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WATER QUALITY AFTER LOGGING SMALL WATERSHEDS WITHIN THE BULL RUN WATERSHED, OREGON[1]

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ABSTRACT: Road building, clearcutting 25 percent of the watershed, and slash disposal by broadcast burning or by natural decomposition caused changes in water quality of two small streams in the Bull Run Watershed in Oregon, which supplies water to the Portland, Oregon, metropolitan area. Concentrations of suspended sediment increased slightly, primarily owing to construction of a permanent logging road that crossed streams. Changes in nutrient cycling occurred due to logging and slash disposal in both watersheds where cutting was done. NO_3-N concentrations, which increased most where logging residue was left to decompose naturally, increased more than sixfold and commonly exceeded 100 $\mu g/l$ during the October-June high-flow season for seven years after logging. Where logging slash was broadcast burned, NO_3-N concentrations increased roughly fourfold, but rarely exceeded 50 $\mu g/l$, and increases had mostly disappeared six years after slash burning. Changes in outflows of cations and other anions were not apparent. Annual maximum stream temperatures increased 2-3°C after logging, but temperature increases had mostly disappeared within three years as vegetation regrowth shaded the streams.
(KEY TERMS: water quality; timber harvest; slash burning; nutrient cycling; suspended sediment; nitrate.)

INTRODUCTION

Streams draining undisturbed forests in the Pacific Northwest usually have water of the highest quality. Forest litter and ground vegetation protect the soil from surface erosion, and the strength added to soil masses from tree roots can add substantially to the stability of steep slopes. In addition, forest vegetation is a sink for nutrients mobilized from the soil by weathering, and its shade minimizes stream heating. This does not mean the quality of water flowing from unlogged watersheds in the Pacific Northwest is always high. Natural processes such as soil mass wasting, stream channel erosion, forest fire, and forest blowdown can result in high concentrations of sediment and increased nutrient content of streamwater even in watersheds undisturbed by human activities.

Logging, road building, and slash disposal can upset natural processes that maintain high quality. Changes in water quality observed after logging in headwater basins in western Oregon have resulted from increased erosion of steep, unstable land and sedimentation (Fredriksen, 1973; Brown and Krygier, 1971), nutrient-enriched runoff (Fredriksen, 1971; Brown *et al.*, 1973), and increased solar heating of streamwater (Brown and Krygier, 1970).

In 1957, the USDA Forest Service and the City of Portland, Oregon, began a cooperative study to determine if logging in two small basins in the Bull Run Watershed, a municipal water supply for the Portland metropolitan area, could increase water yield without increasing concentrations of suspended sediment. In the early 1970's, about the time logging began, the study was broadened to include certain anions and cations. This case study describes the effects of road construction, timber harvest, and two methods of slash disposal on water quality of two small streams. Changes in streamflow were reported by Harr (1980). Study results should apply to the roughly 25 percent of the Bull Run Watershed with similarly gentle topography and to other mid-elevation sites in the western Cascade Range that have similar vegetation, geology and soils, climate, and topography.

THE STUDY

Watershed Characteristics

The study area, which consists of the three Fox Creek experimental watersheds FC1, FC2, and FC3 (Table 1), is located entirely within the Mt. Hood National Forest about 35 km east of Portland, Oregon (Figure 1). Fox Creek is a tributary to the South Fork of the Bull Run River that flows into a reservoir that supplies water to the Portland metropolitan area. The Fox Creek watersheds are incised into a broad ridge that slopes 5 percent to the west and is underlain by massive, slightly weathered andesite (Peck *et al.*, 1964). Slope gradients are generally less than 15 percent except near watershed outlets where some gradients approach 50 percent. All slopes are stable.

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TABLE 1. Summary of Watershed Characteristics and Harvesting Activities for the Fox Creek Watersheds Near Portland, Oregon.

	Watershed		
	FC1	FC2	FC3
Area, ha	59	253	71
Elevation Range, m	845-945	845-1100	845-1000
Aspect	WNW	W	W
Area in Permanent Road, ha[a]	1.2	2.0	0
Type of Cut	Clearcut[b]	Uncut	Clearcut[c]
Size of Logged Area, ha	3.2-4.0	0	8.5 and 9.3
Area Logged	14.8		17.8
Percent Logged	25	0	25
By High Lead	25	0	19
By Tractor	0	0	6
Slash Disposal	Broadcast Burn[d]	None	Decomposition

[a]Road construction was begun in July 1964 and was completed in August 1965.
[b]Logging in FC1 was completed in September 1969.
[c]Timber in FC3 was felled in the summer of 1971. Yarding was completed in August 1972.
[d]Logged areas in FC1 were burned in September 1970.

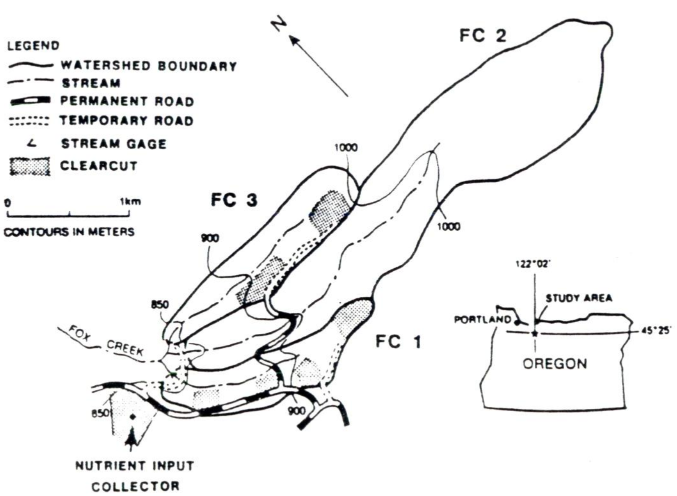

Figure 1. Map of Fox Creek Watersheds, Oregon.

Soils in the watershed consist of two series: the Damsite, a typic haplumbrept (inceptisol), and the Sisi, a typic haplorthod (spodisol). FC3 contains Damsite soil except in the riparian zone where the Sisi soil is found. The Sisi soil covers both FC1 and FC2 except for the riparian zones where the Damsite soil is located. Both soils, which have formed from igneous glacial till, are well drained, stony, cobbly loams with stone contents of 30-60 percent (Stevens, 1964). Organic content ranges from 15 percent near the surface to about 7 percent at the base of the B horizon. These soils differ in acidity and base saturation: Sisi soil pH (A horizon) is 4.0 compared with 5.1 for the Damsite, and Sisi and Damsite base saturations are 10 and 15 percent, respectively. In both soils, roots extend well into the C horizon to depths of 2 m.

Before logging, forest vegetation was dominated by an overstory of Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) and overmature western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Douglas-fir and western hemlock trees were about 415 and 365 years old, respectively.

The climate of the site is maritime with cool, wet winters and relatively dry summers. Over 25 years of record, annual precipitation averaged 262 cm, of which about 10 percent occurred during the June-September period. Fog drip is an additional source of water at Fox Creek (Harr, 1982). Maximum daily air temperatures seldom exceeded 27°C beneath the forest canopy.

Streamflow measured continuously since October 1957 reflects the general climatic pattern of the area. Typically, the major annual peak, which usually occurs in November, December, or January, results from rainfall or rapid snowmelt during rainfall. A second peak may occur during snowmelt in April or May. Minimum streamflow usually occurs between mid-August and mid-September. Because of high soil infiltration and percolation capacities, overland flow was never observed on undisturbed soil.

Streambeds are gravel with minor amounts of exposed bedrock or weathered glacial till. Bedload movement is controlled by well-developed debris dams. Occasional bare soil along the streambanks before logging resulted primarily from naturally falling trees and undercut streambanks. All watersheds are drained by first order streams.

Logging Activities

In July 1964, construction of an all-weather road was begun across watersheds FC1 and FC2 to the southern boundary of watershed FC3 (Figure 1). Road construction disturbed 2 percent of FC1 and 0.8 percent of FC2, but each stream channel immediately downstream from the road crossing was disturbed by crawler tractors that spread debris from the road fill and from culvert installation. Grass seed, straw mulch, and nitrogen fertilizer were applied to road cut and fill surfaces for erosion control in the fall of 1964, and crushed rock was applied to the road surface in August 1965.

Timber was clearcut in patches totaling 25 percent of total area in both FC1 and FC3 but was left uncut in FC2. Clear-cut areas were 3.2-4.0 ha in size in FC1 and 8.5 and 9.3 ha in FC3. All clear-cuts were located on the south side of streams, and sparse strips of leaning trees were left adjacent to streams. Because drainage from temporary spur roads in FC1 and FC3 did not directly enter streams, these roads were included with timber cutting and yarding in data analyses. High-lead yarding of logs was completed in the four clear-cuts in FC1 in August 1969, and logging residue was broadcast burned in early September 1970 after crawler tractors constructed fire lines around the logged areas. Felling of timber and high-lead yarding were completed in FC3 in August 1971, and additional yarding by crawler tractor was completed in August 1972. Logging residue was not burned in FC3.

A point intercept method (Dyrness, 1965) was used to assess soil disturbance. After logging and burning in FC1, 14 percent of the surface soil in logged areas was slightly disturbed, 14 percent was deeply disturbed (surface soil removed and subsoil exposed), 17 percent was compacted by passage of a log or logging equipment, and 55 percent was undisturbed. In addition, 64 percent was lightly burned, and about 2 percent was severely burned. Disturbance of the cable-yarded portion of FC3, although unmeasured, appeared to be similar to that in FC1. About 25 percent of the tractor-yarded ground (1 percent of total watershed area) in FC3 was severely compacted.

Revegetation

Rates of revegetation in the clearcut areas in each watershed were determined from measurements of plant frequency and cover in 16 1-m^2 subplots within eight 4-m^2 permanent plots. Measurements were made annually from 1974 to 1976 and biennially through 1982. Earlier trends in plant cover were estimated from photographs and known times of activities that affected vegetation composition. Vegetation cover after logging and slash disposal was compared with old-growth vegetation sampled in 10 700-m^2 plots in the watersheds.

Water Quality Measurements

Grab sampling at stream gages, begun in October 1957 to determine concentrations of suspended sediment, was replaced by an automatic, pumping, proportional sampling system in 1970 (Fredriksen, 1969). Because the frequency of the proportional sampling was directly related to instantaneous streamflow over a 3-week period, samples estimated the mean concentration over the sampling period. The 20-liter sample containers were enclosed in dark, cool environments beneath gage houses. Inlets to the pumping samplers consisted of 1.6-cm polypropylene tubing positioned about 8 cm above the stream bottoms immediately downstream from the stream gages. Laboratory analyses of water samples followed standard methods described by the American Public Health Association *et al.* (1977). Consistent or comparable methods were used for each water quality constituent throughout the study.

Changes in water quality were determined in two ways. First, water quality parametric relationships between watersheds were compared before and after treatment (road construction, logging, and slash disposal). Second, if adequate prelogging data did not exist, data from treated and untreated watersheds were compared over the postlogging period. For suspended sediment, watershed FC3 is the control watershed because no permanent roads or fire lines were constructed in it. For all other water quality parameters, including stream temperature, FC2 is the control watershed. Maximum three-week stream temperatures after logging in FC1 and FC3 were compared with maximum temperatures before logging.

Because this is a case history, most data comparisons are visual, and the inferences of the few statistical tests are restricted to the two watersheds being compared.

RESULTS

Revegetation

Slash burning in the fall of 1970 left grey wood ash on the soil surface and charred stumps and logs in the four clear-cuts in FC1. Throughout the postlogging phase of study in this watershed, vegetation was dominated by herbs. Herb cover, 13 percent in 1972, increased to 118 percent by 1982. Douglas-fir seedlings planted in the spring of 1972 had reached 22 percent cover by 1982, and western hemlock seedlings established from seed fall in 1972 grew slowly until 1978 when their growth rate began to accelerate. Shrub cover totaled 24 percent of total leaf cover in 1982. Litter cover, most of which resulted from the major herbs, increased in FC1 from near zero after burning in 1970 to 83 percent in 1974 and remained at that level through the remainder of the study.

In contrast, logging residue in FC3 was unburned and remained in place to decompose naturally. In 1973, natural seedlings of Douglas-fir, Pacific silver fir, and western hemlock were evident when Douglas-fir seedlings were planted, but total cover by tree species totaled only 11 percent in 1982. As in FC1, early revegetation in FC3 was dominated by herbs. Growth of shrubs was faster in FC3 than in FC1, and by 1982, shrub cover had reached 38 percent of total leaf cover. As in FC1, litter cover in FC3 increased rapidly and had reached 76 percent by 1974 where it remained through 1982.

Suspended Sediment

Concentrations of suspended sediment measured in grab samples collected before road construction ranged from zero (below detection limits) to 5 mg/l. Concentrations in the 200- to 2600-mg/l range measured immediately below stream crossings during road construction in August 1964 decreased rapidly with distance downstream as sediment was quickly deposited, and turbid water mixed with clear water in pools (Miner, 1968). Concentrations of suspended sediment were relatively low during the 24-year study. In most years, maximum concentration of suspended sediment in 3-week composite samples taken with the proportional sampler was 2-4 mg/l in FC1, 2-5 mg/l in FC2, and 2-6 mg/l in FC3 (Figure 2). The majority of the highest three-week concentrations occurred during periods of high streamflow.

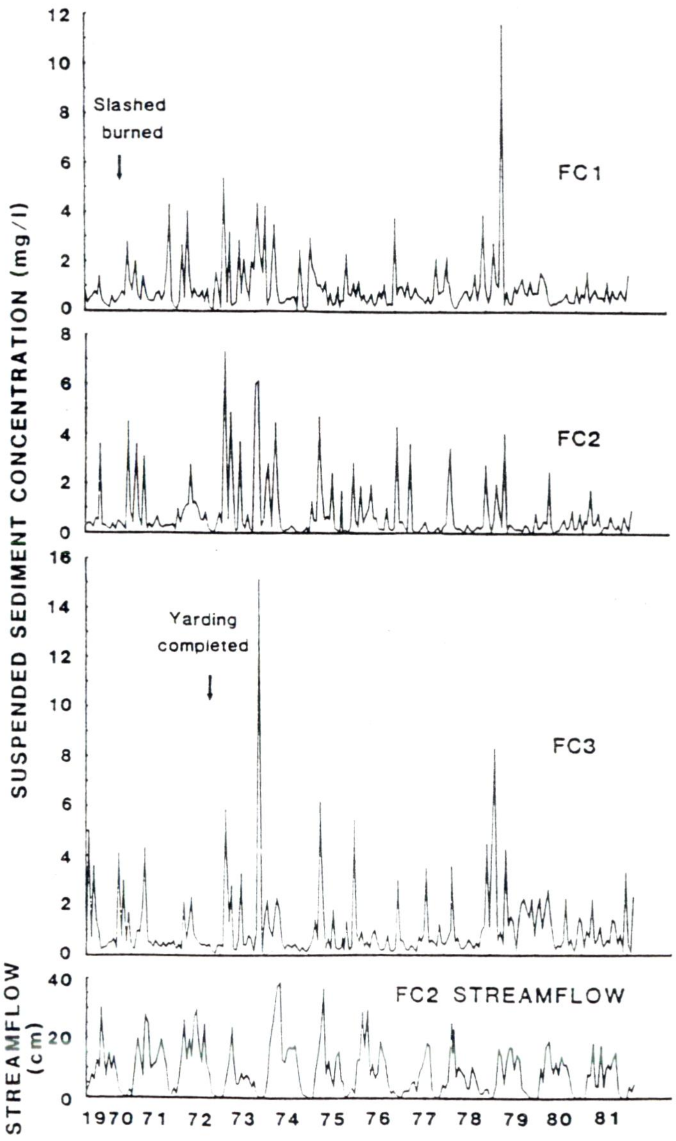

Figure 2. Mean Three-Week Concentrations of Suspended Sediment in FC1, FC2, and FC3 Streamwater.

Double-mass analysis (Anderson, 1955) was used to detect changes in sediment relationships between watersheds. Cumulative suspended sediment concentrations (both grab samples and automatic samples) at FC1 and FC2 are plotted over cumulative suspended sediment concentrations at FC3 (Figure 3). The increase in slope of both double-mass curves in 1964 indicates changes in the sediment outflow relationship between FC3 and each of the other two watersheds; an abrupt increase in suspended sediment in FC1 began with road construction in August 1964 in both FC1 and FC2. The sediment relationship between FC1 and FC3 and that between FC2 and FC3 both returned to pre-road construction levels after sediment was carried out of the watershed during initial fall storm runoff. Immediately after slash burning in 1970, suspended sediment concentrations increased in FC1 relative to those in FC3 and remained elevated until winter 1979, as did sediment concentrations in FC2. According to changes in slope of both plots in Figure 3, sediment output from FC2 relative to that of FC3 was less from 1979 to 1981 than before road construction in FC2.

The change from weekly grab sampling to automatic proportional sampling in 1970 precludes a more rigorous analysis of management-induced changes in sediment concentrations.

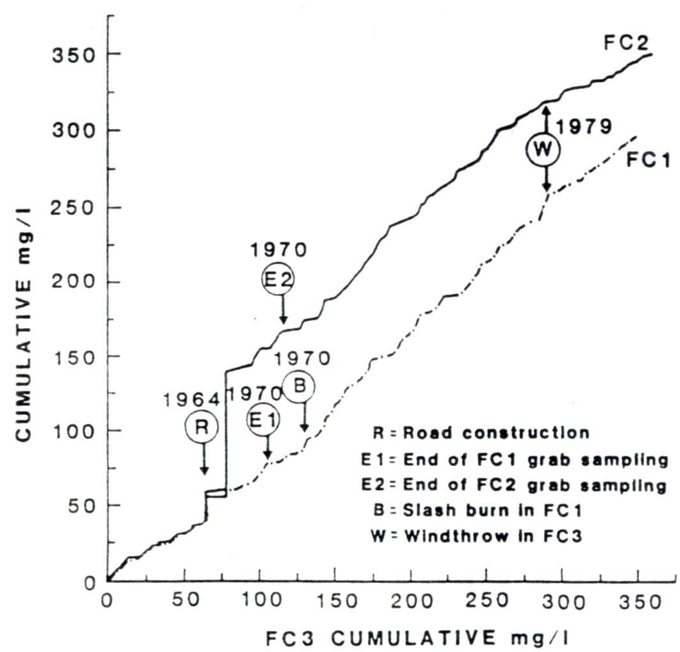

Figure 3. Cumulative Concentrations of Suspended Sediment in FC1, FC2, and FC3 Streamwater.

Nitrogen

We assume nitrogen concentrations in FC1 and FC3 before logging were similar to the levels observed in unlogged FC2 during the postlogging phase of study. Of the four forms of N, particulate N (nitrogen in suspended mineral and organic sediment) and dissolved organic N together accounted for 85 percent of the total; NO_3-N and NH_4-N accounted for the remaining 45 percent. These percentages were estimated for a few years when NH_4-N was measured along with the other forms of nitrogen. NH_4-N measurement was subsequently discontinued because concentrations were near detection levels. Only NO_3-N concentrations were measured before logging.

Despite the lack of prelogging data on particulate nitrogen, outflows of particulate nitrogen appear to have been changed little by logging and slash disposal. There are year-to-year differences among watersheds (Table 2), but paired *t* tests ($p \geqslant 0.05$) showed that these differences are not significant. This does not mean that differences did not exist; it simply means they were not detected in this study by this test.

TABLE 2. Mean Annual Concentrations of Particulate N in Streamwater at Fox Creek Watersheds Near Portland, Oregon (values are weighted by streamflow).

Year	Stream		
	FC1 (μg/l)	FC2 (μg/l)	FC3 (μg/l)
1971	6*	25	19
1972	21	16	14**
1973	15	19	17
1974	17	13	18
1975	21	18	38
1976	11	10	5
1977	10	11	22
1978	30	15	30
1979	23	12	17
1980	13	8	22
1981	23	16	17
Mean, Standard Error	17 ± 2	15 ± 1	20 ± 3

*Logging slash was broadcast burned in FC1 a month before the beginning of the 1971 water year.
**Logging in FC3 was completed in August 1972.

Generally, annual mean concentrations of total dissolved Kjeldahl N, which includes dissolved organic N and NH_4-N, were slightly lower at both FC1 and FC3 than concentrations at unlogged FC2 during the 1970-1981 period (Table 3). However, according to paired *t* tests, only the difference between FC1 and FC3 is significant ($p \geqslant 0.05$). Because there were no prelogging data, we could not determine if differences between logged and unlogged watersheds existed before logging or were caused by logging.

Concentrations of NO_3-N were the most variable of the forms of N examined and were also the most responsive to logging and slash disposal. Before logging, concentrations of NO_3-N in grab samples from all three streams were extremely low and nearly equal (9-10 ± 4 μg/l). Concentrations in the three-week composite samples collected after 1970 but before logging were even lower. After 1970, the change in sample collection and storage may have lowered NO_3-N concentrations somewhat. According to a short-term study of effects of three-week sample storage on NO_3-N concentration, streamwater stored on-site averaged 17 percent less NO_3-N than streamwater analyzed within two days after collection.

TABLE 3. Mean Annual Concentrations of Total Dissolved Kjeldahl N in Streamwater and Precipitation at Fox Creek Watersheds Near Portland, Oregon (values for streamwater are weighted by streamflow).

Year	Stream			Precipitation (μg/l)
	FC1 (μg/l)	FC2 (μg/l)	FC3 (μg/l)	
1970	40[a]	52	37	–[b]
1971	41	46	42	115
1972	41	41	30[c]	76
1973	37	39	35	68
1974	43	34	32	59
1975	40	48	43	75
1976	30	40	34	78
1977	37	44	39	96
1978	40	44	45	70
1979	32	33	33	74
1980	30	38	53	70
1981	40	41	38	65
Mean Standard Error	38 ± 1	42 ± 2	38 ± 2	77 ± 5

[a]FC1 slash was broadcast burned in September 1970.
[b]Chemical analysis of precipitation was begun in April 1970.
[c]FC3 logging was completed in August 1972.

We assume that annual patterns in concentrations of NO_3-N in all three streams during the prelogging period were nearly identical to the pattern for unlogged FC2 during the postlogging phase of study (Figure 4). Concentrations usually remained below 10 μg/l throughout the October-June high flow season, and relatively high concentrations of 20-60 μg/l generally occurred during a two- to four-month low-flow period. When streamflows remained abnormally high during the summer, as in 1978, NO_3-N concentrations were low during the summer, also.

The effects of logging and slash disposal on NO_3-N concentrations are evident in Figure 4. After a 12- to 15-month delay, NO_3-N concentrations began to increase after logging and burning in FC1. When automatic sampling was begun in FC1 in May 1970, 12 months after timber felling was begun, concentrations were only slightly above prelogging concentrations determined from grab sampling. The maximum concentration of 79 μg/l occurred in early January 1971, three months after slash burning. Dormant season concentrations remained at 40-60 μg/l through 1974, declined gradually through 1977, and remained relatively constant at 6-11 μg/l through 1981.

At FC3, where logging residue was not burned, NO_3-N concentrations remained at baseline levels for 28 months after

75 percent of the timber was felled in one logged area in September 1969. Concentrations began to increase in February 1972 and stabilized somewhat at 20-35 μg/l in 1973. A rapid rise was noted in November 1973, more than two years after timber in the second logged area had been felled. Between 1974 and 1980, concentrations generally fluctuated in the 40-120 μg/l range, with a maximum concentration of 266 μg/l in January 1979. NO_3-N concentration in FC3 was still elevated at the close of the study in 1981.

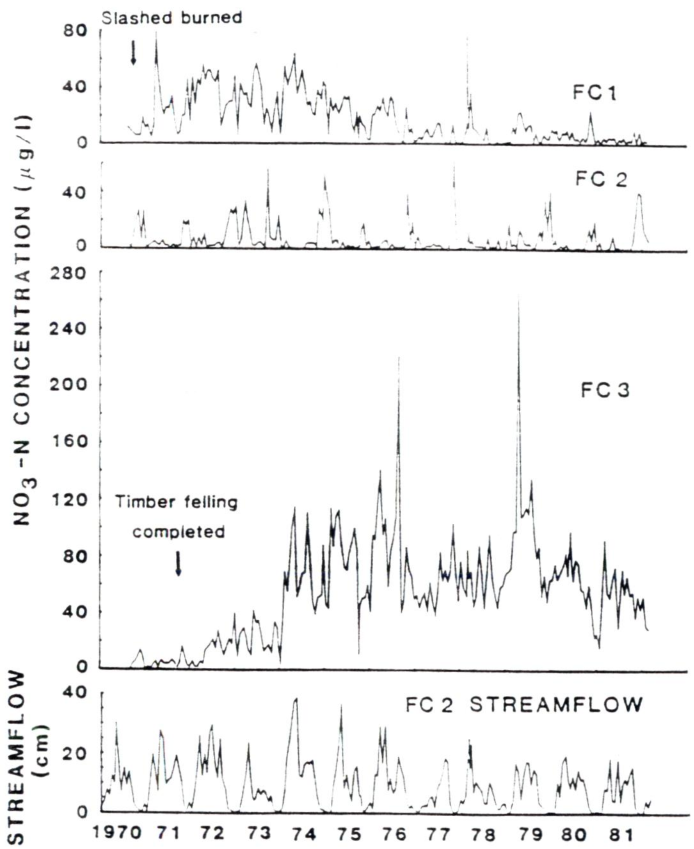

Figure 4. Mean Three-Week Concentrations of NO_3-N in FC1, FC2, and FC3 Streamwater.

Phosphorus

Mean annual concentrations of total dissolved P weighted by streamflow showed nearly identical ranges of fluctuations throughout the postlogging period regardless of the treatment each watershed received (Table 4). Similarly, mean annual concentrations of ortho P, which accounted for about a third to half of total dissolved P, were generally in the 3-9 μg/l range at each logged watershed as well as at the unlogged watershed. Comparison of three-week concentrations of ortho P between logged and unlogged watersheds revealed mainly minor period-to-period differences. On an annual basis, no differences were apparent among watersheds.

Anion/Cation Balance

Charges of the equivalents of anions and cations were determined from a set of six composite samples taken from the three streams from February through September 1979 (Table 5). As expected, Ca, Mg, and Na accounted for most of the cationic charge, whereas the anionic charge came mainly from HCO_3 and Cl ions. The low total charge of anions limited the flow of cations from the site by leaching. That the total charges of anions and cations balance reasonably well indicates that the major ions have been accounted for. The slight excess of anions over cations could have resulted from small, noncompensating errors in laboratory analyses or from the unmeasured charge of organic acids in streamwater.

The lack of appreciable prelogging data and the temporary discontinuance of analyses for Ca, Mg, K, and SiO_2 in streamwater during the 1974-1978 period preclude more detailed analyses to determine effects of logging and slash disposal on the concentrations of these chemical constituents. However, nearly identical ranges of cation concentrations in all three streams during the postlogging period (Table 6) suggest that cation concentrations were probably not affected by logging.

Water Temperature

Clearcut logging in patches on the south sides of FC1 and FC3 removed sufficient shade to raise annual maximum water temperatures 2-3°C. In FC1, annual maximum temperature peaked in 1972, three years after logging, at 15°C, slightly more than 3°C higher than predicted by the prelogging temperature relationship between FC1 and FC2. In FC3, the highest postlogging temperature was 16°C, nearly 2.5°C higher than predicted by the prelogging temperature relationship between FC3 and FC2. Because of rapid growth of shade-producing vegetation adjacent to each stream, increases in annual maximum water temperatures had decreased to less than 1°C above predicted temperatures by 1975.

DISCUSSION

The low levels and the narrow range of concentrations of suspended sediment indicate very low rates of soil erosion in the study watersheds. Geomorphic characteristics of the watersheds contribute to these low rates. Because of the strong structural support provided by the underlying andesitic rock, the inherent stability of the soils, and low relief, surface soils at Fox Creek are not as susceptible to the mass erosion processes common throughout much of western Oregon. In addition, because of gentle topography, watershed drainage networks are poorly developed, and surface erosion is controlled by well-aggregated soils with high porosities, often covered by a stone pavement beneath a thick litter layer. Consequently, little sediment reaches streams. In contrast, sediment concentrations were higher in a much more erosive and less carefully logged watershed in the Oregon Coast

TABLE 4. Mean Annual Concentrations of Total Dissolved P in Streamwater at Fox Creek Watersheds Near Portland, Oregon.

	Total Dissolved P			Ortho P			Total P		
Year	FC1 (µg/l)	FC2 (µg/l)	FC3 (µg/l)	FC1 (µg/l)	FC2 (µg/l)	FC3 (µg/l)	FC1 (µg/l)	FC2 (µg/l)	FC3 (µg/l)
1970	32	36	34	–	–	–	–*	–	–
1971	27	32	33	–	–	–	–	–	–
1972	14	14	13	–	–	–	–	–	–
1973	27	24	21	–	–	–	–	–	–
1974	11	13	11	–	–	–	–	–	–
1975	17	16	19	7	9	9	24	25	28
1976	10	9	9	4	5	5	14	14	14
1977	12	12	11	8	8	11	20	20	22
1978	12	11	11	5	7	5	17	18	16
1979	12	12	11	3	4	6	15	16	17
1980	13	12	10	3	2	4	16	14	14
1981	12	9	9	4	5	5	16	14	14

*No samples were analyzed for total P until 1975.

TABLE 5. Cation/Anion Balances of Streamwater at Fox Creek Watersheds Near Portland, Oregon.

	Stream				Stream		
	FC1	FC2	FC3	Anions	FC1	FC2	FC3
Cations	Milliequivalents						
H+	0.001	0.001	0.001	HCO_3^-	0.102	0.116	0.113
Na+	0.040	0.039	0.040	NO_3^-	0.001	0.000	0.010
K+	0.007	0.006	0.007	PO_4^{---}	0.001	0.001	0.001
Ca++	0.047	0.048	0.053	SO_4^{--}	0.008	0.010	0.008
Mg++	0.043	0.039	0.051	Cl^-	0.038	0.034	0.037
Total	0.138	0.133	0.152		0.150	0.161	0.169

Range (Brown and Krygier, 1971). There, annual mean concentrations of suspended sediment increased from 10-30 mg/l to 60-150 mg/l during the first four years after clearcutting and broadcast burning (Beschta, 1978).

TABLE 6. Average Range of Concentrations of Cations in Three-Week Composite Sampling of Streamwater at Fox Creek Watersheds Near Portland, Oregon.

	Stream		
Cation	FC1 (mg/l)	FC2 (mg/l)	FC3 (mg/l)
Ca	0.3-1.2	0.4-1.3	0.5-1.3
Mg	0.4-0.7	0.4-0.7	0.4-0.8
Na	0.7-1.2	0.6-1.2	0.6-1.2
K	0*-0.3	0*-0.3	0*-0.3
SiO_2	1-3	1-3	1-3

*Below detection limit of 0.05 mg/l for potassium.

Sediment increases were caused primarily by construction of the permanent logging road that crossed the FC1 and FC2 streams, including the grading done by crawler tractors in the stream channels below the culvert crossings. Some sediment also came from the fire lines cleared around the logged areas adjacent to the FC1 streams. In addition, leaving leaning trees along streambanks eventually added small amounts of sediment to streams as trees uprooted by wind deposited soil in or near streams. The 14-month increase in sediment concentration in FC3 in 1979-1980 (Figure 2) is related to the windthrow of a single tree in 1979. This sediment probably is partially responsible for the decrease in slope of the double-mass curves in Figure 3.

By 1974, cover by native plants and their litter had stabilized the sediment-contributing areas in FC1 and all but 0.05 ha of a cut bank in FC2 that continued contributing sediment to the stream. The lack of any detectable effect of road building or logging on suspended sediment at FC3 was expected because disturbance to streambanks there was minor, roads did not cross the stream, surface flow from temporary roads was deposited well away from the stream, and no fire lines were constructed.

Much of the variability in concentrations of suspended sediment throughout the study appears to have been associated with freezing and thawing of exposed soil on streambanks, road cuts, and fill surfaces. Sediment concentrations rose when rain fell after freeze-thaw weather like that indicated by on-site measurement of air temperature during the 1962-1963 and 1972-1974 periods.

The change from grab sampling to automatic proportional sampling in 1970 must be kept in mind when the cumulative sediment curves in Figure 3 are viewed. Although sediment concentrations in grab samples taken during road construction were relatively high, they were extremely short lived. There undoubtedly were short periods of storm runoff during the years of proportional sampling when individual samples had sediment concentrations as high as those measured by grab sampling during road construction, but the proportional sampling system would have diluted those concentrations with relatively sediment-free water between periods of storm runoff.

Because of the nature of the grab sampling procedure, sediment concentrations of grab samples probably underestimated actual rates of sediment production in the watersheds prior to road construction and logging. Most weekly site visits for grab sampling occurred between periods of storm runoff when flow rates were nearly all less than 2.1 l s^{-1} ha^{-1} (13 ft^3 s^{-1} mi^{-2}), far below the flows known to transport most sediment. Nevertheless, including data from grab sampling with that from proportional sampling (Figure 3) does suggest changes in sediment production among watersheds that can be attributed to management activities.

Disposal of logging slash was an obvious cause of the observed differences in NO_3-N shown in Figure 4. Whereas clearcut areas in FC1 were deprived of the readily available N capital in forest floor materials and conifer foliage when logging slash was burned, slowly decomposing slash in FC3 remained a major source of NH_4-N available for nitrification. Rate of growth of vegetation and the dominance of huckleberry in FC3 compared with the dominance of fireweed in FC1 may also have affected the N pool in the soil as well as the NH_4-N available for nitrification.

Increased NO_3-N concentrations in streamwater were generally less than those observed in studies elsewhere. At another site in the western Cascade Range of Oregon, an increase in NO_3-N in streamwater was similarly delayed. Mean annual NO_3-N concentration increased to 67 μg/l the second year after all timber was clearcut in a small, steep watershed, but logging residue was not burned (Sollins and McCorison, 1981). The year after logging slash was broadcast burned in a small, clearcut watershed in the Oregon Coast Range, annual mean NO_3-N concentration increased roughly threefold to 440 μg/l (Brown *et al.*, 1973), three times higher than the highest annual concentration measured at Fox Creek. In an extreme case, where deciduous forest at Hubbard Brook in New Hampshire was clearcut and regrowth of vegetation was prevented by herbicide application (Likens *et al.*, 1970), NO_3-N concentration increased 41-fold to 80 mg/l, 1000 times higher than the highest three-week concentration measured in FC1 and 300 times higher than the highest three-week concentration measured at FC3. (As a point of reference, standards for drinking water allow 10 mg/l of NO_3-N in domestic water supply [U.S. Environmental Protection Agency, 1976, p. 107].) Apart from the prevention of vegetation regrowth at Hubbard Brook, a major reason for the difference in NO_3-N concentrations between Fox Creek and Hubbard Brook is the nature of the respective soils. In contrast to the soils at Hubbard Brook, soils at Fox Creek are relatively deep, high in organic matter, and have low base saturations.

Although increases in nutrient concentrations caused by logging and slash disposal observed in this study are far below maximum concentrations allowed by standards for domestic water, such increases might indirectly affect quality of domestic water through their effects on algae production in reservoirs downstream. However, because limiting nutrients such as NO_3-N and P would likely be rapidly taken up by algae in streams, increases in concentrations of these nutrients would probably not persist more than 500-1000 m downstream.

CONCLUSIONS

Road building, 25 percent patch-cutting, and slash disposal by broadcast burning or by natural decomposition caused changes in water quality of two small streams in the Bull Run watershed.

Low levels of suspended sediment both before and after road building, logging, and slash disposal indicate very low rates of soil erosion in the Fox Creek watersheds. Gentle relief, strong structural support of bedrock, inherent stability and hydraulic characteristics of soils, and poorly developed drainage networks all contributed to low sediment inputs to streams. Increases in suspended sediment were due primarily to construction of a permanent logging road that crossed streams in watersheds FC1 and FC2 and erosion of parts of fire lines built around the clear-cut patches in FC1.

Disposal of logging slash changed NO_3-N outflow from the two patch-cut watersheds. Where logging residue was left to decompose naturally, maximum three-week NO_3-N concentrations increased more than sixfold, and average concentrations commonly exceeded 100 μg/l during the October-June high flow season for seven years after logging, and were still elevated at the end of the study, 10 years after timber felling. Where slash was broadcast burned, NO_3-N concentrations increased nearly fourfold but rarely exceeded 50 μg/l, and increases had mainly disappeared seven years after burning.

Annual maximum stream temperatures increased 2-3°C after logging, but temperature increases had largely disappeared within three years.

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