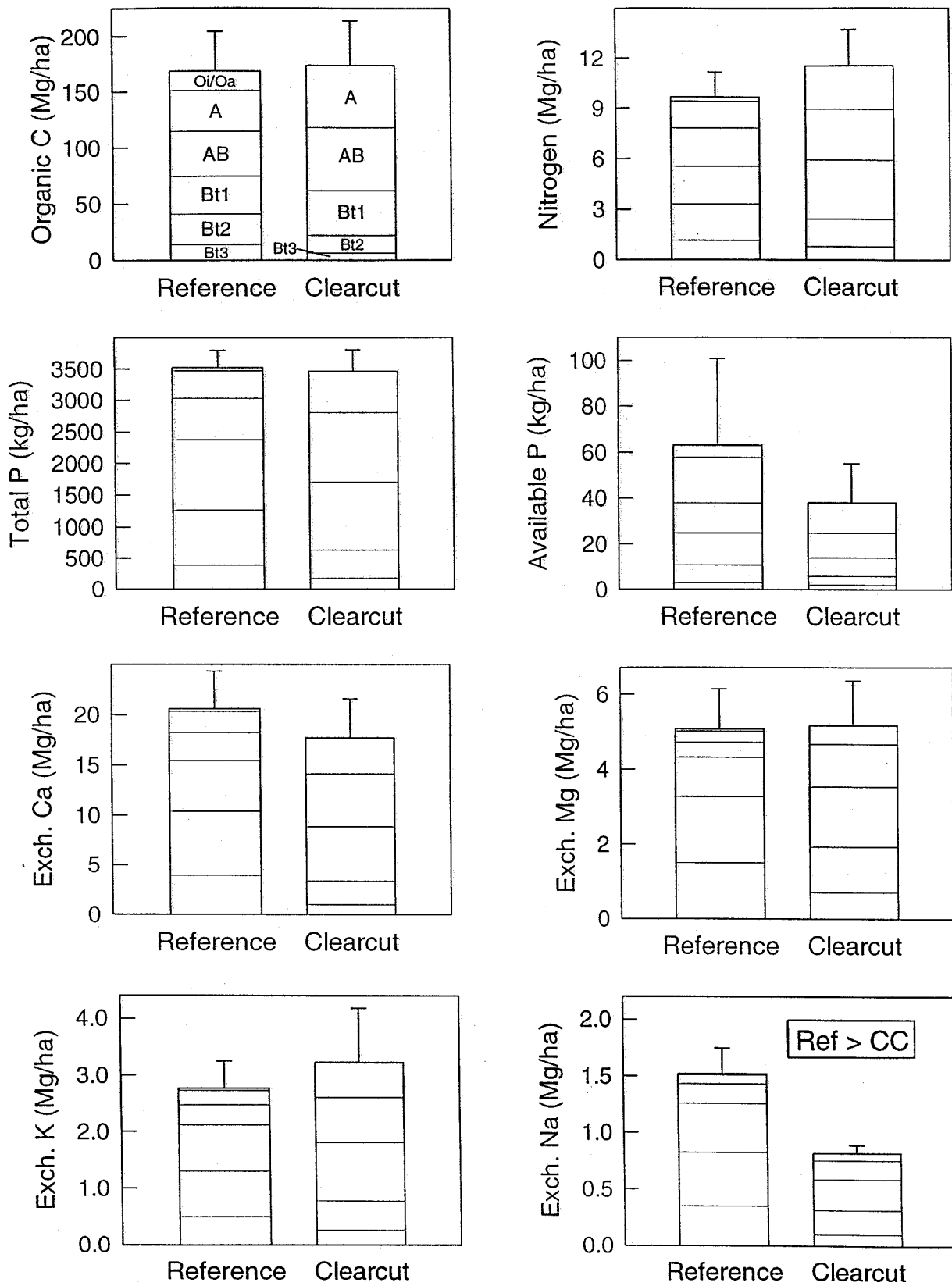


Fig. 4. Nutrient pools in soils of the reference (MUN) and clearcut (KJE) watersheds three years following completion of the harvest. The individual segments of each bar indicate the amount contained within individual soil horizons. Error bar indicates SEM and the only significant difference ($p < 0.05$) between watersheds was for exchangeable sodium.

Biomass Nutrient Concentrations and Pools

Clearcut watershed (KJE)

The number and size distribution of stump sprouting redwoods in watershed ME six years after harvest was determined from an inventory of ten 10 x 10 m plots. This inventory showed 5020 ± 1970 stem/ha (mean \pm std. dev.; range = 2600 - 8300 stems/ha) having a DBH of 2.59 ± 0.71 cm (mean \pm std. dev.). The DBH of the stump sprouts ranged from <1 to 10 cm. The diameter distribution shows that the majority of the stems have DBH values ≤ 3 cm with far fewer stems in the larger diameter classes (Fig. 5). Within a cluster of stems surrounding a given stump, there were generally 1 to 4 dominant stems with DBH values greater than about 6 cm.

Allometric relationships were determined for redwood stump sprouts based on the harvest of 10 individual trees with DBH values ranging between 0.76 and 7.6 cm (Fig. 6 & Table 2). Strong ($r^2 > 0.98$) and significant ($p < 0.001$) relationships were indicated for foliage, twigs (<0.2 cm) and total branches (0.2 - 10 cm) as a function of DBH. The relationship between DBH and branches became weaker when the larger (> 1 cm) branch diameter classes were regressed individually rather than as a summation of all branch diameter classes (Table 2b).

Nutrient concentrations for foliage, twigs (<0.2 cm) and the various diameter-size classes of branches are shown in Table 3. The highest concentrations of nutrients were generally found in the foliage with somewhat lower concentrations in the twigs. Nutrient concentrations in the branches generally showed a progressive decrease with increasing branch diameter. The C/N ratio was 54, 80 and 190-1431 for the foliage, twigs, and various branch components, respectively. Nutrient concentrations within the redwood sprouts were similar to those found in the 80-year old second growth in the adjacent reference watershed (MUN; to be discussed latter). No obvious nutrient deficiencies were indicated based on the foliar nutrient concentrations.

The nutrient concentrations within individual tree components were combined with the total biomass of each component obtained by the allometric relationships and redwood stump sprout inventory to estimate the nutrient pools contained within the redwood sprouts (Table 4). Data for live-root biomass was estimated from the unpublished data of Ziemer and Lewis who examined rooting biomass in similar ecosystems as a function of time since harvest (Table 5). They found that redwood live roots in the <25 mm diameter-size class reached a minimum between 5 and 11 years after harvest. Approximately 63 and 93% of the 0-10 and >10 mm redwood roots died within six years after harvest. The existence of this large rooting mass gives the stump sprouting redwoods a tremendous advantage in establishing dominance following harvest. In contrast, the entire pool of roots from Doug fir and other minor conifer species died following harvest.

Total carbon storage in the above-ground biomass of the six-year-old redwood stump sprouts was 7.8 Mg/ha (Table 4). Assuming an average carbon content of 50% for biomass, there was over 15 Mg/ha (dry weight) of above-ground biomass contained within the redwood sprouts six years following harvest. Based on the estimated carbon pools, the ratio of above-ground to below-ground living biomass in the regenerating redwood was about 3:1 (Table 4). This is a rapid accumulation of

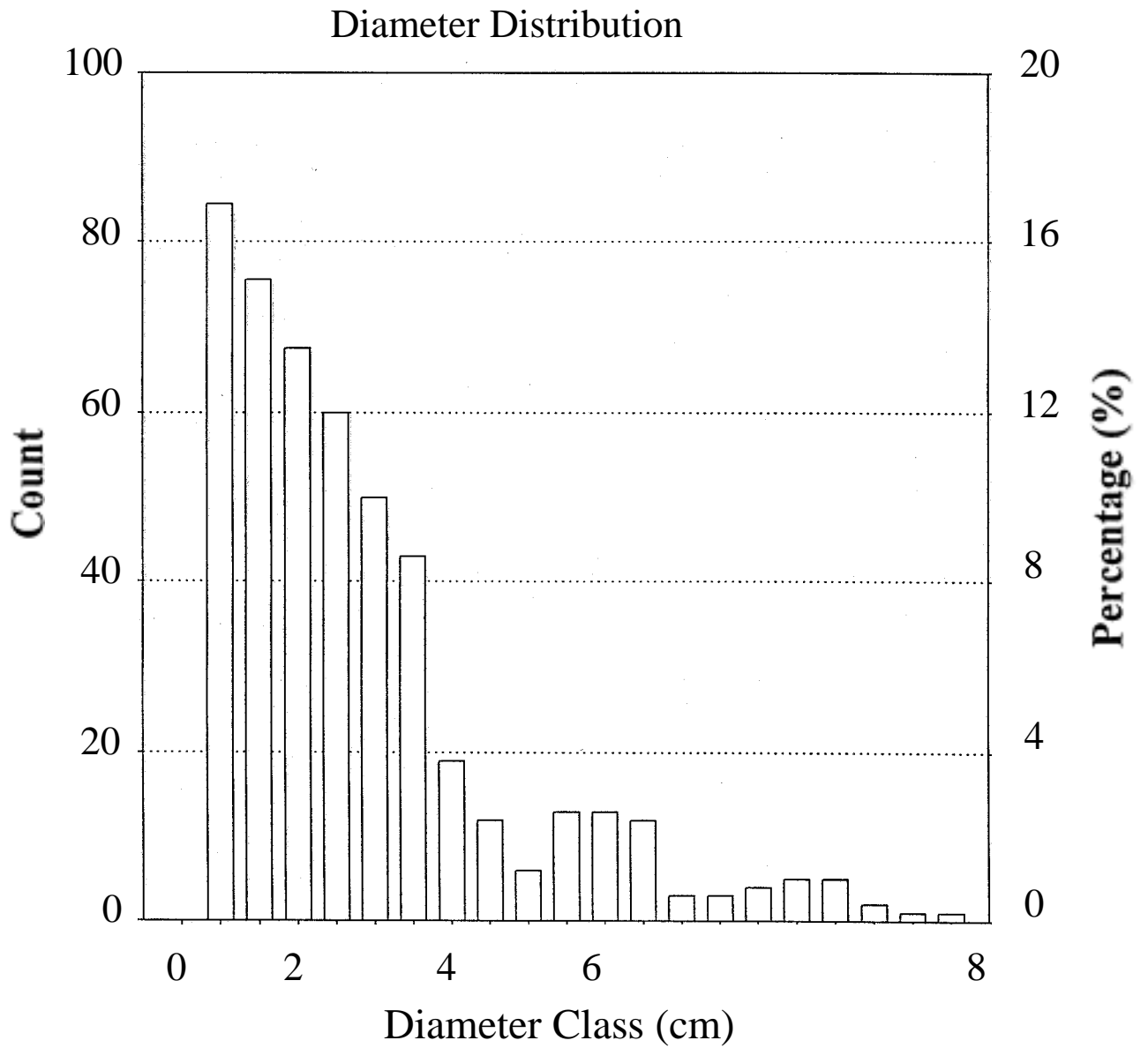


Fig. 5. The diameter distribution at breast-height for redwood stump sprouts six years following harvest (1989—> 1995) in the clearcut watershed (KJE).

Allometric Relations for Redwood Sprouts

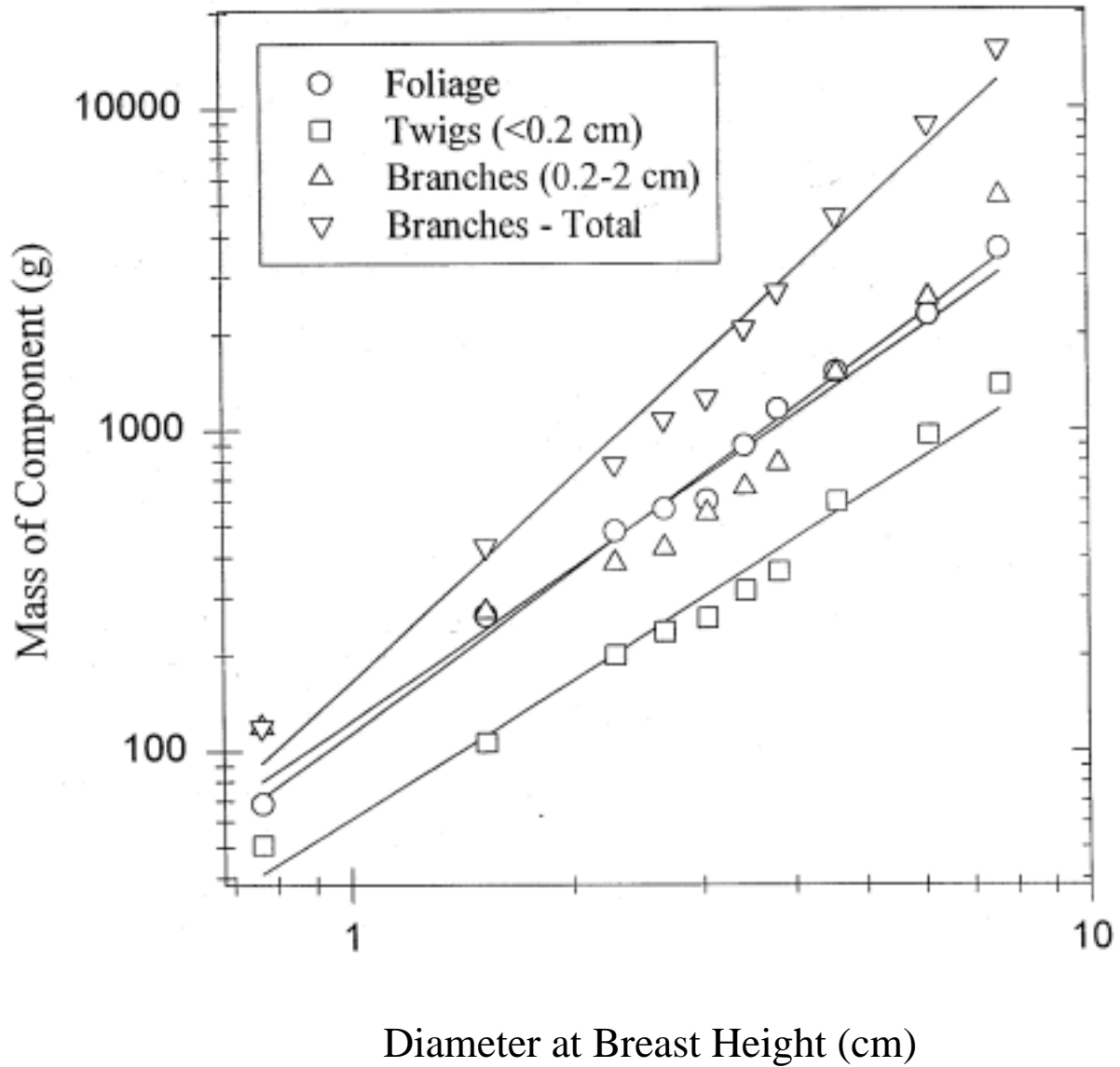


Fig. 6. Allometric relationships for various biomass components of redwood stump sprouts as a function of stem diameter at breast height.

Table 2b. Allometric relationships based on diameter at breast height for foliage, twigs, and various size branch components.

Equation (units = grams and cm)	r²	Significance
$\log(\text{Foliage}) = 1.690 \log(D) + 2.050$	0.99	p<0.001
$\log(\text{Twigs, } <0.2 \text{ cm}) = 1.449 \log(D) + 1.784$	0.98	p<0.001
$\log(\text{Branches-Total}) = 2.125 \log(D) + 2.214$	0.98	p<0.001
$\log(\text{Branches, } 0.2\text{-}2 \text{ cm}) = 1.586 \log(D) + 2.091$	0.92	p<0.001
$\log(\text{Branch, } 0.2\text{-}0.5 \text{ cm}) = 1.443 \log(D) + 1.528$	0.89	p<0.001
$\log(\text{Branch, } 0.5\text{-}1 \text{ cm}) = 1.727 \log(D) + 1.500$	0.92	p<0.001
$\log(\text{Branch, } 1\text{-}2 \text{ cm}) = 1.308 \log(D) + 1.771$	0.50	p=0.021
$\log(\text{Branch, } 2\text{-}5 \text{ cm}) = 0.516 \log(D) + 2.589$	0.28	p=0.176
$\log(\text{Branch, } 5\text{-}10 \text{ cm}) = 2.632 \log(D) + 1.459$	0.71	p=0.075

Table 3. Nutrient concentrations in six-year-old, stump sprouting redwoods growing in the clearcut watershed (KJE).

Element/ Component	Foliage (n= 7)	Twigs (n=7)	Branch (0.2-0.5 cm) (n=7)	Branch (0.5-1 cm) (n=7)	Branch (1-2 cm) (n=7)	Branch (2-5 cm) (n=5)	Branch (5-10 cm) (n=3)	Branch (10-20 cm) (n=1)
N	11600a	7630b	3310c	2340cd	2190cd	1220d	1100d	400
C	521400a	513760ab	501810ab	498100b	509370ab	496660b	499730ab	466000
Ca	7253a	5381b	3647c	2805c	2509cd	1613d	1614cd	1205
Mg	1788a	1330a	581b	390b	456b	276b	319b	353
K	9444ab	12413a	6007bc	3170c	3936c	2006c	1512c	1248
P	1958a	1992a	733b	412b	541b	301b	216b	209
S	942a	676b	341c	250c	298c	201c	185c	232
Fe	95.1ab	53.7ab	18.9a	25.3a	61.2ab	107ab	173b	344
Zn	31.4a	33.3a	17.2b	12.3b	10.4bc	9.0c	8.1c	6.9
Mn	385a	185b	88.9c	56.2c	57.9c	44.5c	38.6c	17.4
Cu	3.0a	1.4a	2.7a	2.0a	3.0a	2.3a	2.9a	3.2
Al	105ab	87.6ab	24.9a	19.0a	60.7ab	101ab	196b	269
C/N	53.5a	79.9ab	190b	259c	282c	507d	554d	1431
C/P	725a	699a	1961ab	3352bc	3179b	5397cd	6092d	5757
C/S	1505a	2068a	4106ab	5458bc	5157bc	7636c	7579c	5367

Values in each column followed by the same lower case letter are not significantly different when comparing a given nutrient between biomass component.

Table 4. Nutrient pools in the above-ground components and live roots of redwood stump sprouts in the clearcut watershed (KJE) six years after harvest. Live root biomass was estimated from the unpublished data of Ziemer and Lewis.

Element	Foliage	Twigs (<0.2 cm)	Branches (0.2 - 2 cm)	Branches (2 - 20 cm)	Total Above- ground	Roots
	----- k a-----					
N	42.6	10.8	9.1	7.6	70.0	15.6
C	1914	726	1746	3443	7829	2660
Ca	26.6	7.60	10.4	10.9	55.5	36.6
Mg	6.56	1.88	1.65	2.08	12.2	4.19
K	35.6	17.5	15.2	12.2	79.7	11.4
P	7.19	2.81	1.95	1.83	13.8	3.31
S	3.46	0.95	1.03	1.39	6.83	3.48
Fe	0.35	0.08	0.12	1.08	1.63	4.44
Zn	0.12	0.05	0.05	0.06	0.27	0.10
Mn	1.41	0.26	0.24	0.28	2.18	1.56
Cu	0.011	0.002	0.009	0.018	0.04	0.03

Table 5. Estimated live-root biomass in the second growth reference watershed (MUN) and the clearcut watershed (KJE) six years following harvest. Root biomass was estimated from the unpublished data of Ziemer and Lewis.

Root size-class	Reference watershed		Clearcut watershed	
	Redwood	Doug fir	Redwood	Doug fir
	----- kg/ha -----			
<1 mm	898	193	321	-
1-2 mm	2645	575	944	-
2-5 mm	1797	1860	642	-
5-10 mm	1298	2391	480	-
>10 mm	43275	28191	3116	-
Total roots	49913	33210	5503	-

biomass following a clearcut which is largely 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 and water to support regrowth. Also important in this rapid regrowth is the immobilization of potentially mobile nutrients into the above-ground biomass following clearcutting. The accumulation of 70, 56, 12, 80, 14 and 7 kg/ha of N, Ca, Mg, K, P and S, respectively, attenuates leaching of these nutrients following the clearcut (Table 4). The warmer and moister soil conditions combined with higher organic matter concentrations from logging slash following clearcutting can result in higher decomposition, mineralization and leaching. Thus, rapid immobilization of nutrients by the aggrading redwood forest will have a strong influence on nutrient dynamics and leaching following harvest in these ecosystems.

Reference watershed (MUN)

The goal of most forest management plans is to assure long-term sustainability of forest ecosystems. From a nutrient cycling perspective, long-term sustainability can only be maintained if nutrient inputs (e.g., atmospheric deposition, nitrogen fixation and rock weathering) equal or exceed nutrient losses (e.g., removal by harvest, stream export of suspended sediment and dissolved nutrients). To address the sustainability issue, nutrient pools within the reference watershed were determined and used to estimate the amount of nutrients lost by biomass removal during harvest.

Nutrient concentrations in the foliage, twigs, branches, wood, bark and roots were determined for the two dominant tree species (redwood and Doug fir) in the reference watershed (MUN) (Tables 6-10). A between species comparison of nutrient concentrations in foliage shows generally higher concentrations of N, P, S, K and Fe in Doug fir while redwood had higher concentrations of Ca and Mg (Table 6). Foliage bearing twigs for redwood and Doug fir had similar concentrations for most nutrients; however, concentrations of Ca and Mg were once again higher in the redwood (Table 7). Nutrient concentrations in the bark and wood were similar between species, while the Doug fir had higher concentrations of P, K and Mn in most size classes of the branches (Tables 8 & 9). There were no consistent differences in nutrient concentrations between species for any of the root size classes (Table 10). These nutrient data suggest that Doug fir will have a somewhat higher demand for N, P and K compared to redwood growing within the same stand.

Ecosystem level nutrient pools were calculated using allometric relationships from the literature, data on root biomass from Ziemer and Lewis (unpublished; Table 5), the stand density data for redwood and Doug fir from the adjacent watershed (KJE; redwood = 201 stems/ha; Doug fir = 97 stems/ha), and the nutrient concentrations discussed above. Because no allometric relationships were available for above-ground biomass in redwood, we used the Doug fir allometric relationships for the redwood. This extrapolation will introduce a potential error into the estimates for the redwood above-ground nutrient estimates; however, this error will most likely be on the order of <20%. The lack of above-ground allometric relationships for redwood should not significantly affect overall conclusions.

Table 6. Mean (\pm SEM) element concentrations and C/N ratio of foliage by age class for the second-growth Doug fir and redwood stand in watershed MUN.

Species	Age Class	C	N	C/N	P	S	K	Ca	Mg	Fe	Zn	Mn	Cu
		----- g kg ⁻¹ -----			mg kg ⁻¹	ratio	----- mg kg ⁻¹ -----						
Doug fir	Current	528aA (5)	11.2aA (0.5)	56aA (2)	1640aA (90)	860aA (50)	9120aA (470)	3020aA (170)	1320aA (90)	83.6aA (6.9)	12.2aA (1.2)	334aA (4.6)	3.4aA (0.5)
	1 Year	531aA (3)	13.7bA (0.4)	46aA (1)	2180bA (150)	1110bA (60)	8140abA (530)	5610bA (270)	1490aA (130)	85.5aA (4.0)	12.7aA (1.2)	530abA (83)	2.4aA (0.3)
	2 Year	527aA (4)	13.1bA (0.7)	50aA (5)	2350bA (170)	1130bA (60)	7500bcA (480)	7230cA (340)	1470aA (150)	99.2aA (6.7)	13.7aA (1.1)	615abA (93)	2.6aA (0.4)
	3 Year	521aA (4)	12.4abA (0.6)	50aA (3)	2160bA (150)	1200bA (80)	6610cA (480)	9240dA (680)	1460aA (180)	83.7aA (7.3)	15.8aA (1.4)	655bA (104)	3.1aA (0.5)
Redwood	Current	521aA (3)	12.0aA (0.4)	51aA (2)	1630aA (70)	1040aB (40)	7530aA (670)	7350aB (300)	2240aB (100)	57.5aB (2.9)	19.8aB (1.2)	397aA (46)	2.3aB (0.2)
	1 Year	515aB (3)	11.0bB (0.3)	55aB (1)	1300bB (110)	970aA (40)	5470bB (550)	8980bB (280)	2150aB (170)	72.3aA (9.6)	12.9bA (1.0)	425aA (47)	2.1aA (0.2)
	2 Year	522aA (3)	10.2bB (0.3)	60bA (2)	1190bB (110)	930aB (70)	5240bB (430)	9850bcB (360)	2140aB (190)	69.1aB (9.4)	12.6bA (1.3)	332abB (56)	1.7aA (0.3)
	3 Year	525aA (2)	9.0cB (0.3)	69cB (3)	1050bB (110)	950aB (40)	4710bB (360)	10450cA (310)	2170aB (200)	63.9aB (5.1)	14.0bA (1.6)	204bB (38)	1.9aB (0.2)

Values in each column followed by the same lower case letter are not significantly different when comparing between age classes within each species (ANOVA with Fisher's least significant difference test, $p < 0.05$). Values in each column followed by the same upper case letter are not significantly different when comparing similar age classes between the two species (t-test, $p < 0.05$).

Table 7. Mean (\pm SEM) element concentrations and C/N ratio of foliage bearing twigs by age class for the second-growth Doug fir and redwood stand in watershed MUN.

Species	Age Class	C	N	C/N	P	S	K	Ca	Mg	Fe	Zn	Mn	Cu
		g kg ⁻¹	mg kg ⁻¹	ratio	----- mg kg ⁻¹ -----								
Doug fir	Current	569aA (9)	8730aA (450)	73aA (3)	1370aA (80)	680aA (40)	6220aA (200)	4430aA (240)	1600aA (70)	58.1aA (6.7)	34.1aA (3.4)	248aA (10)	8.0aA (1.0)
	1 Year	528aA (5)	7180bA (210)	87bA (2)	1090bA (80)	650aA (20)	5520bA (240)	5870bA (240)	900bA (50)	80.2aA (5.4)	40.9aA (3.2)	260aA (12)	7.2aA (1.1)
	2 Year	522aA (4)	7190bA (600)	89bA (5)	940bcA (60)	610abA (30)	4810cA (230)	6490bA (260)	800bcA (40)	83.1aA (11.2)	39.8aA (2.7)	251aA (13)	7.0aA (1.2)
	3 Year	515aA (3)	5510cA (210)	111cA (4)	820cA (50)	560bA (20)	4300cA (280)	6540bA (310)	740cA (40)	90.5aA (16.7)	36.8aA (2.2)	227aA (14)	6.7aA (1.1)
Redwood	Current	511aB (3)	9150aA (290)	66aA (2)	1910aB (80)	860aB (40)	9170aB (770)	7370aB (280)	1890aA (120)	70.0aA (11.5)	19.9aB (1.2)	256aA (31)	2.2aB (0.2)
	1 Year	515aB (4)	6750bA (190)	90bA (2)	1430bB (70)	720bA (30)	6390bA (560)	8250bB (250)	1690aB (160)	85.1aA (12.6)	19.7aB (1.8)	233abA (32)	1.8aB (0.3)
	2 Year	508aB (3)	5280cB (220)	115cB (5)	890cA (70)	570cA (20)	4890cA (320)	8550bB (240)	1310bB (110)	62.4abA (6.6)	20.9aB (1.9)	157bcB (25)	2.3aB (0.7)
	3 Year	508aA (2)	3740dB (210)	164dB (7)	600dB (30)	490dB (10)	3570cB (120)	8520bB (290)	1070bB (130)	42.1bB (3.6)	20.1aB (2.3)	111cB (17)	2.0aB (0.3)

Values in each column followed by the same lower case letter are not significantly different when comparing between age classes within each species (ANOVA with Fisher's least significant difference test, $p < 0.05$). Values in each column followed by the same upper case letter are not significantly different when comparing similar age classes between the two species (t-test, $p < 0.05$).

Table 8. Mean (\pm SEM) element concentrations and C/N ratio of branches by size class for the second-growth Doug fir and redwood stand in watershed MUN.

Species	Diameter Class	C	N	C/N	P	S	K	Ca	Mg	Fe	Zn	Mn	Cu
	--mm--	g kg ⁻¹	mg kg ⁻¹	ratio	----- mg kg ⁻¹ -----								
Doug fir	<5	500aA (4)	4170aA (190)	144aA (7)	740aA (70)	480aA (30)	3910aA (370)	6340aA (240)	660aA (40)	58.4abA (4.3)	33.6aA (2.3)	207aA (16)	5.3aA (0.7)
	5-10	502aA (5)	3330bA (170)	181aA (9)	550bA (80)	390bA (30)	3380abA (380)	5180bA (360)	520bA (30)	45.4aA (5.2)	26.9bA (1.9)	170bA (19)	5.4aA (0.6)
	10-20	506aA (5)	2210cA (190)	289bA (23)	290cA (30)	200cA (20)	2410bA (470)	3170cA (320)	350cA (30)	45.6aA (5.1)	15.6cA (1.0)	112cA (12)	2.9bA (0.4)
	20-50	512abA (3)	1460dA (170)	447cA (29)	140cdA (30)	140dA (10)	1370cA (320)	2280dA (200)	270dA (20)	52.2aA (8.8)	13.0edA (0.8)	89cdA (6)	1.8bA (0.6)
	>50	519bA (4)	1100dA (60)	571dA (31)	100dA (10)	120dA (10)	900cA (16.0)	1710dA, (110)	240dA (20)	78.1bA (14.5)	10.6dA (1.0)	72dA (5)	2.5bA (0.6)
Redwood	<5	503aA (4)	2490aB (220)	273aB (42)	450aB (50)	450aA (40)	262VaB (320)	6510aA (840)	690aA (70)	51.8aA (9.2)	22.3aB (3.3)	101aB (11)	3.4aA (0.7)
	5-10	508abA (5)	1990abB (140)	314aB (23)	310bB (30)	330bA (30)	1980bB (200)	5490aA (520)	570aA (80)	35.1bA (3.8)	14.4bB (1.7)	80bB (8)	2.3abB (0.4)
	10-20	505aA (4)	1300bB (50)	462bB (17)	140cB (20)	180cA (10)	1340cB (110)	3270bA (240)	320bA (50)	29.6bB (3.1)	11.4bcA (1.9)	50cB (5)	2.6abA (0.3)
	20-50	517bA (3)	1080bB (40)	570bB (22)	80cB (<10)	150cA (10)	960cdA (40)	2540bA (130)	280bA (40)	36.5bA (6.6)	7.2cB (0.5)	49cB (4)	LOA (0.3)
	>50	516bA (2)	1110bA (70)	541bA (30)	60cB (10)	120cA (<10)	750dA (40)	2020bA (100)	230bA (30)	24.8bB (4.6)	6.3cB (0.7)	39cB (5)	1.5bA (0.3)

Values in each column followed by the same lower case letter are not significantly different when comparing between branch size classes within each species (ANOVA with Fisher's least significant difference test, $p < 0.05$). Values in each column followed by the same upper case letter are not significantly different when comparing similar branch size classes between the two species (t-test, $p < 0.05$).

Table 9. Mean (\pm SEM) element concentrations and C/N ratio of wood and bark for the second growth Doug fir and redwood stand in watershed MUN.

Species	Component	C	N	C/N	P	S	K	Ca	Mg	Fe	Zn	Mn	Cu
		-g kg ⁻¹ -	-mg kg ⁻¹ -	--ratio--	-----mg kg ⁻¹ -----								
Doug fir	Wood	495aA (4)	630aA (60)	918aA (93)	50aA (10)	60aA (<10)	310aA (20)	180aA (50)	10aA (<10)	204aA (44)	1.7aA (0.2)	8.9aA (1.0)	0.5aA (0.2)
	Bark	557bA (5)	1530bA (200)	444bA (47)	110bA (10)	250bA (10)	460bA (<10)	1190bA (230)	140bA (20)	140aA (3)	10.0aA (3.8)	43.1aA (16.9)	5.0bA (1.8)
Redwood	Wood	508aB (2)	850aB (30)	707aA (22)	50aA (10)	110aB (20)	390aA (50)	350aA (50)	90aB (10)	447aA (153)	4.2aB (0.5)	15.3aA (2.6)	ZOO (0.4)
	Bark	480bB (4)	1700bA (300)	361bA (61)	140bA (30)	300aA (100)	440aA (60)	850aA (250)	150bA (20)	238aA (74)	7.2aA (1.7)	29.2bA (2.4)	2.0aA (0.7)

Values in each column followed by the same lower case letter are not significantly different when comparing wood versus bark within each species (t-test, $p < 0.05$).
 Values in each column followed by the same upper case letter are not significantly different when comparing wood or bark components between the two species (t-test, $p < 0.05$).

Table 10. Mean (\pm SEM) element concentrations and C/N ratio of roots by size class for the second-growth Doug fir and redwood stand in watershed MUN.

Species	Root diameter	C	N	C/N	P	S	K	Ca	Mg	Fe	Zn	Mn	Cu
	-- mm --	g kg ⁻¹	mg kg ⁻¹	ratio	----- mg kg ⁻¹ -----								
Doug fir	<1	488aA (2)	7580aA (430)	76aA (5)	930aA (80)	910aA (60)	2720aA (190)	6990aA (840)	1310aA (150)	1810aA (377)	32.5aA (3.0)	328aA (77)	24.UaA (10.1)
	1-2	486aA (2)	508ObA (360)	114aA (8)	750abA (40)	69OabA (10.0)	2490aA (120)	7240aA (119.0)	9.4.OabA (160)	1060bA (186)	22.ObA (2.0)	268.aA (71)	8.7bA (2.2)
	2-5	497aA (9)	3630cA (460)	168abA (19)	540bcA (180)	620bcA (120)	2250aA (360)	708OaA (1700)	930abA (220)	660bA (132)	21.6bA (3.1)	343aA (129)	4.1bA (0.9)
	5-10	504aA (8)	2950cdA (570)	221bA (37)	670acA (110)	460bcA (60)	1430bA (170)	4880aA (800)	670bcA (40)	489bA (101)	15.3bcA (1.3)	214aA (82)	3.ObA (0.5)
	>10	512aA (8)	1830dA (260)	351cA (61)	400cA (40)	350cA (80)	1070bA (80)	3170aA (1120)	450cA (70)	466bA (96)	12.5cA (1.6)	139aA (28)	2.6bA (0.5)
Redwood	<1	485aA (13)	7880aA (570)	73aA (5)	1080aA (140)	1050aA (120)	305OaA (200)	7650aA (1010)	1280aA (180)	1611aA (394)	36.4aA (2.9)	318aA (48)	23.8aA (7.4)
	1-2	492aA (8)	4980bA (240)	116aA (6)	750aA (90)	760aA (90)	2170bA (130)	7700aA (630)	830aA (90)	912abA (272)	19.5bA (1.2)	445aA (223)	4.8bA (0.3)
	2-5	481aA (8)	3900bA (390)	149abA (15)	710aA (140)	750aA (120)	2160bA (150)	7390aA (930)	930aA (270)	682bA (128)	18.8bA (2.3)	467aA (173)	4.2bA (0.4)
	5-10	479aA (9)	2380cA (520)	288bcA (84)	710aA (260)	670aA (150)	204ObB (140)	7400aA (900)	680aA (120)	503bA (68)	16.6bA (1.9)	264aA (71)	2.5bA (0.1)
	>10	482aA 9	1530cA 300	419cA (91)	470aA (150)	520aA (130)	1940bB (90)	5940aA (940)	530aA (90)	630bA (144)	15.ObA (1.8)	194aA (69)	2.6bA (0.3)

Values in each column followed by the same lower case letter are not significantly different when comparing root diameter classes within each species (ANOVA with Fisher's least significant difference test, $p < 0.05$). Values in each column followed by the same upper case letter are not significantly different when comparing similar root diameter classes between the two species (t-test, $p < 0.05$).

Nutrient pools as a function of species and biomass component are shown in Tables 11-21. There was a total of 644 Mg/ha of carbon (~ 1288 Mg/ha of biomass-dry weight) stored in the redwood and Doug fir in this 80+ year old forest ecosystem (watershed MUN; Table 11). This compares with carbon storage of 10.5 Mg/ha in the 6 year old redwood regrowth in the adjacent watershed (KJE). The wood and bark components contain about 86% of the carbon within the ecosystem and only 6.4% of the total biomass carbon pool is found in the below-ground rooting component. In comparison, the biomass contains nearly four times the amount of organic carbon stored in the soil profile (~ 170 Mg/ha; Fig. 4).

There was a total of 1480 kg/ha of nitrogen in the redwood and Doug fir biomass in this ecosystem (Table 12). Only 10% (166 kg/ha) of the nitrogen pool is found in the below-ground rooting biomass. Approximately 64% (949 kg/ha) of the total nitrogen in the biomass is contained within the wood and bark components. Because conventional clearcutting removes the wood and bark components, it is this 949 kg/ha of nitrogen that will be directly removed from the ecosystem by harvesting. This represents an annual loss of about 12 kg/ha/yr over the 80-year harvest rotation. These values compare to N losses from the ecosystem of 0.15 to 1.85 kg/ha/yr in stream water and inputs of 0.1 to 0.4 kg/ha/yr in precipitation. These inputs/outputs alone would suggest a nonsustainable forest practice; however, nitrogen fixers such as *Ceanothus* species, lichens, and algae contribute to nitrogen inputs into these ecosystems. Furthermore, the pool of total nitrogen contained within the soil profile is on the order of 10 Mg/ha. Thus, <10% of the total soil nitrogen pool is removed by the harvest. However, only a small portion of the total nitrogen pool is available for biota. These data suggest that nitrogen fixation by *Ceanothus* species and other sources may be necessary to maintain the long-term productivity and sustainability of these ecosystems.

A similar analysis can be made for other nutrients to determine whether biomass removal by harvesting will substantially deplete available nutrient pools. Removal of P, K, Ca and Mg by harvesting stems (wood plus bark) results in the loss of 65, 405, 401 and 75 kg/ha/yr, respectively (Tables 13-16). These values compare with available nutrient pools from the soil of about 60, 2800, 20,000 and 5000 for P, K, Ca and Mg, respectively (Fig. 4). This analysis shows that the equivalent of the entire pool of available P is removed by harvest which suggests that continued harvesting could result in serious depletion of available P reserves. However, it must be kept in mind that the total P pool is on the order of 3500 kg/ha which is the equivalent of 50 harvest rotations (Fig. 4). Similarly, additional K, Ca and Mg will be released by rock weathering, and atmospheric deposition of these elements also contributes on the order of 1 to 10 kg/ha/yr of these nutrients. Sulfur is another nutrient that requires consideration since 124 kg/ha are removed by harvesting and there is no appreciable release of S from chemical weathering of the rocks (Table 17). Atmospheric inputs of S are on the order of 1-2 kg/ha/yr which nearly match the losses of S in biomass over a 80 year rotation. Thus, it appears from the preceding analysis that maintaining the reserves of nitrogen and phosphorous are the most critical to long-term sustainability of these redwood/Doug fir ecosystems.

A comparison of nutrient pools contained in the biomass of the reference (MUN) and clearcut (KJE) watersheds is shown in Figure 7. Nutrient pools in living biomass are 1-2 orders of magnitude greater in the reference watershed compared to the six year old clearcut watershed. The nutrients that have the highest demand by vegetation are N, Ca and K, followed by moderate demand for Fe, S, Mg and P, and lesser demand for Mn, Zn and Cu.

Table 11. Estimated carbon pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- Mg/ha -----				
Foliage	7.45		4.95		12.4
New		1.79		1.24	
Old		5.66		3.71	
Branches	20.6		14.3		34.9
<0.5 cm		1.01		0.70	
0.5-1 cm		1.43		0.98	
1-2 cm		2.43		1.69	
2-5 cm		3.94		2.71	
>5 cm		11.8		8.24	
Wood	285		203		488
Bark	36.8		30.7		67.5
Roots	24.0		17.0		41.0
< 1 mm		0.44		0.09	
1-2 mm		1.30		0.28	
2-5 mm		0.86		0.92	
5-10 mm		0.62		1.21	
> 10 mm		20.8		14.5	
Total	374		270		644

Table 12. Estimated nitrogen pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	151		118		269
New		41		26	
Old		110		92	
Branches	50.5		44.9		95.4
<0.5 cm		5.0		5.8	
0.5-1 cm		5.6		6.5	
1-2 cm		6.3		7.4	
2-5 cm		8.2		7.7	
>5 cm		25.4		17.5	
Wood	477		258		735
Bark	130		84		214
Roots	96.5		69.8		166
<1 mm		7.1		1.6	
1-2 mm		13.2		2.9	
2-5 mm		7.0		6.8	
5-10 mm		3.1		7.1	
>10 mm		66.1		51.7	
Total	905		575		1480

Table 13. Estimated phosphorus pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	18		20		38
New		6		4	
Old		12		16	
Branches	4.4		5.4		9.8
<0.5 cm		0.90		1.03	
0.5-1 cm		0.87		1.07	
1-2 cm		0.67		0.97	
2-5 cm		0.61		0.74	
>5 cm		1.37		1.59	
Wood	28		20		48
Bark	11		6		17
Roots	25.5		15		40.5
< 1 mm		0.97		0.18	
1-2 mm		1.98		0.43	
2-5 mm		1.28		1.00	
5-10 mm		0.92		1.60	
> 10 mm		20.3		11.3	
Total	87		66		153

Table 14. Estimated potassium pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	82		74		156
New		26		21	
Old		56		53	
Branches	42		42		84
<0.5 cm		5.26		5.45	
0.5-1 cm		5.56		6.59	
1-2 cm		6.45		8.06	
2-5 cm		7.32		7.25	
>5 cm		17.2		14.3	
Wood	219		127		346
Bark	34		25		59
Roots	99		40		139
<1 mm		2.71		0.52	
1-2 mm		5.76		1.43	
2-5 mm		3.88		4.18	
5-10 mm		2.65		3.42	
>10 mm		83.9		30.2	
Total	476		308		784

Table 15. Estimated calcium pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	131		59		190
New		25		7	
Old		106		52	
Branches	110		69		179
<0.5 cm		13.1		8.83	
0.5-1 cm		15.4		10.1	
1-2 cm		15.8		10.6	
2-5 cm		19.4		12.1	
>5 cm		46.2		27.2	
Wood	197		74		271
Bark	65		65		130
Roots	307		120		427
<1 mm		6.87		1.35	
1-2 mm		20.4		4.16	
2-5 mm		13.3		13.2	
5-10 mm		9.60		11.7	
>10 mm		257		89.5	
Total	810		387		1197

Table 16. Estimated magnesium pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	31		14		45
New		8		3	
Old		23		11	
Branches	11.9		8.3		20.2
<0.5 cm		1.38		0.92	
0.5-1 cm		1.60		1.01	
1-2 cm		1.54		1.17	
2-5 cm		2.13		1.43	
>5 cm		5.26		3.81	
Wood	51		4		55
Bark	12		8		20
Roots	34.8		16.8		51.5
< 1 mm		1.15		0.25	
1-2 mm		2.20		0.54	
2-5 mm		1.67		1.73	
5-10 mm		0.88		1.60	
>10 mm		28.8		12.7	
Total	141		51.1		192

Table 17. Estimated sulfur pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood	Doug fir		Ecosystem
	----- kg/ha -----			
Foliage	14		10	24
New		4		2
Old		10		8
Branches	6.6		4.7	11.3
<0.5 cm		0.90		0.67
0.5-1 cm		0.93		0.76
1-2 cm		0.87		0.67
2-5 cm		1.14		0.74
>5 cm		2.74		1.91
Wood	62		25	87
Bark	23		14	37
Roots	28		13	41
< 1 mm		0.94		0.18
1-2 mm		2.01		0.40
2-5 mm		1.35		1.15
5-10 mm		0.87		1.10
>10 mm		22.5		9.88
Total	134		67	201

Table 18. Estimated iron pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	0.94		0.83		1.8
New		0.20		0.20	
Old		0.74		0.63	
Branches	1.19		1.84		3.0
<0.5 cm		0.10		0.08	
0.5-1 cm		0.10		0.09	
1-2 cm		0.14		0.15	
2-5 cm		0.28		0.28	
>5 cm		0.57		1.24	
Wood	251		83		334
Bark	18.3		7.7		26
Roots	38.7		16.5		56
<1 mm		1.45		0.35	
1-2 mm		2.41		0.61	
2-5 mm		1.23		1.23	
5-10 mm		0.65		1.17	
>10 mm		33.0		13.2	
Total	311		110		421

Table 19. Estimated zinc pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	0.21		0.13		0.34
New		0.07		0.03	
Old		0.14		0.10	
Branches	0.48		0.63		1.11
<0.5 cm		0.20		0.29	
0.5-1 cm		0.04		0.05	
1-2 cm		0.05		0.05	
2-5 cm		0.05		0.07	
>5 cm		0.14		0.17	
Wood	2.36		0.70		3.06
Bark	0.55		0.55		1.10
Roots	0.78		0.45		1.23
<1 mm		0.03		0.01	
1-2 mm		0.05		0.01	
2-5 mm		0.03		0.04	
5-10 mm		0.02		0.04	
>10 mm		0.65		0.35	
Total	4.38		2.46		6.84

Table 20. Estimated manganese pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	4.9		5.0		9.9
New		1.4		0.8	
Old		3.5		4.2	
Branches	1.9		2.6		4.5
<0.5 cm		0.20		0.29	
0.5-1 cm		0.22		0.33	
1-2 cm		0.24		0.37	
2-5 cm		0.37		0.47	
>5 cm		0.89		1.14	
Wood	8.6		3.6		12.2
Bark	2.2		2.4		4.6
Roots	11.0		5.8		16.8
< 1 mm		0.29		0.06	
1-2 mm		1.18		0.15	
2-5 mm		0.84		0.64	
5-10 mm		0.34		0.51	
>10 mm		8.39		3.92	
Total	28.6		19.4		48.0

Table 21. Estimated copper pools contained in above- and below-ground living biomass of the redwood/Doug fir ecosystem in the reference watershed (MUN).

	Redwood		Doug fir		Ecosystem
	----- kg/ha -----				
Foliage	0.03		0.03		0.06
New		0.01		0.01	
Old		0.02		0.02	
Branches	0.07		0.09		0.15
<0.5 cm		0.01		0.01	
0.5-1 cm		0.01		0.01	
1-2 cm		0.01		0.01	
2-5 cm		0.01		0.01	
>5 cm		0.03		0.04	
Wood	1.12		0.20		1.32
Bark	0.15		0.28		0.43
Roots	0.16		0.11		0.27
< 1 mm		0.02		0.01	
1-2 mm		0.01		0.01	
2-5 mm		0.01		0.01	
5-10 mm		0.01		0.01	
>10 mm		0.11		0.07	
Total	1.53		0.70		2.23

Nutrient Pools

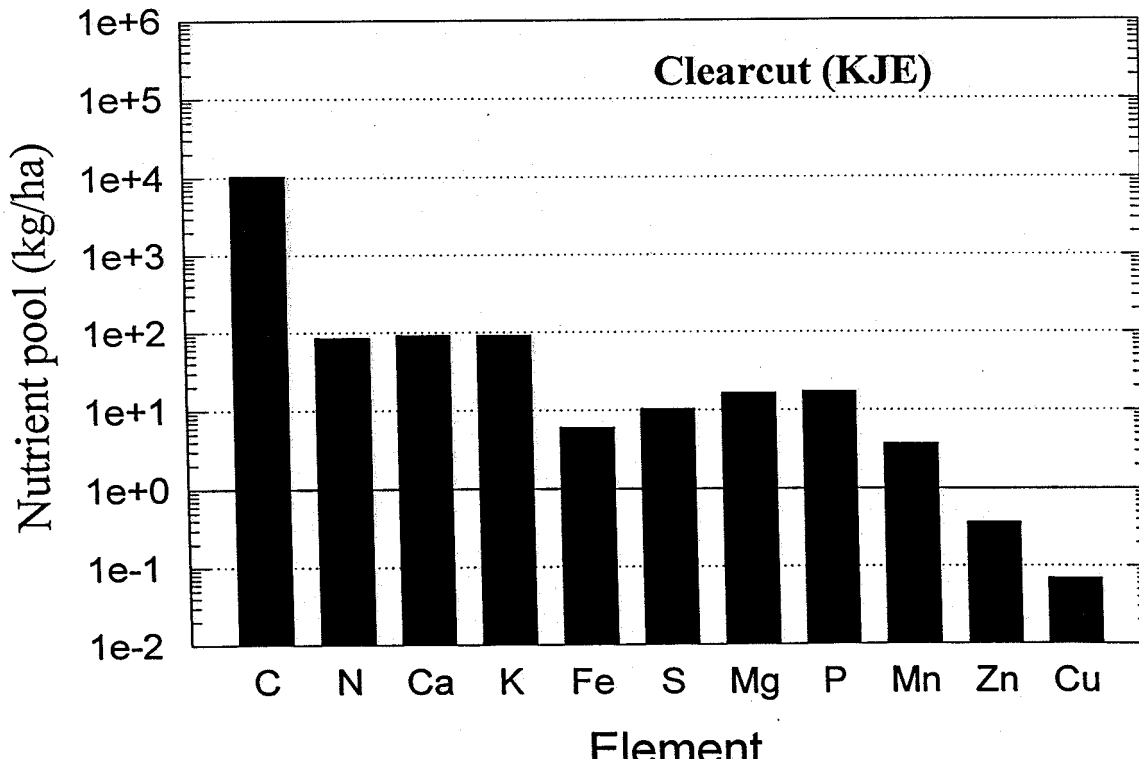
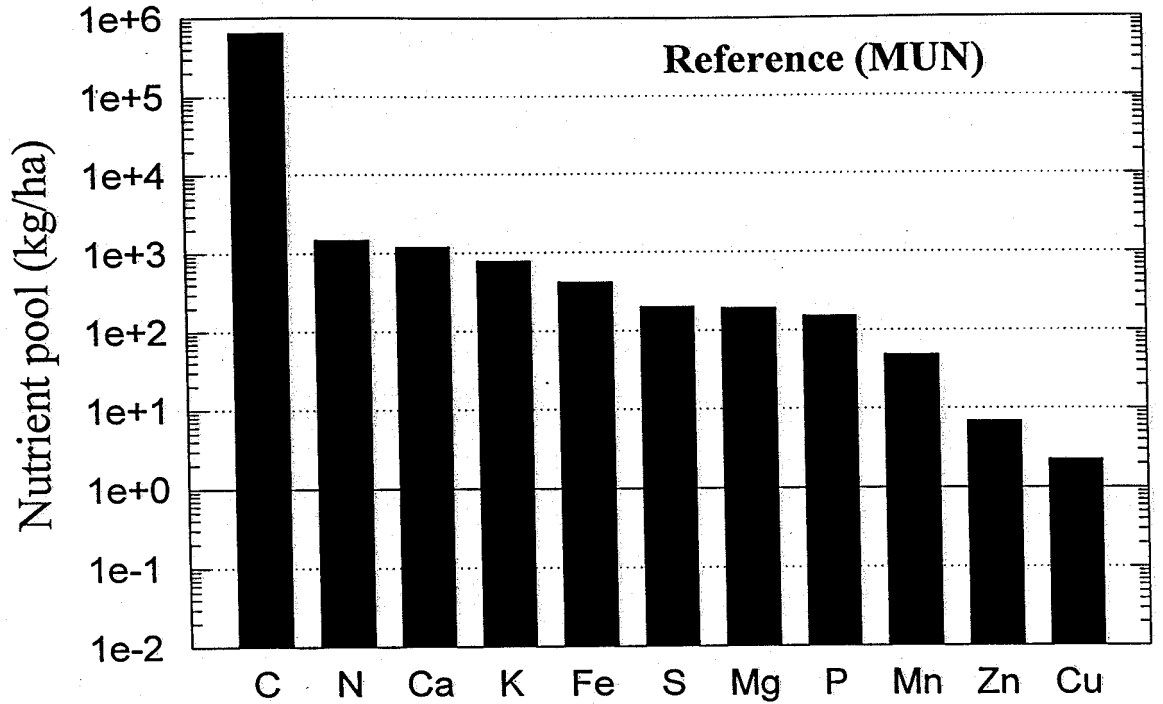


Fig. 7. Nutrient pools contained in the above- and below-ground living biomass in the reference watershed (MUN), and in the clearcut (KJE) watershed six years following the harvest.

Precipitation, Canopy Throughfall and Soil Solution Chemistry

Changes in aqueous chemistry along the hydrologic cycle within the second growth redwood/Doug fir and clearcut ecosystems are shown in Figure 8. Each component of the hydrologic cycle will be discussed below.

Precipitation. The precipitation was strongly influenced by sea salts with the chemical composition dominated by sodium ($48 \mu\text{M}$) and chloride ($49 \mu\text{M}$) in a near-stoichiometric balance (Table 22). There were trace inputs of N ($\text{NH}_4 = 0.8 \mu\text{M}$ & $\text{NO}_3 = 1.0 \mu\text{M}$) and P (ortho- $\text{PO}_4 = 0.5 \mu\text{M}$) adding important macro-nutrients to this ecosystem. Other macro-nutrients present in appreciable concentrations were K ($4.0 \mu\text{M}$), Mg ($13 \mu\text{M}$), Ca ($15 \mu\text{M}$) and SO_4 ($4 \mu\text{M}$). The mean pH of the rainfall was slightly acidic at 6.42.

Canopy Throughfall. Canopy interception ($[\text{precipitation} - \text{canopy throughfall}] / \text{precipitation}$) averaged $10 \pm 14\%$ (mean \pm std deviation; range = -11 to 30%) for Doug fir and $16 \pm 11\%$ (mean \pm std deviation; range = 8 to 36%) for redwood. These canopy interception values are consistent with the range of 9 to 26% measured in this same watershed (MUN) by E. Keppeler of the USDA Forest Service, Caspar Creek Research Team. Mean interception rates for conifers generally range between 10-35%, but are highly dependent on the form, distribution and intensity of precipitation. The lower interception rates in this coastal-fog zone are most probably a result of fog condensation and drip from the canopy. In a few instances, canopy throughfall volumes were actually higher than precipitation volumes indicating capture of fog by the canopy.

The chemical composition of the precipitation was substantially altered by interaction with the redwood and Doug fir canopies (Table 22). Concentrations of Na, Cl, SO_4 , Mg and Ca were enriched by a factor of 2 to 5.5 times on passing through the canopy. The enrichment factor for these elements was generally a factor of two greater for the Doug fir canopy. Since these elements are derived primarily from sea salt capture, these data suggest that the capture efficiency of the Doug fir canopy is appreciably greater than that of the redwood canopy. The large enrichments for ortho- PO_4 (22 times for Doug fir) and K (13-16 times) in the canopy throughfall is probably due to exudation and leaching of these components from the foliage. The enrichment values are substantially larger than for the sea salt dominated elements suggesting that aerosol and particulate capture is not the dominant process affecting ortho- PO_4 and K enrichment. In contrast to the large enrichment factors for the majority of elements, concentrations of NH_4 and NO_3 were not appreciably altered by canopy processes. The pH of the canopy throughfall was 0.4 to 0.5 units lower than that of the incoming precipitation indicating some leaching of acidic components (e.g., organic acids) from the canopy.

Soil Solutions. The soil solution charge balances in the reference (MUN) and clearcut (KJE) watersheds show the following cation and anion distributions (Fig. 8):

Reference Ca = Na > Mg > K

Clearcut Ca > Na > Mg > K

Reference Cl > $\text{HCO}_3 \gg \text{SO}_4$

Clearcut $\text{HCO}_3 > \text{Cl} > \text{SO}_4$.

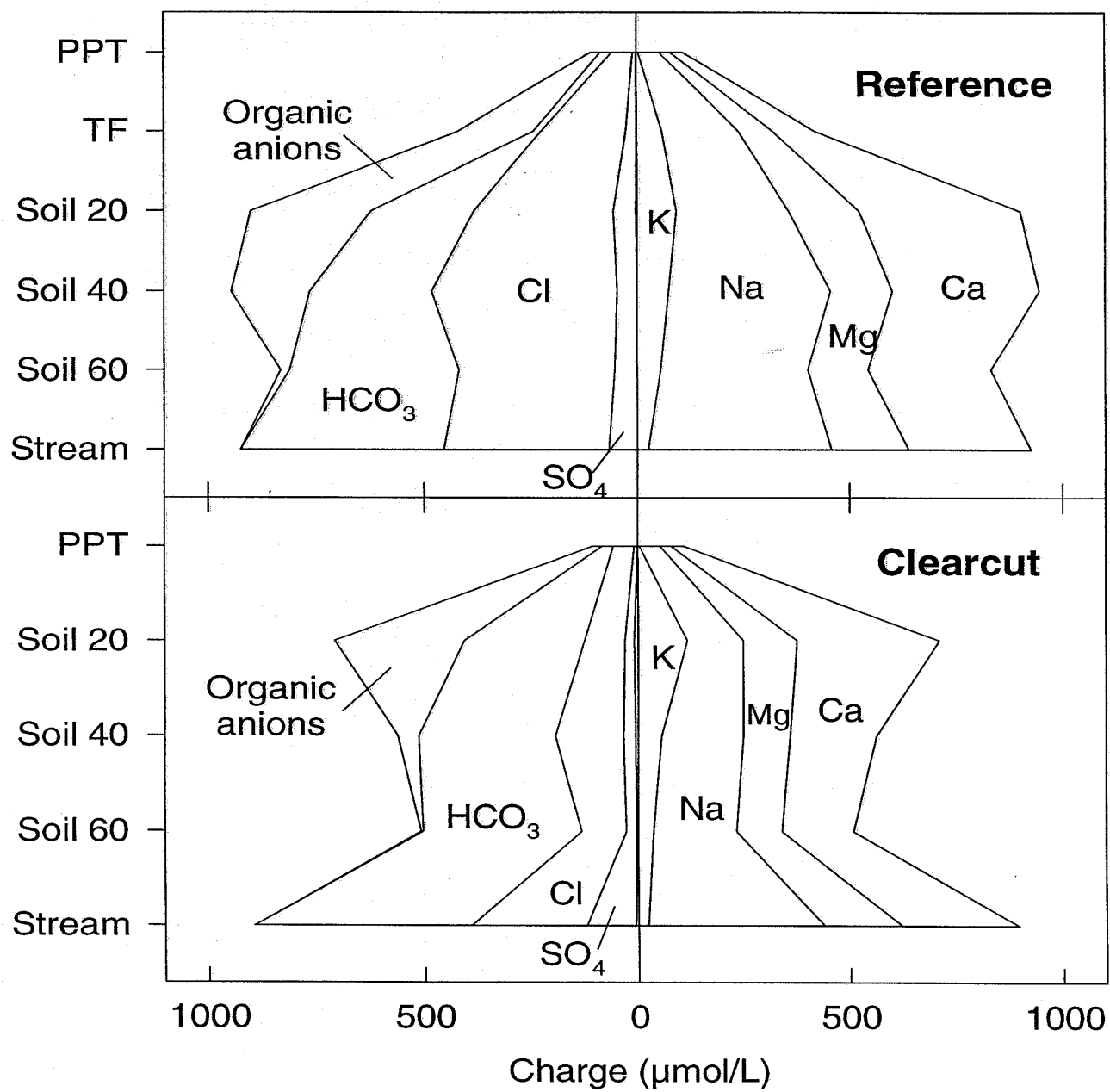


Fig. 8. Solution charge balance diagrams for precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds. The width of each compartment is equal to the charge contributed by each ion. The anion charge deficit is assumed to be the contribution of dissociated organic acids.

Table 22. Mean-±SEM solute concentrations for precipitation and canopy throughfall from Doug fir and redwood.

	Precipitation	Canopy Throughfall	
		Doug fir	Redwood
pH	6.42 (0.11)a	5.92 (0.08)b	6.07 (0.10) b
Cl (μM)	48.6 3.5)a	272.8 43.8)b	123.9 16.0)c
NO ₃ (μM)	1.0 (0.2 a	1.2 (0.9)a	0.6 (0.2)a
PO ₄ (μM)	0.5 (0.3 a	10.8 3.0)b	8.1 2.1 b
SO ₄ (μM)	4.3 0.3 a	16.3 3.1 b	8.0 (0.9 c
Na (μM)	48.3 3.8)a	258.6 33.5 b	98.2 (13.3 c
NH ₄ (μM)	0.8 0.4)ab	0.5 (0.2 a	1.9 (0.5)b
K (μM)	4.0 0.8 a	65.6 (8.9 b	52.7 (8.1)b
Mg (μM)	12.9 0.8)a	49.9 (5.9 b	31.6 (3.2)c
Ca (μM)	14.5 (1.6 a	56.4 (6.9)b	42.2 4.1)b
Si (μM)	2.4 (0.3)a	1.9 (0.4)a	2.7 (0.7)a

Values with the same lower-case letter within a row indicate that these values are not statistically difference at $p < 0.05$.

Soil solution pH values increased by about 0.8 units compared to the incoming canopy throughfall (Fig. 9). Within the soil profile, pH values were similar with increasing depth (range = 6.7 to 6.9). The pH was about 0.1 units lower at the 20 cm depth in the clearcut compared to the reference watershed (Table 23). Concentrations of base cations (Na, Ca, Mg and K) were generally lower in the clearcut compared to the reference catchment (Fig. 10; Table 23). Lower concentrations in the clearcut may result from reduced capture efficiency for sea salts due to removal of the forest canopy and dilution resulting from a reduction in evapotranspiration associated with removal of the forest canopy. Concentrations of the anions, Cl and SO₄, were lower in the clearcut watershed (Fig. 11; Table 23). Reduced capture efficiency for sea salts and dilution resulting from reduced evapotranspiration may also contribute to this pattern. Silicon concentrations were a factor of 1.5 times lower in the reference watershed (Fig. 12; Table 23). Because Si concentrations are regulated primarily by mineral equilibria, it is believed that kinetic factors related to the lower residence time of water (due to less ET and canopy interception) in the soil profiles of the clearcut are responsible for this difference. In contrast, silicon concentrations are virtually identical in the stream waters draining the two watersheds suggesting that Si concentrations reach equilibrium before the soil solutions emerge as stream flow.

Concentrations of NH₄ were very low (<3 μM) and showed no difference between the reference and clearcut catchments (Fig. 13; Table 23). In contrast, concentrations of NO₃ were greater throughout the entire soil profile in the clearcut catchment (Fig. 11; Table 23). Enhanced N mineralization coupled with reduced uptake may contribute to the increased NO₃ concentrations. Within the soil profile, the concentration of N O₃ decreases appreciably with depth due to nitrogen uptake by the stump-sprouting redwoods. In the absence of this N uptake, nutrient losses to stream water would probably be much higher. Similar to NO₃, concentrations of ortho-PO₄ increased in the upper 20 cm of soils in the clearcut catchment, most likely as a result of enhanced mineralization and reduced uptake (Fig. 11; Table 23). Ortho-PO₄ concentrations decreased to trace levels in the lower soil profile which results from nutrient uptake and phosphate sorption to the abundant iron oxides found in the B horizons.

Table 23. Mean±SEM for soil solution concentrations in the reference (MUN) and clearcut (KJE) watersheds at Caspar Creek. Soil solutions were collected at the 20, 40, and 60 cm depths.

	20 cm depth		40 cm depth		60 cm depth	
	Reference	Clearcut	Reference	Clearcut	Reference	Clearcut
pH	6.86 (0.03) *	6.75 (0.03) *	6.76 (0.06)	6.73 (0.05)	6.78 (0.06)	6.70 (0.06)
Cl (μM)	325.6 (39.3) **	94.7 (12.5) **	434.8 (58.1) **	160.7 (22.3) **	360.2 (35.3) **	105.4 (11.2) **
NO ₃ (μM)	2.1 (0.6) **	7.4 (1.8) **	0.3 (0.1) **	4.7 (1.7) **	0.4 (0.3)	2.27 (1.3)
PO ₄ (μM)	0.3 (0.2) **	2.0 (0.6) **	0.3 (0.2)	0.8 (0.5)	0.1 (0.1)	0.3 (0.1)
SO ₄ (μM)	26.5 (4.7) **	10.3 (1.6) **	22.8 (2.1) **	14.2 (2.3) **	25.8 (2.7) **	12.5 (1.7) **
Na (μM)	265.2 (18.5) **	131.9 (16.7) **	381.7 (28.3)**	192.3 (21.8) **	346.1 (28.4) **	195.2 (18.7) **
NH ₄ (μM)	1.9 (1.4)	2.1 (1.2)	0.3 (0.3)	0.7 (0.3)	0.9 (0.5)	0.4 (0.3)
K (μM)	91.2 (5.8)	114.0 (16.4)	74.9 (6.1) *	55.0 (9.1) *	56.4 (3.8) **	35.2 (2.6) **
Mg (μM)	81.6 (4.7) **	64.0 (3.3) **	72.7 (5.0) **	55.5 (3.5) **	70.3 (3.3) **	54.6 (4.3) **
Ca (μM)	188.7 (9.0)	166.3 (11.3)	172.3 (9.6) **	101.1 (8.3) **	143.7 (5.2) **	84.1 (8.1) **
Si (μM)	49.4 (2.8)**	30.0 (3.9)**	67.3 (6.0)*	51.1 (6.3)*	66.6 (5.9)**	47.5 (5.8)**

* and * * indicate that means between reference and clearcut values for a given depth are statistically different at the p=.10 and p=.05 significance level, respectively.

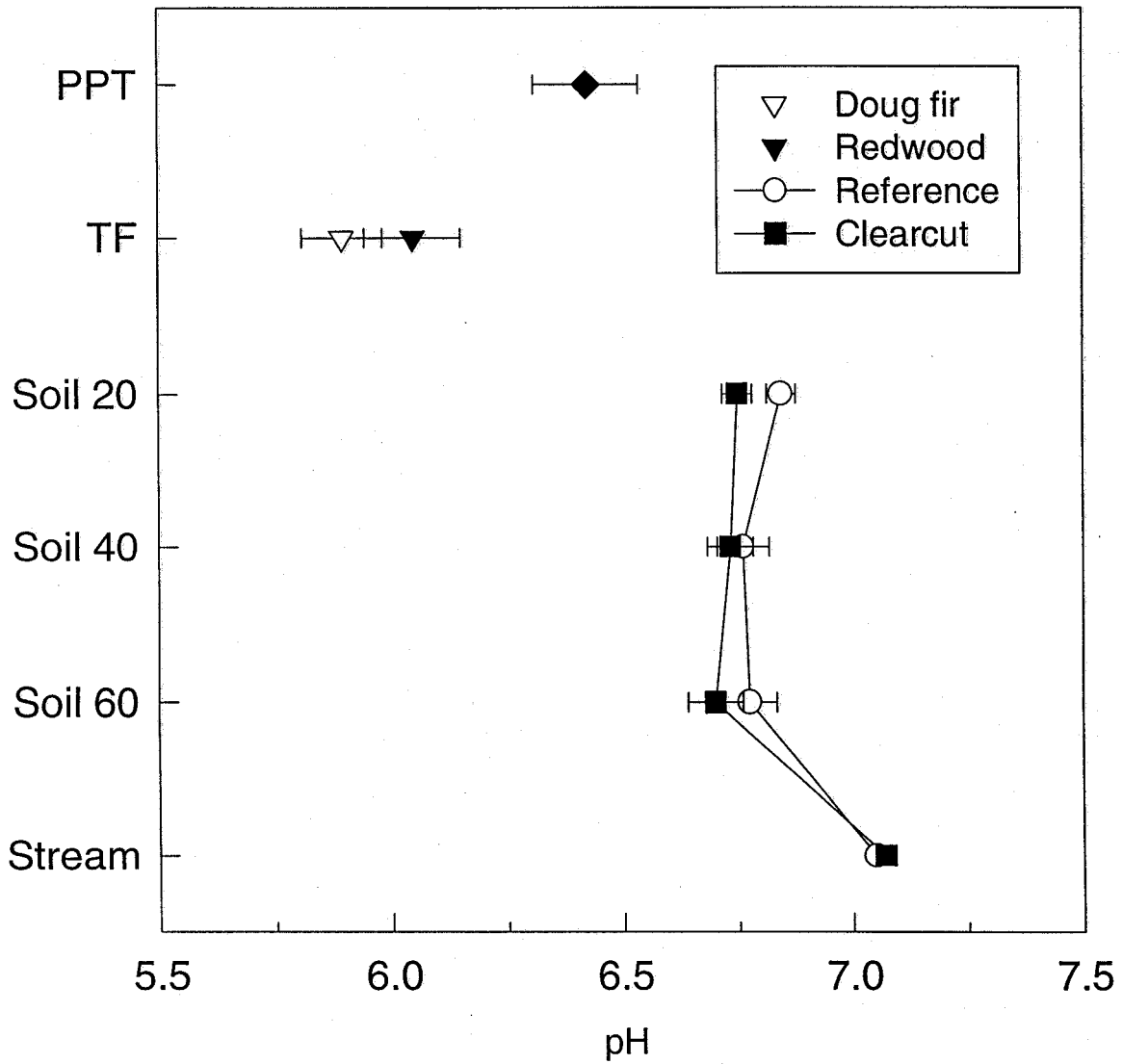


Fig. 9. Mean \pm standard deviation for pH of precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths, and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds.

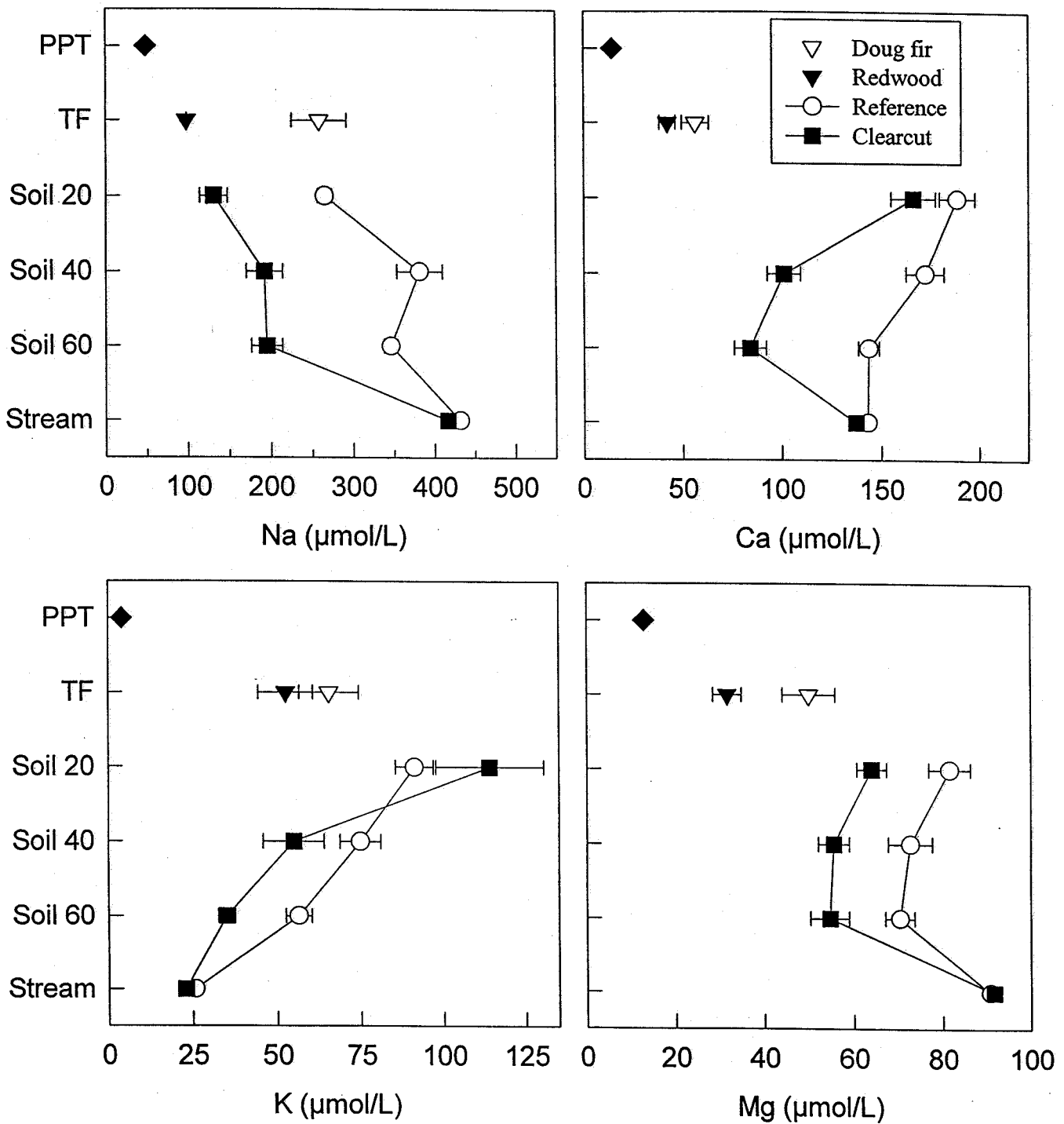


Fig. 10. Mean \pm standard deviation for base cations in precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths, and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds.

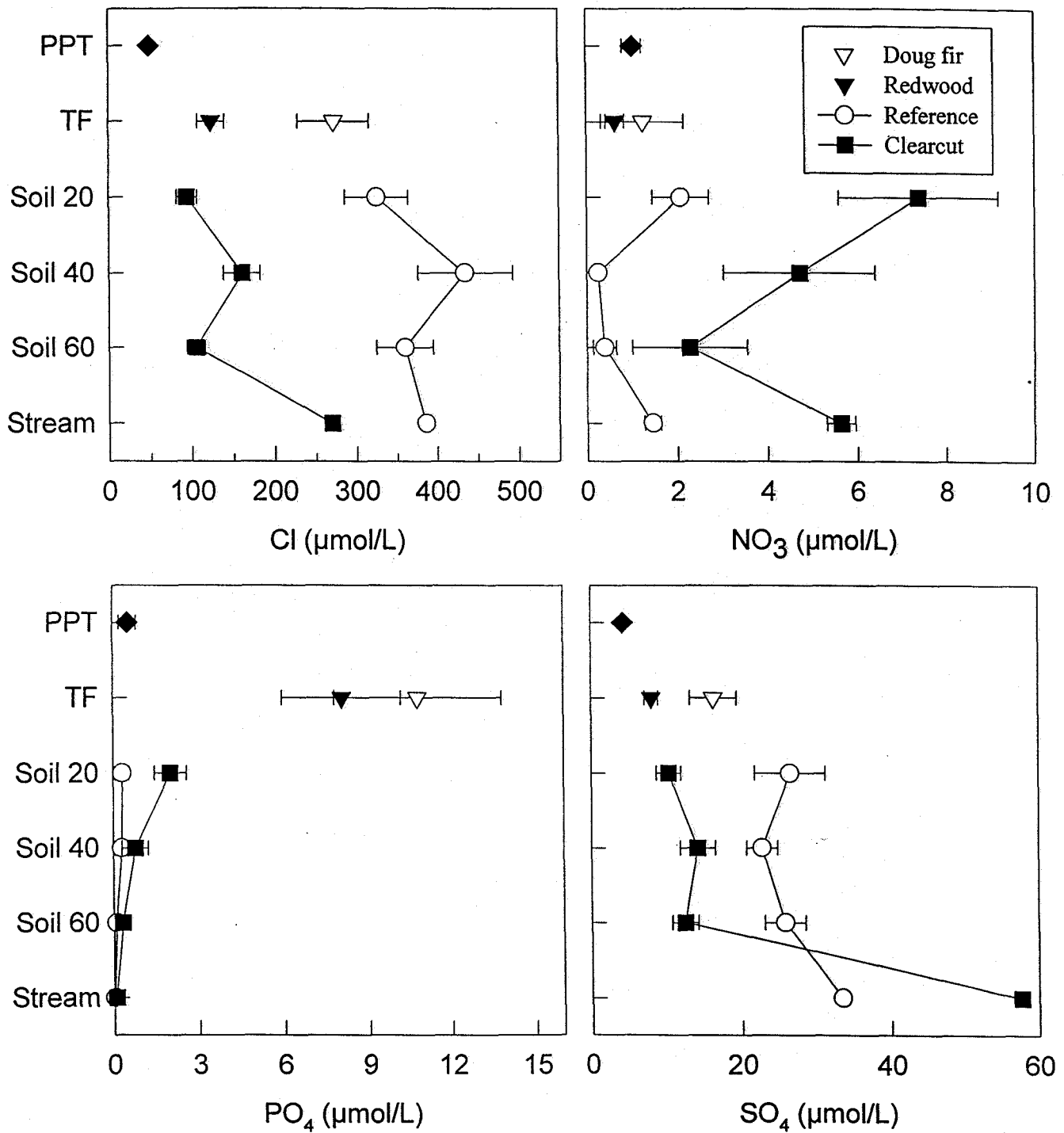


Fig. 11. Mean \pm standard deviation for major anions in precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths, and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds.

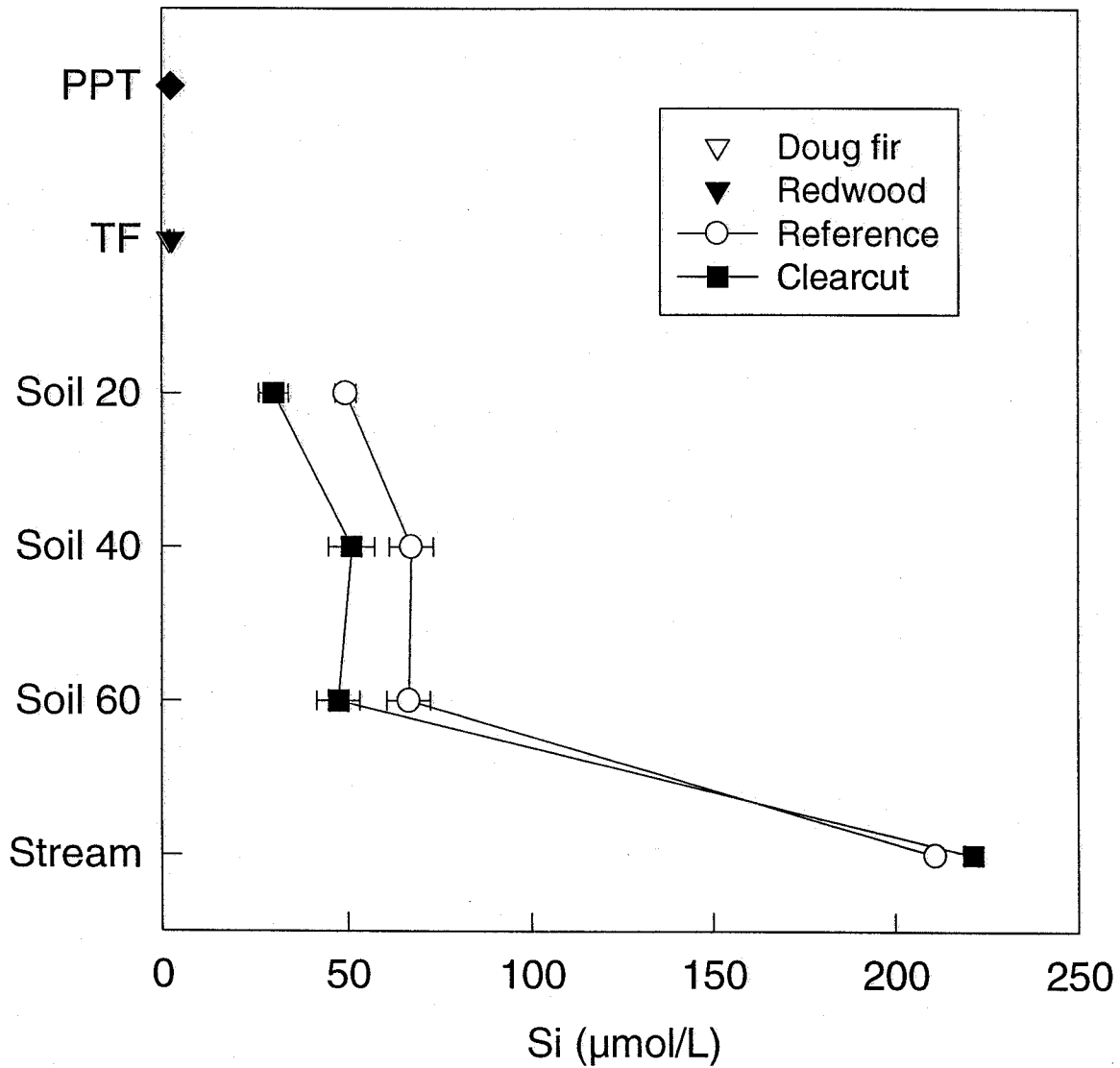


Fig. 12. Mean \pm standard deviation for silicon in precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths, and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds.

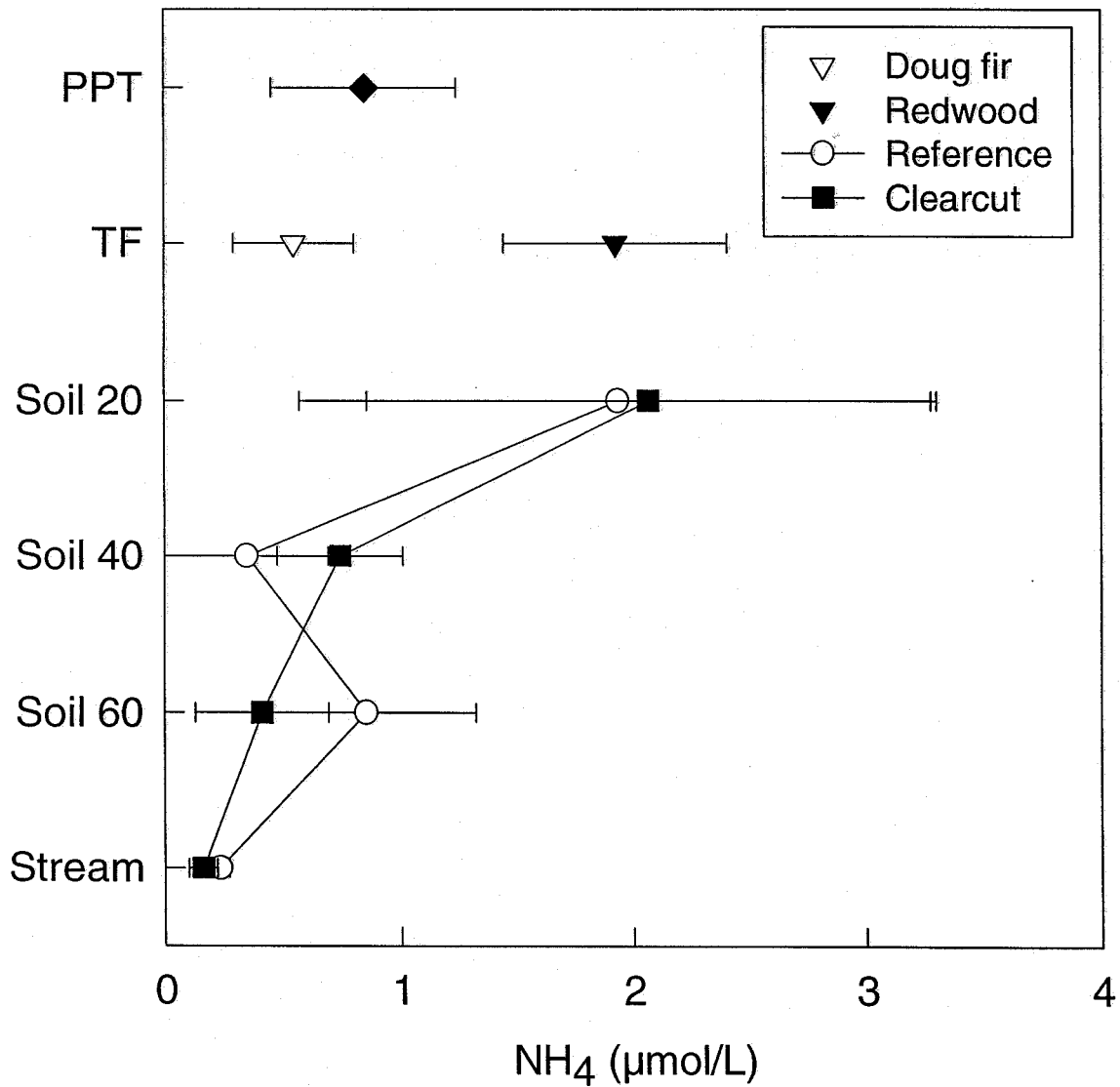


Fig. 13. Mean±standard deviation for ammonium in precipitation (PPT), canopy throughfall (TF), soil solutions at 20, 40 and 60 cm depths, and stream water for the period October, 1993 to June, 1996 in the clearcut (KJE) and reference (MUN) watersheds.

Stream Water Chemistry

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

Nitrate. Nitrate concentrations in the reference watershed were generally less than our detection limits of $0.4 \mu\text{M}$; however, concentrations exceeding $10 \mu\text{M}$ were measured during two storm events in 1995-96 (Fig. 14). In contrast, nitrate concentrations in the clearcut watershed ranged between 10 and $50 \mu\text{M}$ during storm events. Baseflow NO_3 concentrations in the clearcut watershed were low and often below detection limits. It appears that NO_3 concentrations showed a progressive decrease in peak concentrations in the years following the clearcut (1991 to 1994); however, concentrations increased again during storm events in 1995-96. The increased NO_3 concentrations during 1995-96 were observed in both the clearcut and reference watersheds suggesting that the increase was not solely due to the disturbance associated with the clearcut harvesting.

Increased NO_3 concentrations in stream water after clearcutting is a common observation; however, the magnitude of NO_3 leaching varies appreciably between sites. For example, maximum NO_3 concentrations following whole-tree clearcutting of a northern hardwood forest in the Hubbard Brook Ecological Forest of New Hampshire were $500 \mu\text{M}$ (Dahlgren and Driscoll, 1994), an order of magnitude greater than those observed in this study. We feel that the rapid immobilization of nitrogen into the stump sprouting redwood biomass is an important factor limiting the leaching losses of NO_3 in these redwood/Doug fir ecosystems.

The maximum concentrations of NO_3 typically occur in the second year following clearcutting. This results from microbial immobilization of N during decomposition of woody litter with high C/N ratios that is added to the soil organic matter pool as slash during the harvest. Since we missed the January 1990 to March 1991 monitoring period, we can not state specifically the timing of peak NO_3 concentrations following harvest in watershed KJE. We do have immediate post-harvest stream water monitoring from clearcut watersheds EAG and GIB that show maximum NO_3 concentrations in the spring following the cutting (see appendices I & K). The maximum NO_3 concentration in stream water from these two watersheds was $70 \mu\text{M}$ and concentrations decreased over time in a fashion similar to watershed KJE. Thus, we are confident from our monitoring of watersheds EAG and GIB that the data from clearcut watershed KJE is representative of the response of stream water chemistry to clearcutting.

The maximum NO_3 concentrations described above occur during high flow storm events and drop to low levels during baseflow. We interpret these data to indicate that changing hydrologic

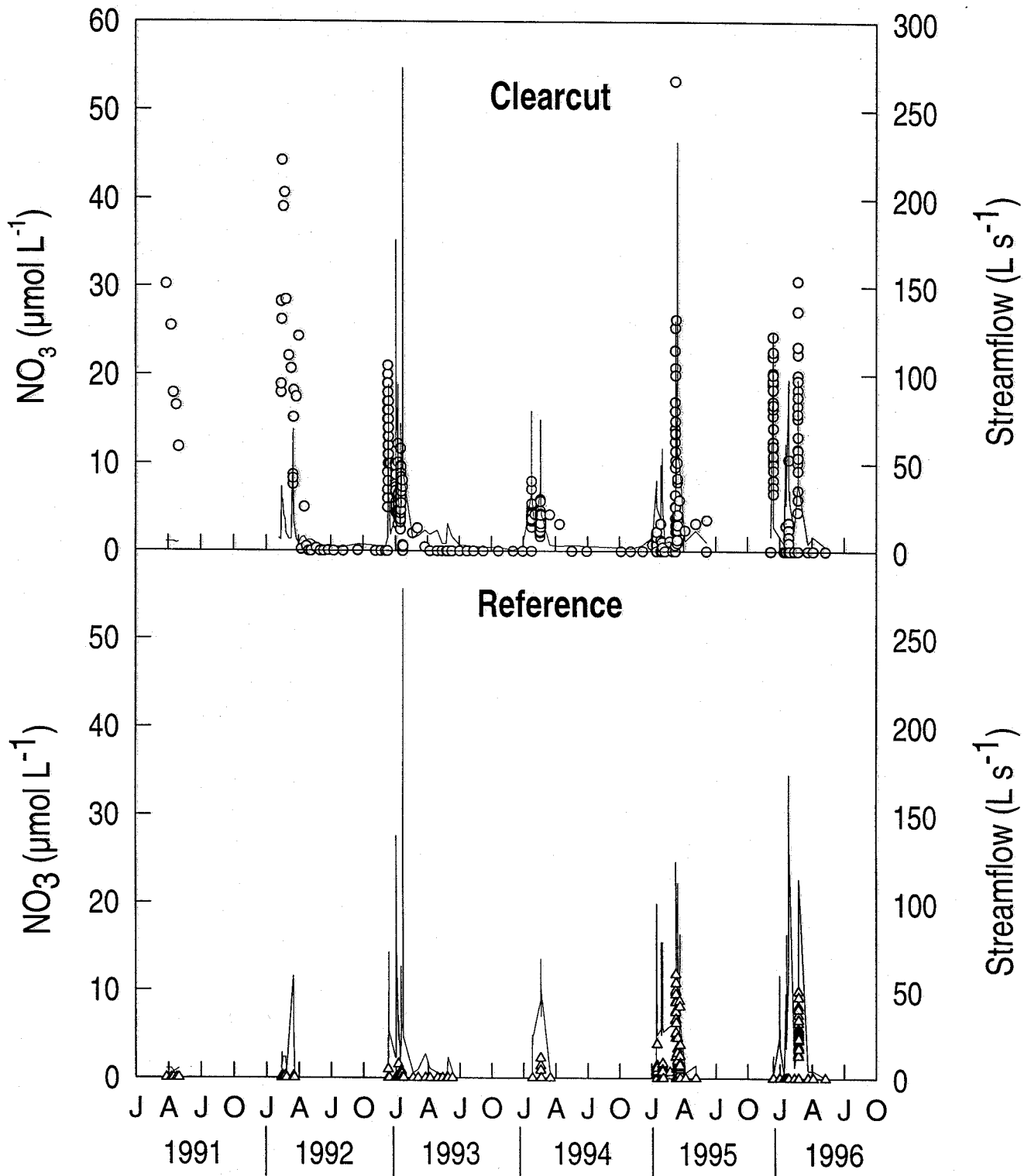


Fig. 14. Streamwater nitrate concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

flowpaths during storm events result in the delivery of high-NO₃ waters to the stream during peak discharge. Soil solution data indicates that the highest NO₃ concentrations occur within the upper soil horizons. The soils within the watershed have a thick argillic horizon (clay-enriched) beginning at a depth of approximately 30 cm. The argillic horizon contains >40% clay, substantially reducing the hydraulic conductivity, which results in saturation above this layer. Given the steep slopes within the watershed, this saturated zone may move laterally downslope, leaching nutrients from within the nutrient-rich rooting zone (upper 30 cm) and delivering them to the stream as subsurface lateral flow during peak discharge. This mechanism is supported by repeated observations of lateral flow above the argillic horizon and through macropores (e.g., root channels) on roadcuts within the Caspar Creek drainage.

Sulfate. Stream water concentrations of SO₄ were consistently higher by approximately 20 μM in the clearcut watershed compared to the reference watershed (Fig. 15). The increased concentrations in the clearcut watershed are most likely due to increased decomposition/mineralization coupled with decreased SO₄ uptake by vegetation. The immobilization of S in redwood sprouts is approximately an order of magnitude less than immobilization of N (70 kg N/ha versus 6.8 kg S/ha). These differences in S mineralization and biological uptake lead to greater SO₄ production and less biological demand, which may contribute to the greater leaching of SO₄ from the watershed. Sulfate concentrations in both watersheds were decreased by 20 to 50 μM during peak flows associated with storm events. This decrease is probably attributable to dilute waters entering the stream as subsurface lateral flow.

Chloride. Chloride concentrations in the clearcut watershed showed a strong temporal pattern at both the seasonal and storm-event scale (Fig. 16). Seasonally, maximum Cl concentrations occurred during the summer period of low streamflow. During storm events, Cl concentrations were reduced by up to 200 μM as a result of dilution, possibly related to changes in the hydrologic flowpath. The decrease in Cl concentrations during peak streamflows is in complete contrast to NO₃ concentrations which peak during maximum streamflow.

Chloride concentrations in the reference watershed were generally 100 μM greater than those in the clearcut watershed. The Cl concentration versus stream discharge relationship was identical between the reference and clearcut watersheds with a large dilution occurring during peak waterflows. Stream water samples were not collected from the reference watershed during the summer dry period because evapotranspiration (ET) was greater in the second growth stand reducing streamflow duration. Similarly, interception water loss of 10-16% by the second growth canopy results in less water reaching the soil surface. The water loss associated with canopy interception and ET results in less water yield and streamflow duration within the reference watershed. The differences in water flux also have an appreciable effect on stream water solute concentrations.

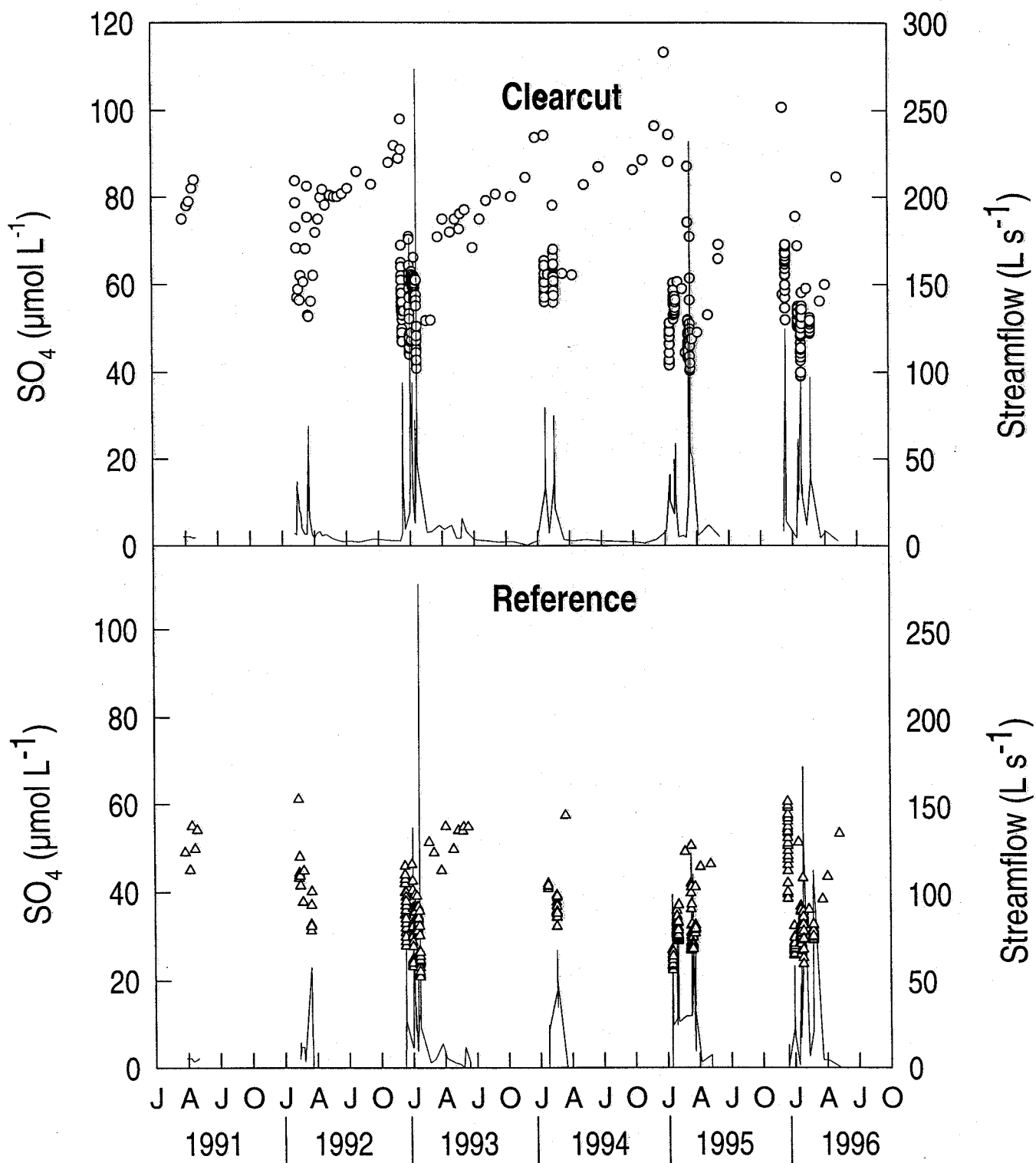


Fig. 15. Streamwater sulfate concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

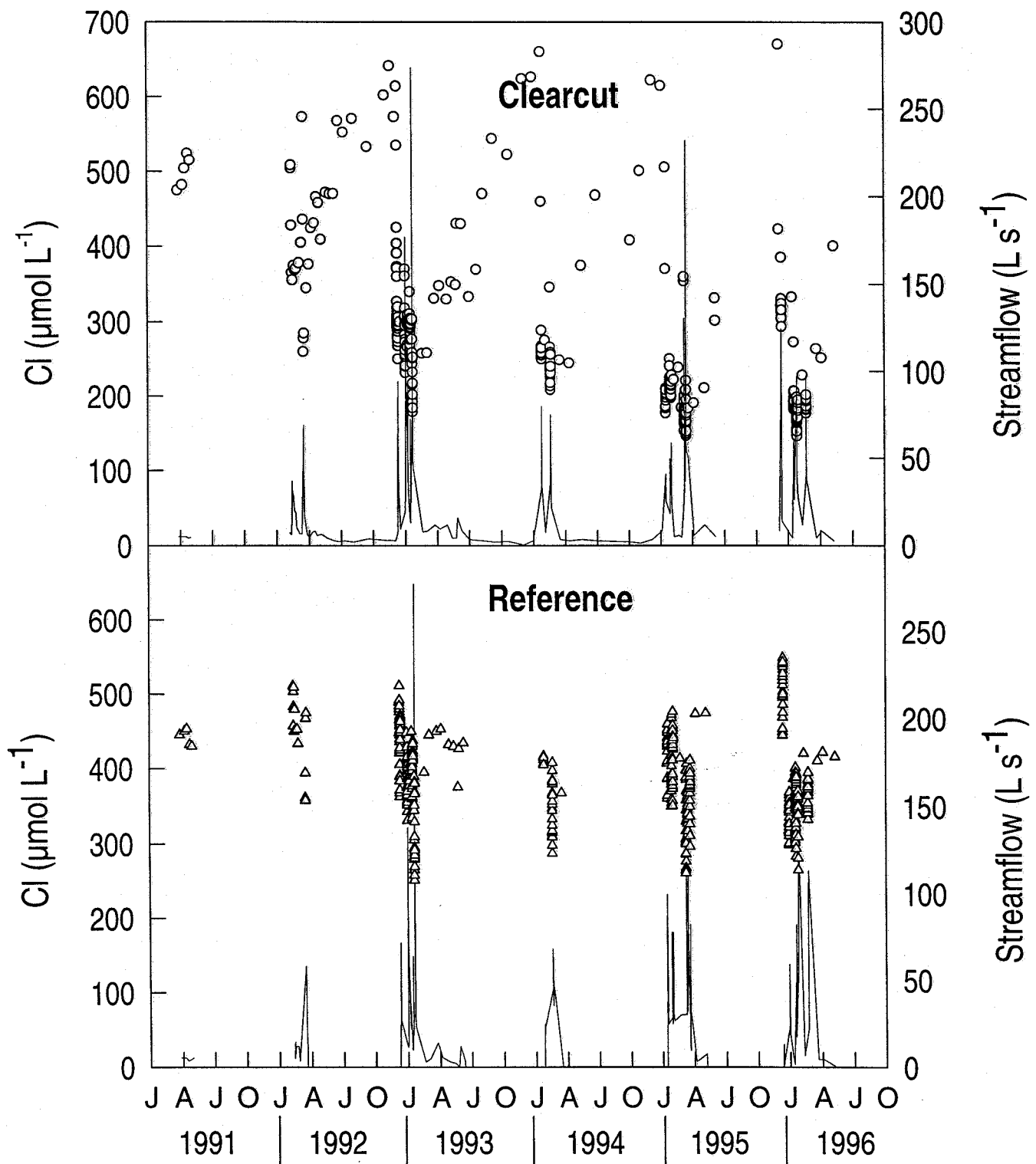


Fig. 16. Streamwater chloride concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

Bicarbonate. Bicarbonate is the major anion in the stream water and is also the dominant source of alkalinity. Concentrations of HCO₃ were very similar between the clearcut and reference watersheds as were the patterns of decreased HCO₃ concentrations in response to increased stream discharge during storm events (Fig. 17). The primary source of bicarbonate is from carbon dioxide released by root and microbial respiration within the soil profile. Thus, as waterflow through the soil profile increases, the HCO₃ concentrations are reduced due to dilution by the percolating waters. This mechanism may explain, in part, the large reduction in stream water HCO₃ concentrations during high discharge events. Changes in the hydrologic flowpath may also result in dilution of HCO₃ concentrations during storm events because water is quickly routed through the soil/bedrock. The primary source of HCO₃ is chemical weathering involving carbonic acid (e.g., H₂CO₃ + NaAlSi₃O₈ + 7H₂O = Na⁺ + 3H₄SiO₄ + Al(OH)_{3(s)} + HCO₃⁻). Rates of chemical weathering are controlled by kinetics factors rather than equilibrium. Thus, the shorter the residence time of water in the soil/bedrock continuum, the less time for chemical weathering and the lower HCO₃ concentrations.

Base cations (Ca, Mg, K, and Na). Concentrations of base cations in stream water responded similarly between the reference and clearcut watersheds (Figs. 18-21). There was no appreciable difference in base cation concentrations between the clearcut and reference watersheds. Similarly, both watersheds showed a similar dilution effect during high discharge events and maintained a similar range of base cation concentrations. There is a distinct increase in base cation concentrations following the end of the rainy season. This is well illustrated by the progressive increase in Ca and Mg concentrations in the clearcut watershed during the June to January period. This response is identical to that of HCO₃ and Cl concentrations since each unit of positive charge must be paired with one unit of negative charge (i.e., electroneutrality). It is the availability of mobile anions which dictates the concentrations of cations in solution (Johnson and Cole, 1980). Thus, since Cl and HCO₃ concentrations are not diluted by water inputs during the summer months, their higher concentrations result in increased concentrations of base cations in stream water.

The identical response between the clearcut and reference watersheds results from base cation buffering by the large pool of exchangeable cations. The pool of exchangeable cations is relatively high (Ca = 18, Mg = 5, K = 3 & Na = 1 Mg/ha; Fig. 4) and soil solutions obtain rapid equilibrium with the exchangeable cations. Thus, the distribution of cations is relatively fixed by equilibrium with the exchange complex while the concentrations of base cations in solution are dictated by the concentration of mobile anions.

Silicon. Silicon is a useful element to monitor in stream water since its concentrations are regulated by mineral equilibrium/kinetics with little influence from biological cycling. The range of Si concentrations is similar between the clearcut and reference watersheds indicating that similar mechanisms are responsible for regulating Si concentrations in both watersheds and that these mechanisms are not appreciably affected by clearcutting (Fig. 22). At baseflow, Si concentrations in both watersheds are within a narrow range of 250 to 300 μM. This level probably reflects equilibrium with silicate minerals. The large decrease observed during high discharge events reflects disequilibrium conditions where Si dissolution kinetics or mixing of waters from different hydrologic flowpaths regulate stream water Si concentrations. As discussed within the NO₃ section, we believe that the hydrologic flowpath is short-circuited through the upper soil horizons (above the argillic horizon) during storm events. This decreases the contact time between the soil solution and the soil minerals which prevents attainment of equilibrium conditions.

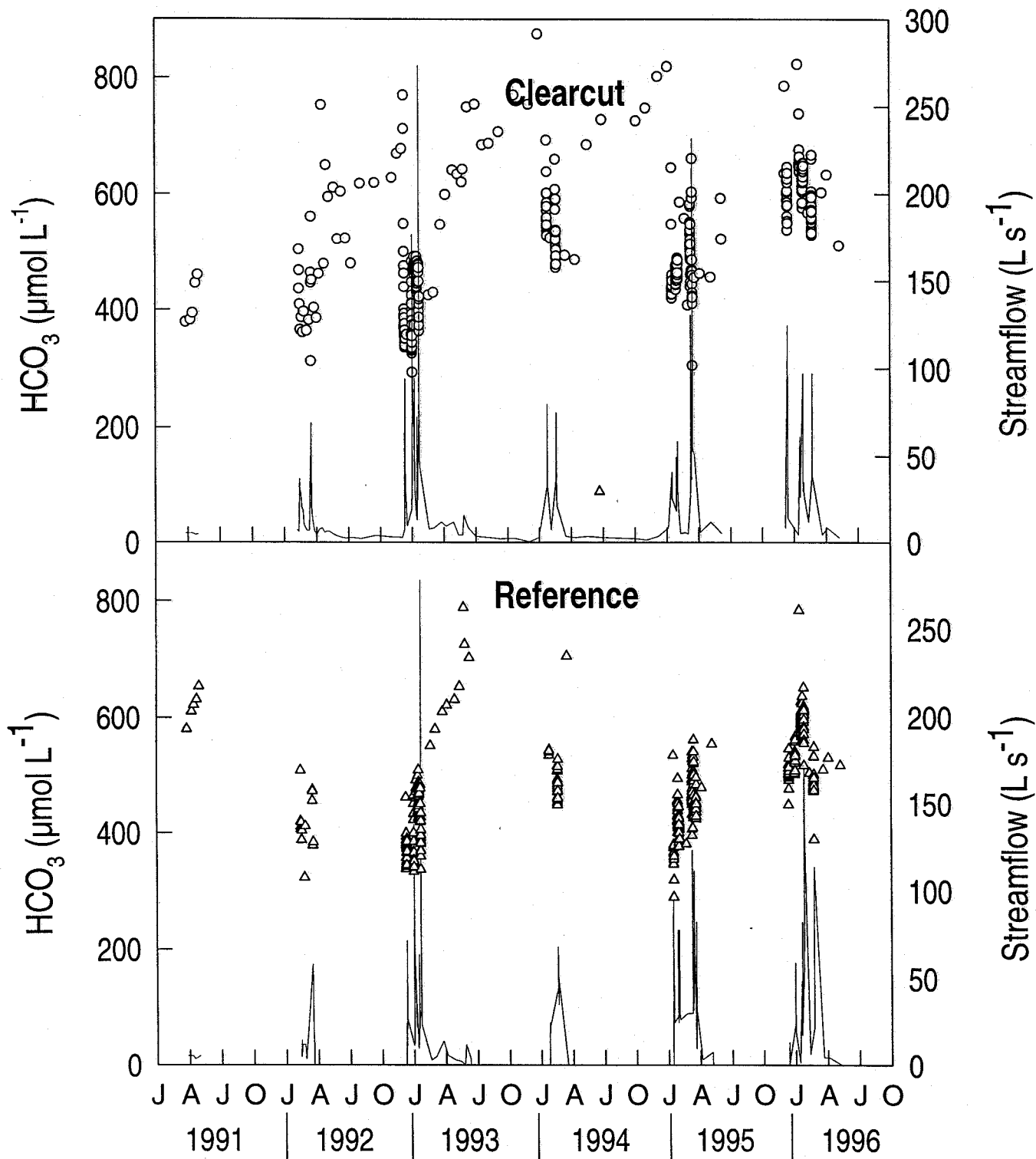


Fig. 17. Streamwater bicarbonate concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

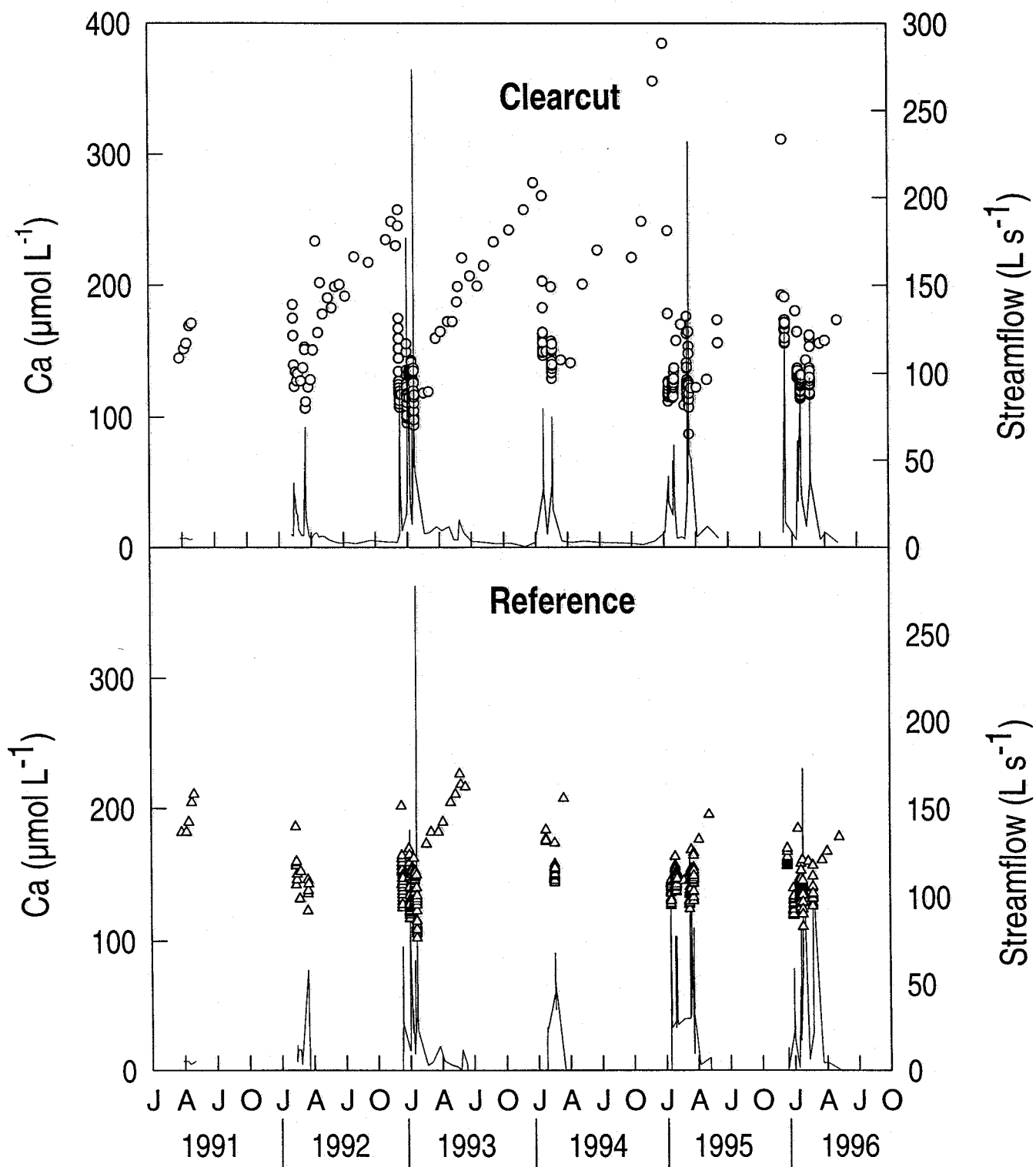


Fig. 18. Streamwater calcium concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

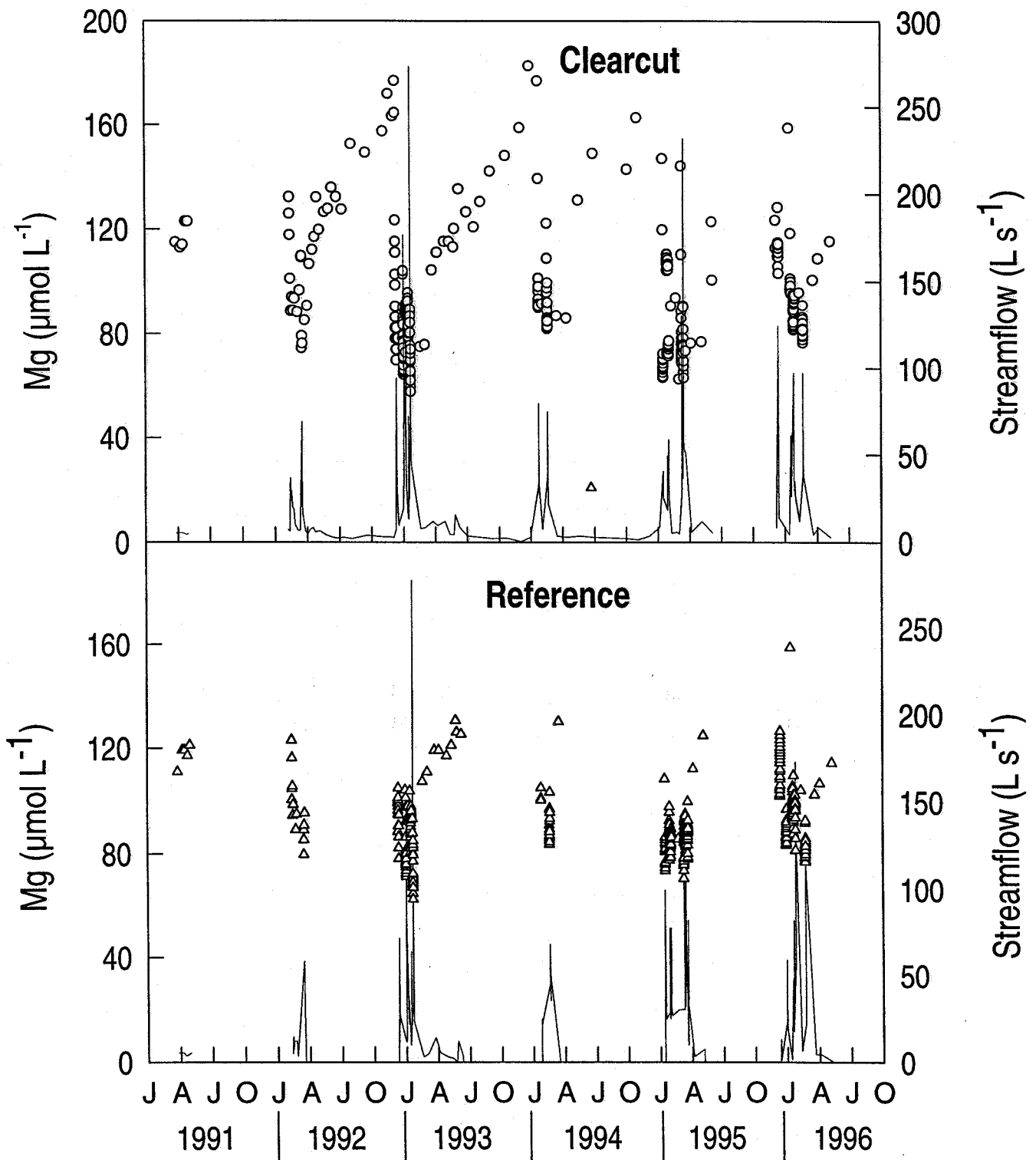


Fig. 19. Streamwater magnesium concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

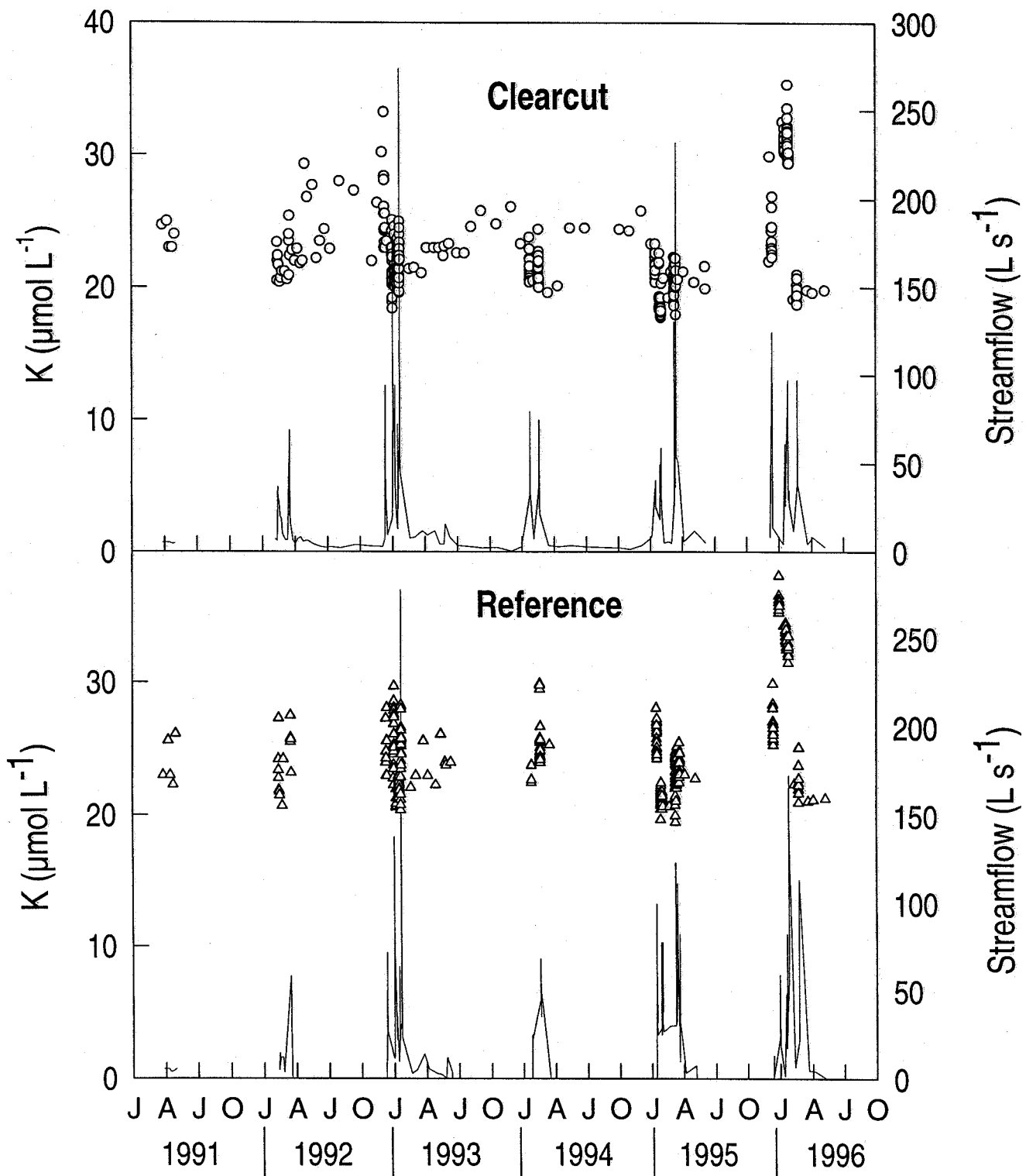


Fig. 20. Streamwater potassium concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

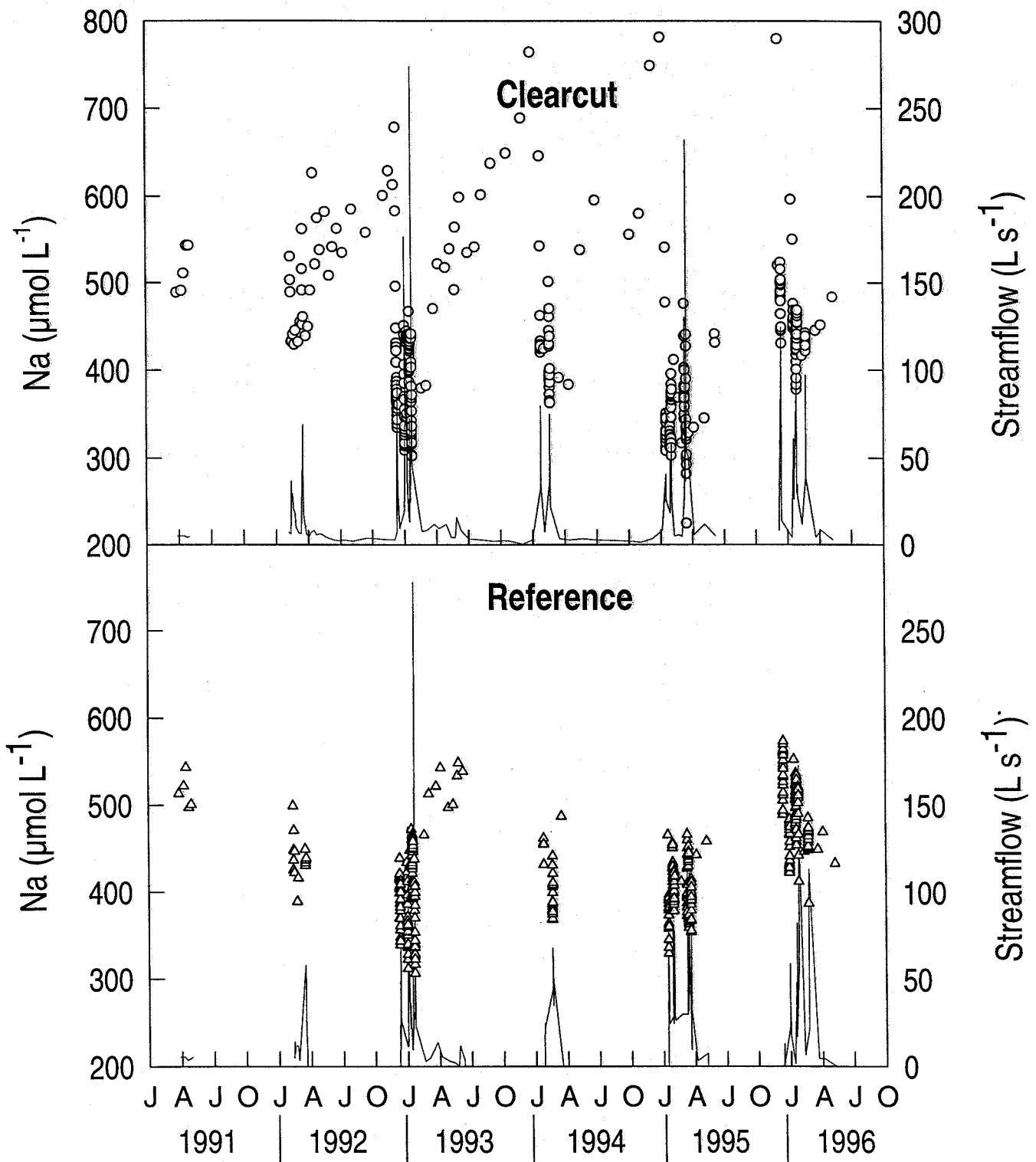


Fig. 21. Streamwater sodium concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

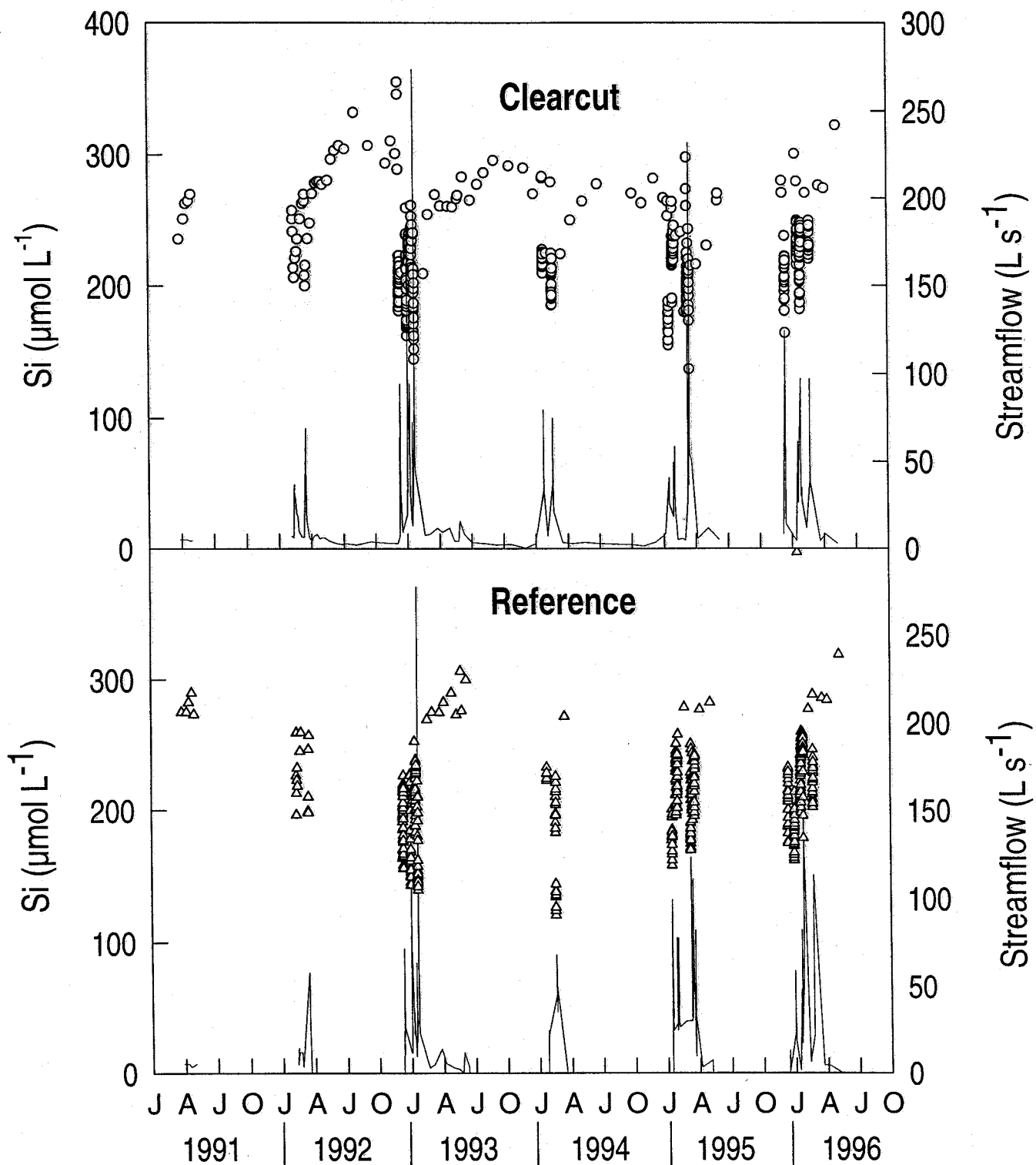


Fig. 22 Streamwater silicon concentrations (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

pH. Stream water pH values were generally consistent between the clearcut and reference watersheds and fell within the range 6.5 to 7.5 (Fig. 23). The pH values were highest during baseflow and decreased by up to one unit during peak streamflows. As with Si concentrations, the decrease in pH during high flow probably reflects incomplete neutralization due to decreased contact time with the soil. Thus, the shorter the residence time of water in the soil/bedrock continuum, the less time for chemical weathering and the lower the pH and concentrations of HCO_3 and Si. During storm events, a large fraction of water is probably routed laterally through the soil (above the argillic or through macropores) which prevents interaction with the lower soil horizons and bedrock. The pH of the soil solution moving through the upper soil horizons is regulated primarily by cation exchange reactions. In fact, the pH of stream water is generally within the range found for soil solution pH values in the upper soil horizons (Table 22) and the solid-phase soil pH (Table 2).

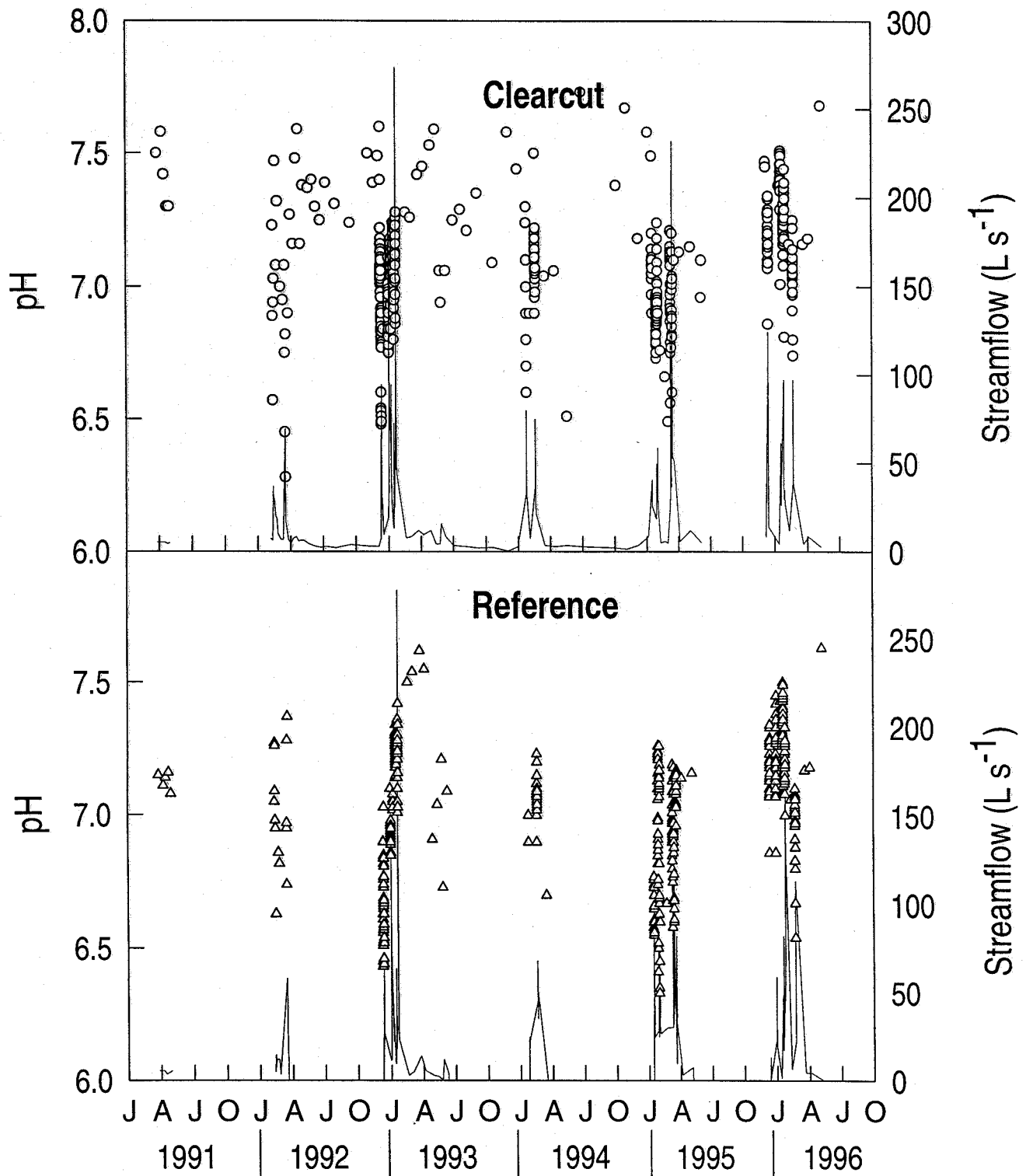


Fig. 23. Streamwater pH (symbols) and streamflow (lines) in the clearcut (KJE) and reference (MUN) watersheds of the North Fork, Caspar Creek. Felling was completed in the clearcut watershed in November 1989. Grab samples were collected biweekly during periods of baseflow while autosamplers were used to collect samples during storm events.

Relationship between Solute Concentrations and Stream Discharge

The preceding discussion indicated that solute concentrations over the five-year monitoring period were strongly affected by stream discharge during a given storm event. Most solute concentrations showed a dilution with increasing discharge, except for NO_3 which increased with increasing discharge. The relationship between solute concentrations as a function of discharge was not as clearly indicated when all the data from the five year study were combined (Figs. 24-33). Some solutes, such as Ca, Mg, Na, Cl, SO_4 and Si, showed a trend of decreasing concentrations with increasing streamflow rates; however, there was appreciable scatter, especially in the 50 to 100 L/s flow range. In contrast, pH, K, HCO_3 and NO_3 concentrations showed little trend with stream discharge rates. We believe that much of the scatter that occurs in the midflow range is due to seasonal changes in biogeochemical processes, such as the fall flushing of solutes that have accumulated over the summer period with no active leaching or periods of especially active plant uptake during the spring.

Relationship of Pipeflow Water Chemistry to Stream Water Chemistry

Pipeflow collected by the Caspar Creek Research Team appears to originate from subsurface macropore flow from the adjacent uplands. There were distinct differences between the solute concentrations of pipeflow and streamflow for several solutes suggesting that the source of the two waterflows was different. Water originating from different hydrologic flowpaths was previously suggested as an explanation for increased NO_3 concentrations in stream water during high flow, storm events.

Among the base cations (Ca, Mg, K and Na), Ca concentrations showed a general trend of being lower in pipeflow than in stream water collected at the same time (Fig. 34). In contrast, K concentrations showed a general trend of being higher in pipeflow than in stream water (Fig. 35). Concentrations of Mg and Na were generally similar between pipeflow and stream water during storm events; however, pipeflow concentrations were greater during baseflow (Fig. 36 & 37). Sodium concentrations behaved differently between the clearcut and reference watersheds as Na concentrations were higher in the pipeflow in the reference watershed but similar to stream water in the clearcut watershed. The contrasting behavior of these base cations could provide a valuable clue concerning the dynamics of hydrologic flowpaths during storm events. Additional information concerning base cation concentrations in potential end-member water sources would facilitate the use of these data in end-member mixing models. For example, water originating from deeper groundwater that is in contact with relatively unweathered bedrock may contain elevated Ca concentrations due to the dissolution of calcium carbonate from the marine bedrock. Thus, water originating from deeper groundwater sources may be Ca-enriched explaining, in part, why Ca concentrations are greater in stream water at base flow. In contrast, K is strongly cycled by the vegetation resulting in the highest K concentrations in the upper soil horizons (Fig. 10; Table 2). If pipeflow were to originate from preferential flowpaths above the clay-rich argillic horizon, the solutions would be expected to have elevated K concentrations relative to solutions originating from deeper groundwater sources.

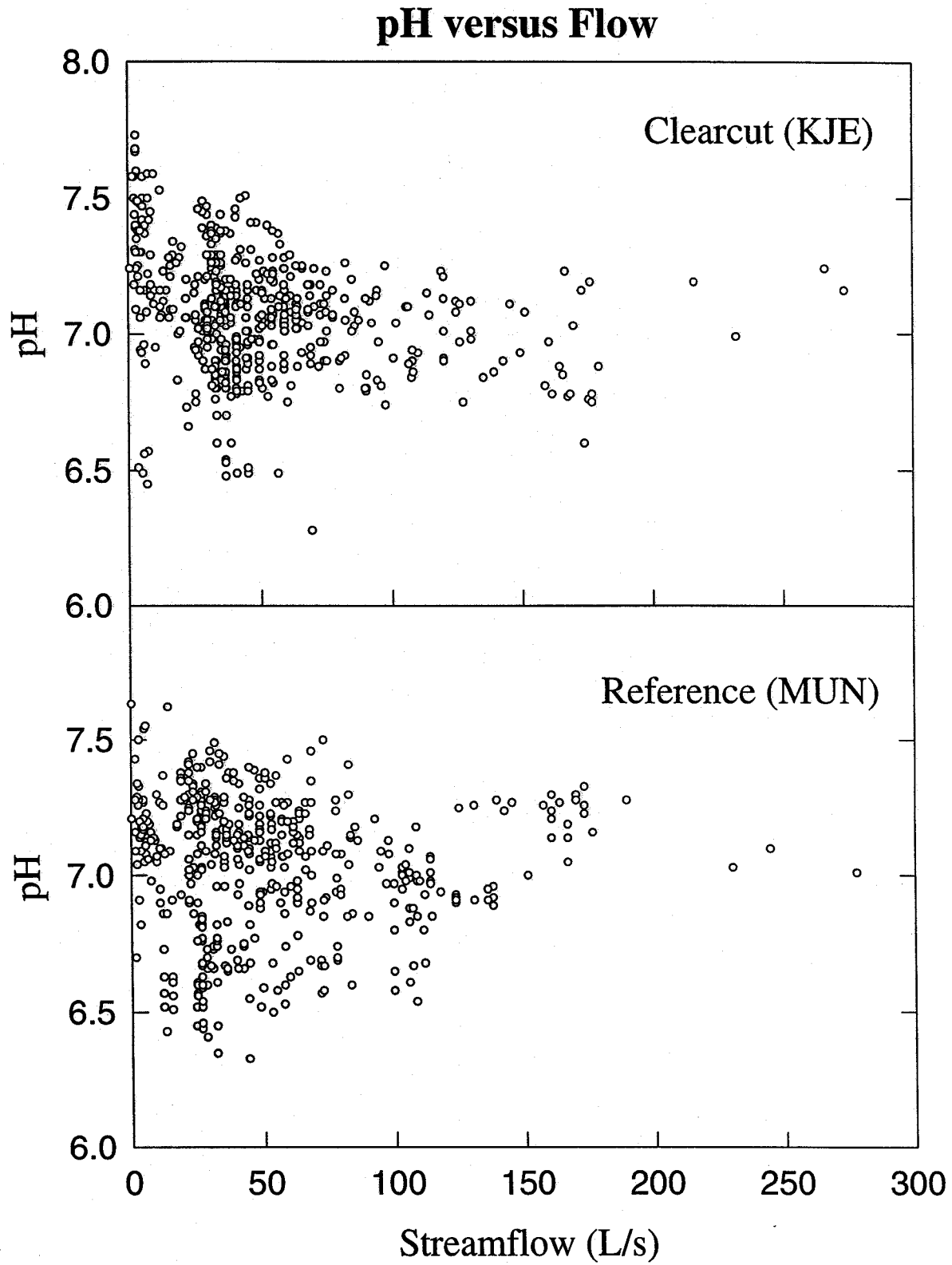


Fig. 24. Relationship between stream water pH and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

Calcium versus Flow

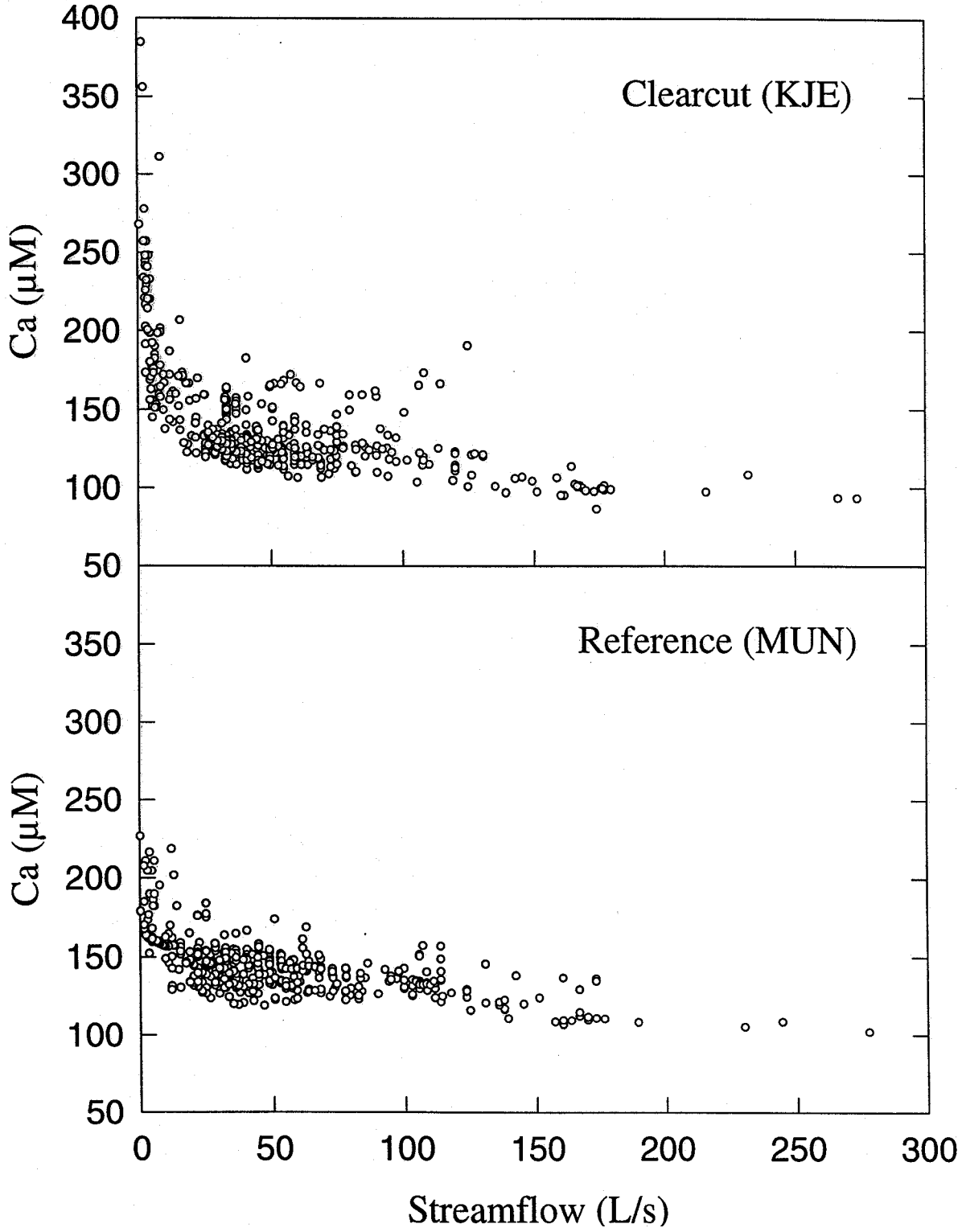


Fig. 25. Relationship between stream water calcium concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

Magnesium versus Flow

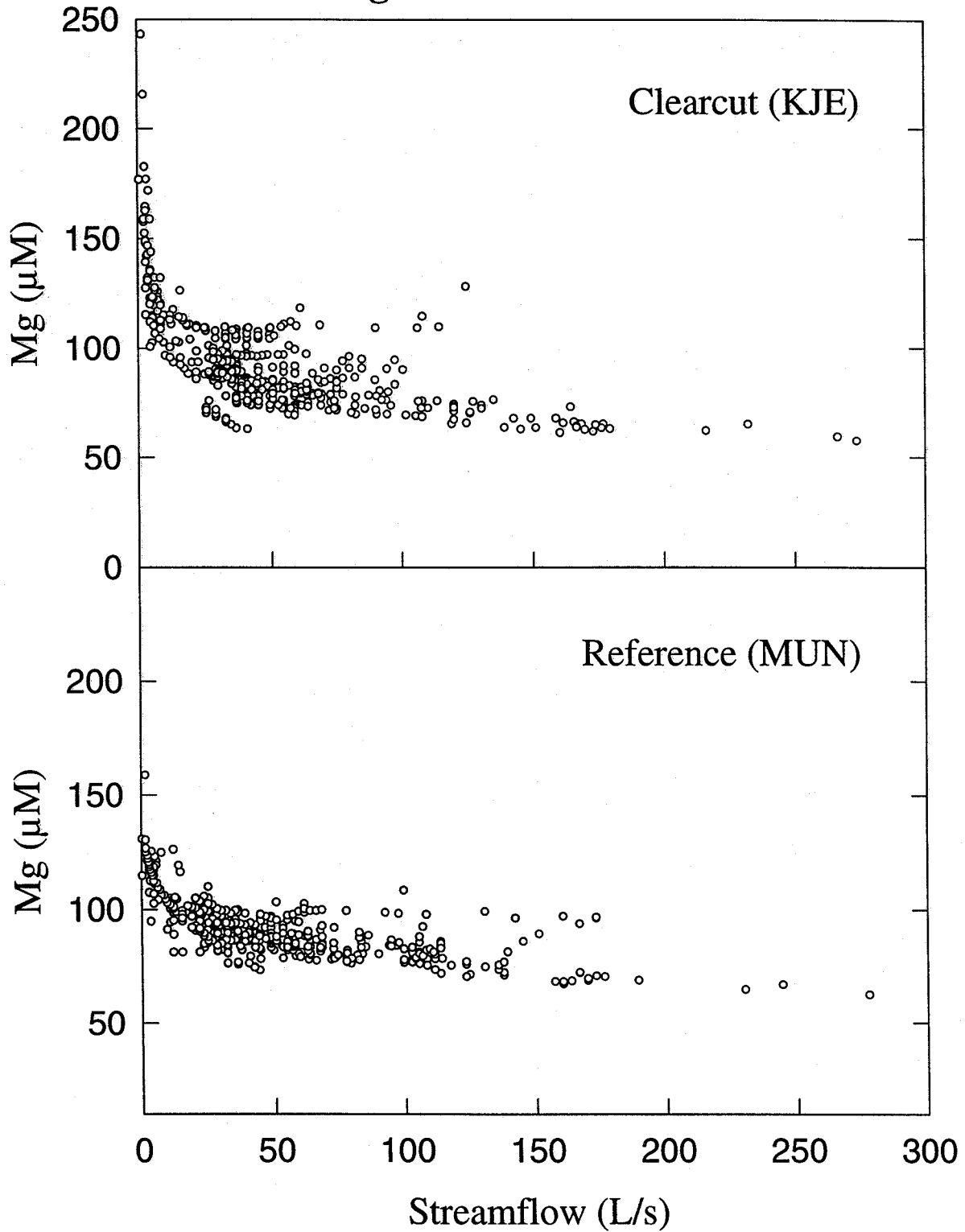


Fig. 26. Relationship between stream water magnesium concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

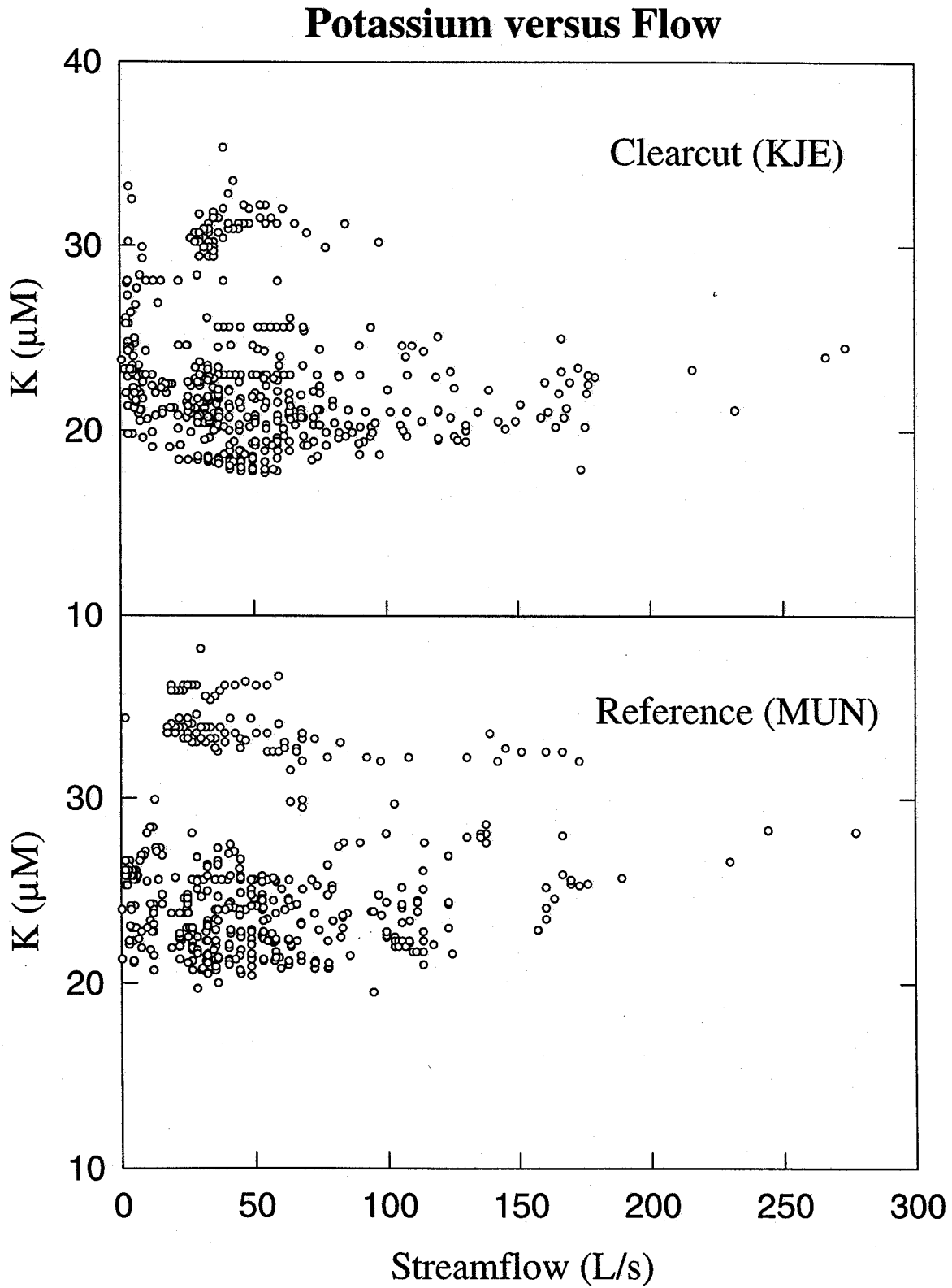


Fig. 27. Relationship between stream water potassium concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

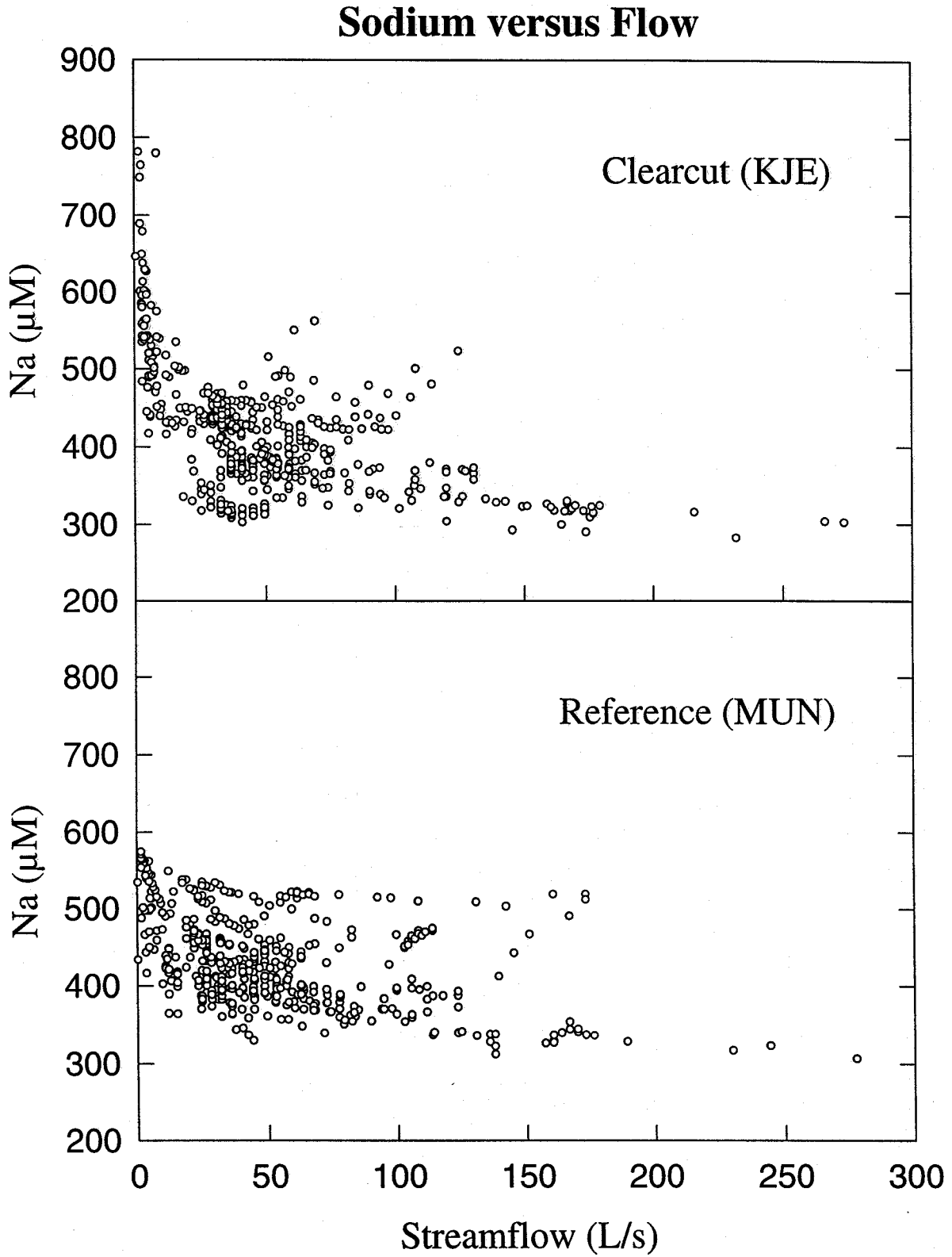


Fig. 28. Relationship between stream water sodium concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

Chloride versus Flow

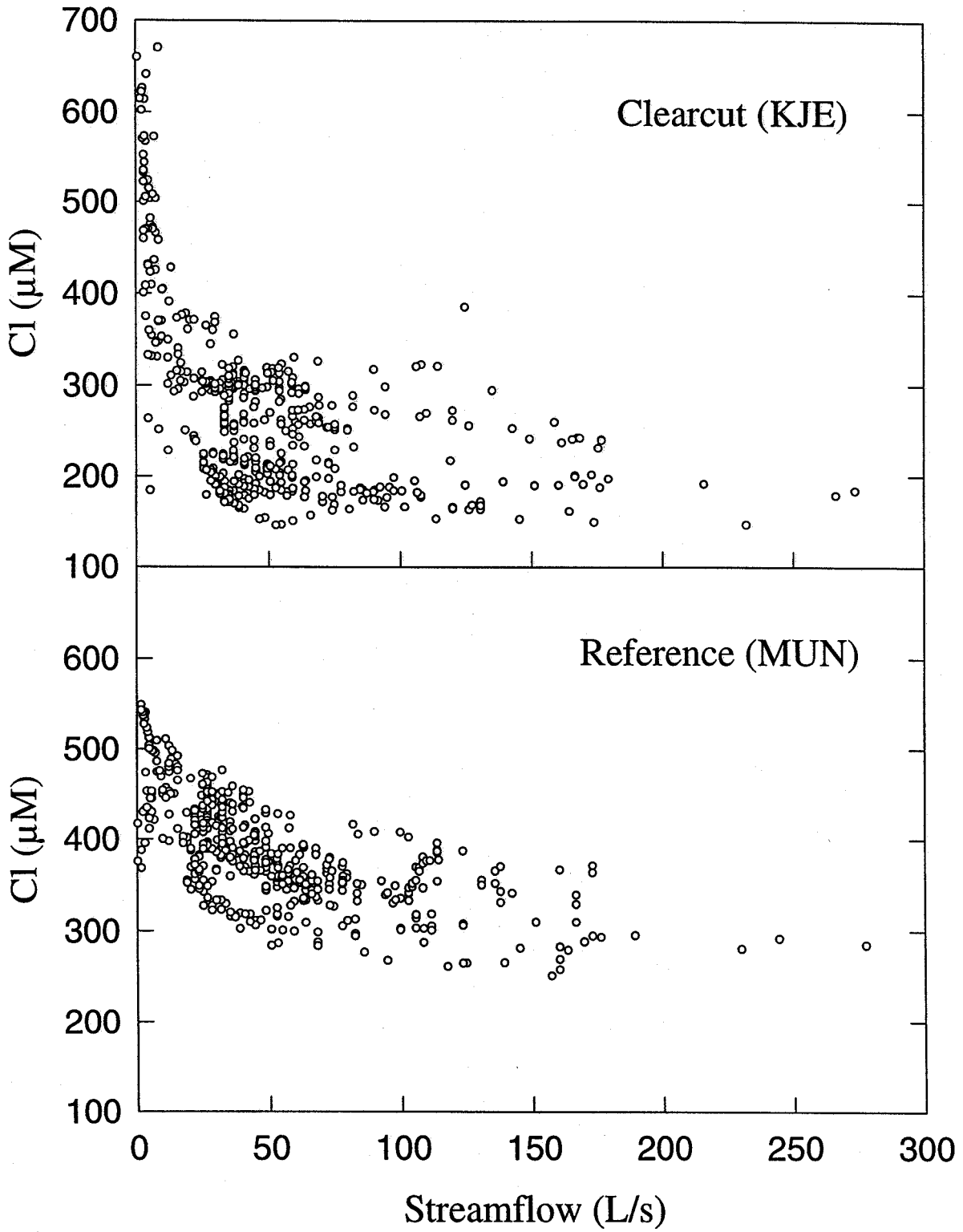


Fig. 29. Relationship between stream water chloride concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

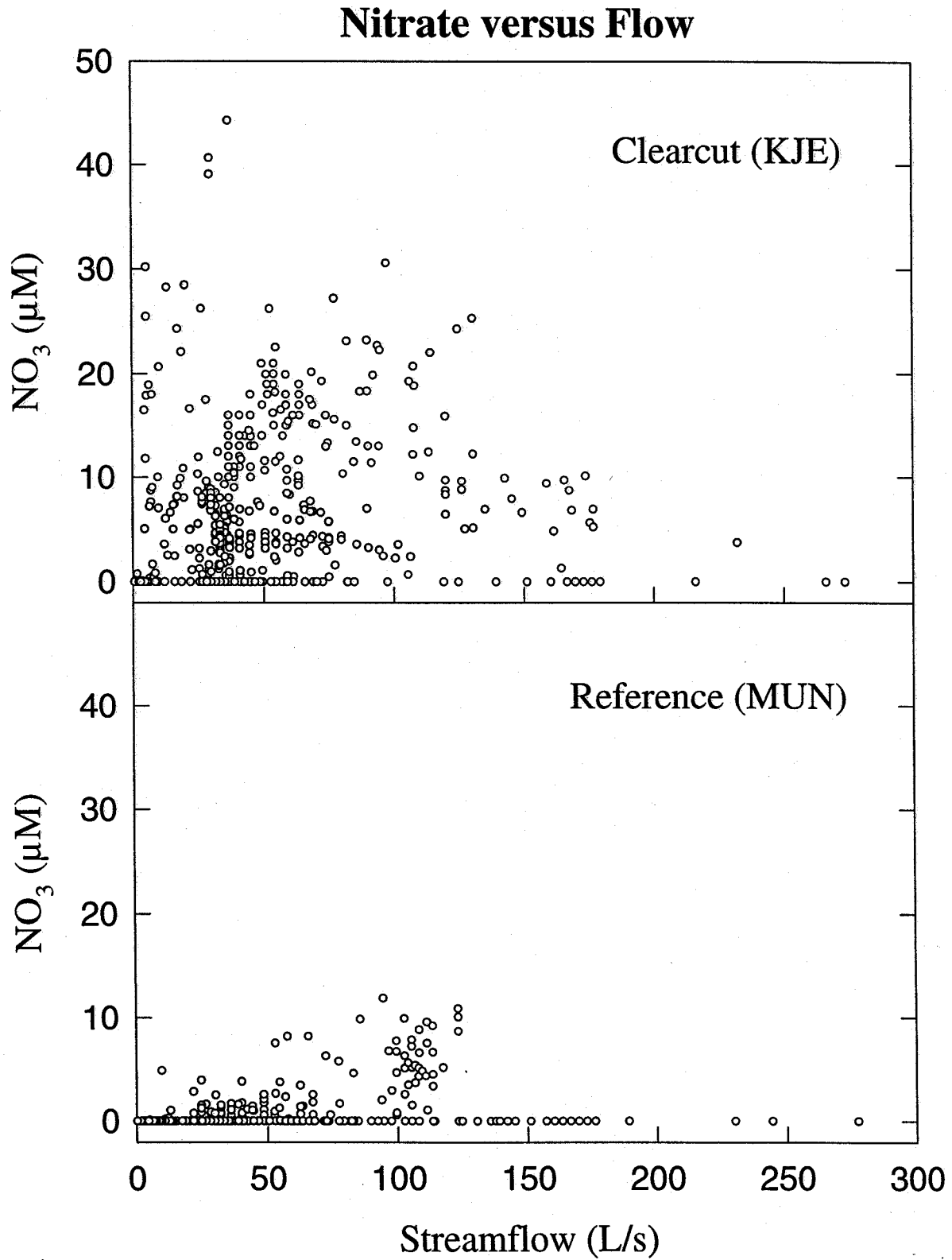


Fig. 30. Relationship between stream water nitrate concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

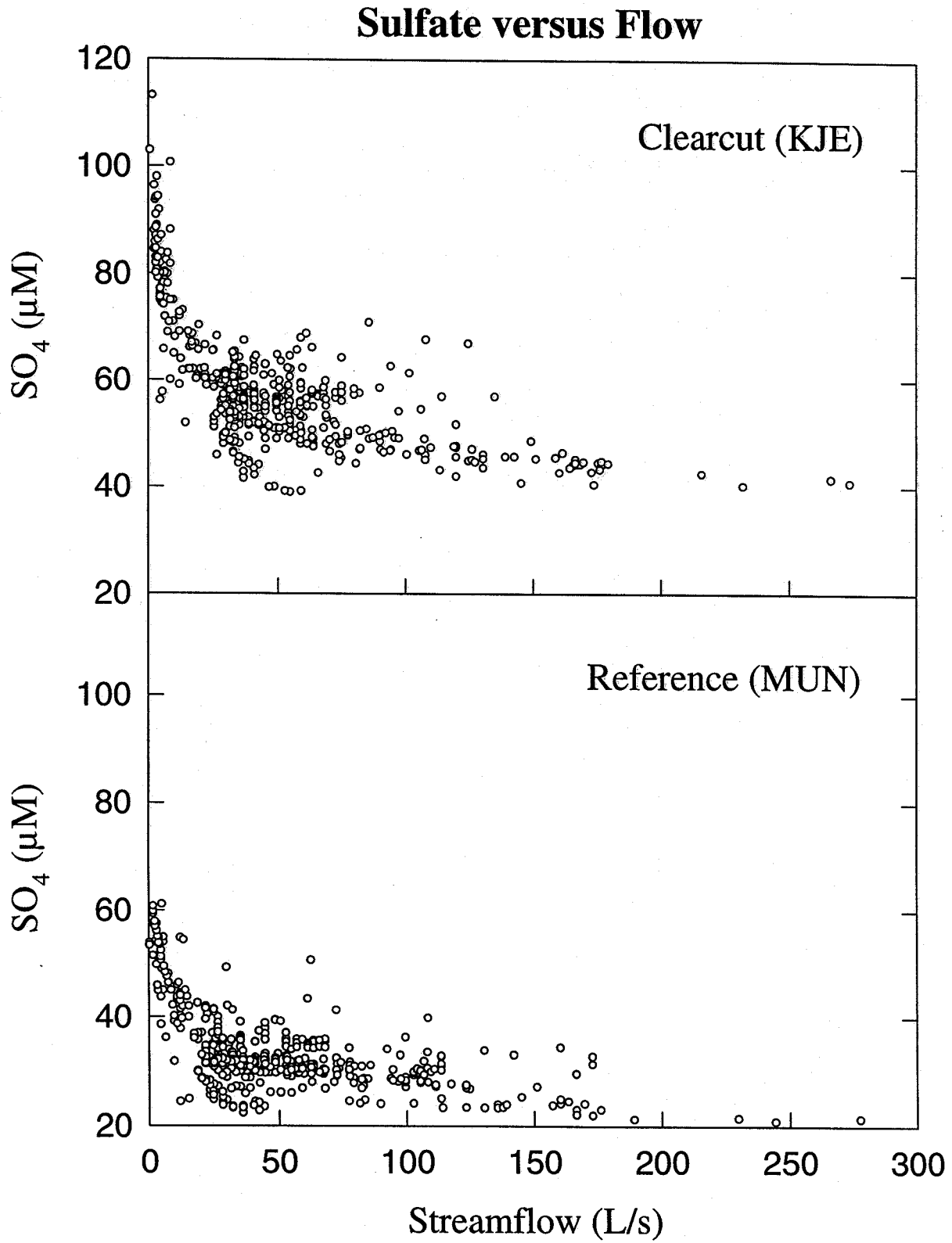


Fig. 31. Relationship between stream water sulfate concentrations and stream discharge for the reference (MW and clearcut (KJE) watersheds during the five year study period.

Bicarbonate versus Flow

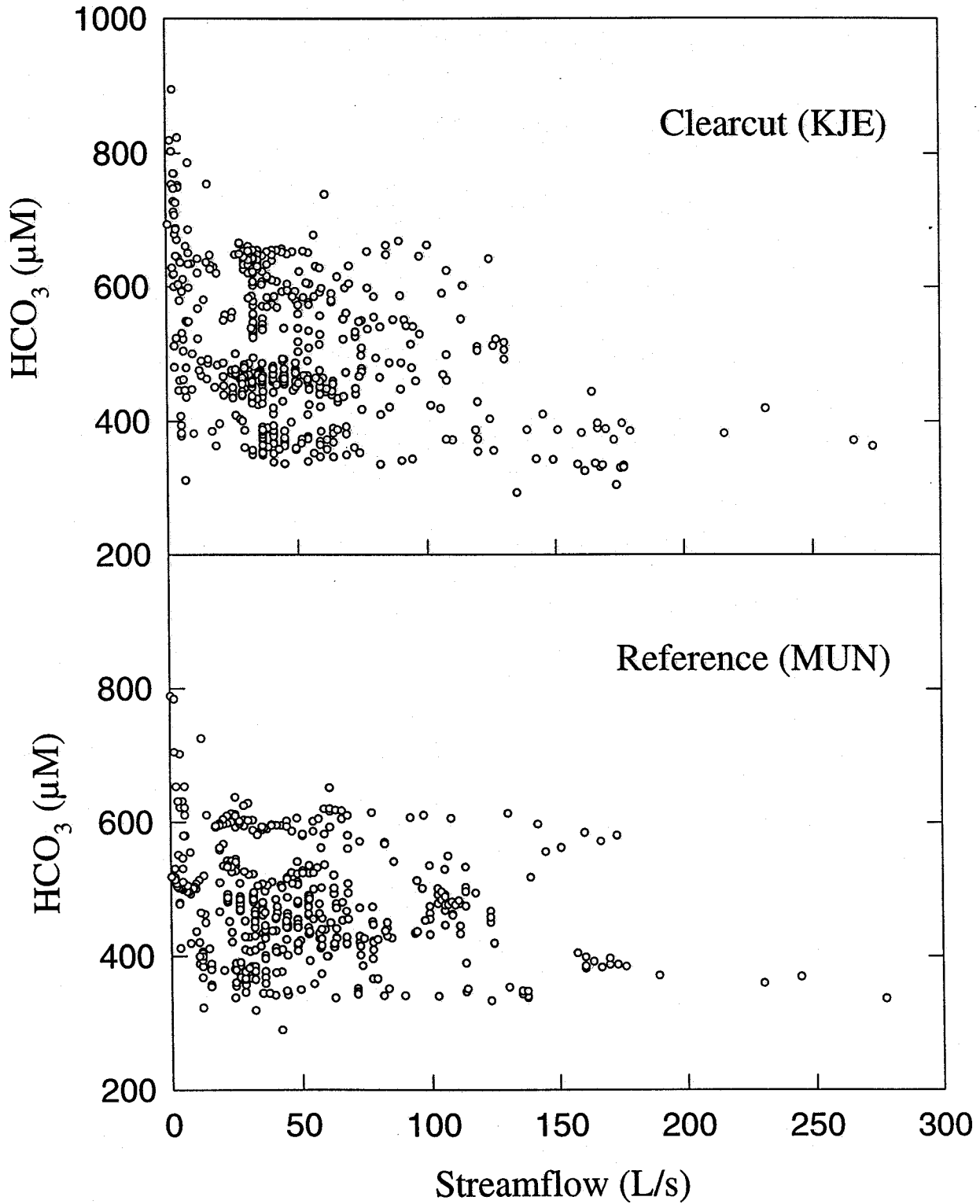


Fig. 32. Relationship between stream water bicarbonate concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

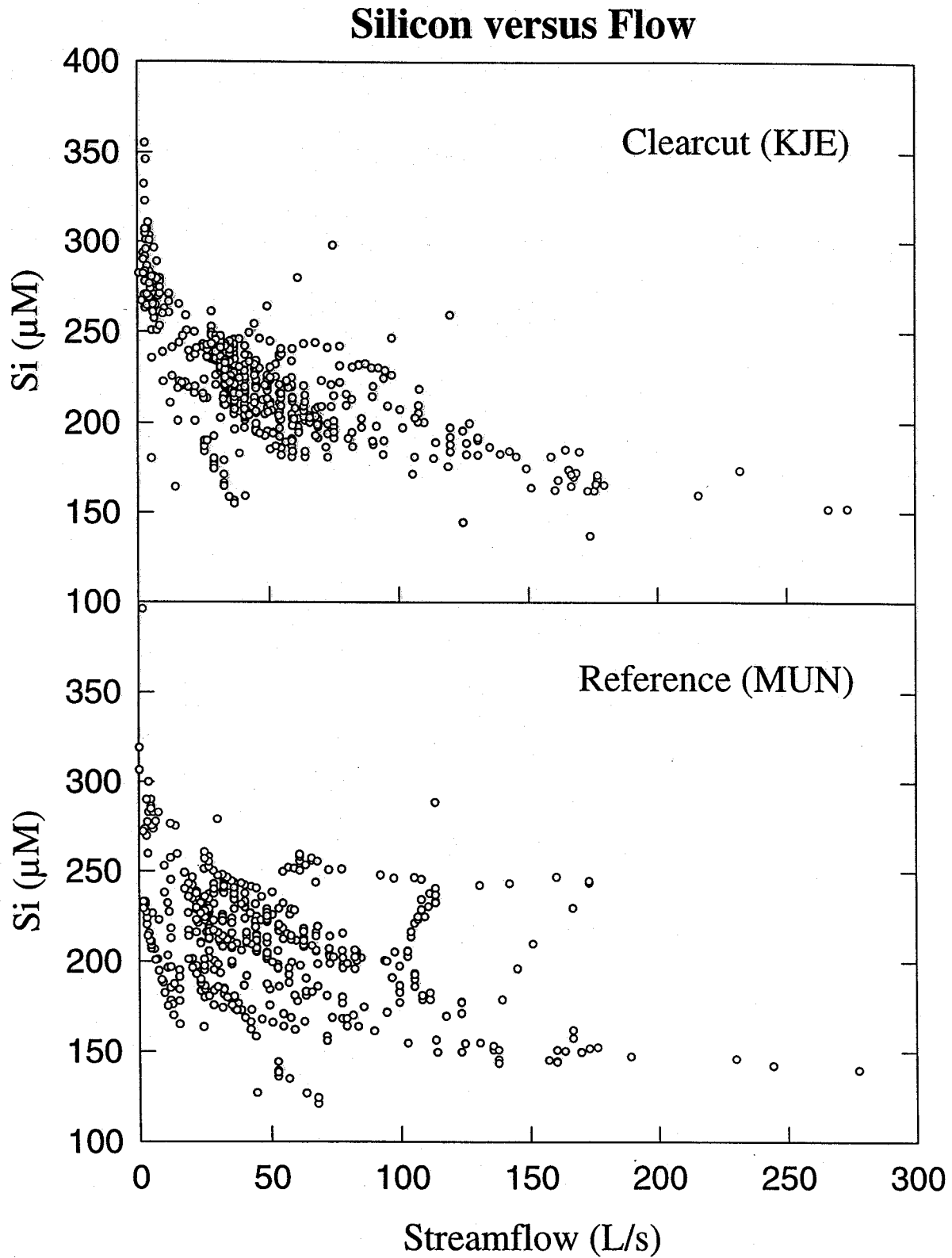


Fig. 33. Relationship between stream water silicon concentrations and stream discharge for the reference (MUN) and clearcut (KJE) watersheds during the five year study period.

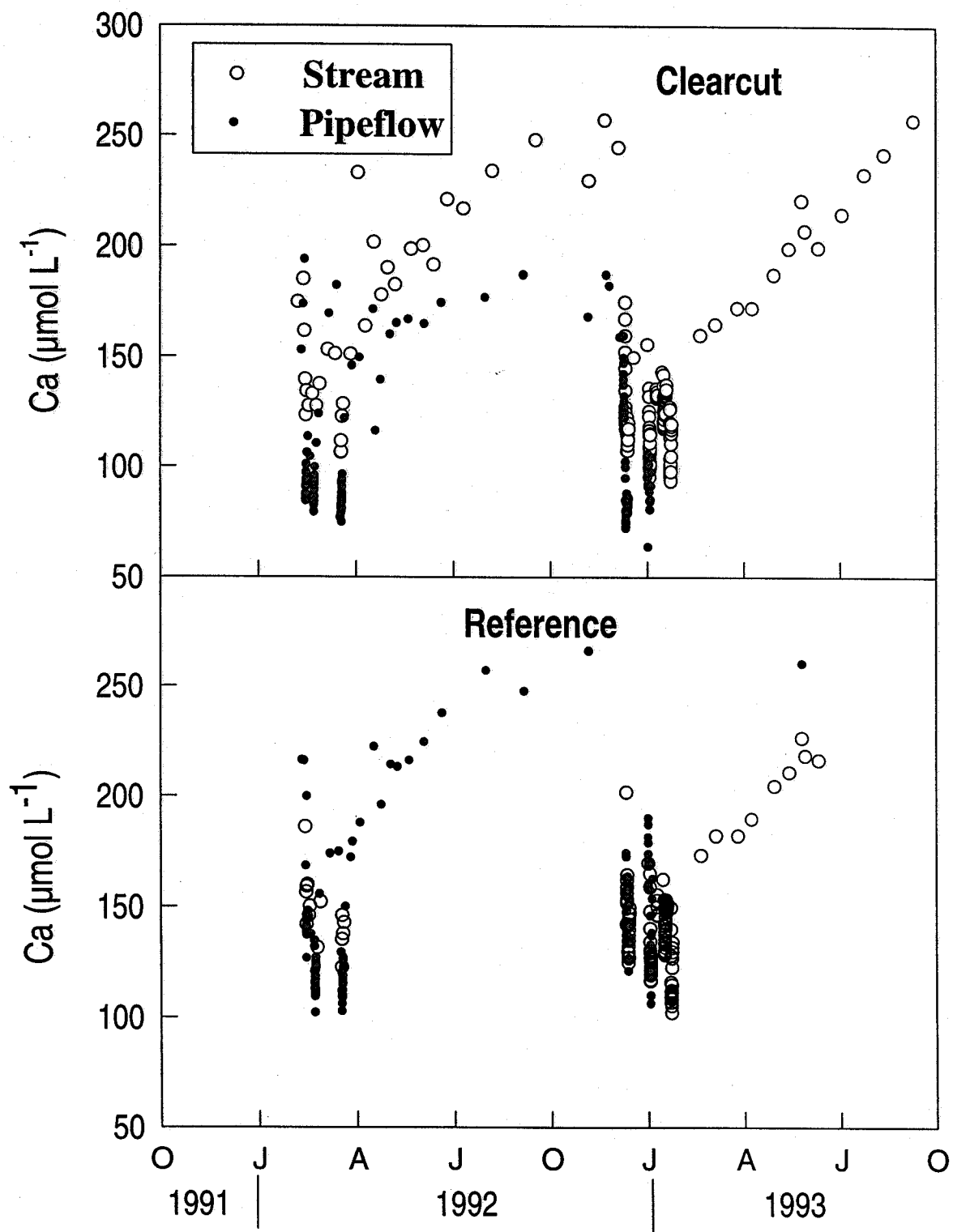


Fig. 34. Comparison of stream water and pipeflow calcium concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

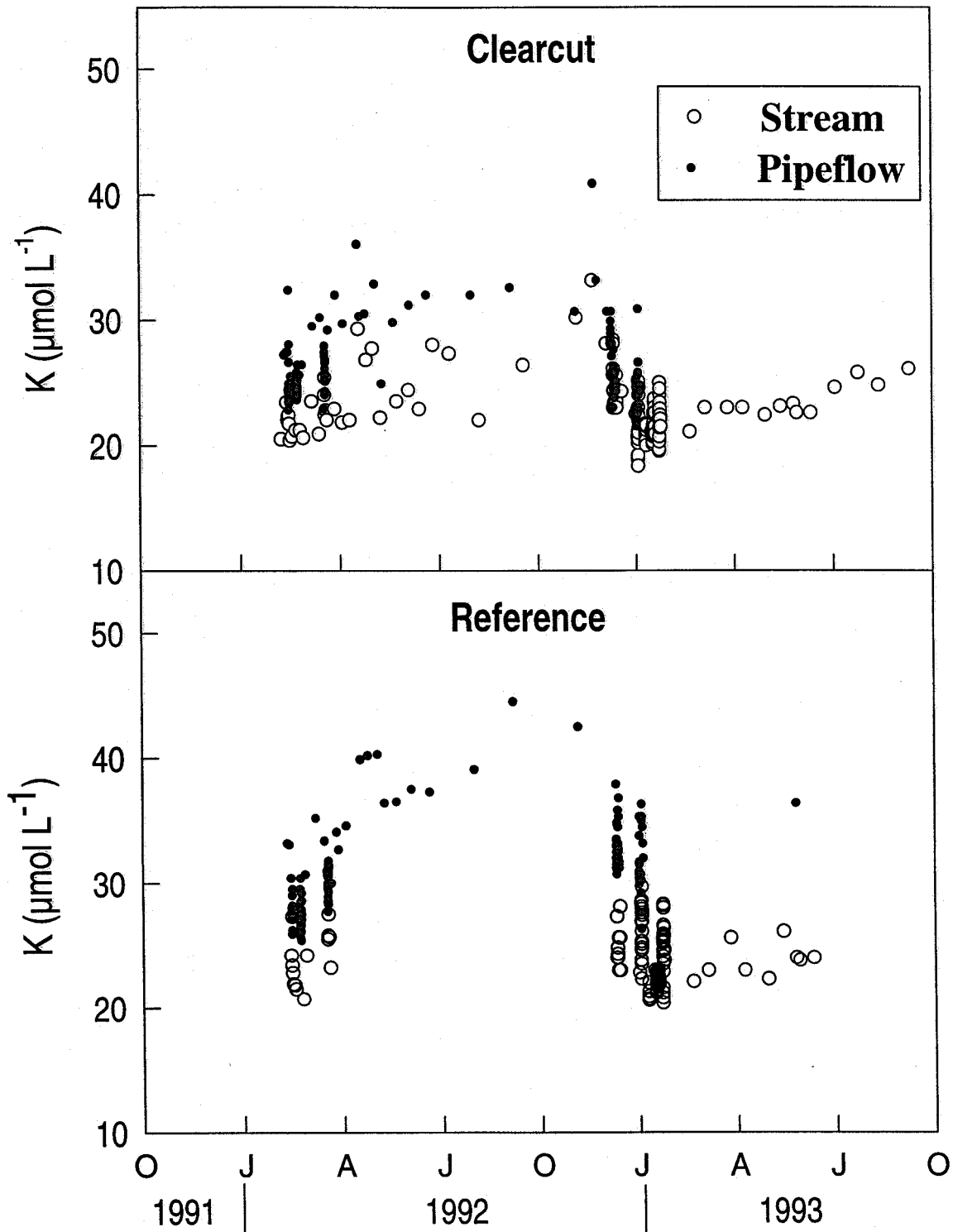


Fig. 35. Comparison of stream water and pipeflow potassium concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

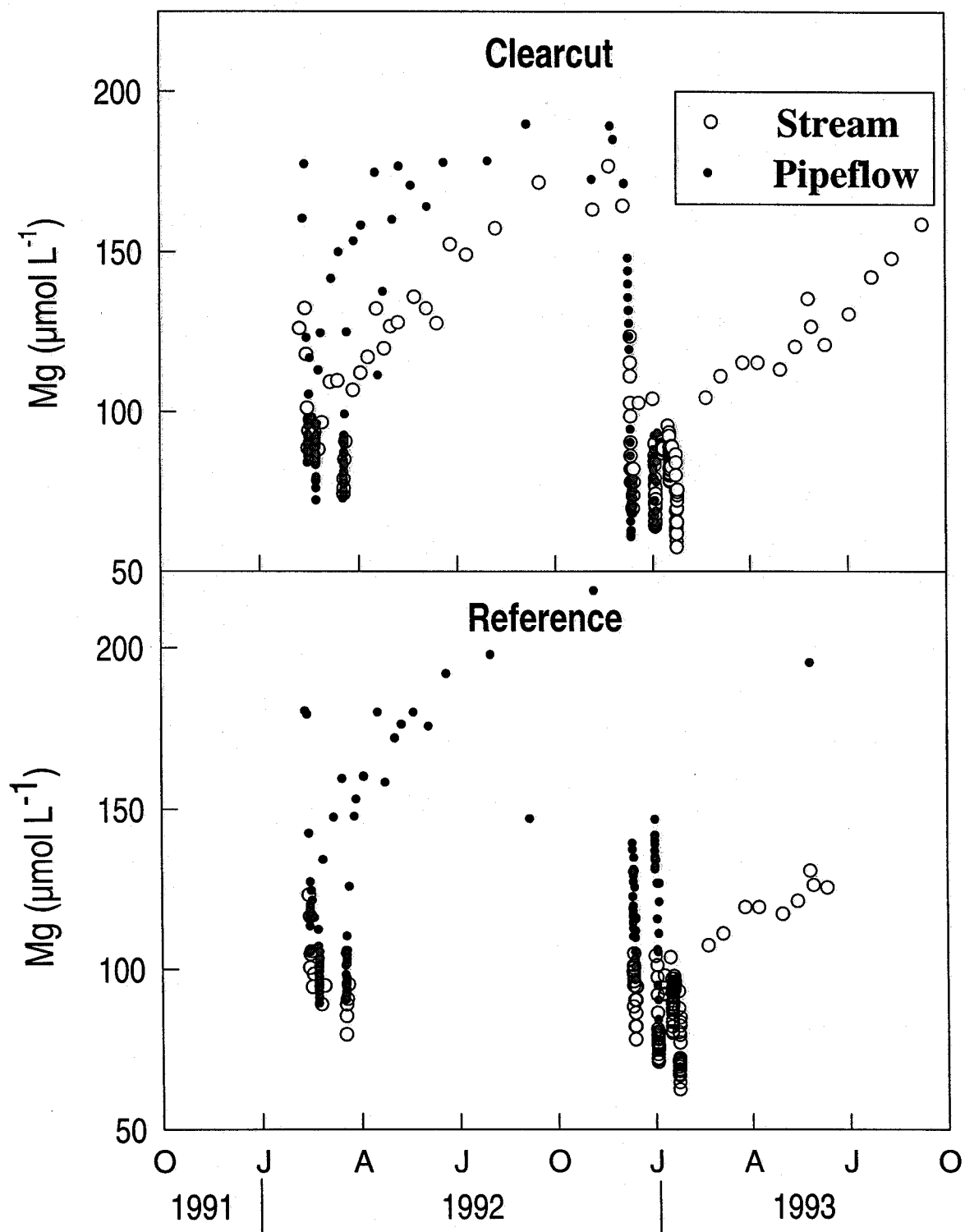


Fig. 36. Comparison of stream water and pipeflow magnesium concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

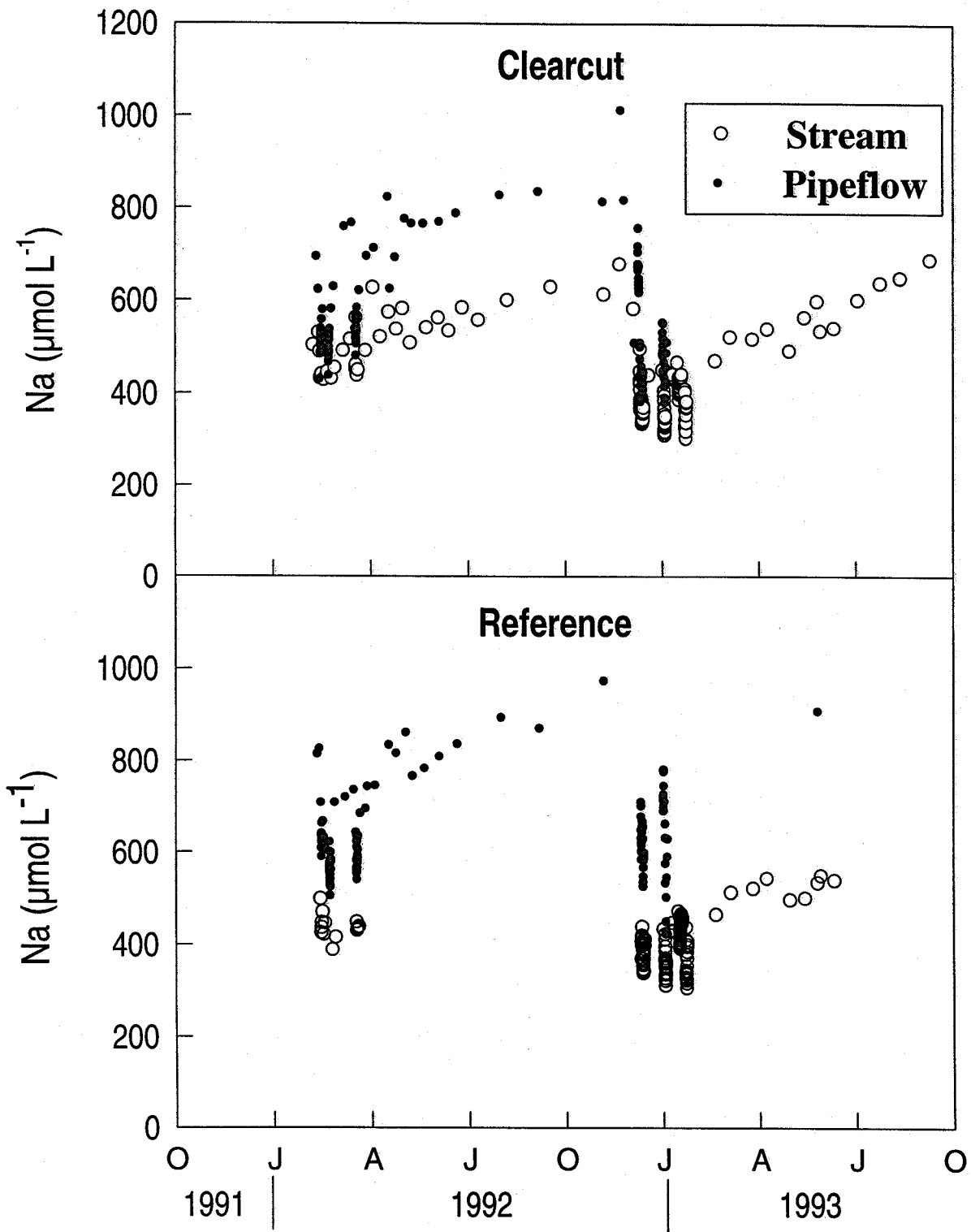


Fig. 37. Comparison of stream water and pipeflow sodium concentrations for the reference(MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

Chloride concentrations in pipeflow and stream water in the clearcut watershed (KJE) were similar during storm events, but were nearly a factor of two greater in pipeflow during baseflow (Fig. 38). In contrast, chloride concentrations were always greater in the pipeflow than in stream waters within the reference watershed. Concentrations of SO_4 were similar for pipeflow and stream waters in both watersheds (Fig. 39). Perhaps the most informative difference between pipeflow and stream water chemistry occurs for NO_3 . Concentrations of NO_3 in pipeflow generally exceeded those in stream water within the clearcut watershed (Fig. 40). In contrast, there was virtually no NO_3 in pipeflow, stream water, or soil solutions in the reference watershed. This behavior indicates that pipeflow originates from a nitrate-rich water source that is strongly affected by clearcutting. The fact that NO_3 in pipeflow is found only in the clearcut suggests that the pipeflow originates largely from the biologically active soil zone. Our data suggests that a primary source of the pipeflow water is from the upper soil horizons (above the argillic horizon) which is the only water source that contains appreciable concentrations of NO_3 (Fig. 11).

Concentrations of Si in pipeflow and stream water were similar during most storm event; however, Si concentrations were greater in pipeflow during baseflow (Fig. 41). This behavior during baseflow suggests that the pipeflow water originates from a more Si-rich environment since kinetic limitations would not be a primary factor controlling Si concentrations during baseflow conditions. Again it would be necessary to know whether the soil zone or the geologic material supports a greater Si solubility. The Si concentrations collected in our soil solution study were very dilute ($<100 \mu\text{M}$) due to the fact that these solutions consist of gravitational water collected only during storm events when the soil water potential exceeds field capacity. Thus, the soil solutions are in disequilibrium and not necessarily representative of the pipeflow chemistry originating from the soil zone.

The pH of pipeflow and stream waters was generally similar; however, the pipeflow from the reference watershed during the early portion of 1992 showed lower pH values during two storm events (Fig. 42). Again, we suggest that this pH depression is due to lower pH waters originating from the upper soil horizons where organic acids decrease soil pH (Oi/Oa horizon solid-phase pH = 5.5; Table 2).

We feel that the differences between pipeflow and stream water chemistry provide great promise for elucidating and quantifying the various end-member water sources and the changing hydrologic flowpaths that occur during storm events. Because there are distinct differences in the behavior of different solutes during baseflow and storm events, the data provide a powerful tool for determining various end-member water sources.

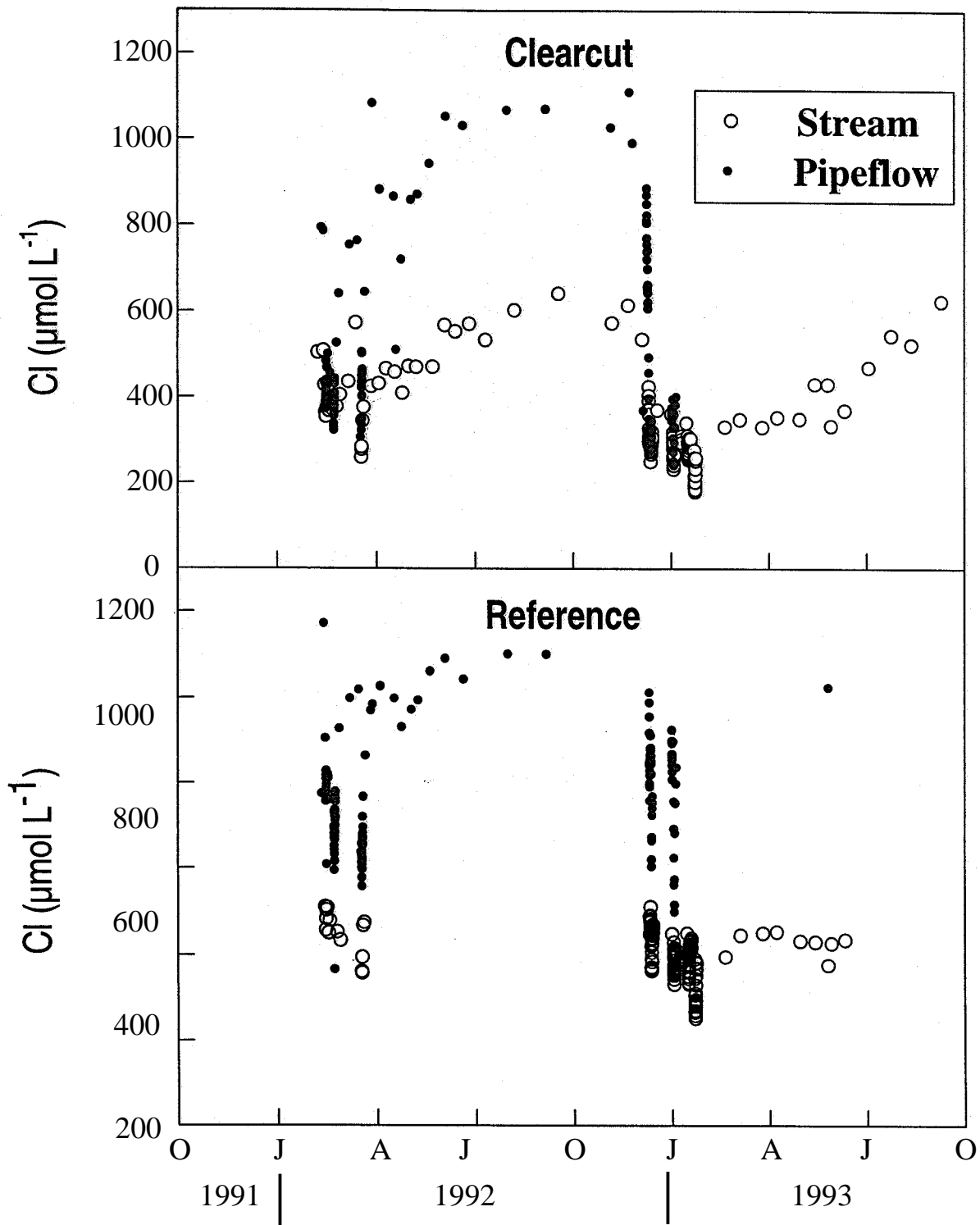


Fig. 38. Comparison of stream water and pipeflow chloride concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

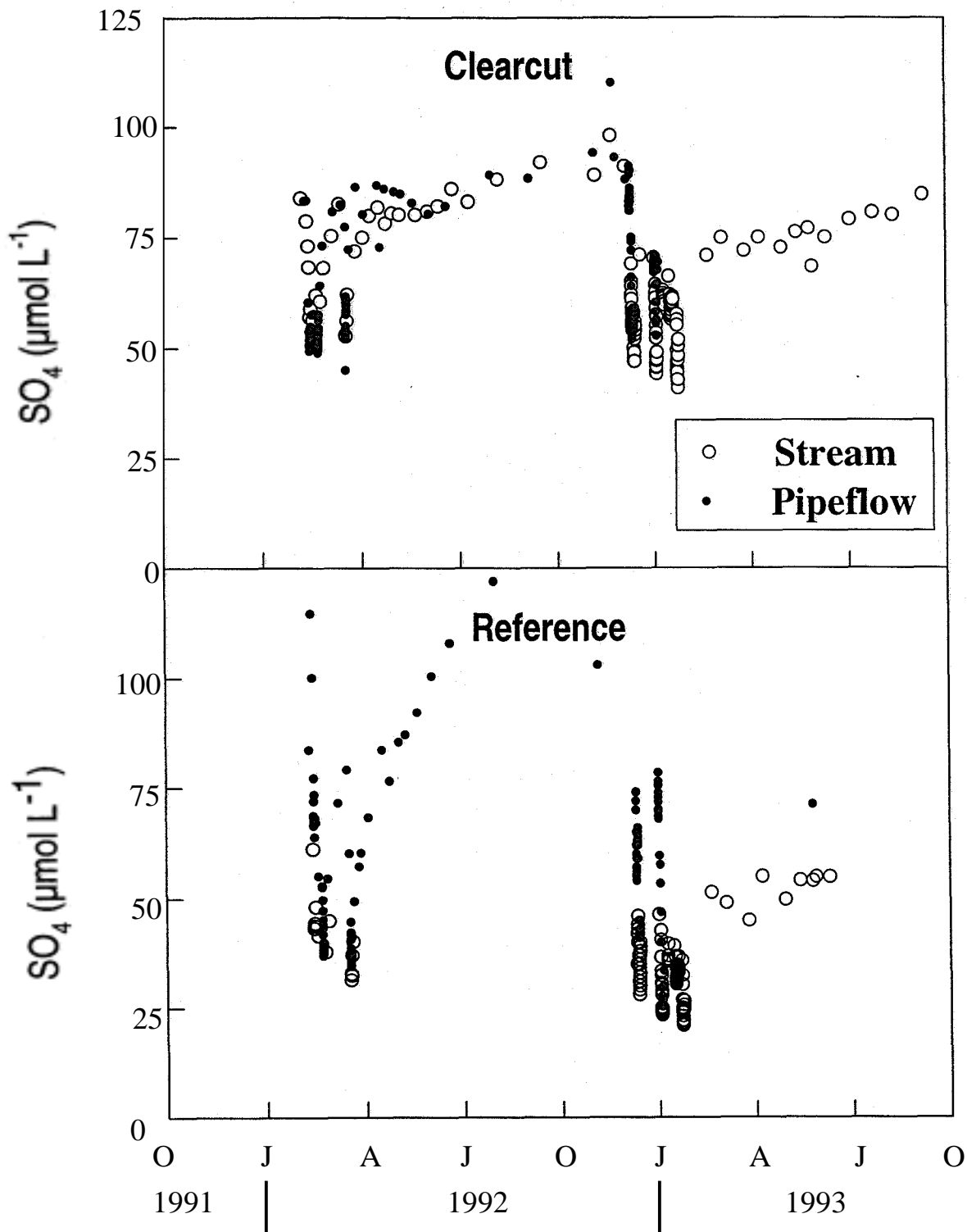


Fig. 39. Comparison of stream water and pipeflow sulfate concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

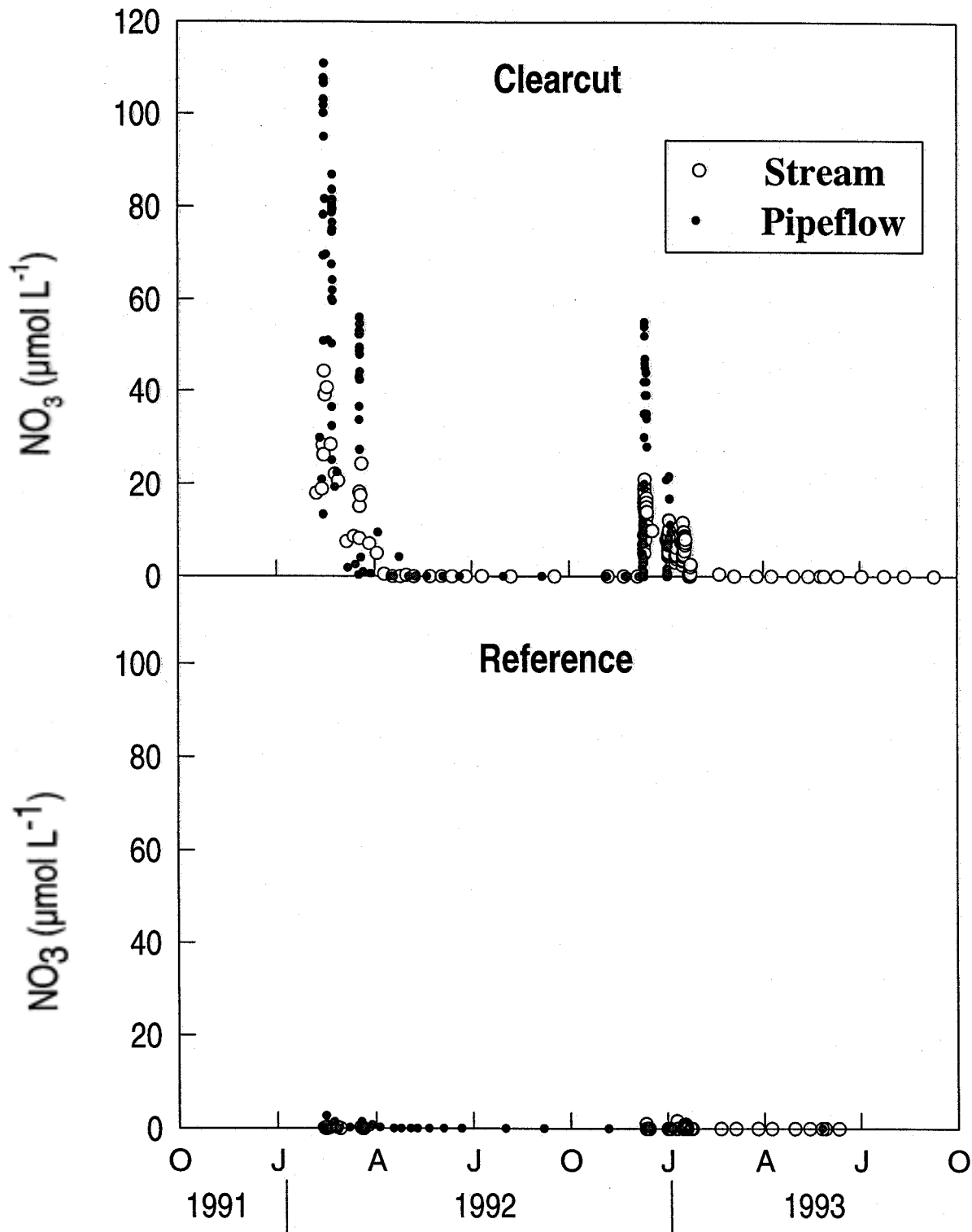


Fig. 40. Comparison of stream water and pipeflow nitrate concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

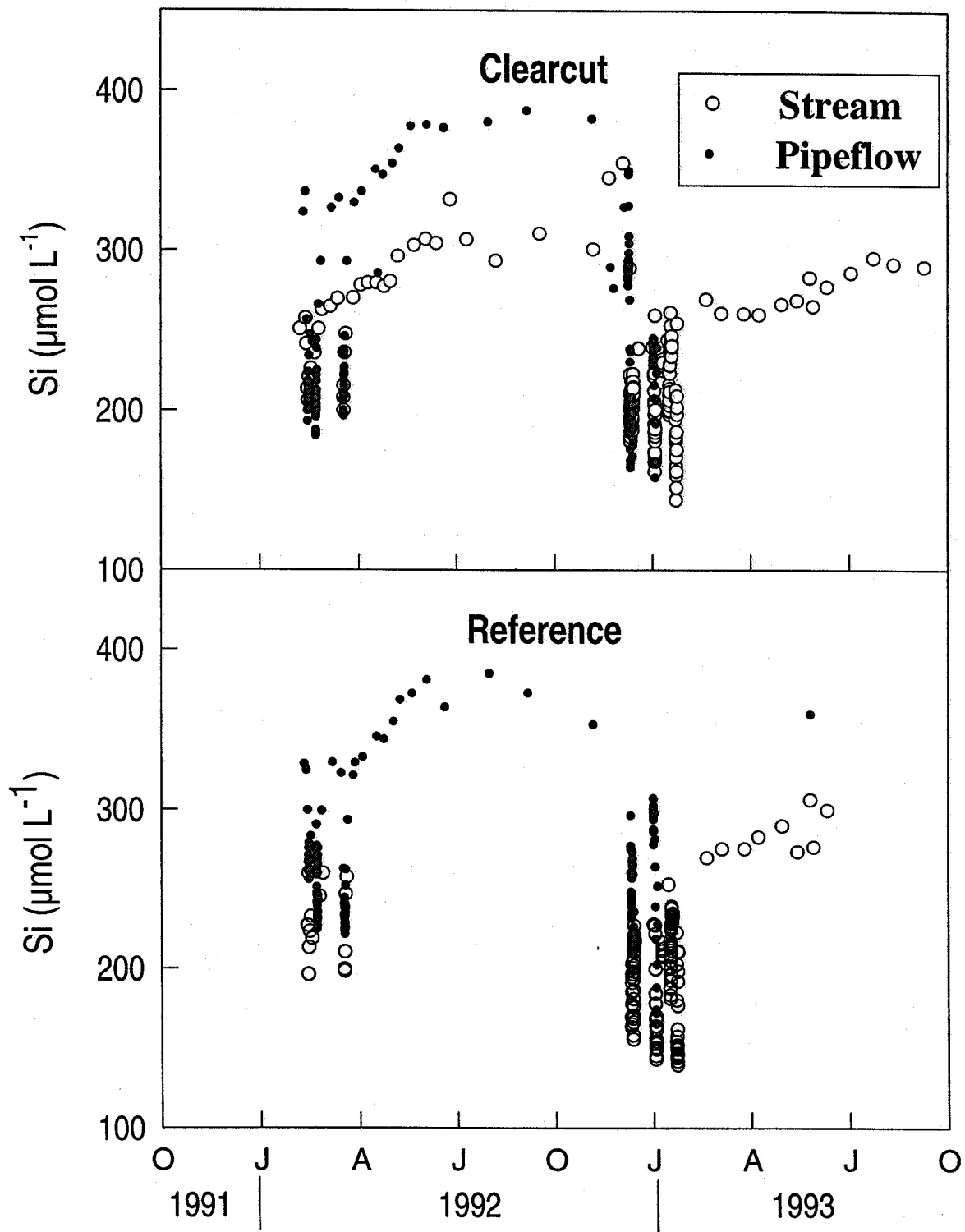


Fig. 41. Comparison of stream water and pipeflow silicon concentrations for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

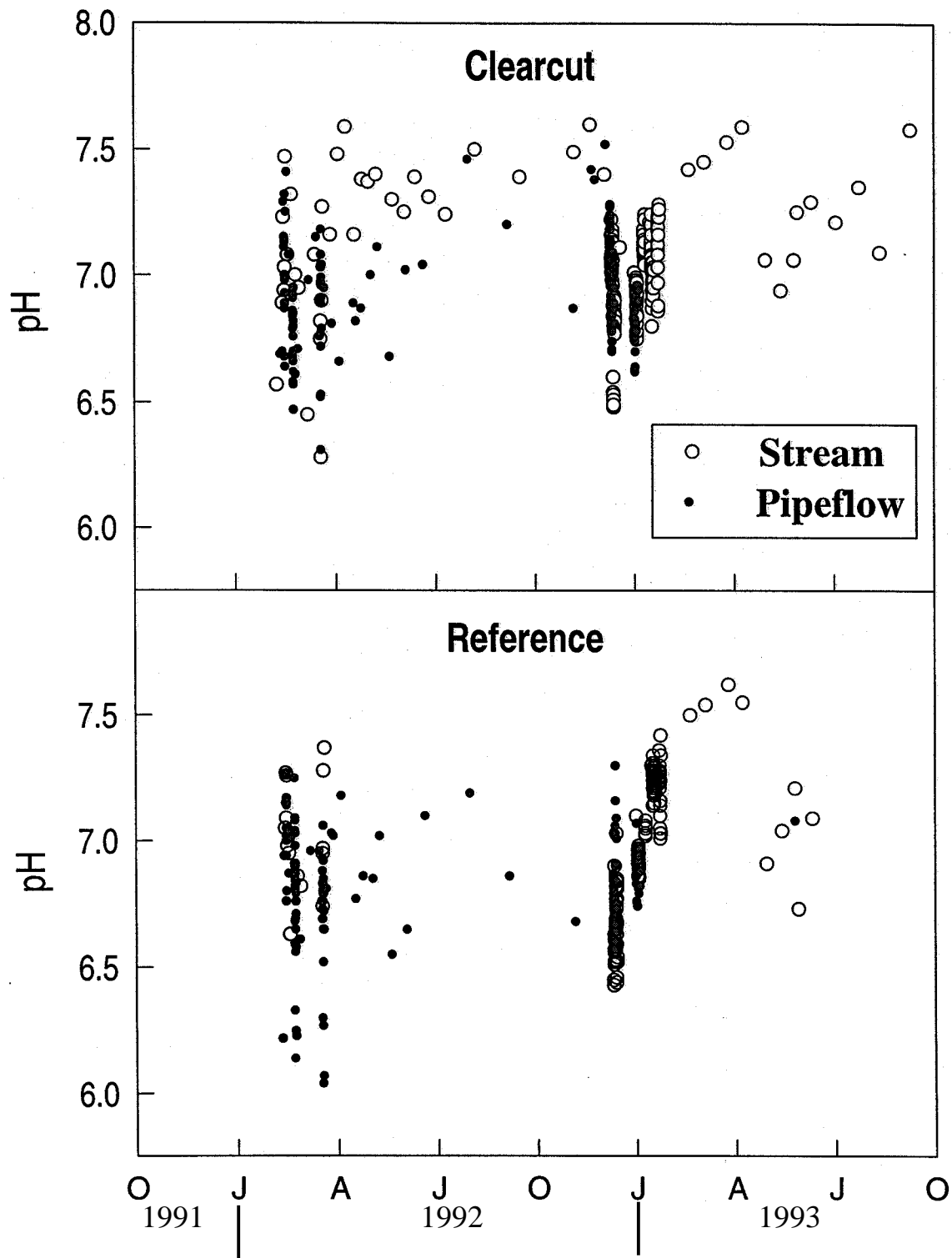


Fig. 42. Comparison of stream water and pipeflow pH values for the reference (MUN) and clearcut (KJE) watersheds during the 1991 - 1993 water years.

Nutrient Fluxes in Stream Water

While elemental concentrations in stream water give a good idea of processes regulating stream water solute concentrations, the most important consideration from a nutrient cycling perspective is the nutrient flux (kg/ha/yr) associated with streamflow. Nutrient fluxes are calculated by combining stream discharge (L/s) with nutrient concentrations (mg/L). Since the water yield between the clearcut and reference watersheds differ appreciably (Keppeler, personal communication), what appears to be small differences in stream water nutrient concentrations result in much larger differences in nutrient fluxes.

Nutrient fluxes in precipitation are shown for the five years of the study in Table 24. The precipitation fluxes are regulated to a large degree by the precipitation amount for a given year. Precipitation from nearby Fort Bragg during the study period ranged from a low of 78 cm during the 1993-94 water year to a high of 148 cm during the 1994-95 water year (Table 24). The highest elemental inputs (2.6 - 23 kg/ha/yr) occur for Cl, Na, Ca and Mg reflecting the close proximity to the ocean, which is the primary source of these constituents. Lesser fluxes (1-2.6 kg/ha/yr) of K and S occur, followed by very low inputs (<0.5 kg/ha/yr) of N and P. Actual elemental inputs to these ecosystems may be somewhat higher since the forest canopy has a much higher efficiency for capturing atmospheric gases, aerosols and particulate matter than the funnel used to collect the bulk precipitation.

Elemental fluxes of anion components in stream water were substantially higher for the clearcut watershed compared to the reference watershed (Table 24). This results from a combination of increased stream water concentrations for some components (NO₃ and SO₄) and from an increase in water yield due to reduced ET and canopy interception. Nitrogen fluxes were negligible (<0.08 kg/ha/yr) in the reference watershed. The nitrogen flux increased following clearcutting to a maximum level of 1.85 kg/ha/yr in the 1991-92 water year and then decreased over time to 0.15 kg/ha/yr in 1995-96 (the 7th water year following harvest). This is consistent with the findings of other studies examining the effects of clearcutting that show a 5-7 year recovery period before nitrogen fluxes return to reference watershed levels. Dissolved P fluxes were very low in both watersheds; however, there may be some indication of a small increase in P fluxes in the clearcut prior to the 1993-94 water year. Sulfur fluxes increased by a factor of about four following clearcutting. This results from both increased stream water concentrations and the increased water yield following clearcutting. Chloride fluxes increased by a factor of 2.1 times in the clearcut watershed over the five years of monitoring. Unlike nitrogen fluxes, the fluxes of S and Cl do not show any trend with time since harvest indicating that these elements are not strongly biocycled by the regenerating redwood vegetation.

Fluxes among the base cations showed the following distribution: Na > Ca > Mg > K. Fluxes of Na, Ca, Mg and K from the clearcut watershed were 2.4, 2.5, 2.6 and 2.2 times greater than those from the reference watershed, respectively. The relative uniformity in base cation fluxes between the two watersheds is consistent with the fact that the distribution of base concentrations in stream water is largely regulated by equilibrium with exchangeable cation concentrations. These base cation fluxes are also consistent with that of Si which showed a 2.4 times greater flux from the clearcut watershed.

Table 24. Nutrient fluxes contained in precipitation and stream water from the reference (MUN) and clearcut (KJE) watersheds for the five year study period.

Watershed	Water year	N	Cl	P	S	Na	K	Mg	Ca	Si	PPT
		Elemental Flux (kg/ha/yr)									cm
PPT	1991-92	0.22	14.3	0.01	1.14	9.2	1.31	2.61	4.82	0.56	83.1
PPT	1992-93	0.4	22.6	0.05	1.86	14.2	1.33	3.85	6.25	1.13	130.9
PPT	1993-94	0.36	14.5	0.04	1.07	9	1.09	2.78	6.37	0.13	78.3
PPT	1994-95	0.15	23.5	<0.01	1.88	15.5	2.65	4.61	9.78	0.54	147.8
PPT	1995-96	0.1	20.7	0.08	1.47	15.8	2.38	4.53	9.03	0.81	118.5
Clearcut	1991-92	1.85	189	0.03	27.6	138	10.6	33.3	80.4	88	
Clearcut	1992-93	1.08	284	0.039	49.4	250	20.8	58.3	147	162	
Clearcut	1993-94	0.188	148	0.014	26.7	129	9.37	34	87.8	76	
Clearcut	1994-95	0.373	181	0.001	35.9	168	14.5	45.6	113	119	
Clearcut	1995-96	0.15	232	<0.001	38.5	223	18.2	48.5	135	133	
Reference	1991-92	0.006	58.8	0.002	4.61	37	3.49	8.28	20.9	25	
Reference	1992-93	0.001	143	0.002	12.5	100	9.06	23.7	62.9	64	
Reference	1993-94	0.001	61.1	0.001	6.91	47	4.46	12.7	34.3	31	
Reference	1994-95	0.08	97.2	0.001	7.98	63.9	5.87	15	40.6	45	
Reference	1995-96	0.037	139	<0.001	11.6	114	11.4	25.2	61.4	73	

Similarly, these elemental ratios are on the same order of magnitude as that of Cl which is a major anion regulating the leaching of base cations from the soil. These ratios could be compared to the differences in water flux between the clearcut and reference watersheds to determine the importance of differences in water fluxes in regulating nutrient fluxes between the two watersheds. Data for this analysis are available from the Caspar Creek Research Team.

Cumulative Effects of Harvesting on Stream Water Quality

The distance to which a harvesting effect (*i.e.*, change in water quality) is observed downstream from the harvested catchment is a very important attribute of watershed biogeochemistry. Some impacts may be observed well downstream of the actual disturbance while other impacts may not be detectable at all downstream of the disturbance. Figures 43 to 51 show solute concentrations in headwater catchments and at sampling points along the North Fork of Caspar Creek. Sampling points HEN, IVE and MUN occur at the base of headwater catchments that were not harvested and therefore serve as reference watersheds (Fig. 3). Sampling points BAN, CAR, EAG, GIB and KJE occur at the base of headwater catchments that were clearcut harvested. Sampling points ARF, FLY, LAN and JOH occur along the main trunk of the North Fork and are listed from downstream to upstream positions, respectively. Sampling point DOL occurs below the EAG gauging station just before this tributary enters the North Fork.

There was considerable variability among the three reference watersheds (HEN, IVE and MUN) for the following solutes: Na, Mg, Ca, Cl, SO₄ and Si (Figs. 43 - 48). Thus, without several years of preharvest data, it is not possible to determine how much of the solute variability is due to harvesting impacts rather than spatial variability between watersheds. It was previously shown that the most obvious effect of harvesting was elevated NO₃ concentrations in stream water. All three reference watersheds showed virtually no detectable concentrations of nitrate indicating that the nitrogen cycle is tightly closed within the second growth forests (Fig. 49). Stream water draining the clearcut watersheds (BAN, CAR, EAG, GIB, and KJE) showed enhanced NO₃ concentrations with a maximum concentration of about 70 μM in watershed EAG (Appendix I). Nitrate concentrations were quickly reduced downstream from the harvested watersheds. For example, sampling point JOH occurs just downstream from the confluence of watersheds MUN and KJE and shows much lower NO₃ concentrations than that of the clearcut watershed (KJE). Sampling point LAN occurs at a point downstream of watersheds MUN, KJE, JOH, IVE and HEN and shows even lower NO₃ concentrations. Similarly, sampling point DOL is immediately downstream of the clearcut watershed EAG and shows a large decrease in NO₃ concentrations relative to that leaving EAG. At the sampling point furthest downstream (ARF), NO₃ concentrations are generally <1μM indicating that little NO₃ is leaving the larger watershed even though concentrations exiting clearcut watersheds may be much higher. The decrease in NO₃ concentrations as the water enters higher order streams is due to dilution, and may also be the result of in-stream immobilization of NO₃ by biota or denitrification within the riparian zone soils. It is most likely that dilution is the primary mechanism, especially at high discharge since the water residence time within the North Fork watershed is very low resulting in little time for biological processes to affect water quality.

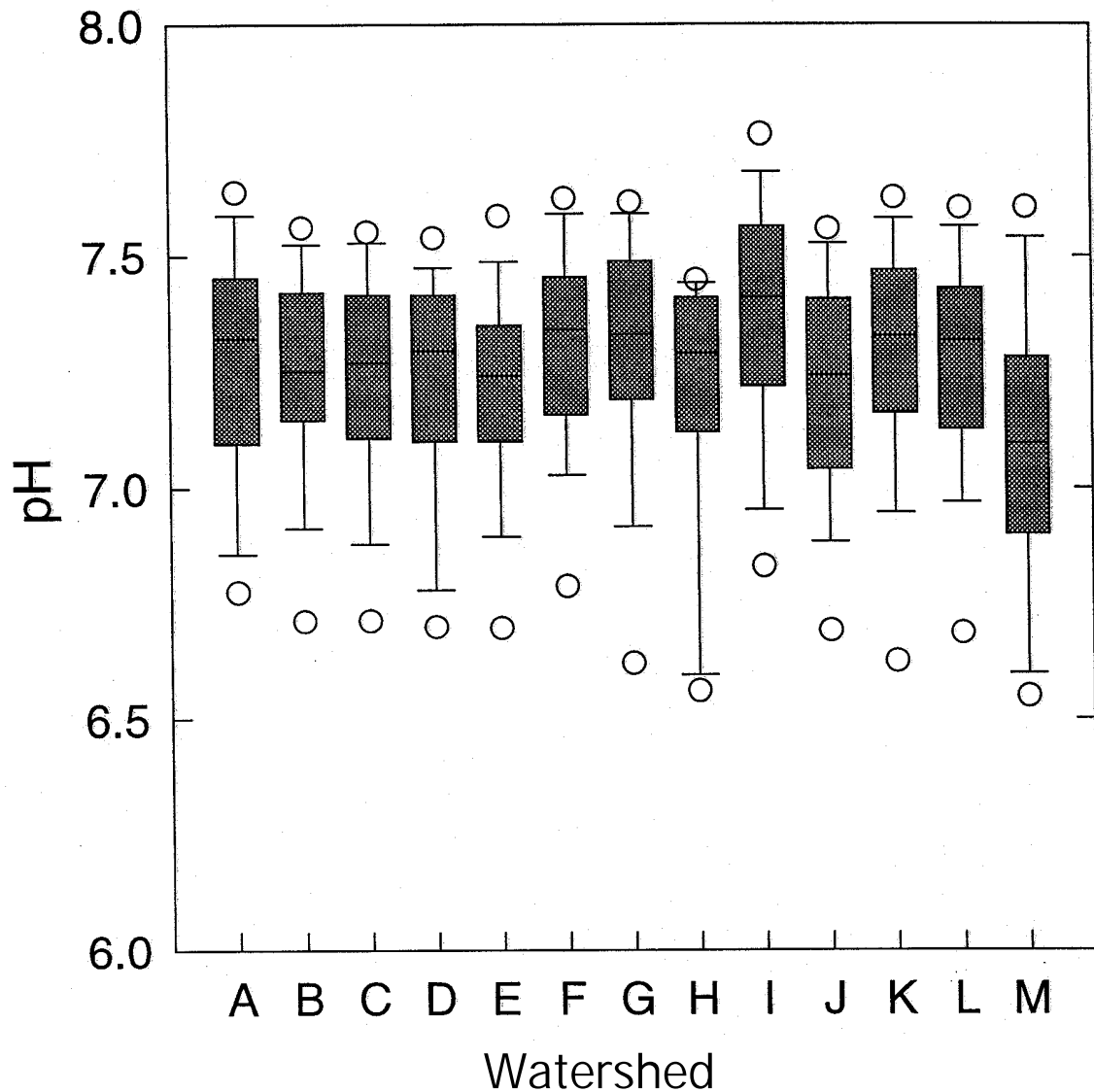


Fig. 43. Box and whisker plots indicating range of stream water pH values in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

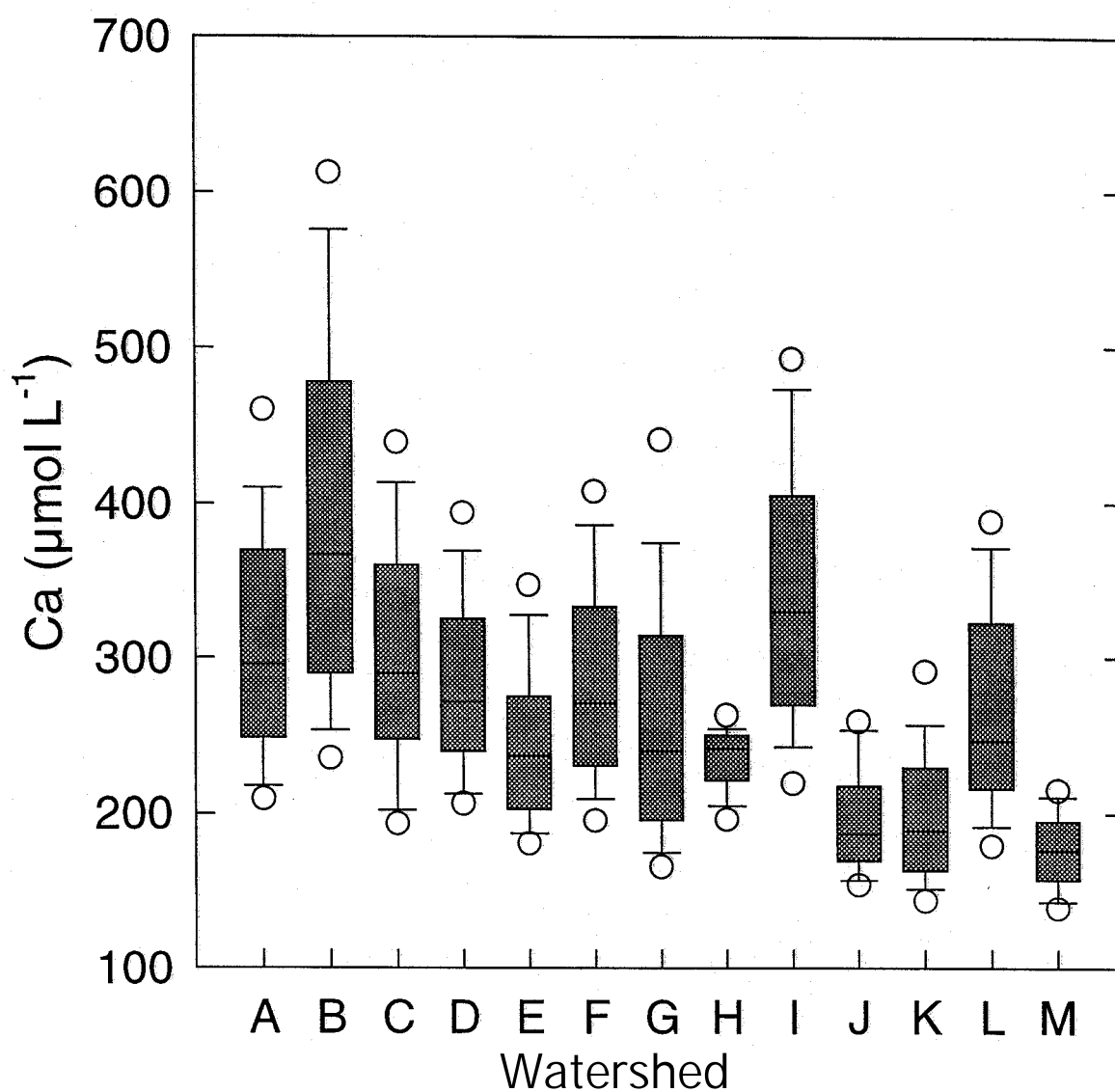


Fig. 44. Box and whisker plots indicating range of stream water calcium concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

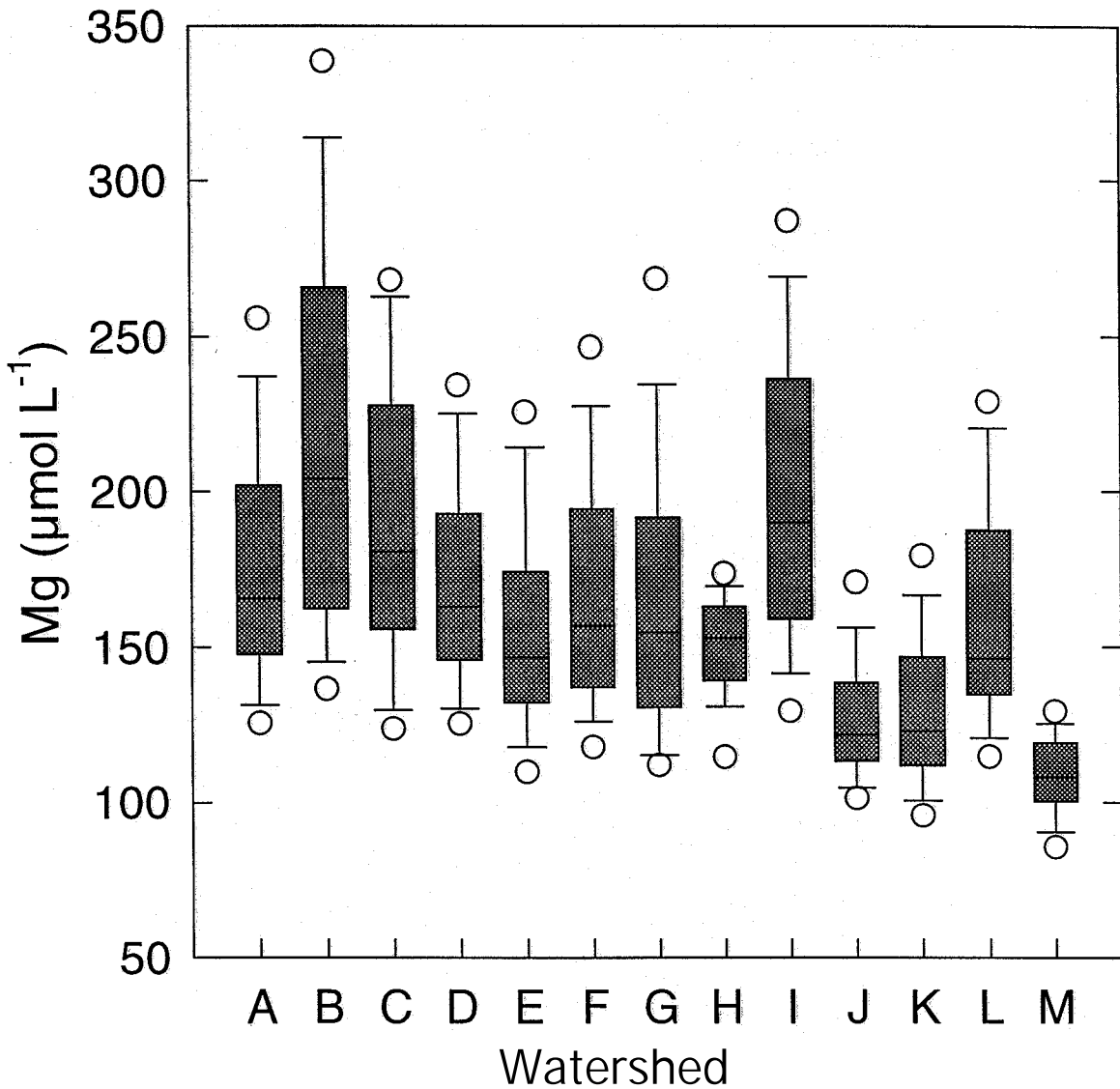


Fig. 45. Box and whisker plots indicating range of stream water magnesium concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

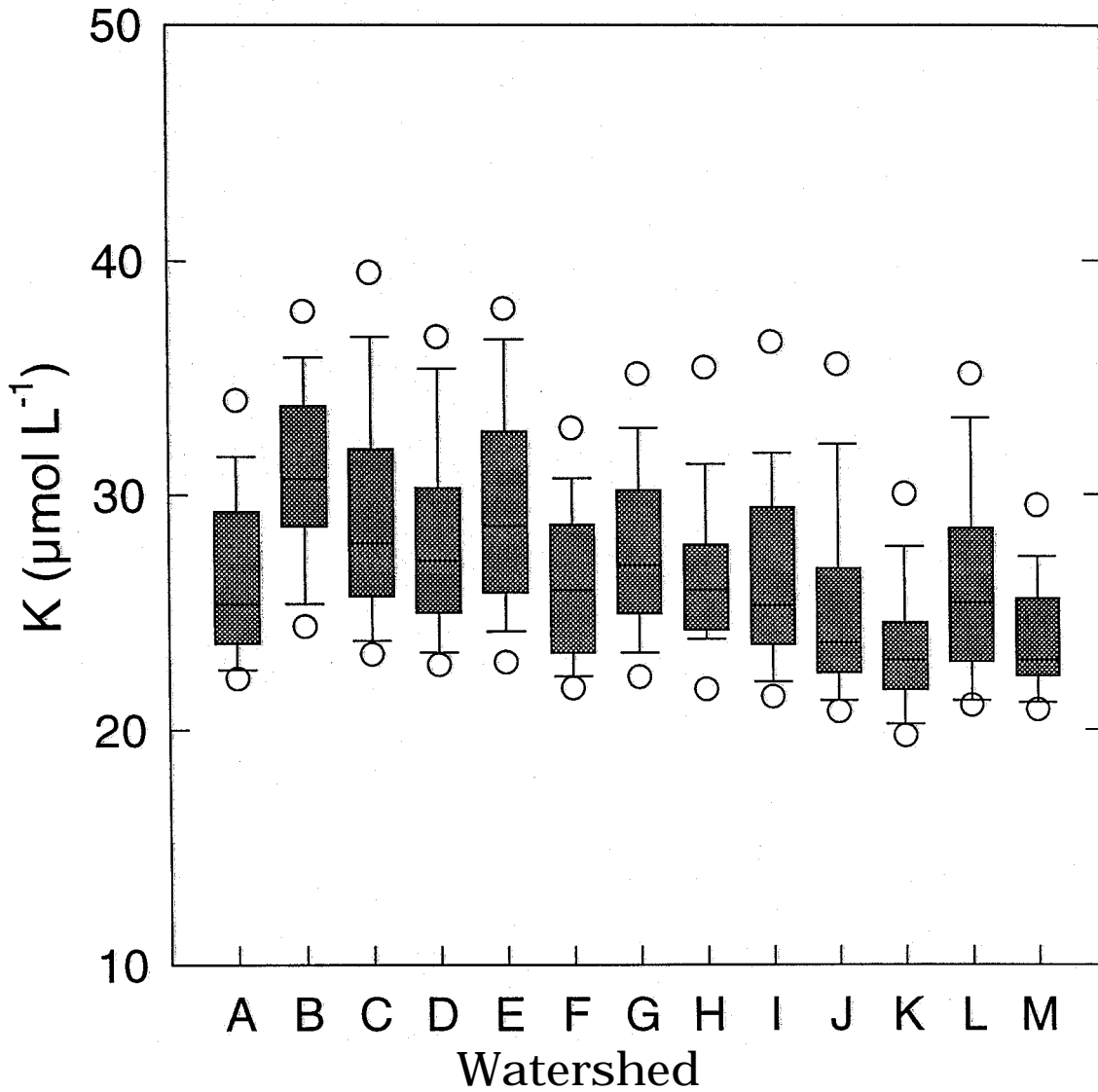


Fig. 46. Box and whisker plots indicating range of stream water potassium concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

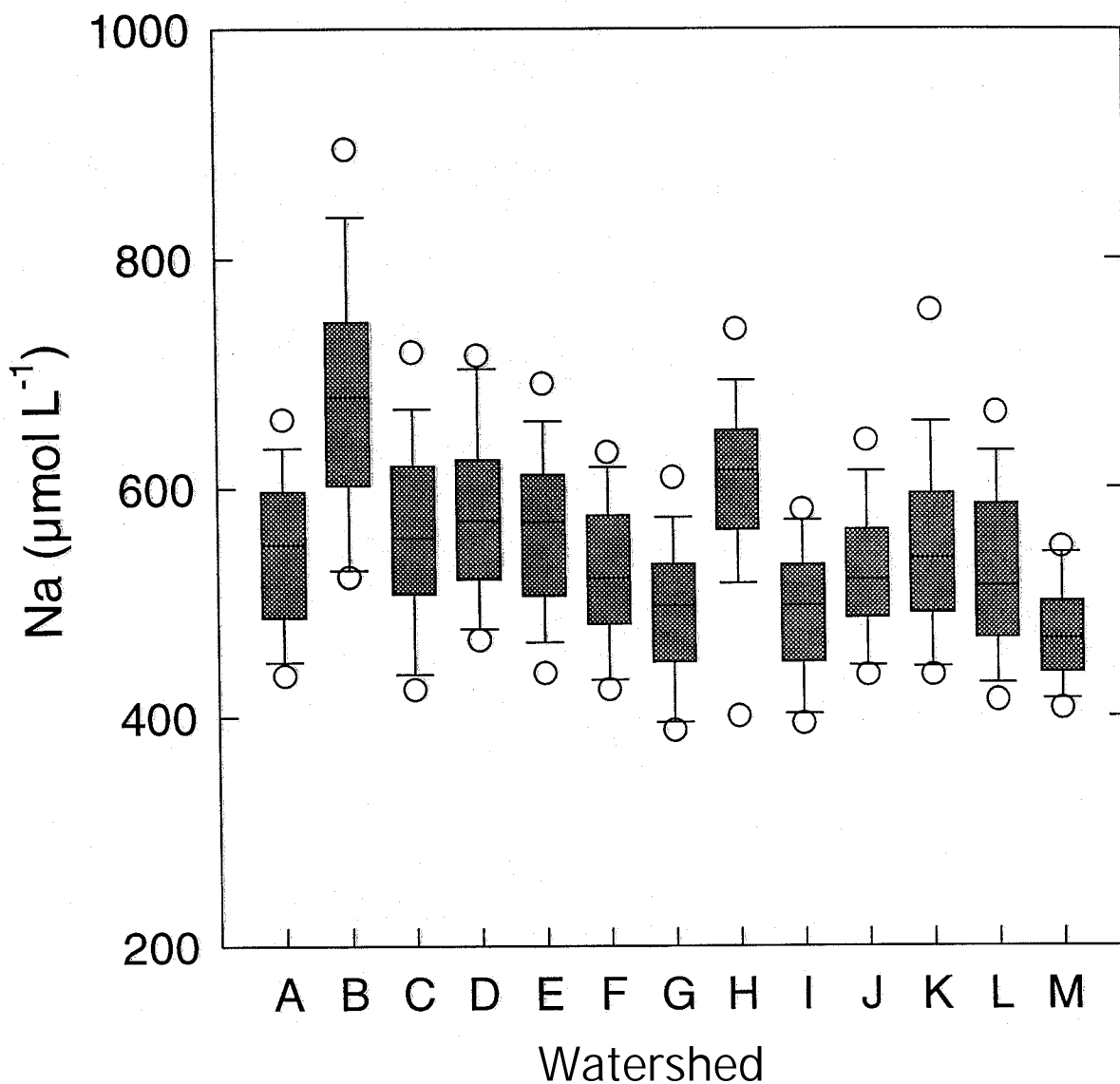


Fig. 47. Box and whisker plots indicating range of stream water sodium concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

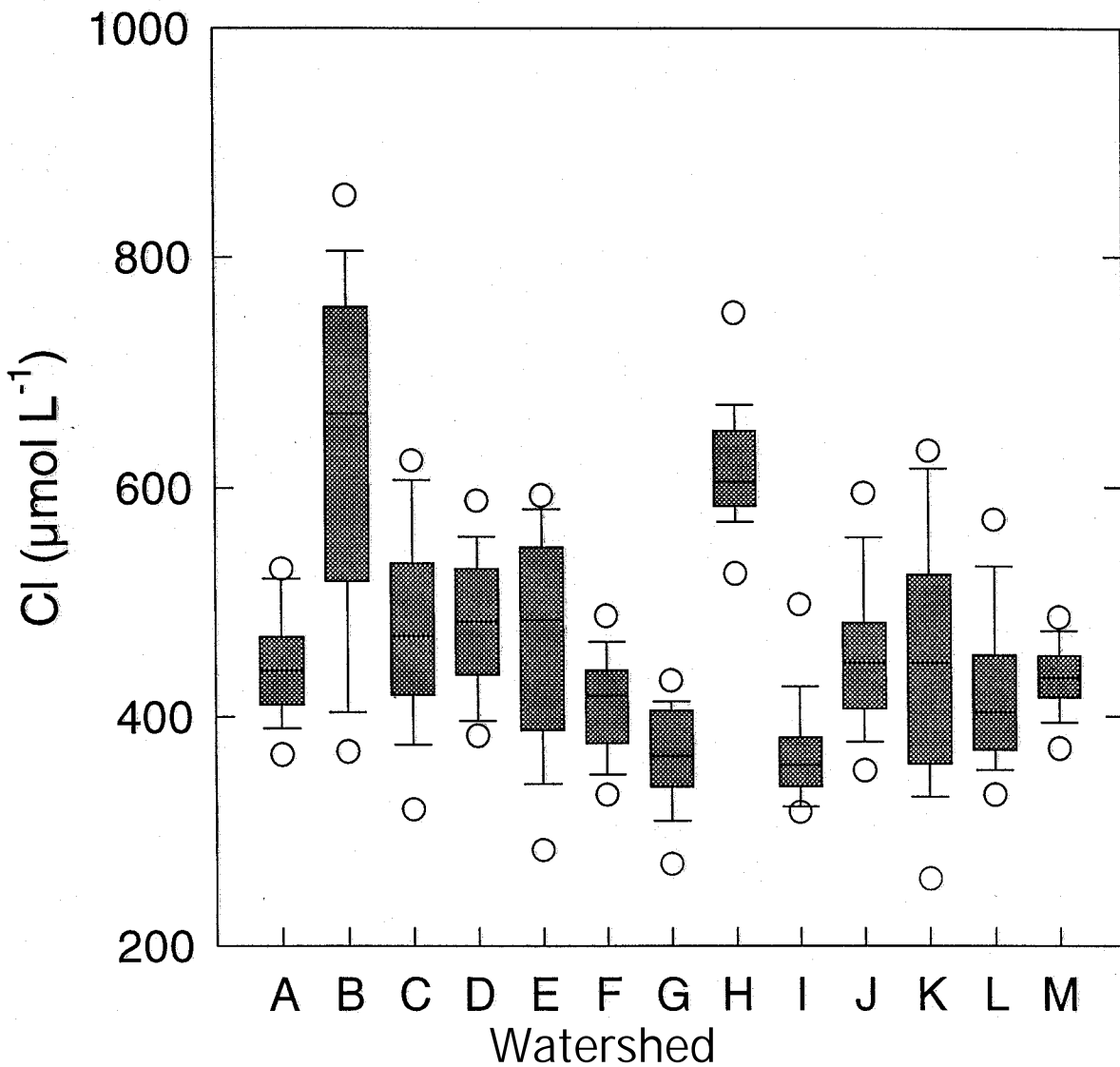


Fig. 48. Box and whisker plots indicating range of stream water chloride concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

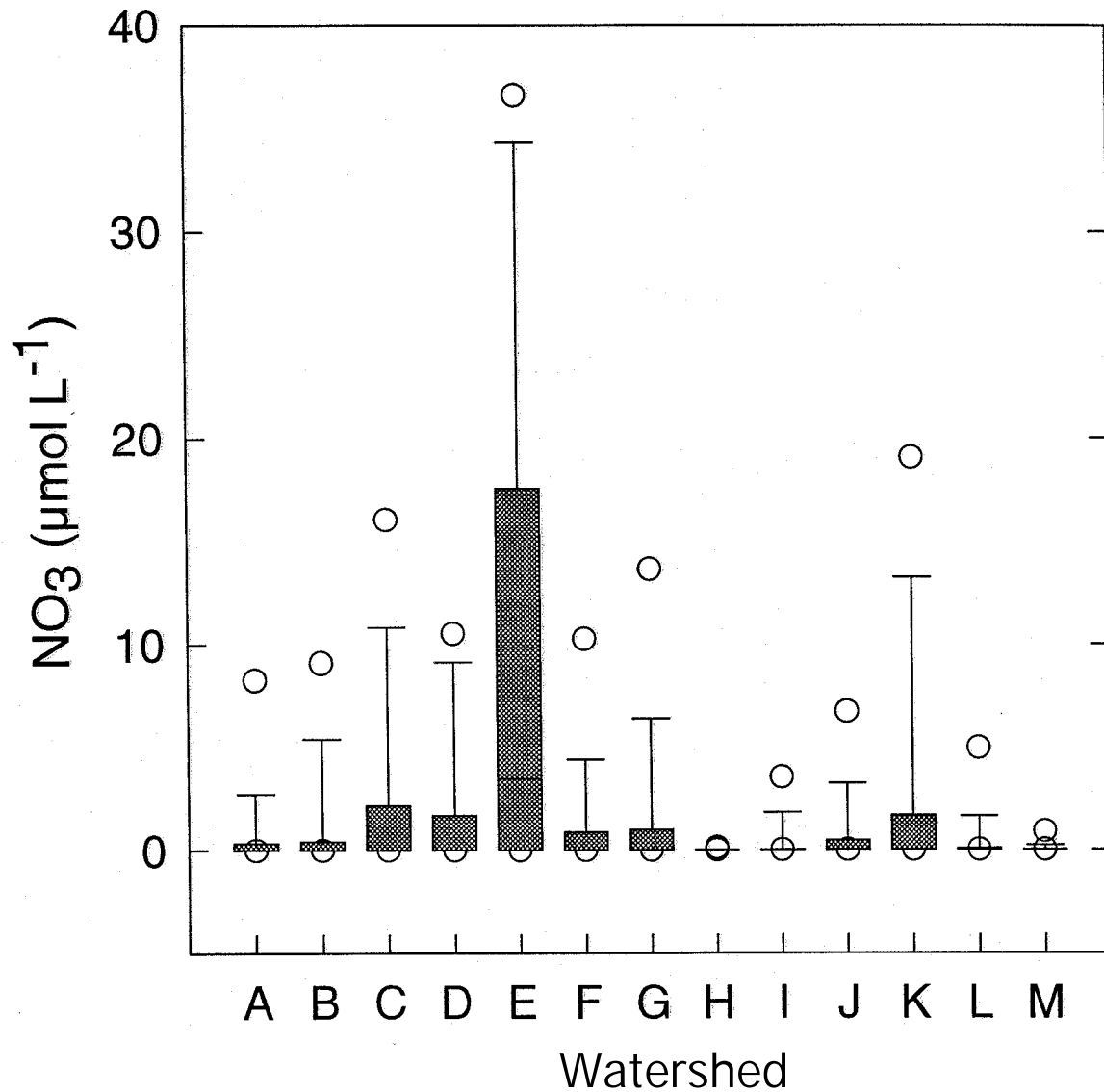


Fig. 49. Box and whisker plots indicating range of stream water nitrate concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

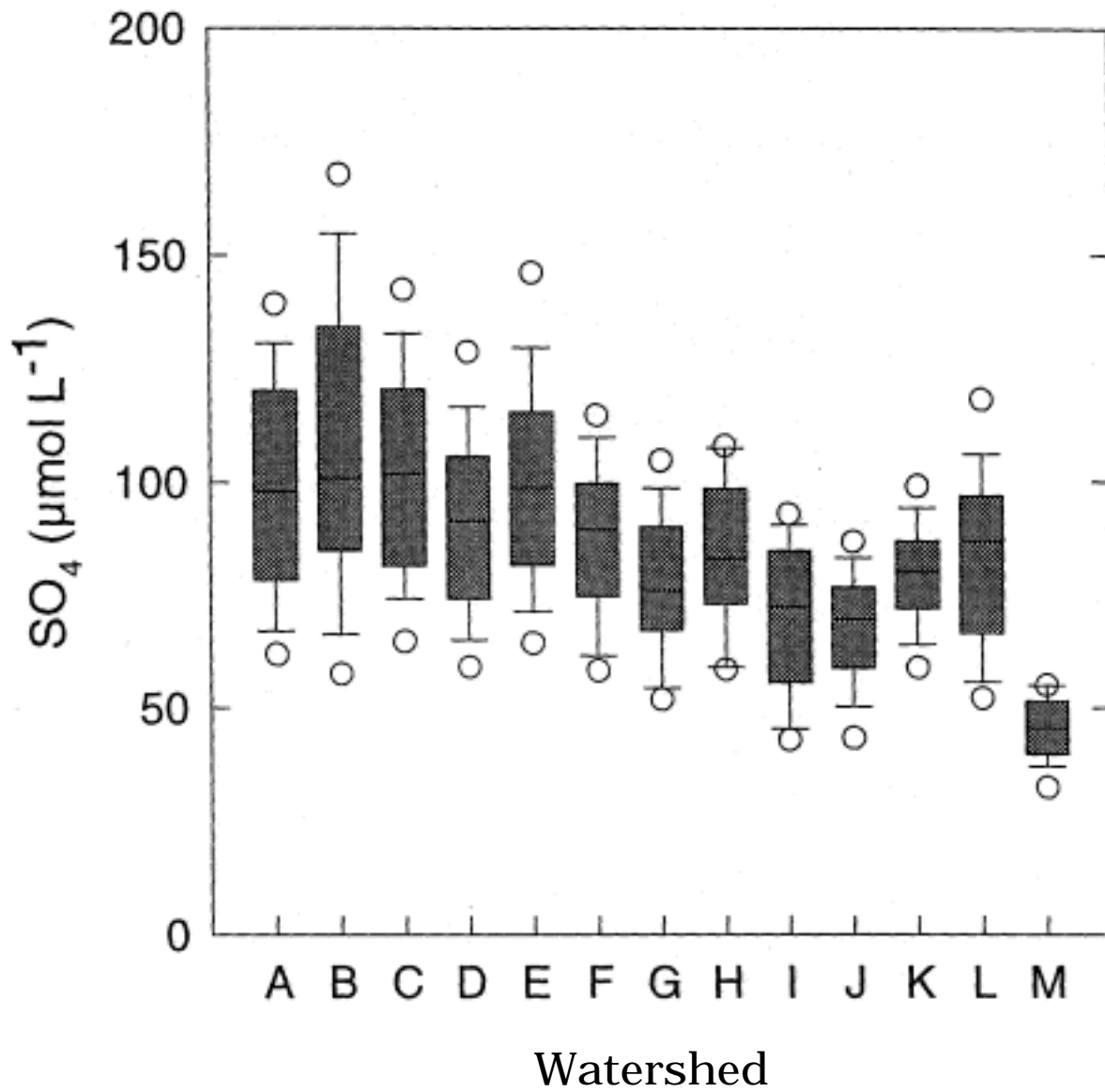


Fig. 50. Box and whisker plots indicating range of stream water sulfate concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

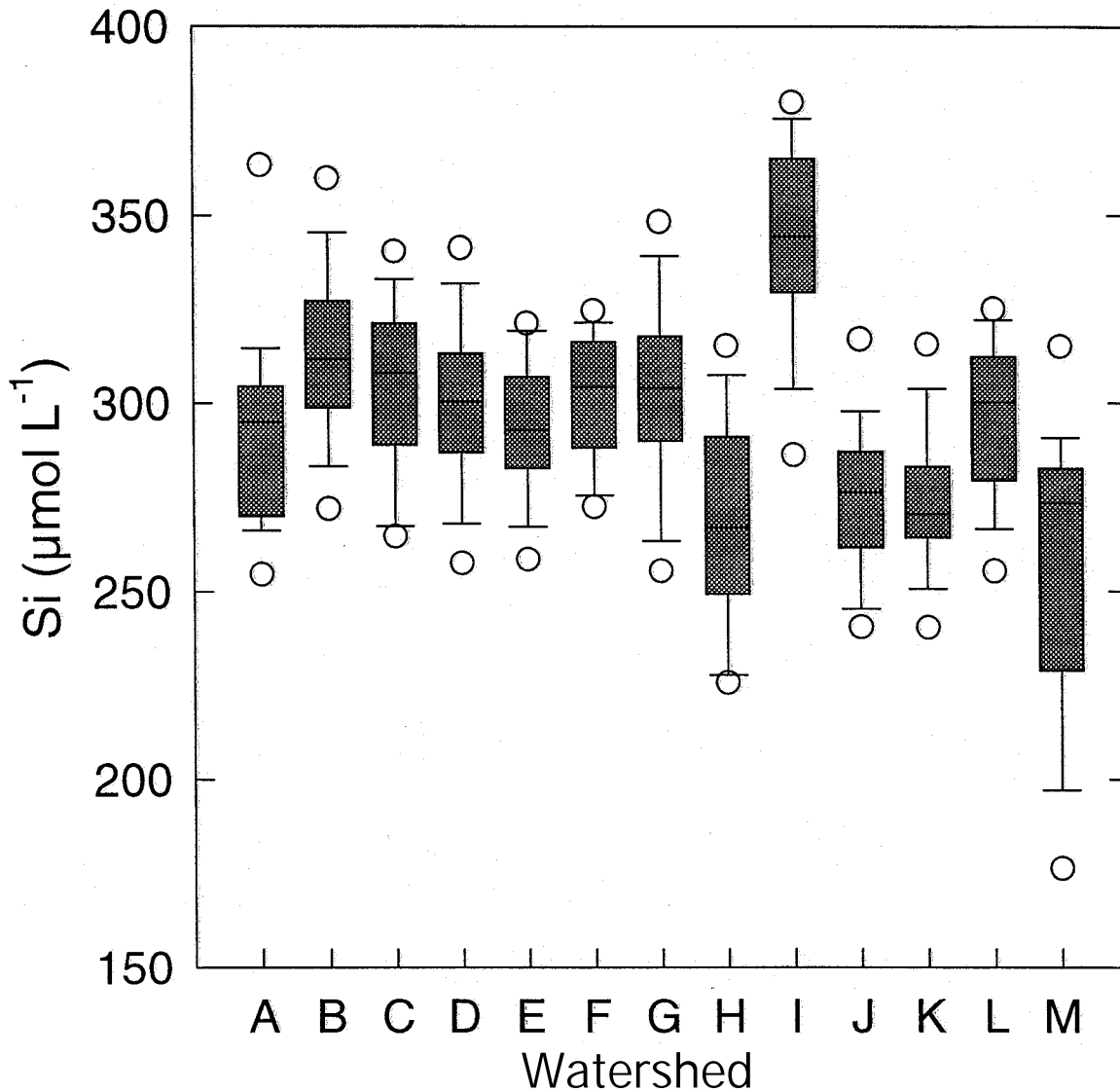


Fig. 51. Box and whisker plots indicating range of stream water silicon concentrations in the various subwatersheds of the North Fork, Caspar Creek watershed for the period April, 1993 to June, 1996. The 10th, 25th, 75th and 90th percentiles are displayed along with the mean line within box and data (circles) outside the 10th and 90th percentiles. Reference watersheds: H=HEN, I=IVE and M=MUN; clearcut watersheds: B=BAN (1991), C=CAR (1991), E=EAG (1991), G=GIB (1991), K=KJE (1989); other sampling points: A=ARF, D=DOL, F=FLY, J=JOH and L=LAN.

With the exception of increased NO₃ concentrations, there was no other obvious impact of harvesting on stream water solute concentrations. Another trend worth noting is the apparent increase in K, Mg, Ca and SO₄ concentrations with decreasing elevations within the watershed (MUN --> ARF) (Figs. 50, 44, 45 & 47). No obvious explanation for this trend is apparent. The pH values are relatively uniform across the various watersheds (Fig. 51) while Na, Cl and Si concentrations (Figs. 43, 46 & 48) are relatively uniform with a few outlying values occurring in some watersheds.

Suspended Sediments

Suspended sediment (>0.4 μm) is often a major form of elemental loss from forested ecosystems following harvest, especially for the elements P, C, Fe, Al and Si. We collected stream water for chemical analysis of suspended sediments from three major storm events during the 1994-95 water year. We obtained sufficient sample from the clearcut watershed (KJE) for all three events, but only enough suspended sediment from the January collection in the reference watershed (MUN). Since the Caspar Creek Research Team has collected the data on suspended sediment fluxes, it would be possible to estimate elemental losses (kg/ha/yr) associated with the suspended sediment fraction.

The composition of the suspended sediments indicates that they consist of a mixture of organic and inorganic materials (Table 25). Elemental concentrations for the three samples from the clearcut watershed were similar; however, carbon concentrations varied by a factor of three between the collection periods. Of the two watersheds, the reference watershed had a substantially greater organic matter component as indicated by higher carbon and nitrogen concentrations. Much of the mineral matter contained in the suspended sediment load of the reference watershed has probably originated from stream channel erosion since the litter layer at the surface of the forest soil minimizes surface runoff and erosion. In contrast, the loss of the litter layer from the clearcut watershed results in a greater potential for surface erosion of mineral soil materials. Thus, the higher organic matter concentration of suspended sediments in the reference watershed probably reflects the contrasting nature of the soil surface in the two watersheds.

The chemical composition of the suspended sediments is dominated by silicon, with appreciable concentrations of aluminum and iron. This is consistent with these constituents representing the dominant rock-forming elements. Similarly, the concentrations of base cations (Ca, Mg, Na and K) are likely regulated by the mineralogical composition of bedrock and soil. The carbon and nitrogen content originates from organic matter. The C/N molar ratio of the suspended sediments ranged between 31 and 59 which falls between the C/N molar ratio of the litter layer (91) and A horizons (26) (Table 2). Phosphorus in the suspended sediment may originate from both organic matter and ortho-phosphate adsorbed on mineral surfaces.

An estimate of nitrogen lost in the suspended sediment fraction from the reference (MUN) and clearcut (KJE) watersheds was made from suspended sediment data collected by the Caspar Creek Research Team. The suspended sediment load predicted for an unlogged condition in water years 1990-96 for the entire North Fork Caspar Creek experimental watershed was about 385 kg/ha/yr before harvest activities (Lewis, personal communication). If the nitrogen concentration (4.4 g N/kg) of the suspended sediments from the reference watershed (MUN) is representative of that for the

Table 25. Elemental composition of suspended sediments contained in the stream water of a clearcut (KJE) and reference (MUN) watershed during selected storm events in the 1994-95 water year.

Element	----- Watershed KJE -----				----- Watershed MUN -----			
	December	January	March	Mean±Std. Dev.	December	January	March	Mean±Std. Dev.
----- mg/kg suspended sediment -----								
Al	3.28	3.51	3.82	3.5±4.27	NA [†]	2.98	NA	
Si	26.1	29.3	30.1	28.5±12.1	NA	25.8	NA	
Fe	2.54	2.47	3.47	2.83±.56	NA	1.83	NA	
Ca	0.52	0.44	0.41	0.46±.06	NA	0.21	NA	
Mg	1.89	1.76	1.82	1.82±.07	NA	1.33	NA	
K	1.30	1.21	1.43	1.31±.11	NA	0.82	NA	
Na	0.63	0.41	0.32	0.45±.16	NA	0.13	NA	
N	0.21	0.15	0.12	0.16±.05	0.65	0.28	0.40	0.44± .19
P	0.11	0.13	0.15	0.13±.02	NA	0.04	NA	
C	9.1	5.8	3.2	6.01±3.0	29.3	14.3	22.6	22.1± 7.5

[†]Not analyzed due to insufficient sample.

entire watershed before harvest, 1.7 kg N/ha/yr 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/yr of suspended sediment (Lewis, personal communication). However, the total nitrogen lost from the clearcut watershed (1.2 kg N/ha/yr) was actually somewhat lower than that lost from the reference watershed because of the lower nitrogen concentration associated with suspended sediment from the clearcut watershed (1.6 g N/kg). 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 Budget

An ecosystem nitrogen budget demonstrating the effects of clearcut harvest management is provided below as an example of how all the data provided in this report can be integrated. 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 transport, 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 budget was calculated on the basis of estimated nitrogen inputs and outputs over the course of an 80-year harvest rotation (Table 26). Nitrogen losses are dominated by biomass removal (~ 950 kg/ha/rotation), 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 to 2.0 kg N/ha/yr or 80 to 160 kg N/ha/rotation. The stream water N flux further results in the loss of about 20 kg N/ha/rotation. The summation of these losses greatly exceed the only measured input of about 20 kg N/ha/rotation in the bulk precipitation. Regardless of the amount of nitrogen lost in the suspended sediment fraction, there is a net loss of nitrogen from this ecosystem based on measured fluxes.

These budget calculations suggest 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/yr (Binkley et al., 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 forest ecosystems. Additional research appears warranted to determine the importance of *Ceanothus* in the post-harvest recovery of the nitrogen capital in this ecosystem.

Table 26. Nitrogen budget 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 pool --- kg/ha --	Nitrogen fluxes -- kg/ha/rotation --
Soil pool	9,500	
Biomass pool	1,480	
Atmospheric deposition		+20
Nitrogen fixation flux		+?
Harvest removal flux		-950
Stream-water flux		-10
Suspended sediment flux		-80 to -160

Conclusions

Soils

There were minimal changes in soil properties and soil nutrient pools following clearcutting. The 1-3 cm thick litter layer (Oi/Oa) was largely lost from the clearcut watershed due to mixing and decomposition following harvest. This may lead to a greater erosion potential in the short-term following harvesting. Soil pH in the A and AB horizons of the clearcut watershed was decreased by 0.2 to 0.5 units following harvest. This pH depression will have little impact on ecosystem processes. There were no significant changes to soil nutrient pools following clearcutting. Thus, clearcutting had no major effect on soil properties and nutrient pools in the three years following harvest.

Biomass Nutrients

Rapid regrowth of redwood stump sprouts immobilized large concentrations of nutrients, thereby reducing their loss by leaching from the watershed. A mean of 5020 redwood stem/ha having an above-ground biomass of 15 Mg/ha was measured six years following the clearcut. The above-ground biomass of the regenerating redwood contained 70, 56, 12, 80, 14 and 7 kg/ha of N, Ca, Mg, K, P and S, respectively. This rapid regrowth of redwoods also provides soil cover which appreciably reduces the erosion potential following harvest. Based on foliar nutrient concentrations in the redwood sprouts, there are no apparent nutrient deficiencies limiting their regrowth. Harvesting of the 80-year-old redwood/Doug fir forest resulted in removal (in wood and bark) of 949, 65, 405, 401 and 75 kg/ha of N, P, K, Ca and Mg, respectively. A comparison of nutrients removed in biomass with soil nutrient pools indicates that N, P and S are the most critical nutrients with respect to long-term forest productivity. The data suggest that nitrogen fixation by *Ceanothus* species may be necessary to maintain the long-term productivity and sustainability of these ecosystems. We conclude that the stump sprouting ability of redwood makes these ecosystems comparatively resilient to the adverse effects of nutrient loss by leaching and erosion.

Ecosystem Waterflows

In the period 4-6 years following clearcutting, concentrations of most solutes in soil solutions were significantly lower in the clearcut watershed. The only solute to show an increase in the clearcut watershed was NO_3 . This is due to increased mineralization from organic matter (due to warmer and moister soil conditions) and decreased uptake due to removal of vegetation. We believe the lower solute concentrations in stream water from the clearcut watersheds reflect a dilution effect. Canopy interception (10-16%) and higher evapotranspiration in the second growth forest substantially decrease the amount of water leaching from the reference watershed. This is also reflected in the lack of streamflow in the reference watershed following cessation of rainfall which is in contrast to water flow in the clearcut watersheds that continued to flow throughout the dry summer months.

Stream water solute concentrations were similar between the reference and clearcut watersheds, except for NO_3 and SO_4 which had higher concentrations in the clearcut watershed. Elevated concentrations of NO_3 and SO_4 are most likely due to increased leaching from the soil as mineralization is enhanced and uptake by vegetation is greatly reduced. With the exception of NO_3 , all solute concentrations display a large decrease due to dilution during high-discharge, storm events. In contrast, NO_3 concentrations increase at peak discharge probably reflecting a change in the hydrologic flowpath and source of the water. We speculate that subsurface lateral flow above the clay-rich, argillic horizon and macropore flow through root channels delivers NO_3 -enriched waters from the upper soil horizons during storm events. Much of this water may reach the stream channel as pipeflow which has solute concentrations that can explain many of the changes in stream water solute concentrations during storm events. The elevated concentration of NO_3 in the clearcut watersheds was rapidly decreased in the higher-order downstream segments. This decrease in NO_3 concentration is believed to be primarily due to dilution, although in-stream immobilization and denitrification in the riparian zone may also have an effect. Thus, the impacts of elevated NO_3 concentrations on the aquatic community are primarily restricted to the stream segment draining the clearcut watershed with little effect on the higher-order downstream segments.

Nutrient fluxes from the clearcut watershed were generally 2 to 2.5 times greater than those from the adjacent reference watershed. Since stream water solute concentrations were similar in both watersheds, the increased fluxes must be primarily due to an increased water flux in the clearcut watershed. While elevated NO_3 concentrations in stream water from the clearcut watershed might suggest a large loss of nitrogen due to clearcutting, conversion to a flux (kg/ha/yr) indicates a maximum loss of only 1.85 kg/ha/yr and fluxes have decreased to $<0.4 \text{ kg/ha/yr}$ three years following the harvest. Thus, stream water loss of nitrogen following clearcutting is not a major environmental concern in this redwood/Doug fir ecosystem.

Suspended Sediment

Nutrient concentrations in suspended sediment ($>0.4 \mu\text{m}$) indicate a mixture of inorganic and organic components. Suspended sediments in the reference watershed had a much larger organic component compare to the clearcut watershed. Concentrations of N (1.2 - 6.5 g/kg) and P (1.1 - 1.5 g/kg) are relatively high in the suspended sediments indicating that enhanced erosion could lead to appreciable nutrient loss following forest harvest. An estimate of nitrogen loss by suspended sediment transport indicates losses on the order of 1 to 2 kg N/ha/yr in both reference and clearcut watersheds. The greater fluxes of suspended sediment in the clearcut watershed were offset by the lower nitrogen concentration of the suspended sediment in the clearcut watershed.

Literature Cited

- Binkley, D., K. Cromack and R.L. Fredriksen. 1982. Nitrogen accretion and availability in some snowbrush ecosystems. *Forest Science*. 28:720-724.
- Dahlgren, R.A. and C.T. Driscoll. 1994. The effects of whole-tree clearcutting on soil processes at the Hubbard Brook Experimental Forest, New Hampshire, USA. *Plant Soil*. 158:239-262.
- Driscoll, C.T., R.D. Fuller and D.M. Simone. 1988. Longitudinal variations in trace metal concentrations in a northern forested ecosystem. *J. Environ. Quality*. 17:101-107.
- Gholz, H.L., C.C. Grier, A.G. Campbell and A.T. Brown. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Research Paper 41. Forest Research Laboratory, Oregon State University, Corvallis, OR. 37 p.
- Johnson, D.W. and D.W. Cole. 1980. Anion mobility in soils: relevance to nutrient transport from terrestrial ecosystems. *Environ. Int.* 3:79-90.
- Keppeler, E.T. and R.R. Ziemer. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in Northwestern California. *Water Resour. Res.* 26:1669-1679.
- Krammes, J.S. and D.M. Burns. 1973. Road construction on Caspar Creek watersheds ... a 10-year progress report. Res. Paper PSW-93. Pac. Southwest For. and Range Exp. Stn. U.S. Dept. of Agric. Berkeley, CA. 10 p.
- Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. pp. 403-430. In: A.L. Page, R.H. Miller and D.R. Kenney (Eds.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*. Agronomy Monogr. No. 9 (2nd ed.). Am. Soc. of Agronomy, Madison, WI.
- Pitt, R.L., H.J. Percival, R.A. Dahlgren and L.F. Hill. 1997. Soil and solution chemistry under pasture and radiata pine in New Zealand. *Plant Soil*. 191:279-290.
- Parkinson, J.A. and S.E. Allen. 1975. A wet oxidation procedure suitable for the determination of N and mineral nutrients in biological material. *Commun. Soil Sci. Plant Anal.* 6:1-11.
- Rice, R.M., F.B. Tilley and P.A. Datzman. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. Res. Paper PSW-146. Pac. Southwest For. and Range Exp. Stn., U.S. Dept. of Agric. Berkeley, CA. 12 p.
- Soil Survey Staff, 1984. Procedures for collecting soil samples and methods of analysis for soil survey. Soil Survey Investigations Rep. No. 1. USDA-SCS Agric. Handbook 436. U.S. Government Printing Office, Washington, DC.

- Swanson, F.J. and JR Franklin. 1992. New forestry principles from ecosystem analysis of Pacific Northwest forest. *Ecological Applications*. 2:262-274.
- 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 Resour. Res.* 26:2079-2087.
- Tilley, F.B. and R.M. Rice. 1977. Caspar Creek watershed study -- A current status report. State Forest Notes 66, State of California Dept. of Forestry. Sacramento, CA 15 p.
- Whittig, L.D. and W.R. Allardice. 1986. X-ray diffraction techniques. pp. 331-362. In: A. Klute (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*. Agronomy Monogr. No. 9 (2nd ed.). Am. Soc. of Agronomy, Madison, WI.
- Wosika, E.P. 1981. Hydrologic properties of one major and two minor soil series of the coast ranges of northern California. M.S. thesis. Humboldt State Univ., Arcata, CA. 15 p.
- Wright, K.A., K.H. Sendek, R.M. Rice and R.B. Thomas. 1990. Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California. *Water Resour. Res.* 26:1657-1667.
- Youngberg, C.T. and A.G. Wollum. 1976. Nitrogen accretion in developing *Ceanothus velutinus* stands. *Soil Sci. Soc. Am. J.* 40:109-112.
- Ziemer, R.R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. *Water Resour. Res.* 17:907-917.

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Caspar Creek - Precipitation Chemistry - Watershed KJE

Type	Date	pH	Na μM	NH4 μM	K μM	Mg μM	Ca μM	Cl μM	N03 μM	P04 μM	S04 μM	Si μM
PPT	11 /03/92	6.93	66.6	0.00	4.1	9.5	0.2	73.0	3.00	0.00	7.0	2.3
PPT	12/07/92	7.71	30.4	0.00	2.6	8.2	5.0	25.0	2.00	0.00	4.0	2.1
PPT	12/07/92	7.63	26.1	0.00	0.0	4.1	5.0	29.0	5.00	1.00	4.0	2.4
PPT	12/09/92	6.96	32.6	0.00	4.1	9.9	11.7	38.0	1.00	0.00	3.0	3.0
PPT	12/15/92	5.97	43.5	0.00	2.6	11.1	8.7	50.0	1.00	0.00	3.0	2.6
PPT	12/15/92	5.82	35.2	0.00	1.5	9.5	5.5	43.0	0.00	0.00	3.0	2.5
PPT	12/31 /92	6.18	98.3	1.11	2.8	17.7	7.2	110.0	1.40	0.00	8.1	3.1
PPT	12/31/92	6.52	95.7	0.00	3.3	19.3	9.2	112.6	1.90	0.00	7.9	3.6
PPT	01 /07/93	5.81	18.7	0.30	0.5	6.3	5.8	24.0	2.01	0.00	2.5	2.8
PPT	01 /07/93	5.84	19.0	0.57	0.5	6.4	8.9	24.4	2.74	0.00	2.5	3.5
PPT	01/13/93	5.84	54.9	0.00	2.1	10.3	6.8	57.3	2.75	0.00	3.7	2.7
PPT	01 /13/93	5.74	41.5	0.59	1.5	9.6	5.8	47.6	4.00	0.58	4.1	2.8
PPT	01/14/93	5.73	21.4	0.52	0.7	7.2	7.3	25.7	0.73	0.60	2.1	2.8
PPT	01/14/93	5.77	24.1	0.00	0.6	7.9	5.6	21.1	1.26	0.50	2.2	2.7
PPT	02/04/93	6.13	38.8	0.50	1.1	13.7	17.6	50.0	0.00	0.00	2.5	2.4
PPT	02/04/93	7.13	36.5	0.75	1.1	9.6	7.3	41.6	2.01	0.00	2.9	3.0
PPT	02/26/93	5.50	87.0	0.00	2.6	20.6	20.0	79.0	1.00	0.00	6.0	3.0
PPT	02/26/93	5.84	91.3	0.00	5.1	16.5	7.5	42.0	0.00	0.00	7.0	2.6
PPT	03/23/93	6.14	69.4	0.00	4.3	15.9	13.4	45.7	1.42	0.00	6.2	2.6
PPT	04/06/93	5.64	43.5	0.00	2.6	12.3	10.0	44.0	0.00	0.00	5.0	1.6
PPT	04/06/93	5.45	47.8	0.00	2.6	12.3	10.0	44.0	.00	0.00	5.0	2.2
PPT	04/29/93	6.43	47.5	0.00	3.4	15.3	19.3	49.5	2.85	0.00	5.4	2.6
PPT	04/29/93	7.10	47.1	3.64	5.3	17.5	28.6	41.8	0.64	0.00	4.8	2.4
PPT	06/03/93	6.96	37.3	9.40	4.0	17.7	35.8	42.7	0.00	0.56	4.9	7.9
PPT	06/03/93	7.38	49.2	0.00	8.0	17.9	36.7	55.0	0.00	0.00	5.6	7.2
PPT	12/18/93	6.05	28.5	6.20	4.8	15.2	30.4	31.3	0.36	3.86	3.3	0.0
PPT	01 /27/94	5.70	27.5	12.40	8.3	19.4	40.1	33.0	0.72	7.73	3.8	0.0
PPT	01 /27/94	6.40	29.5	0.00	1.4	11.0	20.7	29.5	0.00	0.00	2.7	0.0
PPT	02/18/94	5.95	28.3	0.00	1.0	9.3	8.6	30.5	0.00	0.00	3.8	0.0
PPT	03/18/94	5.65	69.6	0.00	3.8	14.4	8.7	43.0	0.00	0.00	6.0	2.4
PPT	12/06/94	7.06	71.3	0.00	1.8	15.6	9.2	76.2	0.00	0.00	4.9	0.0
PPT	12/06/94	7.28	79.2	0.00	5.1	18.9	20.2	76.8	0.00	0.00	5.6	0.0
PPT	12/18/94	5.60	42.2	0.00	1.3	8.2	11.2	46.3	3.53	0.00	4.4	2.9
PPT	01 /05/95	6.01	23.1	0.00	1.0	9.1	9.0	24.6	0.00	0.00	2.4	0.0
PPT	01/05/95	5.88	33.5	0.00	1.0	9.5	8.2	36.3	0.00	0.00	5.2	0.0
PPT	01/15/95	6.68	67.5	0.00	3.8	19.6	15.7	66.2	0.00	0.00	4.4	2.1
PPT	01 /31 /95	7.12	27.5	3.71	1.0	11.1	26.1	33.1	0.95	0.00	2.1	1.3
PPT	01 /31 /95	7.10	38.4	0.00	18.3	7.8	13.1	31.9	0.00	0.00	2.6	1.5
PPT	02/20/95	7.50	37.2	0.36	1.8	10.2	7.4	77.5	0.00	0.00	6.8	2.2
PPT	02/20/95	7.11	91.0	0.00	5.2	22.7	36.0	44.8	0.00	0.00	4.2	2.0
PPT	03/11/95	7.28	37.7	0.00	18.6	7.8	13.8	17.3	0.00	0.00	1.8	1.4
PPT	03/11/95	7.08	28.8	0.00	22.5	10.3	20.6	69.3	0.00	9.48	6.5	1.9
PPT	12/21/95	6.58	56.3	0.00	3.1	14.2	14.2	56.6	0.00	0.00	5.4	0.0
PPT	01 /20/96	5.36	83.0	0.00	3.3	26.3	22.2	52.1	0.00	0.00	3.7	4.3
PPT	02/11/96	5.80	82.2	0.00	4.1	18.5	19.5	57.9	0.00	0.00	3.5	2.1
PPT	03/10/96	5.95	28.3	0.00	1.0	9.3	8.6	30.5	0.00	0.00	3.8	0.0
PPT	03/30/96	7.30	37.8	0.18	10.0	9.0	10.2	54.7	0.00	0.00	4.7	1.9

Caspar Creek - Canopy Throughfall Chemistry - Watershed MUN

Type	Species	Date	pH	Na μM	NH4 μM	K μM	Mg μM	Ca μM	Cl μM	NO3 μM	PO4 μM	SO4 μM	Si μM
TF	RW	01/29/94	7.14	51.1	0.00	24.5	28.8	57.8	61.7	4.06	2.34	5.6	8.2
TF	RW	01 /29/94	7.26	54.3	0.00	26.0	22.7	38.6	52.8	6.03	2.03	5.2	4.8
TF	RW	01 /29/94	7.60	37.0	5.51	19.0	18.8	36.0	48.7	2.35	2.45	3.5	5.3
TF	RW	02/19/94	6.68	46.2	0.00	16.1	15.6	26.2	65.4	0.00	0.00	3.9	0.0
TF	RW	02/19/94	6.44	45.3	0.00	19.7	11.9	19.5	61.3	0.00	0.00	4.8	0.0
TF	RW	02/19/94	6.86	53.7	0.00	18.7	22.2	29.8	68.0	0.00	0.00	4.8	0.0
TF	RW	12/18/94	6.68	244.5	0.00	234.5	81.5	117.5	374.8	0.00	51.53	21.5	18.9
TF	RW	12/18/94	6.57	242.7	0.00	186.7	86.0	117.5	388.8	0.00	55.55	21.9	10.7
TF	RW	12/18/94	6.56	292.3	0.00	171.9	85.6	86.8	434.1	0.57	46.28	26.4	18.3
TF	RW	01 /05/95	5.78	148.3	0.00	48.3	30.9	33.7	175.8	0.00	5.87	9.9	0.0
TF	RW	01/05/95	6.05	108.3	0.00	50.6	39.1	50.2	135.8	0.00	9.35	6.8	0.0
TF	RW	01/05/95	6.10	107.9	0.00	45.5	31.3	41.9	130.2	0.00	6.75	7.2	0.0
TF	RW	01/14/95	5.59	19.3	0.00	21.4	23.4	30.7	93.8	0:00	0.99	4.8	0.6
TF	RW	01/14/95	5.33	20.7	0.00	18.6	22.5	22.5	90.8	0.00	1.84	5.5	4.7
TF	RW	01/14/95	5.08	20.1	0.00	19.6	9.0	15.5	103.1	0.54	1.27	5.9	0.0
TF	RW	02/07/95	6.53	17.9	7.59	9.4	8.3	13.0	42.8	0.00	1.99	3.3	0.0
TF	RW	02/07/95	6.68	16.0	7.59	8.7	8.1	15.5	38.5	0.00	1.83	2.9	0.0
TF	RW	02/07/95	6.77	20.6	0.16	12.0	6.7	20.6	48.6	0.00	3.21	3.4	0.0
TF	RW	02/19/95	5.58	315.6	8.07	94.3	44.5	38.4	174.8	2.05	5.42	10.8	2.9
TF	RW	02/19/95	5.90	83.3	1.78	51.2	23.5	35.1	139.9	0.58	5.99	10.9	1.6
TF	RW	02/19/95	5.63	101.9	1.07	75.0	29.9	35.5	147.0	0.00	2.22	9.3	2.2
TF	RW	03/11 /95	5.49	81.5	0.00	30.0	18.5	25.5	39.2	0.00	1.39	3.1	2.3
TF	RW	03/11/95	7.13	27.1	2.56	23.7	15.7	32.7	36.8	0.00	2.78	3.1	2.1
TF	RW	03/11/95	5.47	29.8	0.00	23.2	14.8	35.5	44.1	0.00	1.41	3.9	1.9
TF	RW	12/17/95	5.67	404.8	4.36	131.5	68.7	65.6	434.4	0.75	28.08	24.4	0.0
TF	RW	12/17/95	5.65	127.0	0.00	119.2	64.6	112.7	175.8	0.00	15.06	10.5	0.0
TF	RW	12/17/95	5.66	135.7	0.00	126.3	56.8	47.4	200.3	0.00	19.05	10.0	0.0
TF	RW	01/02/96	5.56	42.6	2.86	24.8	40.3	24.9	52.3	1.39	0.00	4.0	0.0
TF	RW	01/02/96	6.54	35.7	0.71	18.7	14.4	19.0	41.1	0.00	0.00	2.8	0.0
TF	RW	01/02/96	5.58	32.2	1.43	15.3	7.8	7.7	35.9	0.00	0.00	3.2	0.0
TF	RW	01/20/96	5.74	113.0	0.00	41.9	47.3	37.2	101.2	0.00	3.54	6.2	5.7
TF	RW	01/20/96	5.86	95.7	0.00	49.4	32.5	36.2	82.8	0.00	5.36	5.4	4.6
TF	RW	01/20/96	5.58	111.7	0.00	46.81	40.3	42.4	108.3	0.00	3.94	6.4	5.3
TF	RW	02/11/96	5.78	107.4	0.00	28.91	44.0	63.81	84.9	0.00	2.46	5.0	1.8
TF	RW	02/11/96	5.78	98.7	0.00	28.4	22.2	35.4	73.8	0.00	0.00	4.5	2.1
TF	RW	02/11/96	5.77	90.0	7.14	33.2	32.1	32.7	90.0	1.69	0.00	10.3	2.1
TF	RW	03/17/96	5.35	65.7	2.86	19.7	17.3	33.9	85.9	1.78	0.00	6.1	0.0
TF	RW	03117/96	5.21	71.3	4.29	22.3	16.9	28.9	101.7	2.49	2.71	6.3	0.0
TF	RW	03/17/96	5.25	65.21	2.86	19.9	16.9	33.4	93.3	2.42	0.00	5.7	0.0
TF	RW	06/20/96	6.36	101.9	0.00	67.2	32.6	51.8	133.6	0.00	10.01	9.4	2.2
TF	RW	06/20/96	6.291	104.9	13.05	68.9	31.4	44.7	136.1	0.00	10.56	11.7	2.5
TF	RW	06/20/96	6.18	134.6	6.75	100.8	43.7	80.1	176.7	0.00	24.86	15.1	0.9

Caspar Creek - Canopy Throughfall Chemistry - Watershed MUN

Type	Species	Date	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	Si
				μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
TF	DF	01/29/94	7.02	102.8	6.23	40.8	27.0	36.5	77.4	5.50	6.90	7.1	6.1
TF	DF	01/29/94	6.89	99.9	8.14	30.3	28.1	30.5	95.3	1.76	5.04	8.0	11.3
TF	DF	01/29/94	7.10	175.5	0.00	61.1	24.3	31.8	133.5	0.00	5.51	11.0	5.3
TF	DF	02/19/94	6.89	131.0	0.00	49.1	22.0	26.5	145.3	0.00	4.08	7.4	0.0
TF	DF	02/19/94	6.51	126.2	3.12	31.4	21.4	28.8	144.7	1.60	1.91	8.1	0.0
TF	DF	02/19/94	6.60	103.1	0.00	32.3	24.9	79.5	114.0	2.65	3.89	7.1	0.0
TF	DF	12/18/94	6.35	762.5	0.00	193.9	148.9	107.0	946.6	0.00	61.73	60.7	0.0
TF	DF	12/18/94	6.13	1048.7	0.00	227.1	183.9	124.0	1396.6	37.01	93.39	114.0	2.4
TF	DF	12/18/94	6.67	816.0	0.00	293.1	146.9	106.5	1013.8	0.00	68.48	59.2	0.4
TF	DF	01/05/95	5.59	283.6	0.00	61.6	62.5	86.8	335.1	0.00	8.79	17.4	0.0
TF	DF	01/05/95	5.76	311.9	0.00	74.7	52.3	39.4	351.4	0.00	7.59	16.7	0.0
TF	DF	01/05/95	6.49	342.6	0.00	61.3	47.9	38.2	389.0	0.00	4.91	20.5	0.0
TF	DF	01/14/95	5.58	36.0	0.00	31.4	22.7	24.5	124.4	0.00	2.16	6.7	0.0
TF	DF	01/14/95	5.59	23.6	0.00	53.9	20.1	18.2	103.4	0.00	2.55	5.9	0.0
TF	DF	01/14/95	5.69	111.1	1.64	21.1	20.2	26.0	117.5	0.00	2.33	6.0	0.0
TF	DF	02/07/95	6.26	109.4	0.39	17.7	11.0	13.7	71.2	0.00	3.96	4.2	0.0
TF	DF	02/07/95	6.51	35.8	0.69	13.7	9.4	15.0	54.7	0.00	4.99	4.1	0.0
TF	DF	02/19/95	5.51	201.1	0.00	76.3	39.0	32.2	438.7	0.00	9.63	16.3	5.0
TF	DF	02/19/95	5.34	514.1	0.00	102.2	75.3	191.2	368.6	0.00	8.58	17.3	5.3
TF	DF	02/19/95	5.17	251.8	1.64	84.2	42.5	43.8	291.6	0.00	10.45	13.4	4.5
TF	DF	03/11/95	5.45	355.9	0.00	88.8	68.4	204.6	75.5	0.78	4.26	5.1	2.5
TF	DF	03/11/95	5.58	80.6	0.00	29.8	18.6	24.8	88.0	0.00	4.45	4.8	1.9
TF	DF	03/11/95	5.87	403.9	0.00	20.7	88.2	138.2	49.1	0.00	3.05	3.5	2.6
TF	DF	12/17/95	5.46	407.4	0.00	65.4	65.8	57.9	432.8	0.00	15.30	24.8	0.0
TF	DF	12/17/95	5.66	165.2	0.00	107.4	49.0	50.9	217.4	0.00	21.15	10.1	0.0
TF	DF	12/17/95	5.51	305.7	0.00	111.5	59.7	66.3	283.9	0.58	25.18	21.1	0.0
TF	DF	01/02/96	5.41	113.9	0.00	19.7	17.3	17.7	84.0	0.00	0.00	5.9	0.0
TF	DF	01/02/96	5.61	92.6	0.00	24.8	15.2	19.5	65.5	0.00	0.00	5.7	0.0
TF	DF	01/02/96	5.48	83.0	0.71	28.4	32.5	43.6	73.1	0.00	2.00	4.7	0.0
TF	DF	01/20/96	5.39	310.9	0.00	50.6	67.5	30.2	292.8	0.00	2.56	15.0	5.0
TF	DF	01/20/96	5.54	253.5	0.00	57.3	41.6	38.7	217.1	0.00	4.64	10.9	5.7
TF	DF	01/20/96	5.53	213.0	0.00	48.1	46.9	58.4	195.9	0.00	4.27	10.6	6.0
TF	DF	02/11/96	5.74	208.3	0.00	36.3	31.3	34.2	160.6	0.00	1.32	9.4	2.1
TF	DF	02/11/96	5.83	163.0	0.00	32.5	35.4	41.4	121.7	0.00	1.47	7.3	2.8
TF	DF	02/11/96	5.60	213.9	0.00	32.7	43.2	35.2	173.2	0.00	1.57	9.9	3.6
TF	DF	03/17/96	5.56	170.0	0.00	27.1	23.9	32.7	167.4	1.08	0.00	9.1	0.0
TF	DF	03/17/96	5.61	153.5	0.00	36.3	33.3	67.1	158.8	0.00	4.23	8.5	0.0
TF	DF	03/17/96	5.58	196.1	0.00	36.3	62.1	50.4	179.3	0.00	0.00	10.0	0.0
TF	DF	06/20/96	6.13	413.0	0.00	99.3	76.3	72.4	545.0	0.00	8.88	28.1	1.3
TF	DF	06/20/96	6.38	319.6	0.00	78.9	63.0	57.4	368.3	0.00	10.02	21.9	1.4
TF	DF	06/20/96	5.98	394.7	0.00	79.3	76.3	69.5	523.5	0.00	10.66	29.8	3.2

Caspar Creek - Watershed AEI

#	DATE	TIME	Streamflow	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
1	04/16/92	22:25	85.9	7.33	437.4	0.00	26.3	149.0	257.6	386.0	0.00	0.11	76.8	737.1	278.5
2	04/16/92	23:25	110.5	7.55	428.2	0.00	25.3	149.0	253.9	368.4	0.00	0.00	78.8	733.4	270.8
3	04/17/92	00:25	110.5	7.40	441.8	0.00	25.8	153.5	268.4	353.7	0.00	0.00	76.5	804.8	279.7
4	04/17/92	01:25	138.1	7.46	460.1	0.00	26.5	157.4	274.9	392.4	0.00	0.12	77.6	803.6	286.9
5	04/17/92	02:25	138.1	7.48	464.1	0.00	27.6	158.0	268.6	367.2	0.54	0.08	74.6	827.9	294.3
6	04/17/92	03:25	168.3	7.30	438.6	0.00	25.9	158.6	270.0	404.8	0.00	0.14	77.8	761.1	289.9
7	04/17/92	04:25	168.3	7.30	477.6	0.00	25.8	156.0	265.1	390.3	0.00	0.00	76.4	802.5	293.3
8	04/17/92	05:25	201.2	7.54	469.9	0.00	26.0	156.4	256.8	431.9	0.00	0.10	76.5	737.4	293.2
9	04/17/92	06:25	201.2	7.47	466.7	0.00	25.3	150.3	247.2	420.0	11.80	0.00	75.5	704.3	292.8
10	04/17/92	07:25	201.2	7.43	481.7	0.00	26.7	153.1	257.6	398.6	3.06	0.15	74.1	779.7	299.6
11	04/17/92	08:25	201.2	7.55	483.2	0.00	26.2	151.5	254.8	394.2	4.71	0.00	74.4	774.4	298.4
12	04/17/92	09:25	201.2	7.52	490.3	0.00	26.5	151.4	255.5	411.0	4.32	0.00	74.3	766.7	297.1
13	04/17/92	10:15	201.2	7.42	478.51	0.00	26.4	150.9	254.3	406.5	6.23	0.00	74.9	752.7	297.5

Caspar Creek - Watershed DOL

#	DATE	TIME	Streamwater	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
61	06/29/94	10:28	3.4	7.52	602.8	0.00	37.2	204.9	338.4	534.6	0.00	0.00	107.5	977.0	343.6
62	10/05/94	12:53	3.4	7.17	732.3	0.00	31.4	241.0	421.7	451.2	0.00	0.00	104.0	1429.8	268.2
63	11/02/94	15:20	2.8	7.25	714.6	0.00	30.4	250.5	429.5	498.8	0.00	0.00	107.7	1390.9	267.6
64	12/06/94	13:45	6.8	7.22	605.5	0.00	30.2	234.6	401.2	557.2	5.89	0.00	134.6	1075.0	278.6
65	01/03/95	14:47	17.0	7.48	518.9	0.00	25.1	151.0	241.0	452.3	9.09	0.00	104.4	657.9	280.8
66	02/01/95	15:00	90.4	6.48	383.7	7.21	22.4	86.4	150.11	404.9	6.50	0.00	42.8	389.3	289.7
67	03/01/95	14:03	7.6	6.64	511.8	0.00	24.8	134.1	226.5	456.3	34.43	0.00	91.4	584.2	312.8
68	04/05/95	12:10	11.0	7.24	472.5	0.58	26.1	138.8	239.31	471.8	1.33	0.00	64.7	652.9	313.0
69	05/05/95	13:30	22.7	6.88	468.7	0.00	23.4	131.2	227.6	388.1	0.00	0.00	54.9	711.8	319.6
70	06/05/95	13:52	6.8	7.56	549.4	0.00	26.4	159.7	268.9	484.8	0.82	0.00	65.5	816.4	314.1
71	11/01/95	12:00	missing	7.31	604.3	0.00	28.6	224.3	387.0	380.7	0.00	1.36	99.5	1274.5	249.8
72	12/05/95	12:00	missing	7.40	711.3	0.00	35.8	232.1	363.3	492.3	0.00	0.00	110.6	1224.5	254.4
73	01/11/96	12:00	missing	7.46	650.9	0.00	36.3	160.1	264.8	457.7	0.00	0.00	86.2	906.8	436.3
74	02/09/96	12:51	33.0	7.37	465.1	0.00	22.8	129.0	209.5	386.6	0.00	0.00	71.8	634.8	343.4
75	03/19/96	13:00	22.7	7.29	476.5	0.00	22.6	132.7	215.7	334.0	0.00	0.00	73.9	714.1	336.7
76	04/03/96	13:13	22.7	7.35	493.7	0.00	23.3	143.8	228.0	374.4	0.00	0.00	78.8	728.5	334.9
77	05/08/96	10:13	8.4	7.58	512.2	0.00	22.9	152.6	240.7	532.9	0.00	0.00	85.0	618.9	337.7

Caspar Creek - Watershed EAG

#	DATE	TIME	Streamflow	pH	Na	NH4	K	M	Ca	Cl	NO3	PO4	SO4	HCO3	Si
					μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
61	05/12/93	12:10	6.6	6.97	562.4	0.00	31.7	144.8	246.3	424.7	0.00	0.00	94.1	763.3	283.2
62	05/27/93	12:50	17.9	7.16	583.4	0.00	27.3	148.8	249.2	382.2	0.00	0.00	73.3	878.0	284.2
63	06/09/93	12:40	10.4	7.18	578.6	0.00	28.0	141.7	239.8	423.8	0.00	0.00	93.7	758.3	306.5
64	07/02/93	14:40	6.1	7.16	634.4	0.00	29.9	164.2	275.3	469.8	0.00	0.57	105.0	862.9	300.2
65	07/22/93	15:45	5.5	7.14	663.1	0.00	31.4	185.9	305.0	520.5	0.00	0.00	109.3	937.1	305.2
66	08/10/93	13:30	3.5	7.07	682.6	0.00	32.8	196.8	323.9	478.4	0.00	0.00	115.4	1047.7	303.5
67	09/07/93	13:07	2.7	7.34	723.2	0.00	34.5	214.0	349.2	565.9	0.00	0.54	124.6	1068.4	304.0
68	12/29/93	14:05	3.5	7.32	598.0	0.00	36.1	176.4	278.1	490.0	12.62	0.00	129.2	782.0	291.1
69	02/02/94	12:10	9.1	7.10	533.1	0.00	26.2	135.4	226.7	383.6	14.41	0.00	98.2	689.0	292.6
70	03/16/94	13:50	7.8	6.58	579.3	0.00	31.1	157.5	248.7	396.4	0.00	0.00	105.6	815.1	276.0
71	05/18/94	13:15	6.1	7.35	595.0	0.00	40.9	172.4	275.3	415.7	0.00	0.00	113.7	888.2	290.4
72	06/29/94	10:51	5.5	7.62	611.6	0.00	88.9	197.3	307.2	580.8	0.00	0.00	122.1	884.5	269.1
73	12/06/94	14:11	6.6	7.25	578.5	0.00	30.2	168.3	274.7	508.6	16.20	0.00	121.4	727.2	286.4
74	01/03/95	14:31	11.8	7.16	492.0	0.00	26.1	133.7	205.1	408.2	17.57	0.00	99.9	570.1	272.6
75	02/01/95	15:45	43.3	6.55	397.3	0.00	21.0	100.3	180.3	280.8	21.85	0.83	54.8	566.5	274.2
76	03/01/95	14:56	6.1	6.67	474.9	0.00	22.9	146.5	265.2	399.8	52.20	0.00	95.3	678.6	299.1
77	04/05/95	12:10	9.1	7.14	453.0	0.00	25.9	126.3	204.2	346.1	8.65	0.00	73.3	638.5	291.3
78	05/05/95	12:41	16.3	7.02	443.4	0.00	24.3	114.0	192.6	307.5	4.34	0.00	64.1	641.0	293.2
79	06/05/95	13:33	6.6	7.56	527.4	0.00	28.0	145.2	235.1	413.2	4.32	0.00	72.0	754.7	298.2
80	11/01/95	12:00	missing	7.29	622.6	2.14	32.0	291.4	469.6	388.4	4.30	0.00	100.7	1584.4	260.9
81	12/05/95	12:00	missing	7.30	755.2	0.00	38.1	258.0	381.5	506.7	0.00	0.00	118.3	1329.2	267.6
82	01/11/96	12:00	missing	7.39	622.2	0.00	37.1	142.4	221.9	358.7	0.00	0.00	92.2	844.9	438.1
83	02/09/96	13:01	16.3	7.29	424.4	0.00	22.7	110.2	197.0	224.6	0.00	0.00	76.3	684.2	319.6
84	03/19/96	12:49	16.3	7.31	437.2	0.00	22.9	108.7	169.6	291.7	0.00	0.00	77.6	570.0	318.9
85	04/03/96	13:34	13.2	7.30	466.6	0.00	23.7	127.9	196.3	282.2	0.00	0.00	80.5	695.5	310.3
86	05/08/96	10:23	7.8	7.46	492.4	0.00	24.5	133.1	202.9	376.9	0.00	0.00	83.6	645.0	328.1

Caspar Creek - Watershed GIB

#	DATE	TIME	Streamflow	pH	Na	NH4	K	M	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
71	12/29/93	13:07	1.2	7.48	505.3	0.00	21.0	179.4	305.9	384.4	0.00	0.83	106.8	898.0	310.4
72	12/29/93	13:40	2.8	7.36	515.5	0.00	23.5	191.2	304.0	387.5	0.84	0.63	92.6	955.2	331.0
73	02/02/94	10:10	4.9	7.50	463.8	0.00	24.6	141.0	229.5	347.6	4.17	0.00	69.5	738.6	316.2
74	03/16/94	13:05	4.9	6.62	503.6	0.00	27.9	164.3	256.0	338.3	0.00	0.00	73.6	886.5	304.0
75	04/13/94	13:10	2.8	7.90	550.8	0.00	30.3	191.4	301.8	387.5	0.00	0.00	81.2	1017.6	307.2
76	05/18/94	13:45	3.5	7.43	511.5	0.00	35.4	186.8	290.0	358.9	0.00	0.00	76.1	989.0	308.2
77	06/29/94	14:45	3.5	7.56	521.7	0.00	29.0	211.8	330.8	405.7	0.00	0.00	83.9	1062.4	292.5
78	10/05/94	12:46	1.7	7.12	590.3	0.00	27.0	280.8	472.8	360.5	0.77	0.00	98.6	1566.0	304.8
79	11/02/94	14:05	2.8	7.59	613.2	0.00	26.5	299.8	509.8	362.6	0.00	0.00	108.2	1680.0	316.4
80	12/06/94	12:46	4.2	7.22	506.3	0.00	26.3	191.7	314.4	416.3	1.51	0.00	95.9	935.3	302.6
81	01/03/95	13:37	8.7	7.44	431.1	0.00	23.5	144.0	217.6	357.7	3.76	0.00	76.2	663.9	278.6
82	02/01/95	12:43	29.5	6.62	535.3	0.00	23.7	128.3	216.1	264.9	5.55	0.00	46.6	884.1	281.4
83	03/01/95	14:20	5.7	6.66	449.8	0.00	22.9	175.3	319.4	358.3	0.00	0.00	82.5	938.8	315.1
84	04/05/95	10:03	9.2	7.02	395.5	0.00	24.0	121.2	192.4	311.2	0.00	0.00	58.1	619.3	295.8
85	05/05/95	10:54	12.2	7.12	395.2	0.00	22.4	115.8	184.3	305.6	0.00	0.00	50.7	610.9	298.4
86	06/05/95	11:48	5.7	7.48	461.8	0.00	24.7	151.8	238.2	365.8	1.03	0.00	52.4	794.9	305.3
87	11/01/95	12:00	missing	7.28	560.4	0.00	29.7	261.3	443.1	360.1	0.96	0.00	77.5	1483.0	255.5
88	12/05/95	12:00	missing	7.44	637.0	0.00	32.0	279.4	439.9	411.5	0.00	0.00	122.4	1451.2	303.6
89	01/11/96	12:00	missing	7.32	544.3	0.00	35.0	148.1	227.2	328.3	0.00	0.00	72.2	857.4	423.5
90	02/09/96	12:00	14.3	7.35	389.0	0.00	22.1	113.5	168.3	276.6	0.00	0.00	54.1	590.0	319.2
91	03/19/96	11:19	9.2	7.48	395.3	0.00	21.8	114.1	168.8	241.4	0.00	0.00	72.0	597.6	308.9
92	04/03/96	12:45	8.3	7.63	418.6	0.00	22.4	129.1	190.0	265.2	0.00	0.00	73.2	667.6	314.9
93	05/08/96	10:52	missing	7.61	411.8	0.00	21.0	136.2	210.9	367.5	0.00	0.00	73.7	612.1	331.0

Caspar Creek - Watershed HEN

#	DATE	TIME	Streamflow	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
1	04/24/91	11:30	<1	7.33	636.0	0.00	27.0	169.0	242.0	589.0	0.00	0.00	106.0	684.0	missing
2	05/01/91	10:55	<1	7.26	621.0	0.00	27.0	163.0	241.0	580.0	0.00	0.20	108.0	659.8	missing
3	02/05/92	12:20	<1	7.07	643.9	0.00	24.2	174.9	253.3	649.7	0.15	0.38	87.2	699.8	228.7
4	02/13/92	14:05	16.5	7.12'	533.5	0.00	24.3	135.8	193.8	611.6	0.00	0.10	58.4	488.4	225.3
5	12/30/92	13:45	22.2	7.15	548.5	0.00	30.4	133.3	212.3	584.2	0.00	0.00	67.7	550.5	243.4
6	01/12/93	11:05	12.3	7.32	609.3	0.00	26.4	149.6	229.4	660.7	0.00	0.00	73.1	586.6	255.5
7	03/24/93	13:50	13.9	7.41	652.5	0.00	30.7	164.5	247.0	641.0	0.00	0.00	81.0	703.2	266.4
8	04/07/93	12:55	<1	7.45	687.3	0.00	25.6	160.4	247.0	616.0	0.00	0.00	91.0	729.7	267.6
9	05/27/93	13:50	13.9	6.60	650.2	0.00	27.9	158.4	265.6	511.5	0.00	0.00	79.0	856.4	273.6
10	02/01/95	14:03	missing	6.55	367.6	0.00	21.1	110.2	206.4	576.5	0.00	0.00	59.2	327.1	263.3
11	01/11/96	12:00	missing	7.44	750.9	0.00	36.6	139.5	250.4	657.7	0.00	0.00	98.6	712.3	316.4
12	03/19/96	10:53	missing	7.16	564.1	0.00	24.3	142.8	251.9	597.8	0.00	0.00	82.9	614.3	290.0
13	04/03/96	10:46	missing	7.44	585.4	0.00	25.1	148.1	221.6	599.5	0.00	0.00	83.6	583.3	292.5
14	05/07/96	15:50	missing	7.41	607.5	0.00	24.8	156.5	233.3	774.3	0.00	0.00	107.2	423.4	303.6

Caspar Creek - Watershed JOH

#	DATE	TIME	Streamflow	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
1	04/10/91	10:15	2.8	7.56	485.0	0.00	24.0	114.0	159.0	453.0	11.70	0.00	73.0	444.3	missing
2	04/16/91	10:54	0.0	7.12	520.0	0.00	23.0	119.0	163.0	482.0	5.90	0.00	78.0	463.1	missing
3	05/01/91	09:51	2.3	7.36	513.0	0.00	25.0	122.0	174.0	473.0	1.00	0.00	79.0	498.0	missing
4	02/05/92	11:00	2.8	6.99	532.7	0.00	21.8	126.4	179.2	380.2	3.36	0.16	69.7	642.6	249.4
5	02/13/92	12:00	35.7	7.25	432.7	0.00	20.6	98.4	144.6	410.4	20.78	0.00	55.5	397.3	231.7
6	03/04/92	11:45	5.3	7.03	515.6	0.00	22.8	110.5	159.1	598.5	0.00	0.00	72.2	334.8	271.7
7	03/11/92	10:12	6.1	7.50	611.6	0.00	24.7	117.2	259.2	447.1	0.93	0.00	69.7	801.6	269.3
8	03/25/92	12:25	6.1	7.15	474.9	0.00	23.5	108.4	156.5	477.5	0.00	0.00	60.7	429.5	269.7
9	04/01/92	10:30	4.0	7.23	536.8	0.00	26.5	121.4	172.1	460.5	0.00	0.00	66.5	556.9	276.5
10	04/08/92	09:40	0.9	7.55	506.8	0.00	23.5	118.8	168.8	478.0	0.24	0.00	69.6	488.0	267.2
11	04/16/92	10:10	2.8	6.48	563.7	0.00	28.7	132.2	200.4	492.9	0.00	0.00	74.5	615.7	283.0
12	04/23/92	11:19	6.8	7.27	543.0	0.00	27.2	122.8	186.8	445.5	0.00	0.00	71.2	601.5	276.5
13	04/29/92	10:50	0.9	7.32	547.8	0.00	28.5	126.9	189.1	471.1	0.54	0.14	75.7	584.9	280.8
14	05/06/92	10:20	0.9	7.28	519.2	0.00	26.3	135.9	196.6	480.9	0.00	0.21	77.0	575.4	295.6
15	05/21/92	12:40	0.0	6.88	527.5	0.00	24.1	141.3	201.0	496.3	0.00	0.21	76.1	587.6	295.3
16	12/02/92	12:01	0.3	7.23	587.2	0.00	30.7	172.8	249.5	531.0	0.00	0.00	85.0	761.4	314.6
17	12/16/92	12:50	6.8	6.94	435.0	0.00	22.3	105.3	152.9	407.0	3.00	0.00	64.0	435.7	298.1
18	12/29/92	11:30	44.6	6.77	436.7	0.00	21.5	104.5	160.4	388.2	0.00	0.00	56.9	486.0	237.8
19	01/12/93	12:50	27.7	7.25	479.8	0.00	23.3	100.4	154.1	418.3	3.85	0.00	49.2	491.7	253.2
20	02/17/93	11:55	9.3	7.28	475.8	0.00	29.2	106.6	166.4	377.8	0.00	0.00	58.8	555.5	244.2
21	03/03/93	11:10	8.4	7.48	508.9	0.00	23.0	115.2	174.7	425.0	0.00	0.00	56.0	574.6	269.7
22	03/24/93	11:35	35.7	7.41	491.5	0.00	23.0	111.1	172.2	405.0	0.00	0.00	54.0	568.0	263.6
23	04/07/93	11:26	16.0	7.52	530.7	0.00	23.0	123.4	184.6	408.0	0.00	0.00	63.0	635.8	277.8
24	04/28/93	10:45	13.9	6.90	503.6	0.00	22.9	119.5	201.3	402.6	0.00	0.00	59.1	647.4	276.8
25	05/12/93	11:35	5.3	7.01	530.4	0.00	27.2	126.9	210.9	438.9	0.00	0.00	62.9	668.6	275.7
26	05/24/93	10:13	4.0	7.15	599.0	0.00	23.5	136.8	225.9	469.5	0.00	0.57	68.7	740.2	291.6
27	05/27/93	11:45	27.7	7.19	522.1	0.00	23.7	128.9	218.7	365.5	0.00	0.51	55.4	764.4	272.4
28	06/09/93	10:15	12.0	7.23	540.7	0.00	32.5	125.9	211.2	407.3	0.00	0.00	61.6	716.8	288.0
29	07/01/93	10:50	6.8	7.29	596.1	0.00	23.7	138.7	231.3	491.3	0.00	0.00	69.9	728.9	276.3
30	07/22/93	14:39	6.8	7.49	618.2	0.00	25.1	146.0	241.9	528.4	0.00	0.00	72.6	745.6	294.5
31	08/10/93	09:25	4.0	7.07	635.6	0.00	27.0	156.1	254.5	481.6	0.46	0.00	72.6	856.7	297.8
32	02/02/94	10:48	2.8	7.20	514.8	0.00	21.8	121.6	197.6	395.3	0.44	0.00	72.2	635.1	275.7
33	03/16/94	10:45	2.8	6.58	535.6	0.00	23.9	138.7	216.1	452.5	0.00	0.00	72.3	671.9	272.3
34	04/13/94	10:10	2.8	7.79	615.3	0.00	25.7	156.3	236.2	479.4	0.00	0.00	82.7	781.3	281.7
35	05/18/94	10:13	2.8	7.45	563.1	0.00	48.9	152.4	238.2	427.5	0.00	0.00	81.4	802.9	284.3
36	06/29/94	10:57	0.0	7.53	579.4	0.00	74.0	167.3	255.9	594.5	0.00	0.00	82.8	739.7	259.8
37	12/06/94	10:33	0.0	7.24	574.6	0.00	24.8	153.9	233.8	582.2	0.00	0.00	100.4	591.8	252.0
38	01/03/95	11:20	6.1	7.15	493.7	0.00	21.5	125.5	188.6	430.6	0.00	0.00	85.1	542.6	251.4
39	02/01/95	13:31	71.4	6.71	504.3	0.00	21.6	119.3	185.5	355.0	0.64	0.00	41.0	697.8	245.5
40	03/01/95	11:08	5.3	6.92	495.4	0.00	21.7	113.3	183.9	451.9	0.00	0.00	81.4	497.0	286.2
41	04/05/95	10:04	0.0	6.90	449.2	0.00	22.8	109.7	176.6	435.8	0.00	0.00	51.6	505.7	278.7
42	11/01/95	12.10	missing	7.42	673.0	0.00	26.3	170.4	259.9	562.8	0.00	0.00	83.3	830.4	258.0
43	12/05/95	12:00	missing	7.40	744.3	0.00	32.5	196.7	288.0	626.9	0.00	0.00	96.8	925.8	241.6
44	01/11/96	12:00	missing	7.21	607.4	0.00	33.2	154.7	187.3	434.9	0.75	0.00	66.9	755.2	432.7
45	02/09/96	11:10	18.1	7.30	439.9	0.00	20.8	101.5	154.5	392.9	0.00	0.00	41.5	496.9	281.5
46	03/19/96	10:26	10.1	7.27	443.5	0.00	20.4	103.8	158.0	346.2	0.00	0.00	43.6	553.9	289.0
47	04/03/96	10:45	12.0	7.20	465.8	0.00	21.2	117.4	182.8	343.1	0.00	0.00	49.9	644.4	296.4
48	05/07/96	15:00	0.9	7.56	481.8	0.00	20.9	117.5	176.3	502.3	0.00	0.00	68.4	451.1	322.4

Caspar Creek - Watershed KJE

#	DATE	TIME	Streamflow	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
			L/s		µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM
491	01/27/96	10:20	35.05	7.44	450.9	0.00	29.7	94.2	129.9	175.1	0.00	0.00	53.1	647.6	240.2
492	01/27/96	11:20	35.05	7.38	444.3	0.00	29.7	93.8	127.7	174.3	0.00	0.00	51.5	639.7	233.5
493	01/27/96	12:20	33.25	7.36	448.3	0.00	29.9	94.2	128.9	181.7	0.00	0.00	\$2.2	638.5	234.2
494	01/27/96	13:20	33.25	7.19	453.9	0.00	30.2	94.7	129.4	181.8	0.00	0.00	52.8	644.9	242.7
495	01/27/96	14:20	33.25	7.18	468.7	0.00	30.2	94.2	130.4	187.3	0.00	0.00	53.3	654.2	243.4
496	01/27/96	15:20	33.25	7.26	455.7	0.00	29.9	93.8	129.9	180.9	0.00	0.00	53.9	644.4	242.0
497	01/27/96	16:20	33.25	7.35	440.9	0.00	29.9	94.2	127.9	171.3	0.00	0.00	51.0	641.7	232.7
498	01/27/96	17:20	31.49	7.38	457.0	0.00	29.9	93.4	132.4	182.4	0.00	0.00	54.0	648.2	246.6
499	01/27/96	18:20	31.49	7.37	459.1	0.00	29.9	93.8	132.2	182.0	0.00	0.00	53.6	651.9	242.7
500	01/27/96	19:20	31.49	7.26	454.8	0.00	29.9	94.7	131.9	183.7	0.00	0.00	53.9	646.3	244.5
501	01/27/96	20:20	31.49	7.29	462.6	0.00	29.7	93.4	129.4	180.3	0.00	0.00	52.5	652.7	241.3
502	01/27/96	21:20	31.49	7.33	461.7	0.00	29.9	93.8	129.9	183.4	0.00	0.00	58.1	639.5	247.7
503	01/27/96	22:20	29.77	7.29	465.2	0.00	29.4	95.1	129.9	190.6	0.00	0.00	55.1	643.8	245.6
504	01/27/96	23:20	28.08	7.39	468.7	0.00	30.2	94.7	131.9	194.8	0.00	0.00	64.3	648.6	243.4
505	02/10/96	10:48	11.97	7.16	416.3	0.00	19.1	95.8	143.5	228.3	0.00	0.00	59.1	567.4	270.8
506	02/19/96	14:22	38.74	7.06	424.8	0.00	20.2	82.7	130.2	178.2	10.40	0.00	49.3	583.6	224.6
507	02/19/96	15:22	44.51	6.91	427.4	0.00	18.9	84.0	131.2	179.1	14.49	0.00	50.4	592.2	226.0
508	02/19/96	16:22	50.56	7.03	432.2	0.00	19.2	81.1	125.2	179.4	11.58	0.00	50.3	572.3	224.9
509	02/19/96	17:22	56.88	7.10	427.0	0.00	19.2	83.0	133.4	178.3	16.53	0.00	49.5	585.1	223.1
510	02/19/96	18:22	63.46	7.09	428.7	0.00	19.4	81.1	125.9	176.9	10.12	0.00	49.2	576.8	220.3
511	02/19/96	19:22	70.29	7.10	430.9	0.00	19.2	84.8	137.4	177.7	15.09	0.00	48.8	604.1	223.1
512	02/19/96	20:22	77.36	7.06	435.2	0.00	19.2	86.4	134.2	182.5	15.60	0.00	49.8	597.8	231.3
513	02/19/96	21:22	84.68	7.01	438.7	0.00	19.7	90.9	159.6	185.3	11.50	0.00	50.8	661.1	231.7
514	02/19/96	22:22	89.68	6.80	442.2	0.00	19.3	85.6	162.1	182.9	6.97	0.00	49.6	667.7	230.2
515	02/19/96	23:22	97.38	6.74	422.6	0.00	18.7	83.5	116.7	184.1	30.61	0.00	49.1	528.9	226.3
516	02/20/96	00:22	94.79	6.97	423.0	0.00	19.9	80.2	118.2	176.7	22.31	0.00	50.4	540.1	228.8
517	02/20/96	01:22	92.22	7.04	426.1	0.00	21.0	76.5	124.7	188.2	19.89	0.00	50.1	541.3	230.2
518	02/20/96	02:22	87.17	7.05	423.5	0.00	19.9	78.6	123.9	181.4	18.29	0.00	49.2	550.4	232.4
519	02/20/96	03:22	82.21	7.05	422.6	0.00	19.9	77.8	124.4	183.3	23.17	0.00	50.5	539.4	230.6
520	02/20/96	04:22	77.36	7.07	425.7	0.00	19.9	79.0	125.2	189.9	27.21	0.00	50.3	536.3	242.0
521	02/20/96	05:22	72.62	6.97	426.1	0.00	19.4	79.0	124.2	197.4	19.30	0.00	51.6	532.1	241.3
522	02/20/96	06:22	67.98	7.09	436.5	0.00	20.7	79.4	126.9	199.4	17.51	0.00	51.0	551.2	244.1
523	02/20/96	07:22	63.46	7.25	426.1	0.00	18.9	84.0	135.2	193.5	9.19	0.00	50.6	579.4	243.4
524	02/20/96	08:22	59.04	7.01	425.2	0.00	18.9	79.4	125.2	186.4	10.74	0.00	50.0	556.2	240.6
525	02/20/96	09:22	54.74	7.22	428.7	0.00	19.4	81.9	135.2	193.1	11.51	0.00	52.4	572.9	240.6
526	02/20/96	10:22	50.56	7.07	432.2	0.00	19.4	79.4	127.4	194.0	10.66	0.00	50.9	558.8	244.8
527	02/20/96	11:22	46.49	6.98	421.7	0.00	18.7	81.1	153.6	199.8	13.01	0.00	51.4	594.2	246.3
528	02/20/96	12:22	42.55	7.11	427.8	0.00	19.4	81.1	129.2	195.8	0.00	0.00	51.8	568.5	249.5
529	02/20/96	13:22	38.74	7.14	438.7	0.00	18.7	81.5	130.2	201.4	5.93	0.00	51.8	569.8	245.9
530	03/19/96	10:07	4.52	7.16	445.2	0.00	19.8	100.7	156.1	263.7	0.00	0.00	56.2	602.7	276.5
531	04/03/96	10:20	8.47	7.18	451.4	0.00	19.6	108.9	158.1	251.5	0.00	0.00	60.0	633.4	274.4
532	05/07/96	14:45	2.89	7.68	483.8	0.00	19.8	115.4	173.5	400.9	0.00	0.00	84.7	511.2	322.8

Caspar Creek - Watershed KJE – Pipeflow

#	ID	DATE	TIME	Flow	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	HCO3	Si
				L/s		μM	μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
141	4K20103T	12/09/92	03:05	2.21	6.84	418.9	0.00	26.3	68.3	77.8	285.0	55.00	0.00	55.0	287.5	236.7
142	4K20106T	12/09/92	06:05	1.80	6.97	430.2	0.00	26.1	71.6	79.8	285.0	54.00	0.00	55.0	310.1	191.0
143	4K20109T	12/09/92	09:05	1.60	6.85	435.0	0.00	24.6	73.2	80.6	301.0	55.00	0.00	57.0	297.1	186.8
144	4K20112T	12/09/92	12:05	1.47	6.99	444.1	0.00	27.6	75.7	83.6	313.0	52.00	0.00	56.0	313.3	190.5
145	4K20115T	12/09/92	15:05	1.33	6.85	438.5	0.00	25.1	75.7	83.1	322.0	46.00	0.00	56.0	301.1	197.3
146	4K20118T	12/09/92	18:05	1.18	6.95	458.0	0.00	25.8	79.4	87.8	332.0	47.00	0.00	59.0	321.3	195.6
147	4K20121T	12/09/92	21:05	1.29	7.09	458.5	0.00	25.6	79.0	87.6	344.0	45.00	1.00	58.0	311.1	202.5
148	4K20124T	12/10/92	00:05	1.48	7.03	446.7	0.00	23.8	77.7	85.3	327.0	39.00	0.00	57.0	316.7	208.3
149	5K20103T	12/10/92	19:05	3.30	6.87	403.7	0.00	25.8	68.3	79.1	268.0	44.00	0.00	54.0	304.2	203.8
150	5K20106T	12/10/92	22:05	2.42	7.00	412.8	0.00	25.1	70.3	79.6	279.0	42.00	0.00	55.0	306.7	172.0
151	5K20109T	12/11/92	01:05	1.74	6.89	423.2	0.00	24.3	73.2	81.8	296.0	39.00	0.00	56.0	310.6	178.7
152	5K20112T	12/11/92	04:05	1.41	7.04	436.3	0.00	24.8	75.3	82.8	308.0	34.00	0.00	57.0	321.3	182.6
153	5K20115T	12/11/92	07:05	1.17	7.07	440.6	0.00	25.1	77.3	84.8	319.0	35.00	0.00	58.0	320.0	188.6
154	5K20118T	12/11/92	10:05	1.14	6.95	447.6	0.00	24.6	78.6	86.1	344.0	34.00	0.00	59.0	305.4	193.2
155	5K20121T	12/11/92	13:05	1.14	6.81	445.8	0.00	24.3	79.4	85.8	324.0	28.00	0.00	59.0	330.6	198.6
156	6K20102	12/29/92	16:55	1.29	6.83	532.0	0.00	24.6	79.8	63.9	345.7	20.90	0.00	69.0	339.3	242.4
157	6K20104	12/29/92	17:55	1.29	6.63	552.8	0.00	25.3	82.7	91.1	375.1	7.10	0.00	68.6	406.3	231.1
158	6K20106	12/29/92	18:55	1.29	6.86	481.5	0.00	22.0	83.1	95.6	360.0	0.00	0.00	67.0	366.8	231.3
159	6K20108	12/29/92	19:55	1.28	6.81	485.9	0.00	22.3	82.7	95.3	371.7	0.60	0.00	67.8	356.2	228.2
160	6K20110	12/29/92	20:55	1.26	6.75	503.3	0.00	24.0	82.7	91.6	357.2	0.60	0.00	69.0	360.0	241.1
161	6K20112	12/29/92	21:55	1.24	6.90	518.1	0.00	23.0	88.4	106.0	366.2	1.00	0.00	69.0	424.8	229.3
162	6K20114	12/29/92	22:55	1.22	6.62	448.9	0.00	21.5	81.9	101.3	364.2	0.80	0.00	70.0	331.7	233.7
163	6K20116	12/29/92	23:55	1.19	6.64	484.1	0.00	23.0	81.9	95.3	361.0	1.00	0.00	70.0	359.5	232.0
164	6K20118	12/30/92	00:55	1.17	6.64	504.6	0.00	22.8	86.0	98.3	373.0	1.70	0.00	69.5	382.2	238.2
165	6K20120	12/30/92	01:55	1.12	6.74	493.3	0.00	22.8	85.2	97.1	363.0	0.40	0.00	69.4	378.2	238.2
166	6K20122	12/30/92	02:55	1.09	6.76	480.6	0.00	23.0	81.9	92.6	369.2	0.90	0.00	70.3	341.8	245.0
167	6K20124	12/30/92	03:55	1.06	6.70	551.1	0.00	24.0	84.7	97.6	365.2	1.60	0.00	70.9	431.1	232.2
168	7K20102A	12/30/92	23:42	0.52	6.81	516.3	0.00	22.8	92.6	101.0	395.6	0.00	0.00	68.4	393.9	244.4
169	7K20108A	12/31/92	02:42	0.79	6.79	467.2	0.00	24.0	79.4	91.6	328.6	0.00	0.00	64.1	376.3	216.0
170	7K20114A	12/31/92	05:42	2.17	6.78	435.0	0.00	22.5	72.4	88.6	305.0	7.10	0.00	60.2	346.9	207.7
171	8K20102T	12/31/92	09:15	4.80	6.92	415.8	0.00	25.6	67.5	84.6	271.5	0.60	0.00	58.1	357.2	193.8
172	8K20104T	12/31/92	11:15	5.49	6.96	391.5	0.00	25.8	64.2	80.8	251.4	6.70	0.00	55.5	338.2	168.9
173	8K20108T	12/31/92	15:15	6.96	6.94	380.6	0.00	30.9	63.3	80.6	240.6	21.30	0.00	52.7	332.1	158.5
174	8K20114T	12/31/92	21:15	5.77	6.95	389.7	0.00	26.6	65.4	84.3	245.1	8.40	0.00	56.4	349.5	168.6
175	8K20124T	01/01/93	07:15	2.81	6.89	425.4	0.00	24.0	69.1	85.1	294.7	21.70	0.00	60.2	321.0	192.2
176	9K20102	01/01/93	17:45	1.36	6.96	456.7	0.00	23.3	78.2	91.3	331.7	16.80	0.00	64.4	341.6	207.4
177	9K20108	01/02/93	05:45	0.74	6.94	487.2	0.00	24.8	84.7	97.6	381.8	11.20	0.00	67.6	348.4	223.4
178	9K20114	01/02/93	17:45	0.40	6.90	510.2	0.00	24.3	93.4	104.5	400.4	9.60	0.00	69.3	381.8	239.2

Caspar Creek - Watershed MUN – Pipeflow

#	ID	DATE	TIME	Flow L/s	pH	Na μM	NH4 μM	K μM	Mg μM	Ca μM	Cl μM	NO3 μM	PO4 μM	SO4 μM	HCO3 μM	Si μM
143	4M10603T	12/09/92	02:05	0.62	6.71	622.4	0.00	34.8	119.7	148.5	844.0	0.00	0.00	59.0	231.5	242.2
144	4M10606T	12/09/92	05:05	0.47	6.61	644.6	0.00	31.5	127.1	157.9	866.0	0.00	0.00	62.0	256.2	244.8
145	4M10609T	12/09/92	08:05	0.42	6.57	643.8	0.00	32.5	129.2	160.7	865.0	0.00	0.00	63.0	264.9	256.8
146	4M10612T	12/09/92	11:05	0.42	6.65	649.8	0.00	33.0	130.0	160.4	882.0	0.00	0.00	65.0	251.7	260.8
147	4M10615T	12/09/92	14:05	0.41	6.64	658.1	0.00	32.7	131.2	162.4	912.0	0.00	0.00	65.0	236.1	267.7
148	5M10602T	12/09/92	18:05	0.35	6.77	668.1	0.00	33.2	134.9	163.7	877.0	0.00	0.00	66.0	289.6	266.7
149	5M10604T	12/09/92	20:05	0.43	6.68	661.6	0.00	35.8	130.8	159.4	883.0	0.00	0.00	65.0	264.9	273.0
150	5M10606T	12/09/92	22:05	0.46	6.67	654.2	0.00	33.2	130.8	158.7	844.0	0.00	0.00	64.0	294.4	266.5
151	5M10608T	12/10/92	00:05	0.53	6.64	652.9	0.00	34.5	130.4	158.7	849.0	0.00	0.00	64.0	288.6	265.1
152	5M10610T	12/10/92	02:05	0.55	6.60	659.0	0.00	35.8	130.4	157.2	845.0	0.00	0.00	62.0	301.0	269.1
153	5M10612T	12/10/92	04:05	0.54	6.90	655.9	0.00	33.0	130.4	158.4	864.0	0.00	0.00	63.0	276.6	263.8
154	5M10614T	12/10/92	06:05	0.60	7.06	654.6	0.00	32.7	130.8	157.7	852.0	0.00	0.00	62.0	288.4	266.3
155	5M10616T	12/10/92	08:05	0.77	7.03	630.3	0.00	32.5	125.5	151.4	821.0	0.00	0.00	59.0	277.6	265.1
156	5M10618T	12/10/92	10:05	2.23	7.30	535.9	0.00	32.0	97.5	125.5	621.0	0.00	0.00	45.0	302.8	259.0
157	5M10620T	12/10/92	12:05	2.38	7.16	525.9	0.00	31.5	96.7	121.0	605.0	0.00	0.00	42.0	303.7	214.7
158	5M10622T	12/10/92	14:05	2.33	6.91	536.8	0.00	32.7	100.8	125.7	665.0	0.00	0.00	42.0	273.6	210.6
159	5M10624T	12/10/92	16:05	2.29	6.91	547.6	0.00	31.7	103.2	127.0	673.0	0.00	0.00	41.0	284.8	209.4
160	5M10603T	12/10/92	20:05	1.94	6.84	567.2	0.00	35.3	105.3	126.5	673.0	0.00	0.00	41.0	311.1	216.0
161	5M10606T	12/10/92	23:05	1.61	6.75	581.6	0.00	36.8	109.8	134.0	725.0	0.00	0.00	43.0	295.0	219.0
162	5M10609T	12/11/92	02:05	1.39	6.73	585.0	0.00	31.5	111.9	136.5	741.0	0.00	0.00	43.0	286.2	226.0
163	5M10612T	12/11/92	05:05	1.18	7.09	594.2	0.00	31.7	115.6	140.5	754.0	0.00	0.00	45.0	294.0	222.8
164	5M10615T	12/11/92	08:05	1.05	7.01	599.4	0.00	31.2	116.0	141.2	769.0	0.00	0.00	45.0	286.0	235.5
165	7M10602	12/29/92	09:12	0.36	6.83	724.7	0.00	30.7	141.9	181.4	925.2	0.00	0.00	78.3	320.2	307.3
166	7M10604	12/29/92	10:12	0.39	6.86	720.3	0.00	30.9	140.3	178.9	899.7	0.00	0.00	78.3	333.3	300.7
167	7M10606	12/29/92	11:12	0.41	6.87	690.3	0.00	30.7	131.2	189.9	868.3	0.00	0.00	75.4	344.1	299.3
168	7M10608	12/29/92	12:12	0.43	6.86	713.8	0.00	30.4	137.0	173.9	899.0	0.00	0.00	76.3	314.4	295.8
169	7M10610	12/29/92	13:12	0.48	6.94	727.3	0.00	31.7	139.0	168.4	893.6	0.00	0.00	75.5	329.3	302.6
170	7M10612	12/29/92	14:12	0.52	6.76	700.7	0.00	30.2	135.3	170.7	861.7	0.00	0.00	73.8	333.6	278.1
171	7M10614	12/29/92	15:12	0.56	7.07	724.7	0.00	31.7	146.9	187.1	854.3	0.50	0.00	72.8	423.9	300.6
172	7M10616	12/29/92	16:12	0.58	6.93	697.7	0.00	29.9	135.3	169.7	841.7	0.00	0.00	71.7	352.5	293.8
173	7M10618	12/29/92	17:12	0.61	6.89	781.2	0.00	35.3	134.9	158.7	859.4	0.00	0.00	70.1	404.1	297.3
174	7M10620	12/29/92	18:12	0.63	6.95	691.2	0.00	31.5	134.1	169.9	808.0	0.00	0.00	69.7	383.3	287.5
175	7M10622	12/29/92	19:12	0.65	6.89	776.4	0.00	33.8	132.0	160.4	826.3	0.00	0.00	68.5	431.8	286.1
176	7M10624	12/29/92	20:12	0.67	6.93	745.1	0.00	33.8	141.9	170.4	868.7	0.00	0.00	68.0	398.8	306.8
177	8M10602A	12/31/92	03:31	0.92	6.87	662.5	0.00	30.7	126.7	157.7	757.3	0.00	0.00	57.5	389.6	281.3
178	8M10606A	12/31/92	05:31	1.51	6.92	631.6	0.00	29.2	115.6	146.0	692.6	0.00	0.00	53.3	384.6	263.8
179	9M10604T	12/31/92	08:15	2.38	6.97	575.9	0.00	27.6	106.1	133.0	624.9	0.00	0.00	46.9	363.1	238.7
180	9M10608T	12/31/92	10:15	3.43	6.81	533.7	0.00	26.3	95.0	120.8	562.9	0.00	0.00	40.0	348.7	218.4
181	9M10612T	12/31/92	12:15	7.64	6.88	429.8	0.00	30.2	81.4	106.3	500.3	0.00	0.00	29.5	276.1	174.3
182	M103	01/13/95	10:00	0.13	6.58	577.1	0.00	35.2	113.7	151.5	799.2	0.00	0.00	25.5	292.4	173.4
183	M103	01/14/95	10:00	0.32	6.44	559.0	0.00	33.4	102.1	133.4	715.6	0.71	0.00	28.3	290.5	175.4

Caspar Creek Soil Solutions

Collect	Treat	Site	Depth	Date	pH	Na	NH4	K	Mg	Ca	Cl	NO3	PO4	SO4	Si
			cm			μM	μM	μM	μM	μM	μM	μM	μM	μM	μM
4	Forest	1	20	01/05/95	7.35	492.8	2.86	151.9	120.6	276.7	765.2	0.00	0.00	63.0	50.5
4	Forest	1	20	01/05/95	7.01	578.1	0.00	135.0	156.8	361.3	1175.4	0.00	0.00	51.3	38.9
4	Forest	2	20	01/05/95	6.58	298.0	0.00	102.8	123.0	336.1	710.6	0.00	0.00	43.5	56.4
4	Forest	2	20	01/05/95	6.83	275.3	0.00	124.2	126.7	233.3	740.7	0.00	0.00	40.1	43.8
4	Forest	3	20	01/05/95	6.66	179.2	0.00	41.2	67.9	169.2	338.2	0.00	0.00	15.4	53.4
4	Forest	3	20	01/05/95	6.80	220.5	0.00	45.0	100.4	278.2	503.0	40.17	1.33	11.1	64.1
4	Forest	1	40	01/05/95	6.57	737.7	0.00	176.7	133.3	267.0	1301.8	0.00	2.34	28.0	48.5
4	Forest	3	40	01/05/95	6.04	351.0	0.00	46.0	59.2	166.4	616.3	0.00	0.00	7.4	105.4
4	Forest	1	60	01/05/95	6.45	555.9	0.00	77.2	86.4	176.2	799.6	0.00	0.00	33.2	61.3
4	Forest	2	60	01/05/95	7.03	308.0	0.00	58.3	89.7	194.4	535.6	0.00	0.00	25.1	63.6
4	Forest	3	60	01/05/95	6.11	311.4	0.00	37.6	89.3	189.4	656.6	0.00	0.00	1.5	76.8
4	Cut	4	20	01/05/95	6.64	70.5	2.14	58.6	83.1	231.3	102.9	4.77	1.14	7.5	25.1
4	Cut	4	20	01/05/95	7.40	77.0	2.14	188.2	52.3	209.1	113.7	2.92	12.86	4.7	7.1
4	Cut	5	20	01/05/95	6.71	96.1	0.00	91.1	63.0	107.5	212.5	0.00	0.00	10.3	34.4
4	Cut	4	40	01/05/95	6.63	168.3	0.00	54.2	71.2	156.7	275.4	0.00	1.05	9.2	36.6
4	Cut	5	40	01/05/95	6.52	99.2	0.00	61.1	70.4	92.8	148.9	0.00	0.00	7.1	41.5
4	Cut	6	40	01/05/95	6.72	375.8	0.00	24.3	56.0	78.1	343.9	0.00	0.00	13.2	76.7
4	Cut	4	60	01/05/95	6.24	221.8	0.00	31.5	37.9	46.9	141.4	0.00	0.00	20.1	57.8
4	Cut	5	60	01/05/95	6.26	104.4	0.00	44.2	43.6	59.9	119.4	0.00	0.00	8.0	32.2
5	Forest	1	20	02/07/95	6.52	298.6	0.00	129.5	36.6	159.9	201.2	0.55	0.00	21.4	45.4
5	Forest	1	20	02/07/95	6.34	312.4	0.00	113.2	36.6	164.0	220.0	0.00	0.00	20.8	63.0
5	Forest	2	20	02/07/95	6.68	221.9	0.00	81.9	24.0	124.0	83.3	0.85	0.00	10.9	48.9
5	Forest	2	20	02/07/95	6.69	236.8	0.00	95.3	26.9	124.1	112.7	1.22	0.00	18.6	53.8
6	Forest	2	20	02/19/95	6.78	157.0	0.00	43.3	34.7	112.0	35.9	6.39	0.00	7.3	26.8
6	Forest	2	20	02/19/95	6.41	102.8	0.29	39.1	26.7	96.7	138.9	1.98	0.00	15.3	47.0
6	Forest	3	20	02/19/95	6.15	171.0	3.01	22.0	25.2	90.0	148.4	0.00	0.00	54.4	56.0
6	Forest	3	20	02/19/95	6.12	148.1	0.00	33.5	48.3	139.7	153.5	5.16	0.81	9.4	70.4
6	Forest	1	40	02/19/95	5.91	322.1	0.00	82.2	63.0	178.7	527.1	0.00	0.00	46.3	45.4
6	Forest	2	40	02/19/95	6.54	268.1	0.00	87.8	56.4	106.0	82.9	1.07	0.00	21.5	53.0
6	Forest	3	40	02/19/95	6.31	254.5	0.00	30.1	64.5	178.9	195.2	0.00	0.00	53.9	72.5
6	Forest	2	60	02/19/95	6.04	178.9	0.00	37.6	54.8	160.1	327.0	0.00	3.45	17.9	101.0
6	Forest	3	60	02/19/95	6.10	66.6	2.21	39.2	29.7	64.8	317.0	0.00	0.00	57.1	84.6
6	Cut	4	20	02/19/95	7.02	62.2	0.00	47.1	58.4	197.4	44.7	53.61	2.02	23.6	17.6
6	Cut	4	20	02/19/95	7.00	671.9	2.36	22.3	121.1	434.4	41.0	2.67	0.86	3.4	27.5
6	Cut	5	20	02/19/95	6.26	188.1	0.00	24.5	37.9	49.9	56.5	15.94	1.03	54.0	42.0
6	Cut	4	40	02/19/95	6.21	134.4	0.79	36.7	50.7	144.0	53.1	0.00	0.00	58.1	42.6
6	Cut	4	60	02/19/95	6.07	492.2	0.00	25.0	155.5	289.8	100.1	23.85	0.00	54.5	41.6
7	Forest	1	20	03/11/95	7.06	423.7	0.00	80.0	63.2	168.7	190.5	0.00	0.00	21.4	57.0
7	Forest	1	20	03/11/95	6.68	426.2	0.00	120.8	80.3	209.4	135.3	0.00	0.00	10.3	63.7
7	Forest	2	20	03/11/95	6.68	186.9	1.85	76.9	53.1	147.1	44.2	0.71	0.00	7.2	47.9
7	Forest	2	20	03/11/95	6.90	202.8	0.00	53.2	39.3	123.2	66.8	0.91	0.00	11.0	51.0
7	Forest	3	20	03/11/95	6.97	186.4	4.78	29.0	30.3	88.8	67.0	0.82	0.00	6.6	45.1
7	Forest	3	20	03/11/95	6.91	115.1	1.86	31.2	40.3	114.8	59.1	16.47	0.00	6.5	61.2
7	Forest	1	40	03/11/95	6.84	600.6	0.00	77.2	86.2	181.4	201.6	1.44	0.00	36.3	43.5
7	Forest	2	40	03/11/95	7.07	195.8	0.00	38.5	41.1	135.7	47.5	0.00	0.00	21.5	56.0
7	Forest	3	40	03/11/95	7.12	242.8	0.00	27.9	49.0	121.2	129.1	1.83	0.00	15.9	86.2
7	Forest	1	60	03/11/95	6.61	160.4	0.00	66.5	46.3	143.2	750.3	0.00	0.00	38.4	59.9
7	Forest	2	60	03/11/95	6.44	150.5	9.86	36.7	52.6	134.5	125.2	0.00	0.00	16.3	44.3
7	Forest	3	60	03/11/95	6.71	50.3	4.81	101.4	36.2	153.2	159.3	0.00	0.00	19.8	78.7
7	Cut	5	20	03/11/95	6.63	65.1	3.46	52.7	65.2	193.0	12.1	29.82	1.10	1.5	16.0
7	Cut	5	20	03/11/95	6.69	175.1	0.00	27.5	35.6	71.1	10.6	3.88	0.00	0.9	30.3
7	Cut	5	40	03/11/95	6.34	50.0	0.00	30.7	18.2	24.3	28.5	0.72	0.00	5.7	22.8
7	Cut	5	60	03/11/95	6.30	88.0	0.00	22.4	38.0	105.9	35.6	0.00	0.00	15.1	39.0

