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SEDIMENT TRANSPORT AND SOIL DISTURBANCE AFTER POSTFIRE LOGGING

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ABSTRACT

Recently there has been considerable debate on the practice of postfire logging, in which burned forests are entered soon after fire to recover commercially valuable trees. Proponents of the practice argue that postfire logging is part of a 'restoration package' that can be used to control erosion (e.g., contour logging) and can help to mitigate costs of rehabilitation. Opponents argue that postfire logging damages sensitive soils and can lead to excessive erosion and sediment transport. Review of the literature on postfire logging shows that very little direct scientific information can be brought to bear on this issue. A handful of hydrological studies have indicated that burned sites can be unusually sensitive to logging, especially when ground-based logging systems are used. These studies however, have demonstrated that there is considerable variation in environmental effect, due to differences in soil type, slope, weather conditions after logging, and the type of logging equipment used. In an effort to provide more information on postfire logging effects, an experiment was begun in 1997 to evaluate soil impacts and sediment transport after logging of stands burned by the 1996 Summit Fire on the Malheur National Forest. Soil disturbance and sediment transport were measured in four replicated units in each of three postfire harvest treatments (unharvested control, partial harvest, full harvest). Displacement, compaction, and erosion were the most commonly observed types of machine-caused soil disturbance. There was a significant difference among treatments in the percentage of mechanically disturbed soil area, with controls having less area disturbed than harvested units. Despite significant soil disturbance however, little sediment transport out of experimental units occurred, due largely to: 1) the practice of hand felling; 2) logging over snow or on dry ground; 3) low slopes; 4) heavy soils; 5) no new roads; and 6) the absence of extreme weather events after logging. Visual inspections indicated that relatively little sediment left the experimental units in the short term, and that the existing road system was responsible for most sediment transport.

INTRODUCTION

Considerable public debate has focused on the relative merits of postfire logging on lands in the western United States. Proponents of postfire logging argue that the practice is one of a suite of restoration methods, designed to mitigate the adverse environmental effects of the wildfire itself (Amman and Ryan 1991; Poff 1989), that removal of large woody structure reduces the risk of a severe reburn (the "reburn hypothesis"; Poff 1989), and that the sale of burned timber can be used to offset the cost of postfire restoration (Barker 1989). Opponents argue that postfire logging causes increases in erosion and sediment transport to streams as a result of the harvest operations themselves (Beschta et al. 1995; Minshall et al. 1994), or removes structure that has important ecological functions (Maser 1996; Stone 1993).

There is relatively little direct scientific information on the ecological effects of postfire logging (McIver and Starr 2001). Generally, the available literature emphasizes the sensitivity of burned soils to erosion and sediment transport, and underlines the importance of site conditions, roads, and logging system in explaining patterns of sediment transport. In this paper, I present a brief review of literature on soil and sediment effects of postfire logging (Table 1); and describe short-term results of an experiment designed to assess logging activity effects on one severely burned site in the Blue Mountains of eastern Oregon.

LITERATURE ON POSTFIRE LOGGING EFFECTS

Severe wildfire has several well known effects on vegetation and soil. In particular, tree mortality due to severe wildfire results in decreased evapotranspiration that leads to saturated soil (Walsh et al. 1992), and the development of water repellency (DeBano 1989), both of which can lead to increases in overland flow and sediment transport to streams (Megahan and Molitor 1975). In general, literature on fire effects suggests that soil disturbance will tend to have a greater effect on burned sites compared to green tree sites. These effects however, will depend on site characteristics, burn severity, road condition, road building, logging systems, and the occurrence of extreme weather in the few years following the fire.

A common theme in postfire logging studies is that site characteristics will generally have a profound influence on whether significant sediment is produced by a logging operation. The WRENSS model described by Potts et al. (1985) which calculates the amount of water available for annual streamflow on the basis of the amount of seasonal precipitation and the postfire residual leaf area index, suggests that sediment and water yields will increase with increasing catchment area and slope in logged postfire landscapes. Postfire logging caused an earlier peak flow in the Pack River of northern Idaho, due to earlier snowmelt (Campbell and Morris 1988), although an increase in total water yield was not observed. Work in Australia by Mackay and Cornish (1982) and in California by Chou et al. (1994) shows increased sediment following postfire harvest to be related to catchment area and slope.

Although we could find no studies that looked at the effects of postfire road building and use *per se* (McIver and Starr 2001), it is likely that roads will contribute much to sediment production in the postfire environment, just as they do in unburned stands (Megahan 1971, Beschta 1978). In a postfire study of the Entiat Fire, Helvey (1980) indicated that road-building contributed a substantial amount of sediment in the first year after the wildfire. The comparative significance of roads versus logging *per se* is reflected in the data of Megahan and Kidd (1972), who estimated that logging in unburned stands caused erosion increases from the logged sites of two to seven times that of undisturbed sites, compared to 100- to 220-fold increases in erosion from logging roads.

The effect of postfire logging on sediment production and soil disturbance also depends on logging system type and the extent to which logging residue remains on site. Logging practices, including cutting and log retrieval technologies, have differed widely over the years and across regions. The kind of practice used in any given project will depend on several factors: (1) slope, (2) soil conditions, (3) perceived ecological sensitivity, (4) value of merchantable material, and (5) available equipment. The harvesting economics of postfire logging will dictate to a great extent the harvesting practices used and the prescriptions implemented. There is very little information available comparing soil and erosion effects of different logging systems. Soil compaction from ground-based skidding may increase overland flow; however, ground disturbance produced by logging operations may disrupt water-repellent soil layers and thus decrease overland flow during severe hydrological events (Walter Megahan, pers. comm., NCASI, Pt. Townsend, WA). Further, Mackay and Cornish (1982) working on sites with coarse-grain granitic soils in southeastern Australia, attributed most of the increase in overland flow to decreases in transpiration rates in the postfire environment, a conclusion illustrating the difficulty in distinguishing between erosion due to logging and that from the fire itself.

How does ground-based log retrieval compare to aerial log retrieval in the postfire environment? Working on the Entiat burn of 1970 (Wenatchee National Forest, WA), Klock (1975) and Helvey et al. (1985) compared five different log retrieval systems (after hand felling) with respect to soil disturbance and erosion: tractor skidding over bare ground (<30% slope), tractor skidding over snow (<40% slope), cable skidding over bare ground, skyline (Wyssen skycrane), and helicopter. The study area had slopes that averaged 50%, but slopes of 90% were common. Soil depths ranged from a few centimeters to over 6 m and were formed from weathered grandiorite colluvium covered by volcanic ash and pumice. Vegetation type was ponderosa pine (*Pinus ponderosa*) at lower elevations to Douglas-fir (*Pseudotsuga menziesii*) at higher elevations. Klock (1975) found that tractor skidding over bare ground caused the greatest percentage of area with severe soil disturbance (36%), followed by cable skidding (32%), tractor skidding over snow (9.9%), skyline (2.8%), and helicopter (0.7%). Erosion and sediment transport paralleled soil disturbance, with the highest percentage of area with erosion occurring in the cable skidding units (41%), followed by tractor skidding over bare ground (31%), tractor skidding over snow (13%), and helicopter (3.4%). Some complicating factors behind these numbers that were not isolated are the effects of different slopes among systems, the contribution of road building, and warm temperatures that melted snowpack during logging and caused intense erosive conditions at low elevations, particularly near roads (Klock 1975). Postfire logging with ground-based systems caused soil disturbance on much more area than did logging with helicopters (34-74% area disturbed compared to 12%) and substantially increased area with erosion (13-31% compared to 3%). When compared to studies conducted on similar systems in green-tree stands, area with soil disturbance was generally greater for Klock's study, particularly for cable skidding, probably because of the lack of understory vegetation and litter that was burned by the Entiat fire.

Finally, although logging (particularly ground-based) can have significant effects on sediment yields in postfire watersheds, logging residue can mitigate some of these effects. Shakesby et al. (1996) show that eucalyptus logging litter reduced soil loss in postfire watersheds by up to 95%. In a similar vein, Megahan and Molitor (1975) recommend that managers delay postfire logging until needle fall (for those burned stands in which most trees still possess needles), so that the forest floor will gain some additional protection from erosion.

THE SUMMIT POSTFIRE LOGGING STUDY

This study was designed to evaluate soil disturbance and sediment transport after postfire logging. The 16,000 hectare Summit Fire was caused by a lightning storm on August 13, 1996, on the North Fork John Day Ranger District (Umatilla National Forest), burned south onto the Blue Mountain Ranger District (now a combination of the Long Creek and Bear Valley Districts) of the Malheur National Forest, and was declared officially controlled on September 16, 1996 (Figure 1). In the summer of 1997, three treatments (full salvage, partial salvage, no salvage) were applied to 12 experimental units on the Malheur National Forest that had been severely burned. Soil disturbance was measured before and after logging to estimate the potential for impacts on site productivity. Soil disturbance was also correlated with sediment transport, in an effort to estimate the potential that logging activities would contribute sediment to perennial streams.

STUDY AREA AND TREATMENTS

The study area is located on lands in the southern portion of the burned area (44°40'49" ~ 44°42'57"N; 118°41'40" ~ 118°45'55"W), at relatively low elevations (< 1400 m), and is considered a 'warm/dry' biophysical type, historically dominated by ponderosa pine (*Pinus ponderosa*) in the overstory (with some representation of *Pseudotsuga menziesii* and *Abies grandis*), and pine grass (*Calamagrostis rubescens*) in the understory (Figure 1). Two basic types of soils occur in the study units. The most common are "non-ash soils", which are stoney, clay loam to clay soils with moderate surface erosion and compaction hazard, and low displacement hazard. These soils are more erodible than most soils on the Malheur National Forest, because of their relatively low infiltration rate, relatively low water holding capacity, and relatively low production of ground cover. On the lower boundary of the experimental units are "ash soils", which have a silty loam volcanic ash cap up to 25 cm in thickness. Ash soils absorb much more readily than non-ash soils, and so tend to be less erodible. Precipitation averages about 700 mm per year. Most precipitation falls as snow from November to April, but intense thunderstorms can occur in July, August and September (USDA 1997).

Like most of the Blue Mountains of northeastern Oregon, management activities of the last 90 years, namely fire suppression and the harvest of large pines, have had significant effects on vegetation and fire regimes within the Summit Fire project area (Agee et al. 1994). In particular, fire suppression has encouraged the establishment of grand fir and Douglas fir, and coupled with the widespread removal of large pines, this has led to an increase in fuel and density of small stems, such that fire regimes have shifted toward greater severity compared to historical times (Agee et al. 1994). As a result, within the Malheur Forest portion of the Summit Fire, 8,103 hectares (72%) were judged to have burned at high intensity, including much of the acreage in the lower elevation dry forests, which typically experience lower intensity fires (USDA 1997).

Twelve experimental units ranging in size from 6-16 ha were established in four blocks in August 1997 (Figure 1). All stands within each block had burned severely during the Summit Fire, on the basis of the percentage of trees that survived the wildfire (<20%), and on the percentage of forest floor that was left exposed (>40%). Each block was located in a separate drainage, with perennial streams that flow past each block (Deep, Coyote, Beaver Creeks) emptying into the Middle Fork of the John Day River. Within each block, three treatments (control, full salvage, partial salvage) were assigned randomly to units, for a complete randomized block design. Control units received no logging treatment. The prescription for full harvest units was to remove all dead merchantable trees, leaving six snags per hectare minimum. The prescription for partial harvest units was to remove 2/3 of dead merchantable trees, leaving at least 17 snags per hectare. All logging was required to take place on frozen or dry ground, to minimize soil disturbance. A total of 88 ha were logged between October 1998 and August 1999 (Table 2). Each partial harvest unit was entered once, while full harvest units were entered twice, once to remove the largest boles as part of a timber sale contract, and a second time to remove smaller boles as part of a service contract. Trees were felled by hand, and whole trees were yarded into skid trails and retrieved to landings with a rubber-tire skidder. Slopes in the experimental units averaged 15.8%, closely similar to slopes in other stands of the project area in which logs were retrieved by skidder (mean = 15.9%). In other logged stands of the project area however (outside the experimental units), trees were felled with the use of a feller-buncher. According to the logger, the practice of hand-felling in the experimental units was done to minimize soil disturbance. The practice of hand felling increased cost in these units considerably compared to machine felling. As part of the overall restoration effort, pine seedlings were planted within each of the twelve experimental units, within two years after logging. Finally, no new roads were built in the vicinity of the experimental units.

METHODS AND MATERIALS

Response variables were measured pre- and postlogging from the same permanently established grid points. A total of 330 plots were laid out among the 12 units in August 1997. Grid points were positioned 50 m apart, and at least 50 m from unit boundaries. Pre-treatment data were taken in all twelve units between August and October 1997; post-treatment data were taken from July to September 1999, immediately following the termination of logging.

Soil disturbance was assessed along 30 m transects laid out at random bearings from each grid point. Both compaction and displacement were assessed at 2 m intervals along each transect. Compaction was recorded if the soil surface contained cleat marks, if the soil was depressed more than 5 cm, if a penetrometer (steel rod with 1 cm diameter cone-shaped tip) encountered unusual resistance not due to rocks or roots, or if excavation of soil showed signs of plating. Displacement was defined as the removal of the forest floor or the upper portions of the mineral soil. Soil disturbance data were analyzed with analysis of variance (SPSS 2001), assuming a complete randomized block design. Pair-wise comparisons were examined by least-squared difference.

Sediment transport was measured with the use of silt fences (Robichaud and Brown 2002) installed shortly after the first logging entry was finished in each unit (Table 2). At least three silt fences were installed along the lower boundary of each treated unit, and one fence was installed in each of the four control units. Catchment area above each fence varied from 0.1 to 0.8 ha, and averaged about 0.3 ha. In treated units, fences were placed at three locations that were judged to be highest, lowest, and medium risk for sediment transport. Criteria used for their selections included the size and slope of bare areas upslope, presence of water bars to interrupt overland flow, and the likelihood of overland flow carrying sediment out of the unit. Sediment was collected from fences periodically beginning after snowmelt in spring 1999, until the end of summer 2000. Sediment was weighed and converted to volume (liters) using a bulk density of 0.9g/cm^3. In May and June 1999, the lower boundaries of each unit were also inspected for signs of sediment transport out of the unit, within the context of skid trails, existing roads, and natural watercourse features. Results are reported descriptively.

RESULTS

On average, between 2 and 6% of soil area within experimental units was classified as disturbed prior to logging activity. About 20% of soil area was additionally disturbed by machines in the full harvest units, compared to about 15% in partial harvest units, and 4% for the control units. Additional disturbance in the control was probably caused by machine activity on the unit boundaries. Despite considerable variation among units in the percentage of mechanically disturbed soil area (total compaction + displacement), there was a significant difference among treatments ($P<0.05$). Displacement was the most commonly observed type of machine-caused soil disturbance, followed by compaction (Table 3). There was a significant difference among treatments in percent area displaced ($P<0.05$) with control units differing from full salvage units. While control units also significantly differed from full salvage units in percent area compacted, there was only a trend toward significance difference in compaction overall among treatments.

Most sediment was transported during the spring runoff of 1999, following a winter of higher than normal snowfall. No significant thunderstorms visited the area in the year following postfire logging. Consequently, we collected very little sediment from the 16 fences in blocks 1 and 2, installed in the summer of 1999. Sediment was collected from 10 fences, and in six of these cases, roads contributed to sediment production and transport (Table 3). The greatest amount of sediment (19.3 liters) was collected by a fence located on a haul road that formed a small part of the lower boundary of unit 323 (full logged). Other road-associated features that contributed sediment included landings (0.1 l - unit 323; 0.2 l - unit 327), and culverts (0.3 l - unit 421; 0.0002m^3-unit 522) in both full and partial logged units. Relatively little sediment was collected from fences not affected by roads, including 2.7 l from a skidtrail at the bottom of a step draw in unit 327 (partial logged), and 2.8 l from the bottom of a draw in unit 424 (partial logged). No sediment was collected from the 4 fences placed in the control units. Comparison of sediment transport with data on compaction and displacement indicated that while there was no sediment transport observed in the units with the least soil disturbance (controls), there was little other correspondence in the two data sets. Thus, it was not possible to predict whether or not a silt fence would receive sediment based on the level of soil disturbance within that experimental unit.

Visual inspection of the lower boundaries of the experimental units indicated that most of the overland flow that exited units was at locations influenced by the existing road system. Of 39 such locations, 28 were influenced by roads and 11 were natural draws or ephemeral streams. Most road-caused sediment export from units occurred where a road left a unit (5 cases), where a road formed the lower boundary of a unit (13 cases), and in cases where culverts above units concentrated surface runoff that failed to infiltrate before exiting (4 cases). Probably the greatest influence of roads was in unit 419, where a 335 meter road formed part of its lower boundary, and along which there were 13 locations where sediment exited the unit. In three cases, culverts above units 052 and 522 concentrated runoff, and produced sediment 'trails' that ran down slope more than 300 m. In all, we observed seven cases (25% of total cases) where road-influenced runoff carried sediment into perennial streams. Of the 11 natural sources of sediment transport, units 323 and 052 contained seven, primarily due to the presence in these units of shallow clay soils with poor infiltration. We observed six instances where locations not influenced by roads produced sediment that reached perennial streams (55% of total cases). We did not observe sediment transport out of units that was specifically due to the skid trails produced by the recent logging operation.

DISCUSSION

Logging activity at Summit caused a significant increase in the percentage of soil area disturbed, and consisted primarily of displacement and compaction. While disturbance levels in some units exceeded the 15% recommended standard for Forest Service Region 6 (Howes et al.1983, USDA 1996), it is not clear what implications this had on site productivity. Both compaction and displacement can however, have significant effects on site productivity of interior conifer forests. Cochran and Brock (1985) and Froelich (1979) reported significant reduction in growth of individual ponderosa pine trees growing in compacted soil in eastern Oregon. In central Idaho, Clayton et al. (1987) reported that displacement and compaction of ash-dominated soil were responsible for significant declines in growth of both lodgepole pine (*Pinus contorta.*) and ponderosa pine. Similarly, displacement caused by mechanical site preparation was reported to be responsible for a reduction in seedling growth of Douglas-fir (*Pseudotsuga menziesii*) in northern Idaho (Miller 1984).

Compaction can also impede water infiltration that can lead to increases in overland flow and sediment transport (USDA 1980), and displacement can lead to increases in erosion rates (Klock 1982). Are compaction and displacement linked with sediment transport in the current study? While harvest units varied between 2 and 13% in compacted area, and between 4 and 31% in displaced area, silt fences and visual inspections indicated that relatively little sediment exited the harvest units in the short term. Water flows were observed at very few points along the lower boundary of the units, and little sediment transport was visible at these points. The existing road system was responsible for contributing most of the sediment measured and observed in the study. In fact, there was no correlation between the percentage area disturbed and sediment transport among experimental units. Two reasons for low observed levels of sediment transport at Summit are that slopes were between 10 and 20%, and no significant weather event (e.g. rain on snow) occurred in the first year after postfire logging. Working on the Entiat fire, with slopes that averaged 40%, Klock (1975) measured up to 36% soil area disturbed by logging with ground-based machines, coupled with significant erosion and sediment transport out of the experimental units. In addition, warm weather melted the snowpack during logging at Entiat, and two intense summer storms accelerated erosion in the first year after postfire logging.

No such weather events occurred after logging of the Summit experimental units. Two types of weather events could potentially cause substantial erosion and sediment transport in the Summit Fire area: 1) rain on snow events that would typically occur in the later winter or early spring; and 2) summer thunderstorms. Rain on snow events are caused by large regional storms from the Pacific Ocean, with each event having a high likelihood of delivering precipitation to the entire Middle Fork area. Relatively warm winter storms that deliver rain over snow are fairly rare in the area however -- streamflow measurements taken at the Ritter gauge on the Middle Fork of the John Day River (downstream of the study site) indicate that only 11 'rain-on-snow' events (events that result in stream discharges higher than one standard deviation from the mean) have occurred in the past 72 years, in the basin within which the study area is located (record 1404400 of USGS streamflow record: http://or.water.usgs.gov). One these events occurred on January 1, 1997, four months after the Summit fire, (10 months before logging began), and while this event resulted in the second highest peakflow ever recorded at the Ritter gauge (4540 cubic feet per second), the event caused no observed debris flows. Although summer thunderstorms are common throughout the Middle Fork of the John Day drainage area, they are much smaller in size than Pacific winter storms, and hence the probability of a thunderstorm affecting a given area is relatively low in any given summer. Only two major summer thunderstorms were reported to have caused significant debris flows within the Summit Fire perimeter in the four years after the fire occurred, and both of these events occurred before logging began in the Summit experimental units. The Badger Creek debris flow resulted from a thunderstorm that occurred at relatively high elevations in the upper Badger Creek basin in late July 1998. This debris flow began in an area burned by the Summit Fire, and eventually resulted in the loss of four road crossings downstream. Both the Lemon Creek and Beaver Creek debris flows occurred as a result of a thunderstorm in early September 1998, and originated on steep, grazed pastureland above forested areas. The Lemon Creek flow also eliminated four road crossings, while the Beaver Creek flow plugged a culvert and washed over that road. No major debris flow-causing thunderstorms have recently occurred in the southern portion of the Summit fire area where the experimental units are located. The absence of such extreme weather events in the Summit experiment area in the two years after logging suggests that the experiment did not adequately test logging, with respect to sediment transport.

In summary, despite high wildfire severity, a combination of several factors probably contributed to relatively low levels of soil disturbance and sediment transport observed in the Summit postfire logging study. These factors included: 1) low slopes; 2) low to moderate-risk soils; 3) logging over snow' 4) hand felling; 5) no new roads; and 6) the absence of severe weather events in the two years after postfire logging (Table 4). Given these mitigating factors, results of this study should be considered as representative of the low end of the range of activity effects that would be expected in a typical postfire logging operation. A more thorough understanding of postfire logging effects will only come from additional work aimed at evaluating effects over a wider range of conditions. While replicated experiments offer the most reliable information in this regard, they are typically too expensive to apply over the full range of conditions needed to build this more comprehensive understanding. An alternative method to obtain the necessary information is adaptive management, in which managers themselves (often with the help of scientists) monitor effects of postfire logging, and communicate the results, interpreted in the context of site conditions.

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Table 1. Major postfire logging studies on erosion, runoff, and sediment transport, listed in chronological order of when the study took place.

Author	Study Type	Year	Location	Forest	Control ?	Variables
Klock 1975	Unreplicated experiment	1970	Central WA	Mixed conifer	Yes	Soil disturbance
Helvey 1980	Unreplicated experiment	1970	Central WA	Mixed conifer	Yes	Runoff, sediment transport
Helvey et al. 1985	Unreplicated experiment	1970	Central WA	Mixed conifer	Yes	Sediment transport, nutrients
Campbell & Morris 1988	Observational	1971-1975	Northern Arizona	Ponderosa pine	No	Runoff, sediment transport
McKay & Cornish 1982	Unreplicated experiment	1977-1981	Eastern Australia	Eucalyptus	Yes	Runoff
Potts et al. 1985	Modelling	1985	Northern Rockies	Mixed conifer	Yes	Runoff, sediment transport
Marston & Haire 1990	Observational	1988-1989	Yellowstone National Park	Lodgepole pine	Yes	Erosion, runoff, litter
Skakesby et al. 1994, 1996	Observational	1990-1992	Northern Portugal	Eucalyptus	No	Erosion
Chou et al. 1994	Replicated experiment	1993	Central CA	Mixed conifer	Yes	Sediment transport
Maloney et al. 1995	Observational	1994	Central Idaho	Mixed conifer	No	Sediment transport

Table 2. Characteristics of Summit Fire experimental units, and number and date of silt fences installed.

Unit	Area (ha)	# Plots	Elev (m)	Slope (%)	Aspect	Treatment	Harvest Dates	# Silt Fences	Fence Install. Date
324	8	20	1353	20	W	Control	-----	1	Jul-Aug 1999
327	15	35	1347	25	SW	Partial	Feb-June 1999	4	Jul-Aug 1999
323	19	47	1311	15	W	Full	Feb-Apr, August 1999	4	Jul-Aug 1999
422	6	15	1372	20	W	Control	-----	1	Jul-Aug 1999
424	5	16	1402	20	W	Partial	Dec 1998-Jan 1999	3	Jul-Aug 1999
421	7	19	1402	15	S	Full	Dec 1998-Feb 1999	3	Jul-Aug 1999
420	16	29	1372	10	SW	Control	-----	1	Oct-Nov 1998
418	6	16	1402	20	S	Partial	Oct-Nov 1998	3	Oct-Nov 1998
419	10	14	1387	20	S	Full	Oct-Nov 1998, Feb 99	4	Oct-Nov 1998
520	7	15	1250	20	S	Control	-----	1	Oct-Nov 1998
522	9	18	1271	15	S	Partial	Sep 1998	3	Oct-Nov 1998
052	13	29	1274	20	W	Full	Sep 1998, Feb 1999	3	Oct-Nov 1998

Table 3. Percent area compacted and displaced post-treatment, and sediment transport within control, partial and full salvage experimental units at Summit, 1999. * Indicates significant difference among treatments for each variable (ANOVA; P<.05). Different letters in superscript indicate significant differences between treatments in pairwise comparisons for each variable (LSD; P<.05).

Experiment Unit	% Compacted	% Displaced*	Sediment Transport (kilograms)	Source
CONTROL				
324	2.2	7.8	0.0	
422	0.0	9.6	0.0	
420	0.3	2.7	0.0	
520	0.0	2.2	0.0	
Mean	**0.6^a**	**5.6^a**	**0.0**	
PARTIAL SALVAGE				
327	6.3	11.2	0.2	Road
			2.5	Skid Trail
424	8.9	13.6	0.1	Skid Trail
418	5.5	11.9	2.6	Skid Trail
522	5.0	13.2	0.2	Road
Mean	**6.4^b**	**12.5^a**	**1.4**	
FULL SALVAGE				
323	9.0	15.4	16.2	Road
421	0.0	32.0	0.0	
419	5.8	7.9	0.4	Road
52	12.9	18.6	0.05	Skid Trail
Mean	**6.9^b**	**18.5^b**	**4.5**	

Table 4. Factors behind sediment transport and relative risk after logging at Summit.

Factor	Summit	Relative Risk
Burn Severity	Moderate to High	Moderate to High
Slope	15-25%	Low
Aspect	Southwest	Moderate
Soil Type	Rocky Clay (Klamo)	High for Compaction Low for Displacement
Logging System		
Felling	Hand	Low
Retrieval	Whole Tree Skidding	High
Skid Trail Position	Mostly Ridgeline	Low
Soil Conditions	<20%Moisture	Low
Roads		
New Roads	None	Low
Existing Condition	Good	Low
Post-logging Weather		
Winter	Average Snowfall	Moderate
Snowmelt Duration	Long	Low
Summer Storms	Few	Low
Overall Risk		Relatively Low