Hillslope Erosion Rates in Areas with Volcanic Parent Materials and the Effects of Prescribed Fires in the Blue Mountains of Eastern Oregon and Washington, USA

Robin M. Harris*
Catherine F. Clifton
Umatilla National Forest, Pendleton, Oregon

Steven M. Wondzell
USDA Forest Service, Pacific Northwest Research Station, Olympia, Washington

Prescribed fire is often proposed as a treatment for restoring forest health and reducing long-term risk of wildfires. It is generally assumed that wildfires and wildfire-related erosion pose greater threats to water quality and fish habitat than prescribed fires. However, limited empirical data are available for quantifying background erosion rates and the influence of prescribed fire on those rates. This study in the Blue Mountains of northeastern Oregon and southeastern Washington was designed to quantify background erosion rates and to examine the effects of prescribed fire on hillslope erosion and stream sedimentation. Two study areas were selected on the Umatilla National Forest. The first was a paired-watershed study at Skookum Creek in Oregon where stream discharge and sediment yield have been recorded continuously since the watersheds were gaged in 1992. Measurements within the watersheds were augmented with hillslope erosion plots in 2002. Hillslope erosion plots were also established in 2002 in the Red Fir prescribed burn project in Washington. Preliminary results from the Skookum paired-watershed study showed large differences between hillslope erosion rates measured from plots and watershed sediment yields, suggesting that episodic processes dominated sediment production and transport and therefore controlled watershed-scale sediment budgets. Preliminary analyses of all hillslope erosion data combined indicated that erosion rates were significantly related to aspect and amount of bare ground, but were not influenced by prescribed fire.

Keywords: *fuel treatment, prescribed fire, sediment yield, silt fence, streamflow, surface erosion, water quality*

INTRODUCTION

Changes in forest composition and the mortality of forests in the interior West over the last century are often characterized as forest health problems (Everett et al. 1994; Hessburg et al. 1994; Quigley and Arbelbide 1997). Forest health has been targeted by recent legislation, administrative procedures, and management strategies with the aim of reducing long-term risks to forests from wildfire, drought, insects and disease (USDA FS and USDI 2001; USDA FS 2002, 2003). These management strategies emphasize using prescribed fire and other fuel reduction techniques to reduce wildfire risk, and are often motivated by concerns for protecting water supplies and species listed as threatened or endangered. Implied in the widespread use of prescribed fire as a management tool to reduce the risk of stand-replacing wildfires is the assumption that the direct effects of wildfires, as well as wildfire-related erosion and sedimentation of streams, are greater threats to water quality and fish habitat than are the effects of fuels treatments.

Most previous watershed studies of the impact of fire were focused on the effects of stand-replacing wildfires, salvage logging after fire, or prescribed fire associated with timber harvesting and slash control (McIver and Starr 2000). Despite the existing body of literature that describes the effects of fire and other land-management activities on erosion, sediment, and water quality, there remain significant knowledge gaps specific to effects of prescribed fire and fuels treatments. Few published studies have been conducted in areas with volcanic parent materials or volcanic-ash-derived soils – the soil types most common in central and eastern Oregon and southeastern Washington. Data are lacking on hillslope transport and redistribution of eroded sediment and the delivery of sediment to streams. At the local level, limited data are available to validate planning and assessment tools currently being used. Consequently, analyses rely on results from studies

---

M Furniss, C Clifton, and K Ronnenberg, eds., 2007. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004*, PNW-GTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

* Currently with Confederated Tribes of the Umatilla Indian Reservation, Pendleton, Oregon.

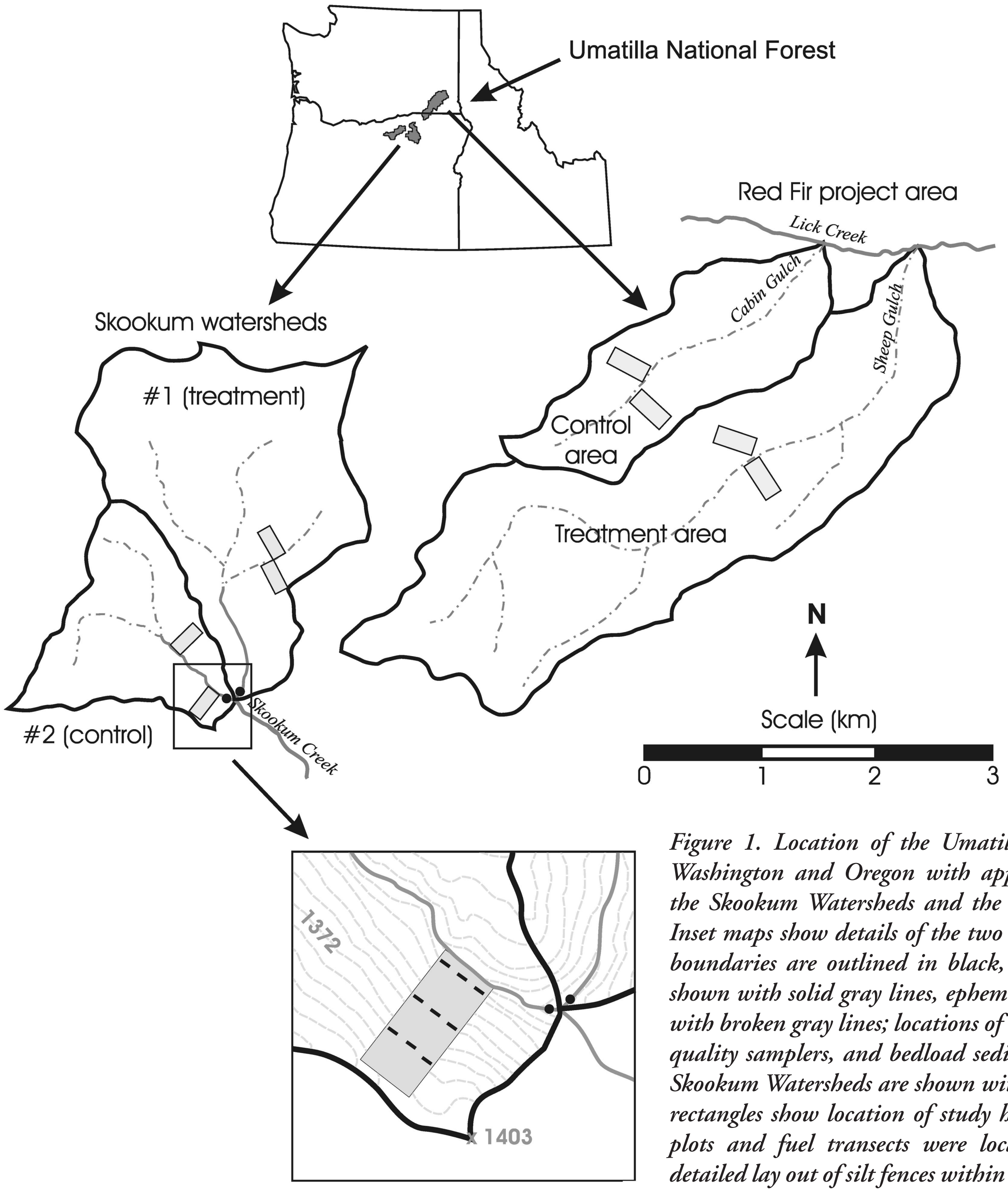

Figure 1. Location of the Umatilla National Forest in Washington and Oregon with approximate locations of the Skookum Watersheds and the Red Fir project areas. Inset maps show details of the two study areas: watershed boundaries are outlined in black, perennial streams are shown with solid gray lines, ephemeral streams are shown with broken gray lines; locations of the gaging weirs, water quality samplers, and bedload sediment boxes within the Skookum Watersheds are shown with filled circles. Shaded rectangles show location of study hillslopes where erosion plots and fuel transects were located. Inset box shows detailed lay out of silt fences within a single study hillslope, dashed lines are topographic contours (contour interval 12 m), dark lines within the study plot denote locations of silt fences. There are three fences each, at upper-, mid-, and toe-slope positions.

conducted in other regions, and from studies of wildfire, logging, and road building practices. Empirically derived data are needed to support revision of National Forest management plans and to plan fuels reduction treatments, particularly in the wildland-urban interface and in watersheds with Endangered Species Act-listed salmon.

This study is designed to collect data on background erosion rates and to examine the effects of prescribed fire on hillslope soil erosion and stream sedimentation. We report 11 years of background discharge and sediment yield data, and two years of background hillslope erosion data, from the Skookum paired-watershed study. We also present preliminary results from two years of post-treatment data from the Red Fir prescribed burn project.

STUDY AREA

The project areas are located in the northern Blue Mountains of the interior Columbia River basin in a region characterized by uplifted, dissected volcanic plateaus. The Skookum paired watersheds are located in the John Day River basin in northeast Oregon. The Red Fir prescribed

Table 1. Skookum, Red Fir, and Lick Creek study area descriptions.

	Skookum Project	Red Fir Project	Lick Creek Project
Area (km^2)	8	6.8	6.3
Elevation range (m)	1,220 - 1,730	915 - 1,370	1,250 - 1,555
Average precipitation (cm)	56	38	89
Aspect	north and south	north and south	north
Treatment date	Deferred	October 2002	October 2004

burn project is located on a tributary of the Asotin River in the Lower Snake River basin in southeast Washington (Figure 1, Table 1). Forest conditions are similar at both project areas. Dry south- and west-facing slopes are characterized by open stands of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*). Hillslope hollows with deeper soils typically have mixed dominance, with abundant western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*). Ridge-tops, north, and east slopes have denser, mixed stands of larch, lodgepole pine, and grand fir (*Abies grandis*). Historically, fire regimes were mixed, with areas of low, moderate, and high-severity fires (Arno 2000), but none of the project areas have experienced a stand-replacing fire in recent times. Fuel loadings on dry south-facing slopes appear to have changed little from historical conditions. In contrast, fuel loadings have changed dramatically in wetter and cooler sites where fire exclusion led to increased density of shade tolerant conifers (Franklin and Agee 2003). In the Skookum watershed, ridge tops and north-facing slopes that previously supported dense stands suffered high mortality in the most recent (1990) spruce budworm (*Choristoneura* spp.) outbreak. Since then, many dead trees have fallen, and loadings of downed woody fuels have reached 224 tonnes/ha in some areas. Grasses and forbs now grow densely within stands of dead timber, especially on north-facing slopes, and a variety of coniferous species are establishing in these areas.

The Skookum project area, about 8 km^2 in size, is located in the headwaters of Skookum Creek (lat 45°5'N, long 119°28'W), a tributary to the North Fork John Day River near the town of Monument, Oregon (Figure 1). Elevations in the project area range from 1220 to 1730 meters. The watershed is within a designated roadless area and is relatively unaffected by past timber management. Two adjacent tributaries (control and planned treatment) were instrumented for a paired catchment study in 1992. The watersheds were fenced to exclude domestic livestock at that time. The larger watershed, Skookum #1 (5 km^2) was designated as the planned treatment watershed and the smaller watershed, Skookum #2 (3 km^2) was designated as the control. In 2002, monitoring in both watersheds was expanded with the installation of erosion plots to measure rates of hillslope erosion, down slope transport, and delivery of sediment to stream channels. A 1998 prescribed burn plan called for controlled burning in the treatment watershed and adjoining areas, leaving the control watershed untreated. By spring of 2004, planned treatments had not been implemented in large part because of weather and fuel conditions, and the existing plan was deemed out of date.

The Red Fir prescribed burn project is located in southeast Washington in tributaries to the North Fork Asotin River (lat 46°15'N, long 117°25'W) in the lower Snake River drainage, near the town of Pomeroy, Washington (Figure 1). Elevations range from 915 to 1555 meters. Treatment hillslopes include both south and north-facing slopes. Control plots were established on hillslopes with similar aspects in an adjacent drainage approximately 1 km away. These control hillslopes had been treated with prescribed fire in 1999 but the effects of this earlier prescribed burn are unlikely to influence erosion rates measured in this study because ground cover vegetation appeared to have recovered completely by 2002. The Red Fir project, implemented in 2002, was a Forest Service district prescribed burn designed to reduce fuel loading.

Methods

The study was designed to take advantage of the existing Skookum paired-watershed study and fuels reductions treatments already planned by the USFS. The Skookum watersheds, with 11 years of pre-treatment data, provided a rare opportunity to examine erosion budgets at multiple scales and within the context of longer-term water and sediment yield. Thus we augmented existing measurements with silt-fence erosion plots to measure hillsope erosion rates within both of the Skookum watersheds. We recognized the possibility that the watersheds would not be treated as planned due to their large size, lack of roads, heavy fuel accumulations, and the fact that they are contiguous with a large roadless area. The risks and consequences of an escaped prescribed fire would be substantial. Therefore we considered other planned prescribed fire projects within the Blue Mountains. The Red Fir prescribed burn project, which had a high probability of taking place as planned, had relatively easy access, and contained planar hillslopes with nearby controls, was selected to measure hillslope erosion and down-slope transport of sediment. This site was not located within gaged, experimental watersheds and therefore lacks the long period of pre-treatment monitoring available at the Skookum watersheds. Also, because of the timing of the treatments, no pre-treatment data could be collected and analyses focus on comparison between treatment and control sites only, without reference to background conditions.

Hillslope Erosion Plots

Variable-area erosion plots were used to measure hillslope erosion rate in both project areas. In the Skookum project area, plots were established at both the control and proposed treatment watersheds in July 2002. At the Red Fir site, erosion plots were established in the control in July 2002, and one week after the sites were burned in October 2002. Erosion plots on the treated hillslopes at the Red Fir site were located and staked with steel fence posts at the time that the control plots were established to avoid unintentionally biasing plot placement to sample areas of greater (or lesser) burn intensity.

Sediment fences were located on planar hillslopes (neither concave nor convex across the contour) so that calculated erosion rates would not be confounded by convergent or divergent patterns of overland flow. Fences were laid out in transects consisting of three replicates, spaced 30 m apart, with transects located at upper-, mid-, and toe-slope positions along the length of the hillslope. Sediment fences were designed following the methods described by Robichaud and Brown (2002), and were made from black silt-fence fabric supported with light-weight metal fence posts (Figure 2). Each fence is 5 m wide and oriented perpendicular to the hillslope (or parallel to the contour). Two features of our design differ from the design described by Robichaud and Brown (2002). First, we used 1.83-m-wide fabric, using the excess width to form a contiguous apron, covering the soil surface and extending 0.5 to 0.8 m upslope of the actual sediment fence, to allow collection of small amounts of sediment without accidentally collecting any of the underlying soil. Secondly, all plots are "unbounded" so the contributing area of each plot is defined by a variable area of hillslope that contributes runoff, surface erosion and dry ravel over the period of measurement. We used unbounded plots because they provided an estimate of cumulative erosion rates along the length of the hillslope so that differences between transects can be used to calculate net erosion and deposition rates along the length of the hillslope. If net downslope transport of eroded sediment occurred, it should be evident in a downslope increase in the amount of sediment collected. The amount of sediment collected in the toe-slope transects, alone, measured the gross delivery of sediment to the valley floor.

Sediment in the fences was collected in late spring (after snowmelt) and again in the fall. Additional collections were planned following all intense summer rainstorms that generated significant overland flow; however, such storms have not occurred in the study areas to date. To collect the accumulated sediment, all large branches, sticks and cones were first removed and discarded. Large accumulations of dirt were collected with a trowel, and the fence apron was then swept with a whisk-broom and fine sediment was collected with a dust pan. Collected materials were labeled, bagged, and transported to the laboratory. In the laboratory, larger organic debris was separated by hand and discarded. The remaining sample was sieved into size-fractions, oven dried (96 hr at 55ºC), and weighed. The oven-dried samples were combusted in a muffle furnace (10 hr at 600ºC) to burn off residual organic matter and

Figure 2. Example of a sediment fence. The fence is 5 meters wide, 0.5 m tall, with a 0.8 m long apron. The upslope edge of the apron is buried in a shallow trench. See Robichaud and Brown (2002) for installation details.

then re-weighed. The weight of the remaining sample was corrected for the residual mineral content from the combusted organic materials, assuming that the mineral content of organic matter averaged 5.05 percent (Wondzell, unpublished data).

A variety of additional measurements were collected to characterize conditions at each erosion plot. These measurements were taken in a plot measuring 10 m wide, starting at the sediment fence and extending upslope for 10 m. Slope and aspect of the plot were recorded. Duff thickness was measured at 0.5-m intervals along the length of the upslope, vertical face of the 0.1-m-wide trench into which the upslope end of the silt-fence material was buried. Visual estimates of the percent cover of ash, charcoal, bare ground, gravel, rock, duff, wood, and vegetation were made. These estimates focused on the ground surface exposed to direct raindrop impact so that the sum cannot exceed 100%. Further visual estimates of vegetation cover were made to break total canopy cover into the following growth forms: grasses, forbs, sub-shrubs, shrubs, and trees. These measurements were collected from both control and treatment plots during the summer prior to the prescribed burn, directly after the burn, and every summer after treatment. Photographs of the plots were taken from the plot perimeters: from the mid-point of the silt fence and from the mid-points of the upper and side boundary lines of each plot (Figure 3 and 4). Fuel load transects were established at each hillslope in the Skookum project area. Four, 15.24-m fuel load transects were spaced across each hillslope position, alternating with the silt fences, for a total of 12 fuel load transects per hillslope. Data were collected following methods described by Brown (1974).

Paired, Small-Watershed Study

The Skookum Experimental Watershed Study was established 1992. Measurements collected within the Skookum study area include stream discharge, suspended sediment, annual bedload sediment yields, water and air temperatures, and precipitation. Annual summaries of total yields are made on a water-year basis – from 1 October through 30 September of the following year. The control and treatment watersheds are instrumented with 120 degree V-notch weirs. Stream stage is measured at the gaging stations by float sensors in stilling wells. From 1992 to 2001, stage was recorded on punch tapes at 15-minute intervals using a Fisher-Porter[1] analog to digital recorder. Stage data were converted to discharge using the program HYDRA and the rating equation for a 120-degree V-notch weir (Rantz et al. 1982). In 2001, the Fisher-Porters were upgraded to Design Analysis H-510 digital recorders.

Figure 3. Red Fir project area, Sheep Gulch South, plot #3, a south-facing plot in an upper slope position. The photograph was taken looking across the erosion plot on 14 August 2002, before the prescribed fire.

Figure 4. Red Fir project area, Sheep Gulch south, plot #3 photographed on 28 October 2002, immediately after the prescribed fire from almost the same location as Figure 3. Much of the large log visible in the foreground of Figure 3 was consumed by the fire. Loss of some shrub cover exposed logs not visible in Figure 3.

Stream water samples were collected using battery-operated pumping samplers with intakes positioned in the deepest part of the channel, approximately 15 cm above the streambed. Samplers were programmed to collect a daily composite sample consisting of four samples drawn at six hour intervals (midnight, 6:00 AM, noon, 6:00 PM). The samples were analyzed for total suspended solids at the Umatilla National Forest water laboratory in Pendleton, Oregon.

Bedload was collected using in-channel bedload boxes, measuring approximately 1.5 m long, 0.7 m wide, and

---

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

0.7 m deep, with plywood sides and bottom, set into the stream channel with the upstream lip set flush with the streambed. The bedload boxes spanned the full width of the active stream channel. Boxes were emptied once a year by diverting the stream, draining the box, and shoveling the collected sediment into a bucket. The total volume of collected sediment was measured in "buckets" and later converted to a dry weight. In both 2002 and 2004 a sub-sample of the bedload sediment was collected from Skookum #1; only small amounts of sediment had accumulated in the bedload box of Skookum #2 in these years so the entire amount was collected. Wet volumes of the collected sediment were measured in a graduated beaker and then oven dried at 55ºC until successive weighings had stabilized, indicating that all water was evaporated from the sample. Samples were sieved into particle-size fractions and weighed. In all cases, samples contained large but variable amounts of water, which had a substantial effect on estimated conversion factors from wet volume to dry weight (mean = 0.55 kg dry sediment per liter wet bedload sample; SD = 0.25). We combined data from both watersheds, weighted by the wet volume of each sample, to estimate a conversion factor, 0.60 kg dry sediment per liter wet bedload sample, that most closely approximated the volumes measured as the bedload traps were emptied.

Water and air temperatures were recorded at hourly intervals using an Onset HOBO[1] temperature logger. From 1992 to 2003, precipitation was measured using a Fisher-Porter punch tape weighing precipitation gage equipped with an antifreeze and methanol reservoir to capture snow precipitation. Measurements were logged at 15-minute intervals. In 2003, a tipping bucket raingauge equipped with a snow conversion kit was installed to replace the Fisher-Porter raingauge.

Data Analysis

A hierarchically nested sampling design was used to study erosion across scales, from the plot scale up to the whole watershed scale. Individual plots provided point estimates of erosion rates, differences between transects in different hillslope positions traced the transport and redistribution of sediment along hillslopes, the toe-slope transect of sediment fences measured the amount of sediment delivered to valley floors. At the Skookum Watersheds, the automated water samplers and bedload boxes quantified the amount of sediment leaving the watershed.

Hillslope Erosion Plots: Erosion rates among blocks of erosion plots were examined for significant differences ($\alpha = 0.05$) using analysis of variance (ANOVA). Data were first natural-log transformed because raw erosion data were highly skewed (many small values and few large values). Because this project is in progress, analyses of the sediment collections completed to date are complicated by an unbalanced number of sampling periods – with three sample collections completed (spring 2003, fall 2003, and spring 2004). Preliminary analyses showed that erosion rates were not significantly different between season (spring 2003, fall 2003) or year (spring 2003, spring 2004), consequently, the amounts of sediment collected from each plot were summed across all measurement dates and divided by the 1.66 years for which the sediment fences have been in place, thereby converting mass of sediment collected to an annual erosion rate. Separate analyses were conducted for each project area. The Skookum project has not been treated, but allows investigation of background erosion rates and the influence of aspect and slope position on these rates. The Red Fir project was treated with prescribed fire and thereby allows investigation of prescribed fire effects on erosion rates.

The first step in the analyses for each project area was to examine the effect of slope position against the hypothesized relation that would be expected if eroded sediment was transported the length of the hillslope resulting in a net, down-slope accumulation of eroded sediment. Separate ANOVA analyses were conducted for each project area. ANOVA analyses showing a significant affect of slope position ($\alpha = 0.05$) were further examined using Tukey means comparisons tests to identify hillslope positions with significant differences. These analyses were conducted by combining plots from all hillslopes within a project area (aspect and treatment combined); by examining plots divided into analysis blocks by aspect (proposed treatments combined); and finally, by examining plots divided into analysis blocks for each individual hillslope. The relatively small number of erosion plots (three within a single transect at a given slope position) and the high variability between plots suggested that this test would have little power to detect small differences. Consequently, we also examined the data looking for non-significant differences that followed the hypothesized trend. If there was no evidence that erosion rates measured within a single hillslope were dependent upon slope position (i.e., lack of significant differences in the means comparison tests; lack of hypothesized trend) we dropped slope position as a categorical variable and treated each plot as an independent replicate in all subsequent analyses.

To examine the effect of aspect on annual erosion rates, all nine erosion plots on a single hillslope were treated as independent replicates, grouped into a single block within the ANOVA. As before, project areas were analyzed separately. Data from treated hillslopes within the Red

Fir project area were not used in this analysis because the results could have been confounded by unbalanced treatment effects. ANOVA analyses showing a significant effect of aspect ($\alpha = 0.05$) were further examined using a Tukey means comparison test to further identify specific differences in annual erosion rates related to aspect.

Erosion rates measured on the Red Fir erosion plots were examined for significant differences ($\alpha = 0.05$) resulting from the prescribed fire treatment using ANOVA. Separate analyses were conducted for north-facing and south-facing hillslopes. These analyses were confounded by an unbalanced treatment effect (despite a balanced experimental design). The prescribed fires were set at ridge top and upper slope positions and allowed to spread downhill, but failed to reach toe-slope transects on the south facing slopes and both toe-slope and mid-slope transects on the north facing slope. Because erosion plots were treated as independent replicates, unburned plots were grouped with control plots, resulting in 6 burned plots and 12 control plots with southerly aspect and 3 burned plots and 15 control plots with northerly aspect. Treatment sample sizes were very small so the data need to be interpreted with caution.

To further clarify the relation between hillslope erosion rates and the factors typically related to surface erosion, a regression analysis was conducted using the continuously distributed variables: slope, average duff thickness, and the natural-log transformed average of bare ground plus ash. A backward, stepwise procedure was used to eliminate non-significant variables ($\alpha = 0.05$). Relating the average annual rate of observed hillslope erosion to the amount of bare ground plus ash was complicated by the fact that ground cover estimates were repeated each summer. Relatively little change was observed, through time, on control plots, but large changes in the amount of bare ground and ash were apparent on the treated plots. Consequently, use of the time-averaged bare ground plus ash in the regression analysis might obscure results. Therefore, the regression analysis used the data from each collection date, expressed as an annualized rate (rather than the average of all three collections). We assumed that ground cover would change little over the winter, so that the bare ground estimates from summer 2002 were regressed against spring 2003 erosion rate; bare ground estimates from summer 2003 were regressed against fall 2003 and spring 2004 erosion rates.

Watershed-scale Sediment Budgets: Data collected from the Skookum Experimental Watersheds provides a time-series of precipitation inputs and water and sediment yield over the 11 pre-treatment years of study. Runoff ratios (total annual precipitation divided by total annual water yield) were calculated from these data. Annual runoff ratios and yields from the two watersheds were analyzed to see if differences between watershed means (the 11-year mean annual unit-area runoff ratios and yields of water, suspended sediment, and bedload sediment) were significantly different than zero ($\alpha = 0.05$). Finally, average annual yields were calculated by averaging total annual yield over the 11 complete years of measurement data currently available (1993 through 2003, inclusive).

Results

Skookum Experimental Watersheds

Precipitation and water yield in the Skookum watershed during the pre-treatment period showed high inter-annual variability with large differences in unit area water yields between catchments (Figure 5). The 20-year average precipitation measured at Madison Butte Lookout, a Natural Resource Conservation Service SNOTEL site located at the headwaters of the Skookum watersheds was about 56 cm per year. Of pre-treatment years sampled, six had below average precipitation, while four years were above average. Unit area water yields from Skookum #1 (proposed treatment watershed) were significantly higher than yields from Skookum #2 (control watershed) ($p = 0.013$). Runoff ratios were also significantly higher in Skookum #1, where annual runoff was 19 percent of precipitation inputs compared to 14 percent of precipitation inputs in Skookum #2 ($p = 0.006$).

Suspended and bedload sediment yields showed high inter-annual variability in both watersheds (Figure 5). Unit area suspended sediment yields were significantly higher in Skookum #1 than in Skookum #2 ($p = 0.037$), even though the two catchments have similar geology, soils and vegetation. Suspended sediment yields from Skookum #1 peaked in 1995 and 1996, and decreased dramatically the following year, 1997, the year with the highest water yield observed over the period of record. Similarly, unit area bedload yields are significantly higher in Skookum #1 than in Skookum #2 ($p = 0.006$). Bedload yields from Skookum #1 peaked in 1995 and decreased gradually thereafter. Suspended sediment comprises more than 99% of the total sediment yield from both watersheds.

There were no significant differences in hillslope erosion rates within the Skookum watersheds among upper-, mid-, and toe-slope positions when the data from all plots was combined or when analyzing north-and south-facing plots separately. Examining the four hillslopes individually resulted in one case where erosion rate varied significantly with slope position ($p = 0.009$). The means comparison test, however, showed that the rate measured at mid slope (50.18 g/m hillslope width) was significantly higher than

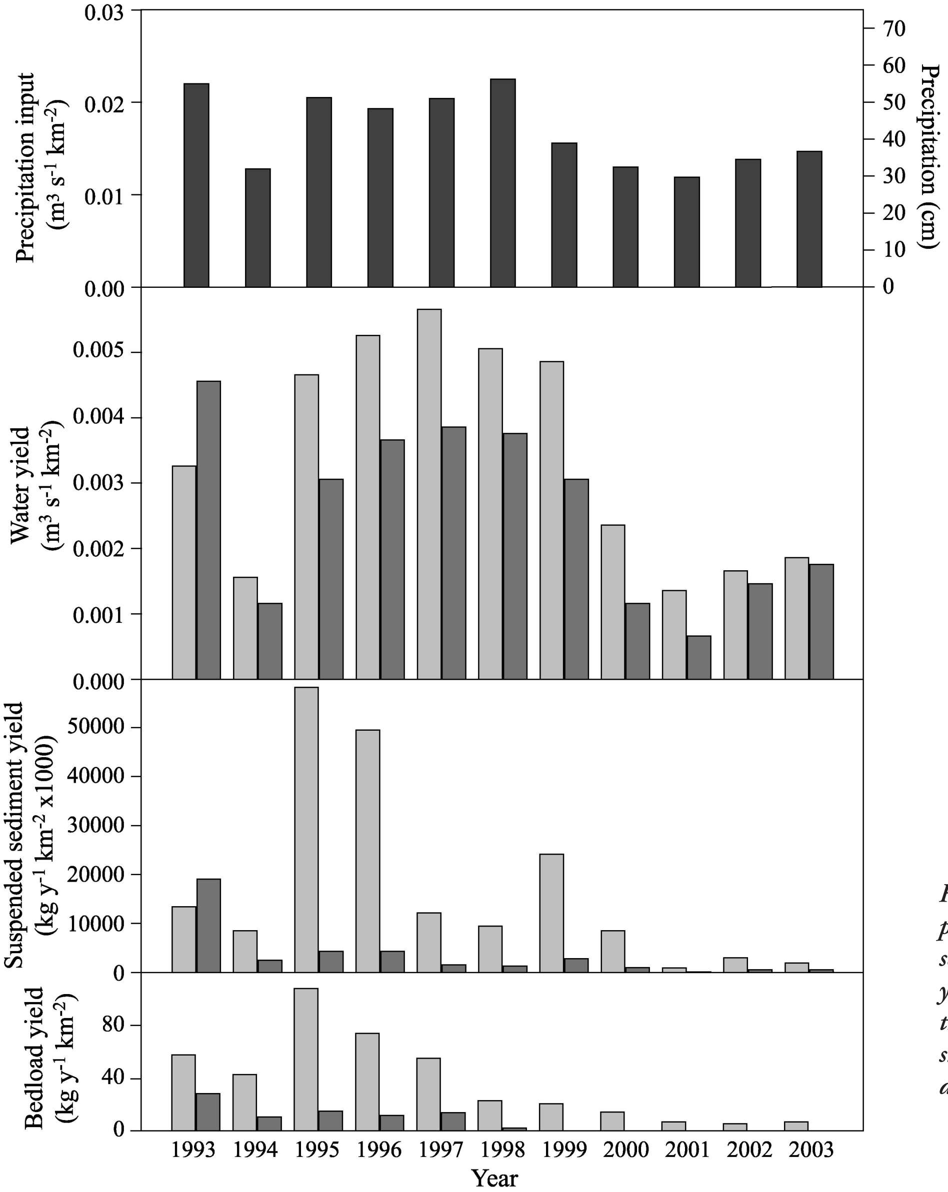

Figure 5. Skookum project area annual precipitation, water yield, suspended sediment yield, and bedload sediment yield from 1993 through 2003. In the lower three panels, Skookum #1 is shown in light gray, Skookum #2 in dark gray.

at either the upper slope (9.04 g/m) or the toe slope (8.08 g/m). In no case did the observed trends support our hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences caused by sediment erosion and subsequent transport along the length of the hillslope.

Annual hillslope erosion rates were strongly influenced by aspect, with significantly higher rates on south-facing hillslopes than north-facing hillslopes (Figure 6). Soils on south-facing slopes were more exposed, with less cover of litter and duff than on north-facing slopes. We observed frequent signs that animal burrowing activity on the south-facing aspects was contributing local sediment to the sediment fences. We did not observe signs of burrowing activity and sediment loading of the fences on the north-facing aspects.

Treatment Effects

At the Red Fir site, there was no significant difference between the burned and unburned plots in the annual hillslope erosion rate averaged from the three collection dates (Figure 7). On the north-facing treatment hillslope, the prescribed fire burned only the upper three plots, leaving six of the plots (middle and lower) unburned. On the south-facing treatment hillslope, the prescribed fire burned the upper and middle plots, leaving the three lower plots unburned. In our analysis, the unburned erosion plots in the planned treatment block were grouped with the control plots. The resulting data structure was highly unbalanced, and had little statistical power to resolve the small differences observed between the burned and unburned plots (Figure 7). At the Red Fir site, elk are

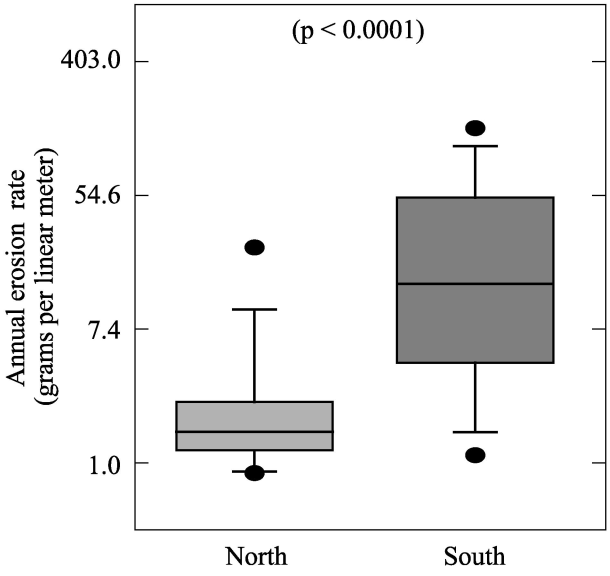

Figure 6. Comparisons of annual erosion rates between north- and south-facing hillslopes in the Skookum project area during the pre-treatment phase of the project (n = 18 for each box). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.

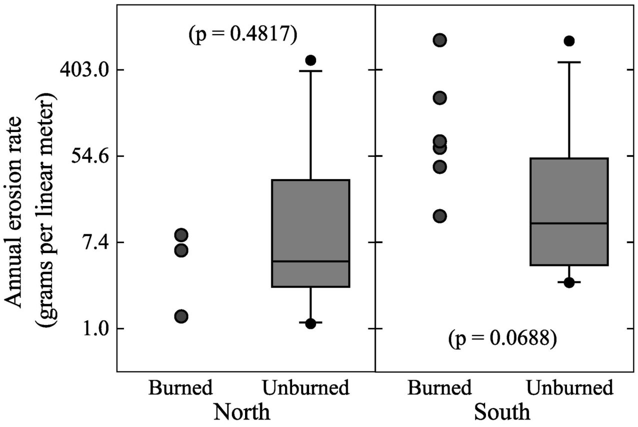

Figure 7. Comparison of annual erosion rates between burned and unburned plots on north and south aspects at the Red Fir project area (north, unburned, n = 15; south, unburned, n = 12). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.

Figure 8. Red Fir project area, Cabin Gulch south, plot #6, a south-facing mid slope plot. Note the obvious bioturbation caused by elk walking above the sediment fence when the ground was wet, accumulation of sediment, short delivery distances, and damage to the sediment fence.

attracted to the erosion plot silt fences, and there is evidence of damage to the plots, especially on the south-facing control hillslope (Figure 8). Much of the erosion measured in these locations appears to be caused by elk trampling above the silt fence.

Exploratory data analysis suggested that the amount of bare ground was positively correlated with the observed annual erosion rates. Backwards, stepwise regression analyses showed that natural-log transformed sum of bare ground plus ash was more highly correlated to erosion than were either slope angle or duff thickness. The relation between the area of bare ground and erosion also appears to vary with aspect, with an equivalent bare ground area supporting higher erosion rates on south-facing aspects than on north-facing aspects (Figure 9). The amount of bare ground plus ash was usually higher in burned plots than in unburned plots, and on south-facing aspects, burned plots had among the highest observed erosion rates. Burning leads to substantially reduced ground cover and increased areas of the soil surface covered by ash in the time immediately after the fire. However, this cannot be linked to the treatment effects in the statistical analysis

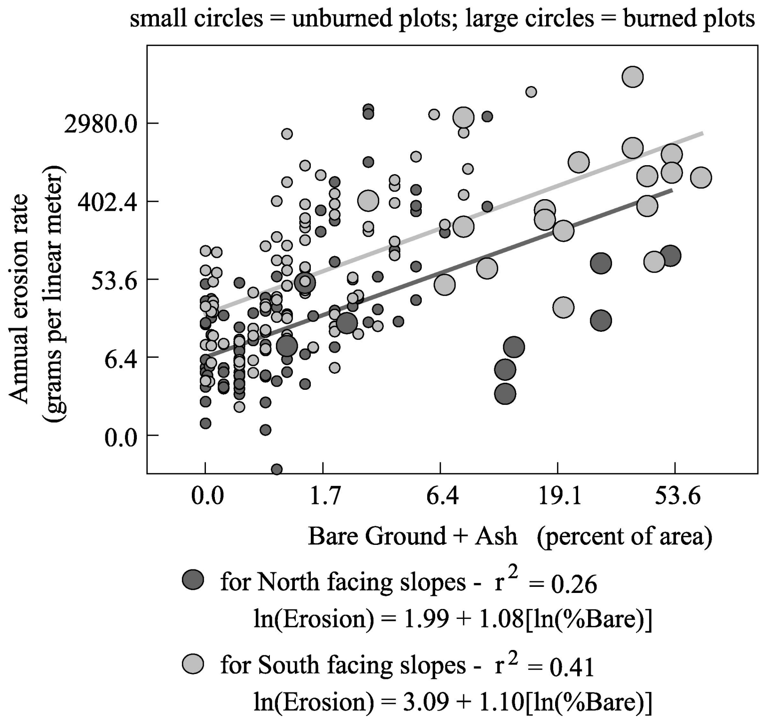

Figure 9. Skookum and Red Fir project areas bare ground plus ash percent of plot area vs. annual erosion rate. Burned plots are denoted with large filled circles; unburned plots with small filled circles.

because of the small number of burned plots and the highly unbalanced sample design.

DISCUSSION

Background Natural Disturbance – The Spruce Budworm Outbreak

The Skookum Experimental Watersheds are a paired watershed study with 11 years of pre-treatment data on discharge, suspended sediment, bedload sediment, and water temperature. Our study design called for establishing erosion plots one full year before implementing the prescribed burn which would allow a “Before-After/Treatment-Control” study design to examine changes in sediment budgets at scales ranging from the plot, to the hillslope, to the whole watershed. For a variety of reasons, however, the Skookum watersheds were not treated, turning this into a study of background erosion rates. The study remains valuable because it provides information on baseline erosion rates from watersheds with volcanic parent materials within the Blue Mountain physiographic province. These results will be useful in the design and evaluation of future projects for purposes of improving erosion estimates, understanding the range of natural variability, and calibrating predictive models.

The degree to which the extensive forest mortality resulting from the spruce budworm outbreak in the early 1990s contributed to the changes in water and sediment yields observed over the period of record is an intriguing question. Suspended sediment yield peaks in 1995 and 1996 may be related to the forest mortality from the spruce budworm outbreak. Loss of the forest canopy would have exposed the soil surface to direct impact of raindrops and decreased transpirational losses might have led to increased runoff, both of which could contribute increased amounts of sediment to channels and help transport this sediment out of the watersheds. Residual live trees remaining in areas where most trees had died would have been more exposed to wind, and were probably more likely to be toppled during windstorms in the years immediately following the catastrophic die off of the canopy. Root wads from toppled trees provided exposed, easily detached soil that was available for erosion. Eroded sediment from root wads in toe-slope, riparian, and stream-bank positions may have contributed to the peak yields of suspended and bedload sediment observed in 1995 and 1996.

Understory vegetation is now dense, especially on northwesterly through easterly aspects because loss of the forest canopy has increased the amount of light available to forest floor vegetation. Further, as root systems and boles of insect-killed trees began to rot away, the trees would have been much less wind-firm, falling under the forces of gravity, snow loading, and wind. Dense vegetative cover now protects the soil from erosion and increased downed logs now provide an abundance of sediment storage locations on the hillslopes. Further, transpiration from the dense understory has probably reduced water yields from the watersheds. A combination of all these processes could explain the reduced water and sediment yield since 2000. However, annual precipitation has also been below average since 1999, which may also contribute to decreased sediment yields in recent years. Without pre-budworm outbreak data, however, the identification of causal mechanism is speculative. Overall, large differences in sediment yields between watersheds, high inter-annual variability, and confounding affects from extensive forest mortality would likely make it difficult to discern prescribed fire effects on watershed-scale sediment yields unless these were very large.

Hillslope-scale Erosion and Sediment Transport

Infiltration-excess overland flow is a major driver of erosion in the intermountain west, especially following fire [see reviews by Wondzell and King (2003)]. While there is little direct research on the influence of prescribed fire on erosion, research following wildfire suggests that the potential to increase erosion rates is correlated to fire severity. Large, stand-replacing wildfires have the greatest impact on soil properties that influence erosion. Most prescribed fires are set when weather and fuel conditions make large, high severity fires unlikely. Even if prescribed fires did increase potential hillslope erosion rates, without large storms to generate overland flow in the year or two after the burn, significant erosion is unlikely.

We never observed evidence of overland flow that would have driven surface erosion and downslope transport of eroded sediment at any of our study sites over the course of this study. Without major storm events to drive extensive overland flow, the physical mechanism that would drive erosion and down-slope sediment transport is lacking. Under these conditions it is not surprising that observed patterns of erosion did not support the hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences. Rather, observations made while emptying the erosion fences suggested that the hillslope area contributing sediment to the erosion fences was very small, perhaps extending no more than a meter upslope of the fence apron. In the most part, erosion resulted from bioturbation. Clods of dirt appeared to have been kicked onto the fence aprons, judging from the deep footprints elk left in wet soil immediately above the fences in several locations. Similarly, small mammals digging immediately above the plots send small amounts of dirt into the fences. All these facts combined suggest that each sediment fence functioned as an independent sample unit under the conditions during which these study was conducted.

Watershed-scale Sediment Budgets

The design of this study allowed estimation of both total sediment delivery to the stream channel and net sediment yield from the watershed. The difference between these two values was the net channel erosion rate, where positive values represented channel aggradation and negative values represented bank erosion or channel incision.

Preliminary estimates of background hillslope erosion rates suggested that low amounts of sediment are delivered to valley floors within each catchment, as measured with the silt fences located in toe-slope positions. A simple, watershed-scale budget of sediment delivery was made by estimating the length of mainstem channel, and clearly defined tributary channels within each watershed and multiplying by a sediment delivery rate. We assumed that the sediment delivery to each meter of valley-floor length equaled two-times the overall average hillslope erosion rate measured from all 32 hillslope erosion plots within the Skookum watersheds (i.e., one side of the valley floor receiving sediment inputs at the rate measured on south-aspect hillslopes; the other side receiving sediment inputs at the rate measured on north-aspect hillslopes). Skookum #1 had 3.40 km of mainstem channel and 5.33 km of tributary channel; Skookum #2 had 2.29 km of mainstem channel and 1.96 km of tributary channel. The calculations showed that, on average, 52 kg of sediment were delivered to the valley floor of Skookum #1, while valley floors in Skookum #2 received an average of 25 kg/y.

Watershed-scale estimates of sediment yield derived from water samples collected at the outlet streams suggest sediment losses hundreds of times greater than sediment delivery rates to the valley floors (12,000 kg/y from Skookum #1 and 3,000 kg/y from Skookum #2). Assuming that the dry bulk density of suspended sediment is 1.7 g cm^{-3} and assuming an average wetted perimeter of 0.70 m for mainstem channels and 0.35 m for tributary channels, and assuming that sediment is eroded evenly from the entire channel network, annual sediment yields could be accounted for by 3 to 12 mm of streambed and streambank erosion. Most of the annual sediment yield is comprised of suspended sediment, and most of this is removed from the watershed by peak flows during spring snowmelt. Our calculations probably overestimate the degree of stream erosion needed to supply annual sediment yields because the calculations do not include sediment eroded from hillslope hollows lacking obvious channels that are connected to the stream network during snowmelt. Because sediment may be stored on valley floors for long periods of time, continued erosion of stored sediment may maintain elevated sediment loads in streams, even when little erosion is occurring on upland sites. The results of both the hillslope- and watershed-scale erosion patterns highlight the influence of episodic hillslope erosion events, sediment storage on floodplains, and minor amounts channel erosion on watershed-scale sediment budgets.

CONCERNS AND ISSUES FOR MANAGEMENT

Requirements for species protection under the Endangered Species Act have caused many changes in project design. In general, riparian protection requirements limit the scope of management activities in these areas. To date, prescribed fire treatments are generally designed to have no measurable effect on streams and riparian areas for consultation purposes under the Endangered Species Act. Design criteria include not burning within the riparian conservation area (riparian and buffer zone) and limiting total area in bare soil in the project area. Results presented in this paper validate the design of treatments for no effect to aquatics under "normal" weather conditions. Avoiding active treatment within riparian areas may, over the short term, prevent direct effects of sedimentation to streams but riparian conditions, including fuel loading, may or may not be at desired levels in a project area. Further, at the landscape scale, effective fuels treatments to reduce uncharacteristic wildfire risk may in some cases conflict with riparian protection management standards (generally interpreted as no active treatment). Active riparian treatment using prescribed fire may be desired in certain circumstances for purposes of improving riparian conditions and reducing landscape-scale wildfire severity.

FUTURE WORK

Sampling of erosion plots will begin at a third fuels treatment project, the Lick Creek site, in June 2005. Fuel conditions forest wide are increasingly complex, and managers are turning to combined treatments of mechanical thinning and burning to reduce fuel loads. These types of treatments will be more common in the future, and the Lick Creek project will provide data on combined treatment effects on hillslope erosion rates. Additional study plans include: 1) analyzing Skookum fuel load measurements; 2) comparing hillslope erosion to changes in channel morphology using stream reference reaches; 3) comparing pre- and post-burn fuel load measurements for Lick Creek; 4) comparing results with FSWEPP modeled results; 5) sharing data with FSWEPP developers for local model calibration; 6) sharing study results with local managers for use in developing project effects analysis; and 7) archiving data in the Pacific Northwest Forest Science Databank.

SUMMARY

Challenges faced in this study include the uncertainty of treatments being implemented and short timeframes during which measurable effects were likely. Successful implementation of planned prescribed fire projects was often uncertain because of stringent requirements for burning, availability of resource personnel, and competing priorities. Once implemented, timeframes in which to measure potential effects were limited by relatively rapid recovery of understory vegetation and the likelihood of significant storms occurring during this period was relatively low. As a result, responses under more extreme weather conditions such as winter rain-on-snow events or intense summer convective storms were difficult to capture.

The preliminary data reported here showed that background hillslope erosion rates varied significantly by aspect and were generally higher on south-facing slopes. At the watershed scale, annual sediment yields were highly variable. Watershed sediment budgets showed that episodic erosion events most likely control sediment delivery to streams but that sediment storage in valley floors and subsequent removal via bank erosion influences annual sediment yields over the long term. Without large storm events in the first two years after prescribed fire, there was no significant difference in hillslope erosion between burned and unburned plots. The significant relationship between bare ground and erosion rates demonstrated the role of soil cover in controlling surface erosion.

Acknowledgements. This project was funded by the Joint Fire Science Program under BLM interagency agreement #1422R220A7-6000. Additional support was provided by the Umatilla National Forest and the Pacific Northwest Research Station. The Skookum project area has been maintained through the dedication of Tom Fritz, hydrologic technician on the Heppner Ranger District. Advice and assistance from Pete Robichaud in erosion plot design and comments from two anonymous reviewers are greatly appreciated.

REFERENCES

Arno, SF. 2000. Chapter 5: Fire in western forest ecosystems. In: JK Brown and J Kapler Smith, eds. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 97-120.

Brown, JK. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Everett, RL, PF Hessburg, ME Jensen, et al. 1994. Eastside forest ecosystem health assessment. Vol. 1, executive summary. Portland, OR: U.S. Department of Agriculture, National Forest System and Forest Service Research. 57 p.

Franklin, JF, and JK Agee. 2003. Forging a science-based National Forest fire policy. *Issues in Science and Technology* Fall: 1-8.

Hessburg, PF, RG Mitchell, and GM Filip. 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p.

McIver, JD, and L Starr, eds. 2000. Environmental effects of postfire logging: literature review and annotated bibliography. Gen. Tech. Rep. PNW-GTR-486. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p.

Quigley, TM, SJ Arbelbide. 1997. An assessment of ecosystem components in the Interior Columbia Basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. [Number of pages unknown].

Rantz, SE and others. 1982. Measurement and computation of streamflow. U.S. Geological Survey Water Supply Paper 2175. Washington, DC: U.S. Government Printing Office. 631 p.

Robichaud, PR, RE Brown. 2002. Silt fences: an economical technique for measuring hillslope soil erosion. Gen. Tech. Rep. RMRS-GTR-94. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 24 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2002. Healthy Forest Initiative. *http://www.fs.fed.us/projects/hfi/.* (6 December 2004).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2003. Healthy Forest Restoration Act. *http://resourcescommittee.house.gov/issues/ffh/hfra.htm.* (6 December 2004).

U.S. Department of Agriculture, Forest Service, and U.S. Department of the Interior [USDA FS and USDI]. 2000. National Fire Plan. *http://www.fireplan.gov.* (6 December 2004).

Wondzell, SM, and JG King. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* 178:75-87