Plant nutrient losses by soil erosion and mass movement after wildfire

J. D. Helvey, A. R. Tiedemann, and T. D. Anderson

ABSTRACT: Annual sediment yields increased as much as 180 times above pre-fire levels after wildfire destroyed all vegetation on three forested watersheds in the Entiat Experimental Forest in the eastern Cascade Range of Washington. Sediment was transported in debris torrents, in suspension, and as bedload. Suspended sediment concentration correlated well with turbidity. Total N losses by erosion processes increased from a pre-fire average of 0.004 kg/ha/yr to 0.16 kg/ha/yr. Available P losses increased from 0.001 kg/ha/yr before the fire to 0.014 kg/ha/yr. The combined erosion loss of Ca, Mg, K, and Na increased from an average of 1.98 kg/ha/yr before the fire to 54.3 kg/ha/yr. Greatest nutrient losses occurred with mass soil movements (debris torrents). Material deposited in alluvial fans represented losses of 13.5 kg/ha of total N, 3.4 kg/ha available P, and 3,850 kg/ha of Ca, Mg, K, and Na combined. An unmeasured but certainly large quantity of soil and rock entered the river during the debris flows. Nutrient losses on eroded soil, although greater than solution losses, were insignificant to site productivity and stability compared with the physical effects of channel scouring associated with greater runoff, higher peak flows, and debris torrents following fire.

SUMMER weather in the eastern Cascade Range of Washington—characterized by high temperature, low humidity, and scant precipitation—is conducive to wildfire. Man-caused or lightning-related fires destroy many hectares of forest nearly every year. No destruction in recent years compares with that of 1970 when about 486 km² were blackened by fire (*17*), including the entire Entiat Experimental Forest, a research facility maintained by the Pacific Northwest Forest and Range Experiment Station.

Based on the reported responses of other watersheds following fire (*22*), we anticipated large, unpredictable increases in sediment production on the forest. An objective of these post-fire studies was to evaluate changes in sediment production. We also determined the effects of fire and fertilization on stream chemistry and solution transport of nutrients (*12, 21*). Because eroded soil carries nutrients, a logical extension of our nutrient budget studies was to determine the magnitude of nutrient losses by soil erosion.

Study area

The experimental forest, located on the eastern slope of the Cascade Range in central Washington, consists of the Fox, Burns, and McCree watersheds, each about 5 km² in area (Figure 1). Elevations range from 610 to 2,135 m above sea level. Slope averages about 50%, but slopes exceeding 90% are common.

Base rock is the Chelan Batholith, a Mesozoic intrusive granodiorite that weathers deeply when exposed. Following glaciation, the area was covered by volcanic ash and pumice from Glacier Peak. The upper 60 cm of soil is a fine sandy loam grading with depth to coarse loamy sand. Beneath is a layer of "popcorn" pumice extending to 6 m deep in many places. Rock outcrops are common above 1,500 m elevation.

The area supported a mature timber stand dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco]. Other overstory species included dense patches of lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and western redcedar (*Thuja plicata* Donn ex D. Don) scattered along streams. Understory vegetation included reproducing overstory species and several shrubs and forbs (*13*). The experimental watersheds were never logged. There was evidence of older fires but none in the past 40 years.

Hydrologic measurements on the experimental forest began in 1959. Annual precipitation at 915 m elevation ranged from 20 to 79 cm and averaged 58 cm between 1961 and 1971. Measurable precipitation usually falls each month, but on the average only 10% of the annual total occurs from June through September. About 70% of total precipitation falls as snow. A snowpack usually forms by December and increases in depth and water content unti March; it usually melts by mid-June.

Streamflow is measured with sharp crested, 120° V-notch weirs. A stillin pond formed by a concrete cut-off wal serves the dual purpose of reducing strean velocity as necessary for accurate flov measurement, and it also traps sedimen eroded by the stream. Sediment is periodi cally removed from these weir ponds an measured.

Streamflow patterns typify areas wher snow is the dominant form of precipita tion. Snowmelt produces peak flows i May and June and gradually declines t low flows in September. Occasional, in tense convection storms in mid-summe sometime produce secondary peaks.

Background

Forest fuels were tinder dry when a se vere lightning storm swept the Entiat Ri er drainage on August 24, 1970. Sever fires ignited on the experimental wate sheds, and within a few hours the entir area was severely and uniformly burne (Figure 2).

Rehabilitation and salvage logging. Im mediately after the fire, plans were deve oped and implemented to test the effectiv ness of rehabilitation programs for stabili ing the burned areas (*19*). McCree wate shed was seeded immediately after the fir with a grass mixture of two parts (b weight) "Latar" orchardgrass and one pa each of "Durar" hard fescue, "Drum mond" timothy, perennial ryegrass, an yellow sweet clover. The mixture was a plied at a rate of 0.67 g/m² and fertilize with 5.6 g/m² of elemental N as ure Burns watershed received the same seedin treatment, but N was applied as amm

Figure 1. Location of the Entiat experime tal watersheds in central Washington.

J. D. Helvey is the project leader for the Timber and Watershed Laboratory, Forest Service, U.S. Department of Agriculture, Parsons, West Virginia 26287. A. R. Tiedemann is a research range scientist and T. D. Anderson is a chemist with the Pacific Northwest Forest and Range Experiment Station, Forest Service, USDA, at La Grande, Oregon 97850, and Wenatchee, Washington 98801, respectively.

September. About 70%
›n falls as snow. A snow-
s by December and in-
nd water content until
nelts by mid-June.
measured with sharp-
notch weirs. A stilling
a concrete cut-off wall
pose of reducing stream
ary for accurate flow
it also traps sediment
m. Sediment is periodi-
n these weir ponds and

terns typify areas where
nant form of precipita-
roduces peak flows in
d gradually declines to
ember. Occasional, in-
storms in mid-summer
secondary peaks.

e tinder dry when a se-
n swept the Entiat Riv-
igust 24, 1970. Several
e experimental water-
a few hours the entire
and uniformly burned

nd salvage logging. Im-
e fire, plans were devel-
nted to test the effective-
on programs for stabiliz-
as (*19*). McCree water-
nmediately after the fire
ture of two parts (by
chardgrass and one part
hard fescue, "Drum-
perennial ryegrass, and
r. The mixture was ap-
0.67 g/m² and fertilized
elemental N as urea.
eceived the same seeding
was applied as ammo-

of the Entiat experimen-
central Washington.

nium sulfate because laboratory and greenhouse tests indicated that these soils were also low in sulfur (*15*). Fox watershed was left as an untreated control to evaluate response of the rehabilitation treatments.

Fire-killed timber was logged under close supervision between 1971 and 1973. Two roughly parallel roads were constructed through McCree watershed; the lower road continued through the Burns watershed. In the absence of snow cover, logging by caterpillar-type tractors and rubber-tired skidders was permitted only on slopes less than 30%; slopes up to 40% could be logged when there was snow cover. Helicopters were used on all slopes steeper than 40%, except for one small area logged with a high-lead system.

Post-fire hydrologic responses. During the first snowmelt season after the fire (1971), peak flow on Burns Creek was about 20% greater than the maximum peak flow observed during calibration (*11*). Annual water yield from each of the three watersheds averaged 50% more than predicted values based on pre-fire vegetation conditions.

Snowpack during the second snowmelt season was nearly 150% of normal; the 114 cm of annual precipitation was 35 cm greater than the maximum observed during calibration. Peak flows on Burns Creek were more than triple, and annual water yield was three-and-one-half times the maximum observed during calibration. The most striking hydrologic response occurred during spring and early summer of 1972 when debris torrents flowed from Fox and McCree Creeks carrying several thousand cubic meters of sediment from both watersheds (*11*) (Figure 3). Unknown amounts of soil and rock were flushed away by the Entiat River.

Sediment and nutrient estimates

Sediment yield is difficult to characterize, especially when rates are high. Slight changes in runoff rates can produce large changes in sediment concentration. When sediment yield is low, as from undisturbed forest, the weir pond is an effective sediment trap. Megahan (*16*) showed that these ponds trapped more than 75% of the nonfilterable solids in an Idaho study. Stream velocity is greatly reduced by such ponds, and all but the very fine particles fall out of suspension and are trapped. We used this method on the experimental watersheds before the fire. Measurements of accumulated material were made as the ponds filled.

Sediment yield increased so much during the second year after the fire that the weir ponds filled within a few hours after cleaning. Because no satisfactory, automatic samplers are available for these high concentrations of coarse materials in streamflow, we used the simple grab sampling technique with 5-liter, wide-mouth bottles, even though that method is flawed. One of the most serious problems is obtaining representative samples when sediment concentrations change rapidly. This problem becomes less serious, however, when runoff is from snowmelt because streamflow usually increases gradually. In contrast, streams respond quicky to intense rainstorms.

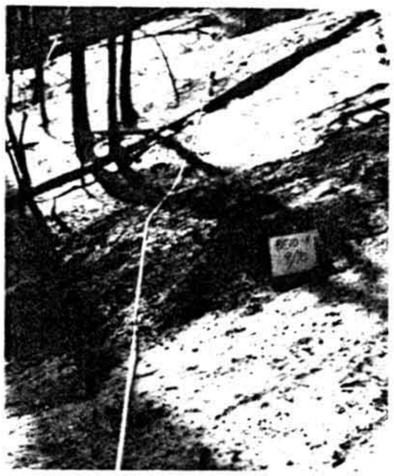

Figure 2. Virtually all of the litter layer was destroyed as the watersheds were severely and uniformly burned.

Figure 3. Rapid snowmelt in March 1972 and intense rainfall in June 1972 produced debris torrents from McCree and Fox watersheds.

Because the weirs on Fox and McCree Creeks were destroyed by debris torrents in 1972, we collected no sediment data during 1973 or 1974. Sampling frequency thereafter depended on flow rates; for example, samples were collected at biweekly intervals during base flow periods and sometimes hourly during peak snowmelt. These small, steep streams have rough channel bottoms. Hence, flow is turbulent, especially during peak discharge, and there is no way to separate suspended sediment from bedload.

In the laboratory, we analyzed the grab samples for nonfilterable solids and turbidity by standard methods (*1*). To estimate sediment yield from each watershed, we assumed that sediment samples were representative of total water yield during the periods including one-half the time since the previous sample and one-half the time until the next sample. We computed total water yield between these dates and applied the sediment concentration of the sample to that volume. Sediment content (mg/liter) was plotted as a function of nephelometric turbidity units (NTU). A close relationship would enable us to estimate sediment concentration using the easier-to-measure NTU.

The grab samples did not provide enough solid material for analysis of total Kjeldahl N, available P, Ca, Mg, Na, or K concentrations. Thus, we collected additional samples during 1976 using a bedload sampler. This sampler effectively captured particles larger than 0.18 mm. And by sampling for 5-minute periods enough material was collected to analyze nutrient concentrations.

To estimate nutrient losses by debris torrents, we first measured the area of each debris fan and estimated its depth by averaging the depth of 10 uniformly spaced pits on each fan. We then randomly located six sites on each debris fan to determine bulk density and nutrient content, taking an 1,800-g soil sample from a 25-cm-deep hole at each site. All material was bagged for weight determination and nutrient analysis. We then lined the excavated sample hole with plastic and filled it to the surface with water to the nearest 10 ml to quantify the soil sample volume. Bulk density (oven-dried weight at 70°C) was determined for each sampling site on each debris fan, a technique that compares well with the paraffin-clod method (*14*).

After oven drying at 70°C to constant weight, samples collected with the bedload sampler and from debris fans were ground to pass a 140-mesh screen. We analyzed samples for (a) concentrations of total N by micro-Kjeldahl digestion (*3*), followed by determination of NH_4-N with an ammonia electrode and a specific ion meter (*4*); (b) available phosphorus by Bray's No. 1 method (*3*); and (c) total Ca, Mg, K, and Na by digestion with hydrofluoric and perchloric acid (*2*, *3*), followed by atomic absorption spectroscopic analysis (*18*).

We calculated average concentration of each nutrient for bedload and debris fan material. We also computed the standard deviation for each nutrient even though the bedload samples were collected during high flows and not randomly throughout the year. Therefore, the standard deviations presented represent relative variation among the sample values, but may not be a valid estimate of the entire population of flow conditions.

We calculated total nutrient output by soil erosion (other than debris flows) as the product of mean sediment nutrient concentration and estimated sediment yield between sampling dates. For debris fans, total nutrient output was the product of bulk density, total debris fan volume, and percent nutrient concentration.

We converted nutrient outputs as soil erosion and debris fans to kg/ha for each watershed to compare sediment to solution losses and to relate our results to other studies.

Results

Sediment yield. Table 1 summarizes sediment yields from the experimental watersheds. Sampling errors associated with these estimates were impossible to quantify, but we believe the values are conservative because our sampling technique was not effective in capturing particles moving along stream bottoms.

The watersheds were stable before the fire, and little sediment was trapped by the weir ponds. In fact, weir ponds on McCree and Burns watersheds, with respective storage capacities of 30 and 50 m^3, did not require cleaning between 1961 and 1970. Annual accumulations at Fox weir averaged 66 kg/ha between 1967 and 1970. Most of this material came from a short stream section where side slopes were steep and sparsely vegetated. Dry ravel from these areas accumulated along the stream channel during the summer (Figure 4), then was transported to the weir pond during snowmelt.

Figure 4. Dry ravel along stream channels became an important erosion process during summer months after the fire.

Table 1. Sediment yield from the Entiat experimental watersheds before and after the wildfire.

Watershed	Pre-fire 1967	1968	1969	1970	Post-fire 1971	1972	1975	1976	1977
					kg/ha				
Fox	70	100	71	21	403	3,800*	480	690	298
Burns	10†	10	10	10	262	1,848	434	338	170
McCree	8†	8	8	8	119	1,411	70	71	25
Average	29	39	29	13	261	2,353	328	366	164

*Does not include material lost in debris torrents.
†Average values, based on 10-year accumulations removed in 1970.

Table 2. Chemical characteristics of sediment in samples collected during spring snowmelt.

Watershed	Total N	Available P	Total Ca	Mg	Na	K
			%			
Fox						
Mean	.008	.001	1.40	.59	2.99	2.53
Standard deviation	.005	.0002	.13	.40	.59	.11
Burns						
Mean	.046	.003	1.55	.59	2.97	1.94
Standard deviation	.175	.006	.03	.10	.08	1.03
McCree						
Mean	.033	.001	1.38	.62	2.92	2.31
Standard deviation	.013	.001	.10	.28	.27	.36
Average	0.027	0.002	1.44	.60	2.96	2.26

One year after burning, sediment trapped on McCree, Burns, and Fox Creeks amounted to 119, 262, and 403 kg/ha, respectively. Vegetative cover was sparse during spring snowmelt when most of the material was transported. Streamflow was 60% above normal as a result of reduced transpiration losses (*10*). Increased flow rates caused channel scouring, the source of most of the transported sediment. Another important source in Burns and McCree watersheds was newly constructed roads; fill material at stream crossings was picked up by swollen streams.

Several factors in 1972 combined to produce record flow rates and sediment yields. First, the soil profile, which normally contained minimal water after the growing season, was near field capacity at the end of 1971. Second, the 1972 snowpack was one of the deepest on record in the Cascades. Third, unusually warm March weather caused rapid snowmelt, producing discharge rates three times greater than the maximum measured during calibration. Finally, intense convection storms during June and August caused extensive overland flow and soil erosion from the channel area.

The results in table 1 do not include material deposited on alluvial fans during debris torrents or the unknown volume carried away by the river. A survey of the fans provided estimates of 16,000 and 14,500 m^3 of soil and rock at the mouths of Fox and McCree watersheds, respectively. When converted to weight per unit watershed area using measured bulk densities of 1.8 and 1.5 g/cm^3 for Fox and McCree, the fans represent transport of 61,000 and 42,000 kg/ha of debris, respectively.

After the debris torrents in 1972, sediment yield declined sharply on McCree Creek and remained low through 1977. Yields from Fox and Burns watersheds remained substantially above pre-fire levels and were greater than on McCree watershed through 1977. Reductions in sediment yield between 1972 and 1977 on all watersheds were concurrent with slope revegetation. Vegetative cover increased from an average of 8% on the three watersheds in the first post-fire year (Figure 5) to 30% cover by 1974 (*19*) (Figure 6). By 1976, cover averaged 44% on the three watersheds (Figure 7).

A linear model produced the greatest coefficient of determination (R^2) between NTU and sediment concentration, but a single regression overestimated sediment concentrations below 10 NTU. Therefore, we computed two linear regressions: one rted to the weir pond dur-

iter burning, sediment Cree, Burns, and Fox to 119, 262, and 403 kg Vegetative cover was ing snowmelt when most vas transported. Stream ove normal as a result of tion losses (10). Increased d channel scouring, the the transported sediment nt source in Burns and ds was newly constructed al at stream crossings was llen streams.

in 1972 combined to pro- rates and sediment yields file, which normally con- water after the growing field capacity at the end the 1972 snowpack was st on record in the Cas- nusually warm March rapid snowmelt, produc- s three times greater than easured during calibra- tense convection storms August caused extensive nd soil erosion from the

able 1 do not include ma- n alluvial fans during de- he unknown volume car- river. A survey of the fans es of 16,000 and 14,500 ck at the mouths of Fox vatersheds, respectively to weight per unit water- neasured bulk densities of for Fox and McCree, the ransport of 61,000 and debris, respectively.

ris torrents in 1972, sed- ined sharply on McCree ined low through 1977 and Burns watersheds re- ially above pre-fire levels than on McCree water- 7. Reductions in sediment 72 and 1977 on all water- rrent with slope revegeta- cover increased from n the three watersheds e year (Figure 5) to 30% 19) (Figure 6). By 1977 44% on the three water-

produced the greatest co- rmination (R^2) between ent concentration, but overestimated sediment elow 10 NTU. Therefore vo linear regressions: one

Figure 5. Vegetative cover was sparse during the first year after the fire.

Figure 6. By the end of four growing seasons, vegetative cover had increased to 30% at the same site as in figure 5.

Figure 7. Vegetation covered 44% of the watershed at the end of the sixth growing season, again at the same site shown in figures 5 and 6.

Table 3. Sediment transport of total N before and after wildfire.

Watershed	*1967*	*1968*	*1969*	*1970*	*Average Yearly Pre-fire*	*1971*	*1972*	*1975*	*1976*	*1977*	*Average Yearly Post-fire*
					kg/ha						
Fox	.006	.008	.006	.002	.006	.03	.30	.04	.06	.02	.09
Burns	.004	.004	.004	.004	.004	.12	.85	.20	.16	.08	.28
McCree	.003	.003	.003	.003	.003	.04	.47	.02	.02	.01	.11
Average	.004	.005	.004	.003	.004	.06	.54	.09	.08	.04	.16
Solution losses of N*	-†	-	0	.066		.27	3.35	.86			
Percent of combined solution and sediment loss occurring as sediment	-	-	-	4.3		18.2	13.9	9.4	-	-	

*From Tiedemann and Helvey (*20*) and Tiedemann and associates (*21*).
†No data.

for turbidity < 10 NTU, and one for turbidity ≥ 10 NTU. Because regression slopes and intercepts did not differ significantly among watersheds, the following are combined equations (Figure 8): For turbidity levels ≥ 10 NTU, sediment concentration (mg/liter) = 4.57 + 4.64 (turbidity, NTU). R^2 was 0.982, and the standard deviation was 70.5 mg/liter. For turbidity levels < 10 NTU, sediment concentration (mg/liter) = − 3.12 + 5.63 (turbidity, NTU). R^2 was 0.723, and the standard deviation was 8.16.

Sediment transport of nutrients. Analysis of sediment samples collected with the bedload sampler indicated considerable variation in total N among streams. Percentages of other measured nutrients, in contrast, were relatively uniform among watersheds (Table 2). Total N varied from 0.008% in sediment from Fox Creek to 0.046% for McCree Creek. Higher levels from Burns and McCree watersheds may be partly caused by fertilization on these watersheds, but we have no way to trace the sources. Na and K were the predominant cations, averaging 2.96 and 2.26%, respectively.

Post-fire sediment losses of total N increased 40 times, from pre-fire levels of 0.003 to 0.16 kg/ha (Table 3). Maximum loss of 0.85 kg/ha occurred during 1972 on Burns watershed. Pre-fire total N losses were only 4.3% of combined, post-fire solution and sediment losses (Table 3). Soil erosion increased in importance as an N loss mechanism after the fire, carrying nearly 10% of the total N loss.

Concentrations of P, Ca, Mg, K, and Na were relatively uniform among watersheds; thus, average values are presented (Table 4). Pre-fire available P losses averaged 0.001 kg/ha/yr and increased to an average of 0.014 kg/ha/yr after the fire. Maximum annual loss averaged only 0.05 kg/ha in 1972. Average annual sediment losses of P were substantially below solution losses after the fire of 0.06 to 0.15 kg/ha.

Pre-fire average sediment-borne losses of the four cations (sum of Ca, Mg, K, and Na) was 1.98 kg/ha/yr for the three watersheds. Pre-fire solution losses, in contrast, were 19.3 kg/ha/yr (*20*). Average post-fire sediment transport of these cations was 54.3 kg/ha/yr. Maximum annual losses occurred in 1972 when 170.0 kg/ha were removed. Post-fire average solution transport of cations was 42.3 kg/ha/yr (*21*). Thus, cation transport on eroded soil became a major part of the post-fire output, exceeding solution losses by 12 kg/ha/yr.

Nutrient transport via debris torrents. Table 5 records chemical composition of samples from debris fans. These percentages differ little from comparable nutrient percentages for suspended sediment (Table 2).

Because of the tremendous volume of material transported in debris torrents, nutrient losses by this process exceeded losses

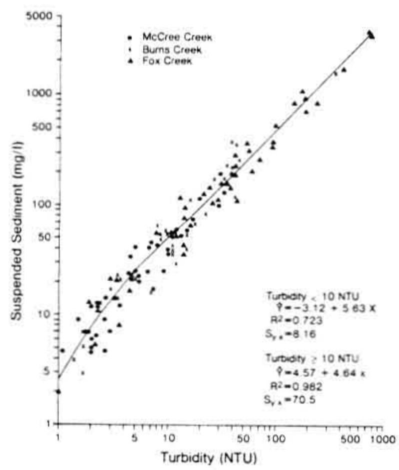

Figure 8. The relationship between turbidity and suspended sediment.

by other soil erosion processes or by solution losses. The alluvial fans represented average losses from Fox and McCree watersheds of 13.9 kg/ha of total N, 3.4 kg/ha of available P, and 3,851 kg/ha of Ca, Mg, K, and Na combined (Table 6). Compared to suspended sediment yields, nutrient losses in debris flows were 83 times greater for total N, 243 times greater for available P, and 71 times greater for the measured cations. Again, an additional but unknown amount of material was transported to the river during the debris torrents and escaped measurement.

Discussion

Table 1 indicates a sharp, protracted reduction in sediment yield from McCree watershed after 1972 and slower reductions from the Fox and Burns watersheds. This difference probably resulted from the two debris torrents that scoured the McCree watershed channel to bedrock; thus, the channel area was resistant to additional soil erosion. Also, Burns and Fox watersheds have well-developed, periglacial alluvial fans at elevations of 1,200 to 1,300 m; the McCree watershed has no periglacial deposit.

Annual losses of total N by sediment transport (Table 3) were lower than the 1.9 to 3.8 kg/ha for clearcut and burned areas reported by Fredriksen (8) for western Oregon. DeByle and Packer (7) reported total N losses of 0.9 and 1.0 kg/ha on sediment eroded from small plots in the first and second years, respectively, following logging and burning. Losses during the fourth year were only 0.12 kg/ha.

Our pre-fire soil erosion losses of cations (Table 4) compared well with values reported by Fredriksen (8) and Brown and associates (5) for watersheds that were clearcut and later burned. Post-fire losses of the four cations in our study, however, were substantially greater than they observed after treatment. Our values were more comparable with those measured by DeByle and Packer (7) following clearcutting and slash burning in western Montana (37 kg/ha/yr) and by DeBano and Conrad (6) following prescribed fire in southern California (131 kg/ha/yr).

To our knowledge, nutrient removal by debris torrents has not been documented in any other study, probably because the physical nature of such events overshadows the nutrient implications for vegetation establishment and site productivity. Channels are scoured to bedrock in most places, limiting vegetation establishment until the material is replaced by creep, dry ravel, and to a lesser extent by breakdown of parent rock. Thus, losses of plant nutrients by soil erosion and debris torrents, although substantial, are probably of minor importance to vegetation establishment relative to the severe physical effect of scouring the stream channel to parent rock.

Interpreting losses of nutrients by soil erosion and debris torrents in terms of site productivity is only speculation because we have no data for vegetation productivity or cover in the channel area. We know from observation, however, that the channels are difficult sites to revegetate. Side slopes normally exceed 1:1, and without vegetation they are subject to erosion by dry ravel. Sediment from dry ravel accumulates in the stream channel during summer dry periods when streamflow is minimal. This sediment discourages vegetation establishment because it covers germinating seedlings. During spring snowmelt, the stream erodes the sediment, thus creating slope conditions conducive to more dry ravel. As late as 1976 (5 years after the fire), most of the riparian zone still had little vegetation cover.

Comparing nutrient losses by soil erosion and debris torrents with solution losses may not be realistic because erosion processes primarily are restricted to the riparian zone, which occupies only 5 to 10% of the watershed area. A major drawback to making such a comparison is that most nutrients in sediment and alluvial fans are in stable inorganic compounds that are not readily available to plants. Solution losses, in contrast, represent a loss from the available (exchangeable) capital of nutrients. Thus, from the standpoint of watershed productivity, solution losses are probably more important than the larger nutrient losses from soil erosion and debris torrent processes. Tiedemann and associates (21) found that solution losses from these watersheds between 1971-1978 comprised 17, 13, 4, and 39% of the exchangeable nutrient capitals of Ca, Mg, K, and Na measured by Grier (9) in the upper 30 cm of soil.

No measurements of sediment loss have been made since 1977 and no vegetation measurements since 1976. However, cursory observations found the burned watersheds were well vegetated in 1982, largely by snowbrush ceanothus (*Ceanothus velutinus* Dougl.), a nitrogen-fixing species. Sediment yield also appears to be much lower than when our last measurements were made. Finally, even with the large losses of nutrients in solution and by erosion processes (including mass movement).

Table 4. Annual losses of sediment-born nutrients.

Year	Available P	Ca	Mg	Na	K	Cation Summation
	kg/ha					
1967	.001	.42	.17	.86	.66	2.11
1968	.001	.56	.23	1.15	.88	2.82
1969	.001	.42	.17	.86	.66	2.11
1970	.0003	.19	.08	.38	.29	.94
Pre-fire average annual	.001	.39	.16	.81	.62	1.98
1971	.005	3.76	1.57	7.73	5.90	18.9
1972	.050	33.88	14.12	69.65	53.18	170.0
1975	.007	4.72	1.96	9.71	7.41	23.8
1976	.007	5.27	2.20	10.83	8.27	26.6
1977	.003	2.36	.98	4.85	3.71	11.9
Post-fire average annual	.014	10.0	4.17	20.55	19.61	54.3

Table 5. Chemical characteristics of debris fans.

Watershed	Total N	Available P	Ca	Mg	Na	K
	%					
McCree	.027	.007	1.60	.57	3.00	2.44
Standard deviation		.001	.05	.04	.18	.11
Fox	.027	.006	1.52	.48	2.98	2.24
Standard deviation		.001	.08	.02	.11	.18

Table 6. Nutrient transport by debris flows from Fox and McCree watersheds

Watershed	Total Mass	Total N	Available P	Ca	Mg	Na	K
	kg/ha						
Fox	61,000	16.5	4.3	976	347	1,860	1,488
McCree	42,000	11.3	2.4	638	201	1,252	941