Soil Disturbance and Hill-Slope Sediment Transport After Logging of a Severely Burned Site in Northeastern Oregon

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ABSTRACT: *Despite considerable public debate in recent years on the practice of postfire logging, few studies have directly evaluated its effects. Soil disturbance and hill-slope sediment transport were measured after a postfire logging operation conducted two years after the 1996 Summit Wildfire (Malheur National Forest), in northeastern Oregon. The wildfire was relatively severe, killing an average of 86% of the trees in experimental units, and leaving an average of 34% mineral soil exposed one year after the fire. Soil disturbance was measured both pre- and postharvest in four replicate units in each of three postfire harvest treatments (unlogged control, commercial harvest [most dead merchantable trees removed], fuel reduction harvest [most dead merchantable trees removed plus most dead trees >10-cm diameter]). There was a significant difference among treatments in the percentage of mechanically disturbed soil area, with an average of 19.4% disturbed in fuel reduction units and 15.2% in commercial units. Displacement (13.7% of soil area), apparent compaction (3.1%), and erosion (0.4%) were the most common types of machine-caused soil disturbance. Controls had significantly less change in mean displacement from pre- to posttreatment compared to fuel reduction units, and significantly less change in erosion compared to commercial units. At the experimental unit level, there was a significant correlation between the number of stems removed and the total amount of mechanical soil disturbance observed. Multiple regressions indicated that logging activity, reflected by the number of stems removed, explained more variation in soil disturbance than relative fire severity, reflected by tree mortality, forest floor mass, or the percentage of mineral soil exposed. There was no correspondence between disturbance within units and hill-slope sediment collected in silt fences below units. Visual inspections and sediment collected in silt fences indicated that little sediment exited the experimental units in the short term, and that the existing road system caused most of the observed hill-slope sediment transport. Low observed levels of sediment transport were likely due to a combination of low-to-moderate slopes, low-to-moderate–risk soils, logging over snow or dry ground, hand felling, no new roads, two years recovery of ground cover between the fire and the logging, problems with measuring hill-slope sediment, and the absence of severe weather events in the two years after postfire logging. Given these mitigating factors, hill-slope sediment transport measured in this study should be considered as representative of the low end of the range that would be expected in a postfire tractor logging operation on similar soils and under similar burn severity conditions. West. J. Appl. For. 21(3):123–133.*

Key Words: Salvage logging, postfire logging, soil compaction, erosion, restoration.

After stand replacement fires in the western United States, standard policy has been to salvage fire-killed trees as quickly as possible to recoup their economic value before decay (Aho and Cahill 1984, USDA 1996b). Considerable

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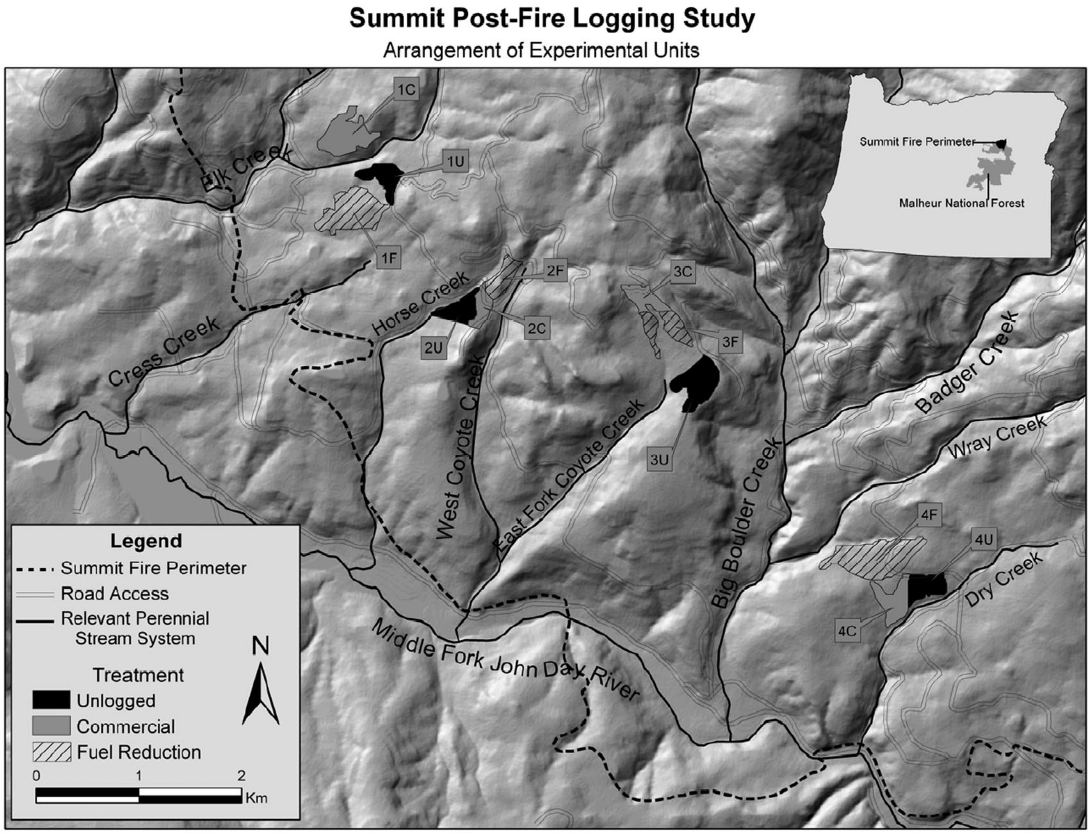

Figure 1. Location of Summit Fire study experimental units, Summit Fire study area, Malheur National Forest, northeastern Oregon.

public debate has focused on the relative merits of postfire logging on federal lands, as evidenced from extensive public comment received on both the east-side and interior Columbia River basin environment impact statements (USDA and USDI 1997a,b). 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 (Poff 1989, Amman and Ryan 1991), 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 transport to streams as a result of the harvest operations themselves (Minshall et al. 1994, Beschta et al. 1995, 2004), and removes structure that has important ecological functions (Stone 1993, Maser 1996).

The debate has taken place in the context of relatively little direct scientific information on the ecological effects of postfire logging. McIver and Starr (2001) found only 21 studies worldwide that have examined the environmental effects of postfire logging, 14 of which had an unlogged control, and just seven of which were replicated experiments. In particular, they found just three experiments (1 replicated) in which logging effects on soils and sediment transport were measured in an operational context (MacKay and Cornish 1982, Helvey et al. 1985, Chou et al. 1994), despite the well-known effects fire has on vegetation and soil. Effects of more severe wildfires include decreased evapotranspiration that leads to increased soil moisture (Walsh et al. 1992), exposure of mineral soil due to removal of the forest floor, and occasional development of water repellency in the upper soil horizons (DeBano 1989), all of which can lead to increases in overland flow and sediment transport to streams (Megahan and Molitor 1975). Thus, severely burned sites will tend to be more sensitive to ground-disturbing activities (including logging), compared to unburned conditions. This greater sensitivity in the soil is of particular concern because human-induced siltation of perennial streams has been identified as a significant factor behind stream degradation in the United States (USEPA 1990). When deposited, excessive fine sediments can alter channel morphology, leading to decreases in habitat quality for stream biota, including plants, insects, and fish (Wood and Armitage 1997).

This study was designed to experimentally evaluate soil disturbance and hill-slope sediment transport after postfire logging of a severely burned forest in the Blue Mountains of northeastern Oregon. The 16,000-ha Summit Fire was caused by a lightning storm on Aug. 13, 1996, on the North Fork John Day Ranger District (Umatilla National Forest), burned South onto the Long Creek Ranger District (now the Blue Mountains District) of the Malheur National Forest, and was declared officially controlled on Sept. 16, 1996 (Figure 1). In the summer of 1997, three treatments (unlogged control, commercial, fuel reduction) were planned for 12 experimental units on the Malheur National Forest that had been severely burned. The primary study objective was to measure soil disturbance before and after logging and compare with postlogging measurements of hill-slope sediment transport, in an effort to estimate the potential that logging activities would contribute sediment to streams flowing nearby.

Methods and Materials

The study area (Figure 1) is located on lands in the southern portion of the burned area (44º40′49″~44º42′57″N, 118º41′40″~118º45′55″W), at relatively low elevations (<1,400 m), and is considered a warm/dry biophysical type, historically dominated by ponderosa pine (*Pinus ponderosa* Dougl.) in the overstory (with some *Pseudotsuga menziesii* Carr. and *Abies grandis* [Dougl.]), and pine grass (*Calamagrostis rubescens* Buckl.) in the understory.

Two basic types of soils occur in the study units. The most common are nonash soils, which are rocky, clay loam-to-clay soils. The proposed soil series "Humarel" best fits soil conditions in the Summit project area. Humarel is classified as clayey-skeletal, smectitic, frigid Vitrandic Argixeroll. These soils are more erodible than most forested soils on slopes less than 35% in the Malheur National Forest, because of their relatively low infiltration rate, and relatively low production of ground cover. On the lower boundary of several experimental units are ash soils, which have a silty loam volcanic ash cap up to 25 cm in thickness. Ash soils are common in forested areas that lie northeast of Crater Lake, which represents the remains of the Mount Mazama volcano, that erupted about 7,000 years ago. Ash soils absorb water more readily than nonash soils, and so tend to be less erodible.

Precipitation in the project area averages about 700 mm per year. Most precipitation falls as snow from November to April, but intense thunderstorms can occur June through September.

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). One possible result of these changes is that, within the Malheur National Forest portion of the Summit Fire, 8,103 ha (72%) were judged to have burned with high severity, including much of the acreage in the lower elevation dry forests, which typically experienced frequent, low severity fires before fire suppression (Agee et al. 1994, USDA 1997).

Twelve experimental units ranging in size from 5 to 19 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 (most <20%), and on the percentage of mineral soil that was left exposed (most >40% one year after the fire). Each block was located in a separate drainage, with perennial streams that flow past each block (Elk, West Coyote, East Horse, Coyote, Dry, and Wray Creeks) emptying into the Middle Fork of the John Day River. Blocks are numbered 1 through 4, from northwest to southeast (Figure 1; Table 1).

Within each of the four replicate blocks, three treatments (unlogged control, commercial, fuel reduction) were assigned randomly to units, for a complete randomized block design. Control units (Table 1; Units 1–4U) received no logging treatment. The prescription for commercial units (Table 1; Units 1–4C) was to remove ⅔ of dead merchantable trees, leaving at least 17 snags per hectare. The prescription for fuel reduction units (Table 1; Units 1–4F) was to remove all dead merchantable trees, leaving six snags per hectare minimum, and to remove sufficient noncommercial trees in an effort to reduce the potential for a severe reburn in the same place in the future. According to prescription, all logging was required to take place on frozen or dry (<20% soil moisture) ground, to minimize soil disturbance. In units 1C and 1F however, some skidding occurred on thawed, wet soil (Table 1; see Harvest Dates). Erosion control practices included: 1) skid trails were widely spaced, generally at 30–40-m intervals; 2) where skid trails were liable to channel overland flow, water bars were to be

Table 1. Characteristics of Summit Fire experimental units, and number and date of silt fences installed. Units arranged in blocks, from northeast to southwest.

Unit	Area (ha)	Grid points	Elev. (m)	Slope (%)	Aspect	Treatment	Harvest dates	No. of silt fences	Fence install. date
1U	8	20	1353	20	W	Control	—	1	Jul-Aug 1999
1C	15	35	1347	25	SW	Comm	Feb-June 1999	4	Jul-Aug 1999
1F	19	47	1311	15	W	Fuel	Feb-Apr, Aug 1999	4	Jul-Aug 1999
2U	6	15	1372	20	W	Control	—	1	Jul-Aug 1999
2C	5	16	1402	20	W	Comm	Dec 1998-Jan 1999	3	Jul-Aug 1999
2F	7	19	1402	15	S	Fuel	Dec 1998-Feb 1999	3	Jul-Aug 1999
3U	16	29	1372	10	SW	Control	—	1	Oct-Nov1998
3C	6	16	1402	20	S	Comm	Oct-Nov 1998	3	Oct-Nov1998
3F	10	14	1387	20	S	Fuel	Oct-Nov 1998, Feb 1999	4	Oct-Nov1998
4U	7	15	1250	20	S	Control	—	1	Oct-Nov1998
4C	9	18	1271	15	S	Comm	Sep 1998	3	Oct-Nov1998
4F	13	29	1274	20	W	Fuel	Sep 1998, Feb 1999	3	Oct-Nov1998

placed at 10–20-ft vertical spacing; and 3) all skid trails were to be seeded with grass.

A total of 84 ha were logged between Oct. 1998 and Aug. 1999 (Table 1). Landings were located on roads or near roads in the units, except unit 1C where the landing was outside of the unit. Each commercial harvest unit was entered once as part of a timber sale contract, to remove merchantable trees. Each fuel reduction unit was 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. While logs from all commercial units and the first entry of fuel reduction units were removed from the site and sold, logs from second fuel reduction entry were stacked on the landings and left on site. For the initial logging entry, trees were felled by hand, and whole trees were cable-winched into skid trails with a tracked D6 Crawler-tractor [1].

Hand-felling of relatively small trees is not a standard practice. In other logged stands of the project area (outside the experimental units; see Figure 1), all trees were felled with the use of a Timbco feller-buncher] [1]. According to the logger (Charlie O'Rorke, John Day, Oregon), the practice of hand-felling for the initial entry in the experimental units was done to minimize soil disturbance. Hand felling increased cost in these units considerably compared to machine felling. Thus results from this study are not entirely representative of standard postfire logging practices, and should be considered with this caveat in mind.

After winching to skid trails, whole trees were retrieved to landings with a Caterpillar 518 rubber-tire grapple-skidder [1]. For the second entry in the fuel reduction units, a Timbco feller-buncher was used to fell trees, and logs were retrieved in the same way as in the first entry. The timber sale and service contracts required one-end suspension on all skidded logs. 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 (15.9%).

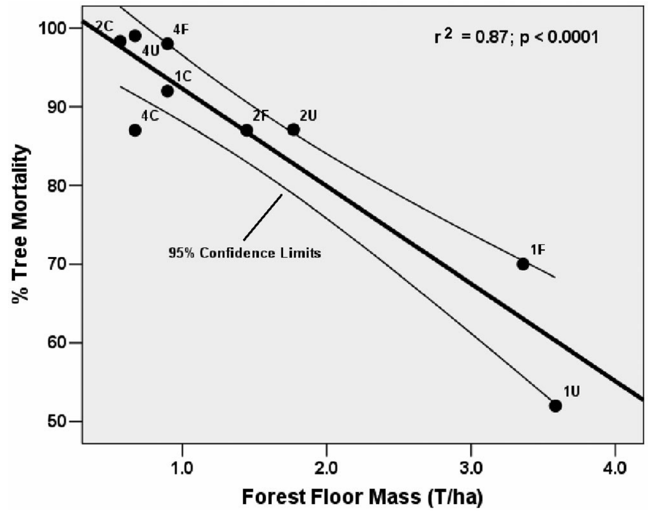

Figure 2. Correlation between forest floor mass one year post-fire (1997), and the percentage of dead trees in experimental units at Summit Fire study area, Malheur National Forest, northeastern Oregon.

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 within the study area, although road-building did occur in other logged units within the Summit Fire perimeter.

Methods were based on the expectation that variation in soil disturbance and hill-slope sediment transport among units would likely correspond to variation in burn severity before logging and to variation in levels of logging activity. We therefore measured not only soil disturbance and sediment transport, but estimated burn severity by measuring percent soil area exposed by wildfire, the mass of fuels left after fire, and the percentage of trees killed. We estimated logging activity by measuring stem density and diameter before and after logging.

All data (except hill-slope sediment transport data) were collected from a total of 273 systematically established grid

Table 2. Tree mortality, forest floor and woody fuel mass, and percent mineral soil exposure before logging at the Summit Fire study site, northeastern Oregon. Experiment units are arranged in decreasing order of tree mortality.

Experimental unit	Year	Treatment[a]	Block	Grid points	% Tree mortality	Forest floor (T/ha)	% Mineral soil exposed	Woody fuel (T/ha)
3C**	1998	Commercial	E Coyote	16	100	3.5	26	6.3
4U	1997	Control	Wray	15	99	0.7	25	1.3
2C	1997	Commercial	W Coyote	16	98	0.6	65	6.5
4F	1997	Fuel Red	Wray	29	98	0.9	47	2.2
1C	1997	Commercial	Elk	35	92	0.9	52	2.9
2U	1997	Control	W Coyote	15	87	1.8	33	7.0
4C	1997	Commercial	Wray	18	87	0.7	29	3.4
2F	1997	Fuel Red	W Coyote	19	87	1.5	26	7.5
3F**	1998	Fuel Red	E Coyote	14	85	1.5	0	7.6
3U**	1998	Control	E Coyote	29	78	5.4	2	3.8
1F	1997	Fuel Red	Elk	47	70	3.4	23	3.4
IU	1997	Control	Elk	20	52	3.6	5	1.1

** Indicates experiment units (East Coyote Block) in which measurements were taken 2 years after the wildfire; all other units were measured one year after the wildfire.
[a] Control = unlogged; Commercial = merchantible trees removed in one entry, to leave minimum 17 snags/ha; Fuel Red = most merchantable trees removed in first entry and smaller trees down to 10-cm diameter removed in second entry, to leave minimum six (6) snags/ha.

Table 3. Mean (± SE) % soil area disturbed prelogging, postlogging, and change, in control, commercial and fuel reduction units, Summit Fire postfire logging study, northeastern Oregon, 1997–1999. Only change variables were analyzed in ANOVA (indicated in bold), with different letters in superscript representing significant difference in paired comparisons (LSD test).

Disturbance (%)	1997/98 (pre)			1999 (post)			**Change pre–post**		
	Control	Comm	Fuel	Control	Comm	Fuel	**Control**	**Comm**	**Fuel**
Total Mechanical	2.0 (0.86)	4.3 (1.2)	6.4 (3.4)	6.4 (2.20)	19.5 (1.8)	25.7 (4.4)	**4.4[a]* (2.4)**	**15.2[ab] (2.3)**	**19.4[b] (5.2)**
Displacement	0.0 (0.0)	1.1 (0.4)	1.1 (0.7)	5.1 (1.9)	11.4 (0.8)	18.2 (4.8)	**5.1[a] (1.9)**	**10.3[ab] (0.9)**	**17.1[b] (5.3)**
Compaction	1.3 (0.8)	2.6 (1.2)	4.5 (2.6)	0.7 (0.5)	6.4 (0.9)	6.9 (2.7)	**−0.6[a] (0.6)**	**3.8[a](1.7)**	**2.4[a] (5.3)**
Erosion	0.6 (0.3)	0.3 (0.2)	0.1 (0.1)	0.4 (0.3)	0.8 (0.2)	0.3 (0.2)	**−0.2[a] (0.2)**	**0.5[b] (0.2)**	**0.3[ab] (0.2)**
Deposition	0.1 (0.1)	0.4 (0.3)	0.7 (0.6)	0.2 (0.2)	0.7 (0.4)	0.3 (0.3)	**0.0[a] 0.2**	**0.4[a] (0.6)**	**−0.4[a] (0.4)**
Burning	16.1 (7.5)	43.1 (9.2)	24.1 (9.6)	0.6 (0.6)	2.4 (1.7)	0.0 (0.0)	**−15.5[a] (7.8)**	**−40.6[a] (9.8)**	**−24.1[a] (9.6)**

* Denotes significant difference in paired comparisons between treatment means for the change variable analyzed ($P < 0.05$).

points laid out in the 12 units in August 1997 (Table 1). Grid points were positioned 50 m apart, and at least 50 m from unit boundaries. The first grid point within each unit was referenced to a point on a permanent road just outside the unit. Each grid point was marked with a wooden surveyor's stake and with a uniquely numbered aluminum tag attached to the base with a steel wire. A steel rod (rebar) was substituted with the same numbered tag for the wooden stake at each plot center after harvest in 1999. Pretreatment data were taken in nine of the experimental units between August and October 1997, and in the other three units (East Coyote Block; Units 3U, 3C, 3F; see Table 1) in August and September 1998. All posttreatment data were collected from July to September 1999, immediately after the termination of logging.

To provide an index of machine activity within each unit, we measured the change in basal area and density of live and dead trees (dbh > 10 cm). Trees were tallied from within a fixed 8-radius circular plot centered on each grid point. We recorded species, status (dead or alive), and dbh for each tree. Basal area (m^2/ha) was calculated from dbh of each tree within each plot.

Fuel (woody and forest floor) was measured following the protocol of Brown (1974). Three 30.5-m transects were established from each grid point, the first selected randomly, and the others established at 120° and 240° from the first. Fuel between 0.6 and 2.5-m diameter was tallied for the first 1.9 m of each transect, and fuel between 2.5 and 7.6-m diameter was tallied along the full 30.5 m. Fuel > 7.6-m diameter was tallied along the full transect and recorded as to species, decay class, and diameter at intersection point. Woody fuel masses were calculated using standard equations (Brown 1974). Litter and duff (forest floor) was measured to the nearest 0.25-m depth at the 12, 18, and 24-m points on the transect. Depths were converted to mass using standard bulk-density values (2.9 T/ha/cm for litter, and 11.8 T/ha/cm for duff; Ottmar et al. 1993).

Soil disturbance was assessed along a single 30-m transect laid out at random bearings from each grid point. Both compaction and surface disturbance (displacement, erosion, deposition, and burning) were assessed at 2-m intervals along each transect. Apparent compaction was recorded if the soil surface contained cleat marks, if the soil was depressed more than 5 cm, or if a penetrometer (steel rod with 1-cm diameter cone-shaped tip) encountered resistance not due to rocks or roots. Displacement was defined as the removal of the forest floor or the upper portions of the mineral soil. This definition of displacement counts many spots as "displaced" that would not be counted under the USDA Forest Service Region 6 definition (USDA 1996a). Erosion was recorded if there were signs of recent scouring or hill-slope sediment transport. Deposition was defined as the addition of soil or forest floor material. If a transect point included more than one type of soil disturbance, each type was recorded as having occurred. Percent soil area mechanically disturbed was then calculated at the unit level by dividing the number of transect points recorded in each disturbance category by the total number of transect points assessed.

Tree, fuel, and soil disturbance response variables were examined with analysis of variance (SPSS 2001), with a complete randomized block design. Pair-wise comparisons were examined by least-squared difference. Stepwise multiple regression was used to analyze for the relative effects of burn severity (measured in terms of soil exposure, forest floor mass, and tree mortality), and of logging activity (measured in terms of basal area change, tree density change, and woody fuel change) on soil compaction and displacement.

Hill-slope sediment transport was measured with the use of silt fences installed shortly after the first logging entry was finished in each unit (Table 1). In treated units, fences were placed at three or four locations: the one or two locations that were judged to be highest risk for sediment transport, a medium-risk location, and a low-risk location. In control units, one fence was placed at a low-risk location. Criteria used for judging the likelihood of sediment transport at a given location included the location, size, and slope of bare areas and waterbars upslope, and the likelihood of overland flow leaving the unit. Contributing area varied among silt fences. We expected that roads and topography would cause more variation in hill-slope sediment than the contributing area per se.

Silt fences were installed by methods of Robichaud and Brown (2002). Each fence was made of erosion-control fabric 1.2 m high, and was laid out along the contour in an arc about 11 m long, with the middle of the fence about 1.2 horizontal m below the contour. A trench about 18 cm deep and 10 cm wide was excavated along the upslope edge of the arc, the fabric was laid in on the bottom of the trench, and secured by refilling and compacting with soil. The fabric was then laid back across the top of the compacted soil, and stapled to stakes placed to support the fence at about 1-m intervals along the length of the arc. This procedure created an ~18-cm-wide swath of fabric onto which sediment could be transported. Hill-slope 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 using a bulk density of 0.9 g/cm^3 (after Geist and Strickler 1978). 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

The severity of the Summit Fire was indicated by the observation that all 12 experimental units lost more than half of their trees due to direct fire effects (Table 2). Nine of the units experienced more than 85% tree mortality, and mortality was generally greater in the blocks located to the southeast (Dry/Wray Creeks, E. Coyote; Figure 1). Tree mortality was negatively correlated with the mass of forest floor remaining after the fire (Figure 2: $r^2 = 0.87$; $P < 0.0001$; $n = 8$), and was positively correlated with the percent mineral soil exposed for those units measured within one year after the fire (Data not shown: $r^2 = 0.57$; $P = 0.02$; $n = 9$). In particular, the mass of forest floor remaining in units measured one year after the fire (1997) was generally less than two T per hectare (Table 2). (E. Coyote block units measured 2 years after the fire had already recovered most of their ground cover, in the form of grasses and needles). Thus, the wildfire was likely severe enough to create conditions on the soil surface that would be expected to cause erosion and produce sediment.

On average, between 2 and 6% of soil area within experimental units was classified as disturbed before logging activity (Table 3). About 19% of soil area was additionally disturbed by machines in the fuel reduction units, compared to about 15% in commercial units, and 4% for the controls (apparent additional disturbance in the control was likely due to a combination of measurement error and the presence of machine activity on the unit boundaries). Despite considerable variation among units in the percentage of mechanically disturbed soil area, there was a significant difference among treatments, with controls differing from fuel reduction units (Table 3). There were no statistical differences in total mechanical disturbance between fuel reduction and commercial, or between commercial and control units. There was a significant correlation between the change in percent area disturbed among units, and the change in stem density due to logging (Figure 3: $r^2 = 0.51$; $P = 0.01$). In general, fuel reduction units had the greatest percent soil area disturbed and experienced the greatest change in stem density.

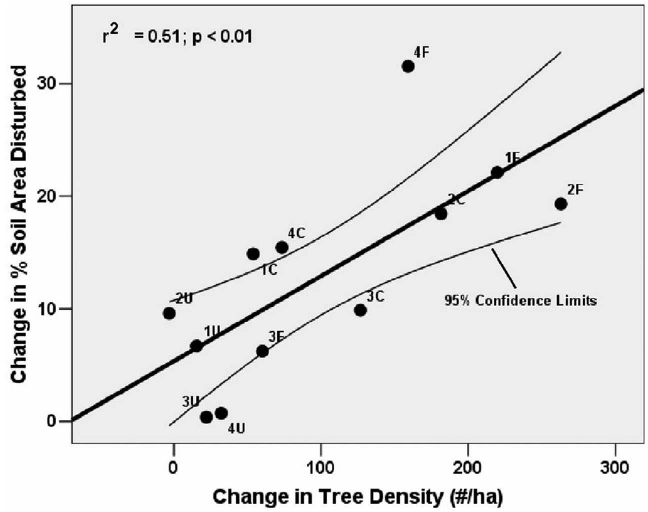

Figure 3. Correlation between the number of stems removed during logging and the percent soil area mechanically disturbed at the Summit Fire study area, Malheur National Forest, northeastern Oregon.

Displacement was the most commonly observed type of machine-caused soil disturbance (13.7% average of commercial and fuel reduction) followed by apparent compaction (3.1%) and, to a much lesser extent, erosion (0.4%) (Table 3). Mean changes in displacement ranged from 5% in controls to about 17% in fuel reduction units, and there was a trend toward significant difference among the treatments ($P = 0.07$). Control units had significantly less soil area displaced than fuel reduction units, but there was no difference in displacement between control and commercial units or between commercial and fuel reduction units. Changes in mean percent area displaced were highly correlated with changes in stem density (Figure 4: $r^2 = 0.69$; $P < 0.001$), indicating that logging activity was an important factor behind observed levels of soil displacement. There was a

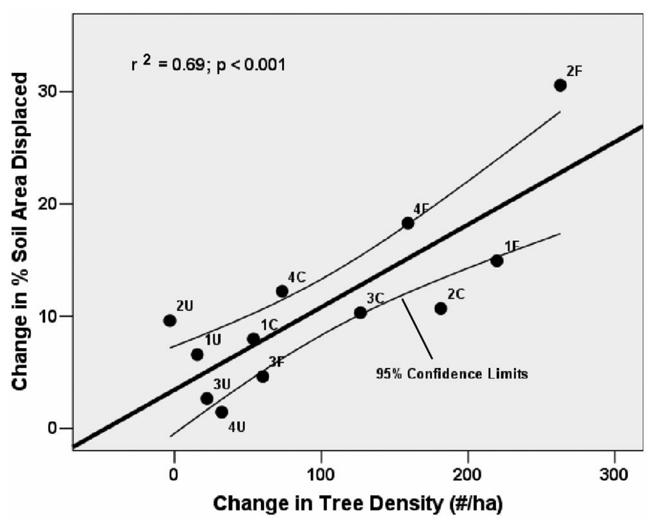

Figure 4. Correlation between the number of stems removed during logging and the percent soil area displaced at the Summit Fire study area, Malheur National Forest, northeastern Oregon.

Table 4. Sediment collected (liters) in first year from fences installed at lower boundary of experimental units, Summit Fire study, northeastern Oregon.

Unit	Location	Liters collected	Comments
Roads not involved			
1C	Draw at head of scoured channel	2.7	Sediment probably from skidtrail
3C	Draw at head of scoured channel	Trace	
2C*	In draw bottom	2.8	Sediment from unknown source
4F	In draw bottom below landing	Trace	
Roads involved			
1F*	Below drain dip	19.3	
1F*	Below drain dip, below landing	0.1	Sediment collected less than if this were a non-experimental operation, due to interception by log deck upslope
1C*	Below drain dip, below landing	0.2	Part of fence collapsed, so some sediment probably lost
2F*	Below culvert	0.3	
2F*	Road ditch	0.1	
4C	215m below culvert	0.2	Part of fence collapsed, so some sediment probably lost

* These sediment fences were installed in the summer, after winter logging, so main flush of sediment probably not captured.

trend toward a correlation between total percent area displaced after logging and the percent soil area exposed due to the wildfire ($r^2 = 0.53$; $P = 0.10$).

Changes in apparent compaction varied from less than 0% in controls to about 4% in commercial units, but differences among units were not significant. Also, despite significantly different levels of apparent compaction between control and both commercial and fuel reduction units measured just after logging (1999; Table 3), pairwise comparisons of the *change* in compaction between pre- and post-treatment were not significant.

Changes in mean erosion ranged from less than 0% in controls to 0.5% in commercial units, but these differences were not significant. Control units had less erosion than commercial units. There were no significant differences in deposition, with changes ranging from less than 0% in fuel reduction units to 0.4% in commercial units. The percentage of soil area classified as severely burned (mineral soil exposure) declined from a range of 16–43% 1 year postburn to a range of 0–2% 3 years postburn (Table 3). There were no significant differences among treatments in the change in mineral soil exposure due to burning.

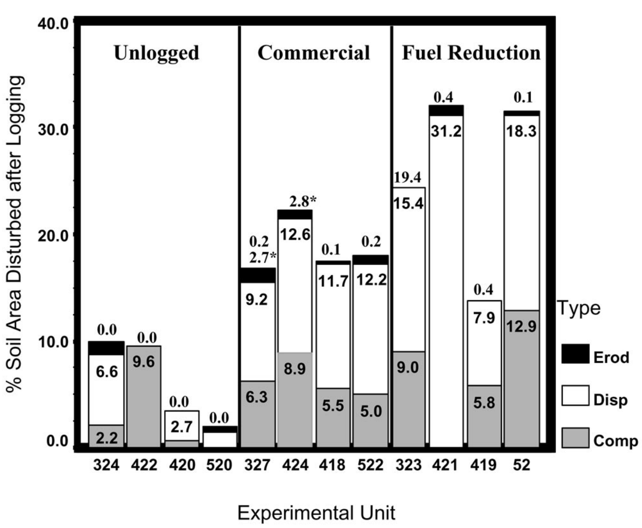

Figure 5. Postlogging percent soil area displaced (Disp), compacted (Comp), and eroded (Erod) in experimental units (bar graphs) and hill-slope sediment transport levels (in liters above bars) observed in the first 2 years after logging (numbers above bar graphs), at the Summit Fire study area, Malheur National Forest, northeastern Oregon. * Indicates hill-slope sediment transport caused by skid trails within logging units.

Stepwise multiple regression of logging activity and fire severity on soil disturbance generally indicated that logging activity explained most observed variation. For example, variation in changes in displacement was significantly explained by changes in stem density (used as index of logging activity), regardless of whether stem density was evaluated with soil exposure ($P = 0.01$), tree mortality ($P = 0.002$), or forest floor mass ($P = 0.006$) in the stepwise multiple regression.

Most sediment was probably transported during the spring snowmelt runoff of 1999, because this was the first runoff after most of the disturbance. No significant thunderstorms occurred in the project area in the two years after postfire logging. Hill-slope sediment was collected from 10 fences and, in six of these cases, visual assessment indicated that roads contributed to sediment production and transport (Table 4). 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 1F (fuel reduction). Other road-associated features that contributed sediment included landings (0.1 l: unit 1F; 0.2 l: unit 1C), and culverts (0.3 l: unit 2F; 0.0002 m^3: unit 4C) in both fuel reduction and commercial units. Relatively little sediment was collected from fences not affected by roads, other than 2.7: l from a skidtrail at the bottom of a steep draw in unit 1C (commercial) and 2.8 from the bottom of a draw in unit 2C (commercial). No sediment was collected from any of the fences in low-risk locations, including the four fences placed in the control units.

Qualitative comparison of hill-slope sediment transport with data on compaction and displacement (Figure 5) showed little relationship between these variables. For example, although unit 2F had more than 32% soil area disturbed, only 0.4 liters of sediment was collected within its perimeter. On the contrary, units 1C and 2C had the greatest volume of sediment collected (2.9, 2.8 liters, respectively), but had relatively low levels of soil disturbance observed (~17%).

There were also no apparent patterns of soil disturbance and hill-slope sediment transport among units in relation to the time of year that the logging took place. For example, fuel reduction units 3F and 4F were both entered in the fall of 1998 and again in Febuary 1999, and yet experienced different levels of soil disturbance (14.7% and 31.6%, respectively). Similarly, commercial units 1C and 2C, entered in spring and winter of 1999, respectively, experienced nearly identical levels of sediment transport.

Visual inspection of the lower boundaries of the experimental units indicated that most of the sediment that exited units was at locations influenced by the existing road system. Of 39 such locations, 28 were influenced by roads and 11 were not. Most road-influenced overland flow from experimental units occurred where a road left a unit (five cases), where a road formed the lower boundary of a unit (19 cases), and in cases where culverts above units concentrated surface runoff that failed to completely infiltrate before exiting (four cases). Probably the greatest influence of roads was in unit 3F, where a native surface road below a landing exited the unit and sloped down 30 m to a ford on an intermittent stream. In three cases, culverts above units 4F and 4C concentrated runoff and produced small continuous rills that ran down slope more than 300 m across nonash soil. In all, we observed seven cases (25% of total cases) where road-influenced runoff probably reached intermittent streams. Of the 11 natural sources of runoff, units 1F and 4F 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 intermittent streams (55% of total cases). In one case, we observed sediment transport out of units that was specifically caused by a skid trail.

Discussion

Available literature suggests that the immediate environmental effects of logging in the postfire environment will depend on several specific features of burned stands, including the severity of the burn, slope, soil texture and composition, the presence or building of roads, the type of logging system, and postfire weather conditions (Potts et al. 1985, Chou et al. 1994, McIver and Starr 2001). Results of this study will be interpreted in the context of these features.

Logging activity at Summit caused a significant increase in the percentage of soil area disturbed, ranging from 17 to 22% in commercial units and from 12 to 32% in fuel reduction units. Most of the change in soil area disturbed was in the form of displacement, averaging 10.3 and 17.1% increase in commercial and fuel reduction units, respectively. Assuming that tree roots quickly capture local areas of soil deposition, small-scale displacement of soil, like that observed at Summit, is not likely to have practical significance to site productivity and tree growth (Senyk 2001, Clayton et al. 1987). Although apparent compaction did occur, levels were much lower, averaging 3.8% in commercial units and 2.4% in fuel reduction units. Although significant compaction usually leads to decreases in tree growth rate (Cochran and Brock 1985, Froehlich et al. 1986a, Clayton et al. 1987, Roche 1997), percent soil areas compacted in the present study are very low compared to other published logging studies (Froelich et al. 1986b, Geist et al. 1989, Lanford and Stokes 1995). For example, soil bulk density samples taken several years after ground-based harvesting on 11 federal timber sales in the 1970s and 1980s in the Blue Mountains indicated that between 12 and 36% of the soil area was still compacted (Geist et al. 1989). Although most of these projects also involved hand felling and skidding, logging was not limited to frozen or dry soil conditions. Finally, although estimated levels of erosion were higher in harvested units than in controls, the change

Table 5. Factors contributing to hill-slope sediment transport and relative risk after logging at Summit Fire study site, northeastern Oregon.

Factor	Summit	Relative risk
Burn severity	Moderate to high	Moderate to high
Water repellency	None	Low
Recovery of ground cover	2–3 growing seasons	Low
Slope	15–25%	Low
Aspect	Southwest	Low
Soil type	Rocky clay (Klarno)	High for infiltration Moderate for compaction Low for displacement
Logging system		
Felling	Hand	Low
Retrieval	Whole tree skidding	Moderate to high
Soil conditions	<20% Moisture, or frozen	Low
Roads		
New roads	None	Low
Existing condition	Good (only a little rilling visible on road surfaces or ditches).	Low
Post-logging weather		
Snowmelt duration	Long	Low
Summer storms	Few	Low
Overall risk		Relatively low

in percent area eroded was just 0.5% in commercial units and 0.3% in fuel reduction units.

Observed levels of hill-slope sediment transport within units were relatively low, with most transport attributed to the existing road system. Only two experimental units (commercial units 1C and 2C) experienced even moderate levels of sediment movement that could be attributed to skid trails, with just 2.7 and 2.8 liters measured, respectively. Additionally, no sediment was observed leaving any of the experimental units within two years after the logging operation. These levels of soil disturbance (displacement, compaction, erosion) and hill-slope sediment transport are relatively low compared to results from other postfire logging studies. On the Entiat fire for example, 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.

These relatively low observed levels of soil disturbance and hill-slope sediment transport are likely due to the absence of extreme weather events in the two years after postfire logging, and to a combination of other factors, including two years of recovery of the ground cover between fire and logging, low slopes, heavy soils, logging over dry or frozen ground, hand-felling, condition of existing roads, and no new roads (Table 5). Slopes in the experimental units averaged between 15 and 25% (Table 1). The WRENS model (Potts et al.1985) and experimental work in California (Chou et al. 1994) and Australia (Mackay and Cornish (1982) suggest that sediment and water yields will increase with increasing catchment area and slope in logged postfire landscapes. Generally, the 15–25% slopes present in the Summit experimental units are not considered to be high risk for hill-slope sediment transport (Bill Elliot, Rocky Mount Research Station, USDA Forest Service, personal communication, 1999).

The heavy Klarno soils present at the Summit site are not considered to be unusually sensitive to sediment transport, especially compared to granitic soils (Robert Ottersberg, Soil Scientist, Wallowa-Whitman National Forest, personal communication, 2000). Severe fires on coarse granitic soils will tend to develop water-repellency, which can lead to increases in sediment and water yields (Megahan and Molitor 1975, Marston and Haire 1990). Ash-dominated soils can also be conducive to sediment transport, but not at the snowmelt rate or rainfall intensities that occurred during this study.

The type of logging system and the time that logging occurs relative to soil moisture are both important in determining soil disturbance and sediment transport (McIver and Starr 2001). 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. They 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%). In particular, the relatively low levels of soil disturbance and erosion in Klock's tractor-skidding-over-snow units compares favorably to levels observed in our study, in which hand felling and skidding also were conducted primarily on either dry or frozen ground.

Although there are no available studies that have examined the effects of postfire road building and use per se, it is likely that roads will contribute more 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. At Summit, no new roads were built in the vicinity of the study units, and the condition of the existing road system was considered to be good, relative to National Forest System standards (USDA 1997). Nonetheless, it is noteworthy that the greatest amount of hill-slope sediment transport observed at Summit (19.3 liters) was attributed to a haul road that formed a small part of the lower boundary of fuel reduction unit 1F. Further, of the 10 cases of measurable sediment transport observed at Summit, six could be attributed to the existing road system.

One of the most important factors that typically explains the amount of sediment transport observed in burned areas is the occurrence of extreme weather events in the first few years after the fire. 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 SD from the mean) have occurred in the past 72 years, in the basin within which the study area is located (record 14041304500 of USGS streamflow record: or.water.usgs.gov). One of these events occurred on Jan. 1, 1997, 4 months after the Summit fire, (10 months before logging began), and although this event resulted in the second highest stream volume ever recorded at the Ritter gauge (4,540 ft^3/s), no significant debris torrents were observed to be caused by it. 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. Two major summer thunderstorms were reported to have caused significant debris torrents 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. Both of the debris flows originated on steep slopes at higher elevations above forested areas. The Badger Creek debris torrent 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. The Lemon Creek flow also eliminated four road crossings, and the Beaver Creek flow plugged a culvert and washed over that road. No major debris torrent-causing thunderstorms have recently occurred in the southern portion of the Summit fire area where the experimental units are located. The magnitude of these thunderstorm-caused debris torrents, measured by the amount of material transported, dwarfs any of the effects we observed in the current study. This demonstrates that postfire logging effects occur within the context of a burned landscape that is much more susceptible to catastrophic events, even in the absence of postfire management activities. Interestingly, in his comparison of logging systems, Klock (1975) observed that a substantial amount of erosion and sediment transport occurred during a period of warm temperatures that melted snowpack during logging. In addition, Helvey et al. (1985) reported that unlogged controls in the Entiat study area produced the greatest amount of sediment in the few years after the Entiat Fire, and that this was most likely due to the occurrence of intense storms during that period of time.

At Summit, although we have no quantitative information on local precipitation in the two years after the logging operation, no thunderstorms were reported to have visited the area during that time. We do have precipitation data from four SNOTEL stations surrounding the Summit study area, and within 15 miles of it (Lucky Strike [NNW], County Line [NNE], Tipton [SW], and Blue Mount Springs [SSE]), and only the Blue Mount Springs station recorded a summer precipitation event between June 1998 and September 2000, that had greater than 1″ in total rainfall delivery within a two-day period. SNOTEL data are not reliable for recording thunderstorms at Summit however, because these storms are relatively small and local in their effect. Support for this contention is indicated by the fact that none of the four stations recorded the thunderstorms that caused the debris flows described above (Badger, Beaver, and Lemon Creeks), just north of the Summit study area. In any case, the absence of any observed extreme weather events in the Summit experiment area in the two years after logging suggests that the experiment did not thoroughly test logging, nor the natural effects of wildfire, in our unlogged control areas.

Fire severity probably contributed somewhat to observed levels of soil disturbance in the present study. The Summit Wildfire was severe (USDA 1997, McIver, J.D., and R. Ottmar. Fuel mass and stand structure after postfire logging of a severely burned ponderosa pine stand in northeastern Oregon. submitted for publication), especially for low-elevation, ponderosa pine-dominated forests of western North America (Agee et al. 1994). In the year after the fire, the average stand consisted of between 200 and 300 stems/ha of largely dead, charred tree boles, standing above a forest floor swept clean of debris, with a substantial amount of exposed mineral soil. These conditions set up the potential for significant soil impact and erosion due to postfire logging at Summit. There was evidence that fire severity was related to soil disturbance, with experimental units having higher levels of displacement and compaction also tending to have higher levels of soil exposure due to fire. There was no evidence however, that any measure of fire severity was related to the amount of hill-slope sediment transport observed.

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. The most important factor probably was the absence of severe weather events in the 2 years after postfire logging. Other factors included 2 years of recovery of the ground cover between the fire and logging, low slopes, low-to-moderate–risk soils, logging over snow, hand felling, and no new roads. 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 postfire logging operation using what might be considered as "best management practices." A more thorough understanding of postfire logging effects will only come from additional work aimed at evaluating effects over a wider range of conditions. Although 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 interpret the results in the context of site conditions.

[1]Mention of product name for information only and does not imply endorsement by the Federal Government.

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