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Evaluating Post-fire Salvage Logging Effects on Erosion

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Evaluating Post-fire Salvage Logging Effects on Erosion

(Proposal P06-3-4-21) Final Report

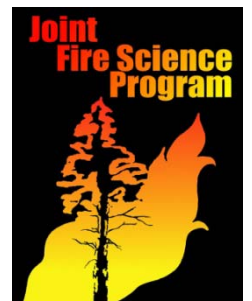
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I. Abstract

Legal challenges have delayed numerous post-fire salvage logging operations, which often results in lost economic value of the burned timber and unrecovered legal expenses. The scientific literature has shed little light on the additive effect of salvage logging operations on post-fire runoff, erosion, flooding, and sedimentation. Hence, there is an urgent need to better understand the impacts of post-fire salvage operations so that land managers can evaluate the relative and cumulative effects of different salvage logging practices. Intensive, multi-scale studies are needed because the effects of post-fire logging are superimposed on the effect of wildfires; rates and processes change according to the spatial and temporal scales of the investigation; and the studies to date indicate tremendous variability in the effects of post-fire salvage logging with the type and extent of the logging, site characteristics, and climatic conditions.

To address this need, the current project was established in the Northern Rockies to integrate experiments at the hillslope and small watershed scale that focus on erosion processes. Replicated plots were used to measure sediment production rates from burned and unlogged plots, logged areas, tracked areas due to ground-based logging, and tracked areas with added slash as an erosion control treatment. Measured erosion rates were related to detailed measurements of site characteristics including ground cover, rilling, water repellency, amount of area disturbed due to salvage logging operations, number of passes of logging equipment, soil compaction, and the number and type of erosion mitigation practices (e.g., application of logging slash, mulch, and water bars). Runoff and sediment yield data were collected from two pairs of small watersheds to determine how salvage logging affects runoff, peak flow, and erosion rates, and whether the erosion estimates from the hillslope plots can be extrapolated to the small watershed scale. Rill simulation studies were conducted on three sites affected by ground-based salvage logging to evaluate the various types of equipment and identify site factors that affect runoff and erosion rates.

The information gained from the rill simulations and hillslope-scale plots has provided a process-based understanding of the factors which exacerbate or alleviate the impacts of salvage logging, and developed implementation guidelines for reducing the negative impacts. The runoff and sediment yield data from the small watersheds and rill simulations were used to determine the interactions between hydrology and erosion, and will be applied to future efforts to incorporate and validate salvage logging disturbances into erosion prediction models such as the Water Erosion Prediction Project (WEPP). Finally, the information and knowledge gained in these studies has been incorporated into specific guidelines and best management practices (BMPs) for ground-based post-fire salvage logging operations, including suggestions for mitigation practices that can minimize the potential increase in runoff and erosion resulting from post-fire salvage logging. Results from these studies have been disseminated through a publication on regional BMPs for post-fire salvage logging, peer-reviewed technical articles on the hillslope and small watershed erosion rates from natural rainfall, a peer-reviewed technical article on the simulated rill experiments, 10 technical conference presentations, 5 regional workshops for land managers, and 9 workshops for post-fire emergency response and restoration teams.

II. Background and Purpose

In recent years, there has been a substantial increase in the occurrence of large, high severity wildfires in the western US. After such fires, land managers determine whether salvage logging should be included in the post-fire management plan. The harvest of dead but marketable timber can provide economic benefits and reduce fuel loads (McIver and Starr, 2001). The effects of post-fire salvage logging on runoff and erosion rates are of particular concern to land managers. Burned forest soils are more vulnerable to increased runoff and erosion rates, which can lead to flooding and increased risk to human life and property (DeBano et al., 1998; Moody and Martin, 2008). However, there is considerable controversy surrounding the implementation of post-fire salvage logging operations, and numerous salvage sales, affecting thousands of acres of burned timber, have been challenged in court.

Information concerning the effects of post-fire salvage operations on erosion is often anecdotal and inconclusive. The 21 studies examined by McIver and Starr (2000, 2001) and others (Peterson et al., 2009) indicate a paucity of data to evaluate salvage logging impacts on either runoff or erosion. The combined results indicate that the effects of salvage logging are highly variable and depend on site conditions as well as the type and execution of salvage logging operations. For example, Chase (2005) used hillslope plots to analyze sediment production rates from areas affected by tractor, cable, and helicopter salvage logging in the central Sierra Nevada in California. The greatest sediment production rates were from cable-logged sites, but the large variability within the data made it impossible to discern significant differences in sediment production between logging types (Chase, 2005).

Beschta et al. (2004) concluded that most post-fire logging is “not likely to be consistent with ecosystem restoration.” Lindemayer et al. (2004) presents examples of negative ecological

effects following post-fire logging, but concedes that post-fire logging may be appropriate in some given situation. However, the rationales to support these and other more adamantly critical studies are often based on the effects of salvage logging on the biotic components of the ecosystem such as habitat loss, altered community composition, delayed vegetative recovery, and increased colonization of non-native species. The effects of post-fire salvage logging on runoff, erosion, and sediment yields are of particular concern to land managers and the public. Burned forest soils are more vulnerable to increased runoff and erosion rates, which can lead to flooding, sedimentation, degradation of stream water quality, and increased risk to human life and property (DeBano et al., 1998; Moody and Martin, 2008). Often it is assumed that salvage logging operations will exacerbate these effects, but little data exists to support or refute this assumption.

The effects of forest fires on runoff and erosion are site specific and strongly dependent on burn severity, ground cover, regrowth rates, slope, soil type, and postfire weather (Moody and Martin 2008). The effects of post-fire salvage logging depend on this same set of factors with the addition of variables related to the logging operation, such as road building, type of logging system used, and extent of the logging operation (McIver and Starr, 2001). In order to make informed, defensible decisions, forest managers need to realistically predict the change in risk for flooding and erosion that results from superimposing a salvage logging operation onto an already burned area. Previous research in unburned forests suggests that the effects of logging operations on runoff and erosion can vary greatly with site conditions, type of logging operation, and erosion mitigation treatments applied in conjunction with the timber harvest operation (McIver and Starr, 2001). These same factors may also be an important control on salvage logging, but there is almost no data to determine the effects of post-fire salvage logging.

Rapid loss in economic value of timber in the first two to three years after a wildfire requires that decisions about salvage logging must be made rapidly after a wildfire (Lowell et. al., 1992). Post-fire assessment teams must evaluate the effects of salvage logging on flooding, erosion, sedimentation, and slope stabilization as part of the regulatory process. Some land managers have used predictions from existing hillslope or watershed erosion models to estimate the potential changes in erosion resulting from post-fire salvage operations; however, the lack of parameterization makes these predictions difficult to support or defend under regulatory or legal scrutiny. Quantitative descriptions of the changes in runoff and erosion due to selected salvage practices and a regional Best Management Practices (BMP) guide for post-fire salvage logging operations are needed to improve postfire management decisions as well as the defensibility of those decisions.

The need to understand and predict hillslope erosion rates due to various pre- and post-fire management activities (road building, forest thinning, prescribed fire, wildfire, and post-fire erosion mitigation treatments) has driven much of our recent work (funded, in part, by our previous JFSP projects). The resulting runoff and erosion prediction tools are web-based (<http://forest.moscowfsl.wsc.edu/fswepp/>) and include WEPP-Road (Elliot, 2004), Disturbed WEPP (Elliot, 2004), the Erosion Risk Management Tool (ERMiT) (Robichaud et al., 2006),

Peak Flow Calculator (Elliot et al., 2010) and Fuel Management (FUME) (Elliot et al., 2004). The field data from salvage operations collected under this project will be essential for future development of a complementary erosion prediction tool for salvage logging that will tie into our other web-based erosion prediction tools.

Some of the challenges in predicting the effects of post-fire salvage logging are the wide variation in the magnitude of runoff and erosion response given the various site conditions, and that these effects are compounded by variations in harvest method, time of harvest, storm magnitudes during and after harvesting operations, and local site conditions. Hence the development of post-fire management alternatives and any associated best management practices must be based on a rigorous, site-specific assessment of post-fire processes, and an understanding of how specific salvage logging activities can affect each of these processes. Given that the magnitude of post-fire and salvage logging effects will depend on the magnitude, frequency and timing of subsequent rain events, and that these events are random in nature, there will always be some risk of a substantial runoff or erosion event. However, with a process-based understanding, a manager should be able to estimate the most likely outcomes under a given set of conditions.

Project Objectives:

1. Directly measure the impacts of specific post-fire salvage logging practices on runoff and erosion rates at the watershed scale.
2. Directly measure the impacts of specific post-fire salvage logging practices, both with and without erosion mitigation treatments, on erosion rates at the hillslope scale.
3. Directly measure the impacts of specific post-fire salvage logging practices, both with and without erosion mitigation treatments, on rill erodibility.
4. Develop specific results for several key eco-regions and develop regional BMP guidelines. These are based on the process-based understanding developed from the field studies, and specific erosion mitigation practices needed to minimize the potential increases in erosion rates resulting from post-fire salvage logging operations.
5. Collect field data from salvage operations to eventually be used in developing an erosion prediction tool for salvage logging that will compliment our other web-based erosion prediction tools.

III. Study Description and Location

Study Sites

Two pairs of small watersheds (3 ha) were established to compare runoff and sediment yields from a salvaged logged and a burned but unlogged control. These were developed on the Hayman Fire in Colorado and the Kraft Springs Fire in Montana. Detailed site measurements were collected to directly compare these data with the hillslope-scale erosion rates. The runoff

data is critical for relating the measured sediment yields to runoff and peak flow, and for calibrating the hydrologic component of future erosion models.

Swales-scale erosion measurement sites (0.5 ha) were established at the Red Eagle Fire and Tripod Fire to compare sediment yields from areas that were salvage logged to burned but unlogged control areas.

At Tripod, the start of logging operations was delayed, and the extent of logging was less than expected. However, sediment fences were still installed on the Tripod Fire in Washington and the Red Eagle Fire in Montana (Figure 1). The two study areas compared hillslope-scale sediment production rates from control sites against the two types of salvage logging operations with and without erosion mitigation treatments.

Rill erosion is the primary source of sediment from severely-burned areas, thus, rill simulations were used to determine erodibility values. Rill simulations were conducted on the Red Eagle Fire in Montana, the Terrace Mountain Fire in Canada, and the School Fire in Washington (Figure 1). Rill erodibility values were determined for the different salvage log conditions described in Table 1.

All sites were characterized by moderate or high burn severity and the soil properties, topography, and vegetation types were documented. Rigorous data quality standards were used for all measurements including precipitation, disturbed area measurement, runoff, peak flow, sediment yield, ground cover, and soil water repellency.



Figure 1. Post-fire salvage logging research sites in the northern Rockies. The Tripod and Red Eagle sites have sediment fences at the hillslope-and swale-scale; the Hayman and Kraft Springs sites have paired small watersheds ; and the rill experiments were conducted at Terrace Mountain, School, and Red Eagle.

Table 1. Characteristics of salvaged logged studies.

Year and Fire Location	Years of data collection Reps per site/ Total reps	Ground-based logged conditions/treatments
Rill Simulation Studies		
2005 School Fire Umatilla NF, OR	4 5/30	control (high and low slope), high traffic (high and low slope), low traffic; all 3 treatments at both high and low slope
2007 Red Eagle Fire Blackfoot Indian Reservation, MT	3 5/30	control, rubber-tired skidder (untreated and treated with slash), tracked skid (untreated and treated with slash), feller buncher
2009 Terrace Mountain Fire Central Okanagan Regional District, Ministry of Forests, B.C. Canada	2 7/14	control, tracked skidder
Swale/Watershed Monitoring Sites		
2002 Hayman Fire Pike and San Isabel NF, CO	8 2/2	control, logged
2003 Kraft Springs Fire Custer NF, MT	6 2/2	control, logged
2007 Red Eagle Fire Blackfoot Indian Reservation, MT	4 6/9	control, logged
2002 Tripod Fire Wenatchee-Okanagan N F, WA	2 7/17	control, logged
Hillslope scale Monitoring sites		
2002 Tripod Fire Okanagan-Wenatchee N F, WA	5 6/24	control, skidded, skidded treated, feller buncher
2007 Red Eagle Fire Blackfoot Indian Reservation, MT	4 6/36	control, rubber-tired skidder (untreated and treated with slash), tracked skidder (untreated and treated with slash), feller buncher

Data Collection and Sampling

At three different locations, the rill simulation studies included the replications, logging conditions and treatments described in Table 1. The basic design was 2 to 4 treatments by 5 to 7 reps at two sites. These simulations were conducted immediately after the salvage logging was completed and in each of the following one to three years (two to four years per site) to measure post-disturbance site recovery. Rill simulations were conducted on 2 m by 9 m plots. In each simulation, water was released at the top of the plot at flow rates of 7, 15, 22, 30 and 48 L/min for 12 minutes at each rate. Flow velocity, flow width, and flow depth were measured at each flow rate. Six samples of runoff and suspended sediment were collected at the base of the plot throughout the 12-min run and processed in the laboratory to determine runoff rates, sediment concentrations, total sediment yields, and rill erodibility (response variables). The measured site characteristics (covariates) included soil water repellency, bulk density, surface particle-size distribution, and ground cover.

Sediment fence plots included the replicates, treatments and erosion mitigation described in Table 1. Unit-area sediment yields were measured with sediment fences installed in swales or zero-order catchments with drainage areas of approximately 0.1 to 0.5 ha. The fences ponded the surface runoff and allowed the sediment to settle out; multiple fences were installed as needed to increase sediment storage capacity and catch efficiency. To the extent possible, the fences were emptied on a storm-by-storm basis. The sediment removed from the fence was sub-sampled, dried, and weighed to convert the wet field weights to dry mass. The site characteristics (covariates) measured on each plot included contributing area, percent area disturbed, slope, aspect, soil water repellency at 2.5-cm depth intervals, surface cover, rill density (where a rill is defined as a concentrated flow path at least 5 cm deep), and surface soil texture. Logging slash cover was assessed when surface cover was measured. The effectiveness of each water bar was assessed by measuring the length and cross-sectional area of any rills. The site data were used to ensure that treated and control areas were comparable and to quantify the roles of the various factors that may affect sediment production rates. Two logging operations and erosion mitigation are described in Table 1.

Two small watershed pairs (3 ha each) were established to directly compare logged and unlogged watersheds subject to natural rainfall. In each of these watersheds a metal headwall was installed to form a sediment trap and direct runoff through a 90 degree V-notch weir. This allowed both runoff and sediment yield to be measured. The runoff and sediment yields were related to specific rain events by installing a weather station at each site to monitor precipitation and temperature. Wind speed and direction, relative humidity and solar radiation measurements provide a record of the weather conditions before, during, and after each storm event. As in the case of the sediment fences, the sediment traps were cleaned (sediment is removed, weighed, and sub-sampled) on a storm-by-storm basis to the extent possible. Sediment samples were taken to determine the moisture content, organic matter content, and particle-size distribution. The moisture content and percent organic matter were needed to determine the mass of dry sediment. Site characteristics (covariates) were measured as in the hillslope-scale sites described above.

Statistical Analysis

For comparing treatment effects, we used GLIMMIX (General Linear Mixed Model in SAS, SAS Institute, 1999). For water repellency, infiltration, soil strength, and sediment yield, we used replicate nested within plot type as a random variable, and a repeated measures structure with replicate within plot type as the subject, to test for effects of year (Littel et al., 2006). For sediment, we calculated the days since the fire, and used a power function of that variable as a covariate in the repeated measures structure. In order to find the best suites of explanatory covariates (e.g. slope, precipitation, percent cover) we used step-wise multiple regression. For sediment and infiltration, lognormal distributions were specified; for other dependent variables, Gaussian distributions were used. Pair-wise comparisons using least-square means (LSMeans) were used to compare treatment effects between plot types, and means and standard deviations were calculated for each year and plot type, for graph plotting.

At the Tripod and Hayman, the start of logging was delayed thus we treated the pre-logging and post-logging periods and two treatments, using the PROC MIXED procedure (SAS Institute 1999). The model was $\log(\text{sediment yield}) = f(\text{treatment})$, with maximum 10-min rainfall intensity (max I_{10}) and years since burning as covariates, and a repeated measurements structure with plot, and the type of covariance structure as “spatial” with a power function based on the number of days from burning to date of the maximum I_{10} in the clean-out period.

For the rill experiment, generalized linear mixed statistical models (Schabenberger, 2005) were developed for each site using the treatments, slope classes, and post-fire years as fixed effects, while the replicate was a random effect. Dependent variables were runoff rate (total runoff minus the suspended sediment), sediment flux rate, and runoff velocity. The runoff and sediment flux rates approached a steady state condition by the fourth sample in each experimental flow rate, so only samples 4-6 were used to compare treatments (Robichaud et al., 2010). The runoff rates, sediment flux rates, and runoff velocities showed some heteroscedasticity, so square-root (runoff rate and runoff velocity) or fourth-root (sediment flux rate) transformations were used to make the data more homoscedastic. A repeated measures structure was applied to each plot in the statistical model, and the year of the measurement was used as the period of repetition. Least-squares means with a Tukey-Kramer adjustment were used to test the significance of multiple comparisons among treatments and years (Ott, 1993). The significance level was 0.05 for all statistical tests.

IV. Key Findings

1) Objective: Directly measure the impacts of specific post-fire salvage logging practices on runoff and erosion on the watershed scale.

- At the Red Eagle site, sediment production in the first year after salvage logging was lower from the control and logged swales, with the control swales averaging just over 0.01 Mg ha^{-1} and the logged swales averaging just under 0.01 Mg ha^{-1} due to low rainfall amounts and intensities. However, in the second year sediment production from the logged swales averaged 0.1 Mg ha^{-1} in 2009, more than an order of magnitude greater than in 2008 ($p < 0.01$). In contrast, sediment production from the control swales in 2009 was only 0.003 Mg ha^{-1} , 25% of the value from 2008, and the 34-fold difference in sediment production between the logged and the control swales was highly significant ($p < 0.001$). Statistically the amount and intensity of rainfall had a surprisingly small effect on sediment production in this study. This is probably due in part to the higher rainfall intensities in 2009 relative to 2008, which increased sediment production on the disturbed plots while sediment production decreased on the control plots in the second year in part due to greater regrowth. This indicates that an increase in ground cover can compensate for higher rainfall intensities.
- At the Red Eagle site, sediment production from the swales and plots was significantly ($p \leq 0.05$) and positively correlated with percent bare soil, percent non-repellent soil, and

bulk density and percent slope. Sediment production was negatively correlated with percent litter plus vegetation and percent moderate plus severe water repellency. The strongest rainfall variable was the maximum 10-minute intensity, but this was only significant at $p=0.10$.

- The comparison of pre-logging and post-logging sediment yields at Hayman Fire did not show a significant effect of logging on sediment yield during the 7 years of post-logging measurements; however this site had the largest sediment yields by 2 orders of magnitude larger than any of the other sites in this study. These high sediment yields were attributed to the highly erosive granitic soils, slow vegetation recovery (semi-arid climate), combined with sporadic high intensity convection events. At Kraft Springs, only one rainstorm produced measurable sediment on both the logged and control swales. For this storm the control swale produced about 10 times as much sediment per unit area as the logged swale. Part of this difference can be attributed to a slightly higher slope, and slightly higher 10-minute intensity, and the diversion of runoff and sediment away from measurement sediment traps by a skidder trail at the logged swale.
- The low level of demonstrable increases in sediment production at the swale and small watershed scale may be attributed to:
 - the lack of high intensity rainfall events in the post-logging period at some of these sites
 - the trapping and storage of sediment in shallow depressions (microsites) before it reached the sediment traps
 - the high background sediment yields that resulted from severe wildfire
 - the difficulties of coordinating a research project with a salvage logging project, since salvage is often delayed (months to years) due to litigation and administrative delays, which created problems of timing and lack of logging on some plots designated for treatment.

2) Objective: Directly measure the impacts of specific post-fire salvage logging practices, both with and without erosion mitigation treatments, on runoff and erosion on the hillslope scale.

- At the plot scale, salvage logging reduces litter and vegetation ground cover in the machine tracks and on skid trails. The recovery of ground cover, especially vegetation, on skid trails may lag behind unlogged controls by up to three years.
- Skidding of logs breaks up the water repellent layer, which may have the effect of increasing infiltration locally.
- Skidding of logs increased soil strength and bulk density (soil compaction), especially at the surface (0 to 5 cm). The impact was consistent over the time of the study.
- Changes in water repellency, soil compaction, ground cover and sediment production were less on feller-buncher tracks (one or two passes over the same area) as compared to skid trails where machines and dragged logs made several passes over the same route.

- At the Red Eagle Fire during the first year, the control plots had a mean sediment production of only 0.11 Mg ha⁻¹, while the mean sediment production for the skid trail plots was 0.28 Mg ha⁻¹. Mean sediment production from the feller-buncher plots was intermediate at 0.19 Mg ha⁻¹. With the high variability within each group, there were no significant differences among the three groups.
- Whereas after the second year at Red Eagle Fire, the mean sediment production from the skid trail plots was 8.3 Mg ha⁻¹, and this was more than three orders of magnitude higher than the mean sediment yield from the control plots of 0.006 Mg ha⁻¹. Both the year-to-year increase for the skid trail plots and the difference from the controls were highly significant (p<0.001). Sediment production from the feller-buncher plots was again intermediate at 0.3 Mg ha⁻¹. This was only 4% of the value from the skid trails but 55 times the mean value from the controls (p< 0.02).
- The sediment production data from the Tripod site confirmed the general trends from the Red Eagle site, but it also showed that the application of logging slash decreased sediment production relative to the untreated skid trails. In 2009 the untreated skid trails produced 0.7 Mg ha⁻¹, which was about 5 times the values from the skid trails treated with logging slash and 16 times the yield from the unlogged control plots. The feller-buncher trails produced only two-thirds as much sediment as the treated skid trails, confirming that more passes by logging machinery traffic can increase sediment yields.
- Logging may increase sediment production by 1-2 orders of magnitude at both the plot and swale scale compared to the controls. Sediment yield was positively related to maximum 10-min rainfall intensity, bare soil, slope and negatively correlated to vegetative cover. An apparent negative relationship between sediment yield and water repellency is probably due to heavy equipment decreasing water repellency but increasing sediment yield.
- The treatment of skid trails with lopped and scattered slash had no measurable effect on any of the soil hydrologic properties (infiltration and water repellency) that were measured at the Red Eagle site. Analysis of the cover data showed that the slash-treated skid plots had more woody debris than the untreated plots, but the difference in cover was not enough to impact differences in sediment yield. The multiple regression analysis, however, supports the well-established notion that vegetation and fine litter reduces surface erosion. The scattered slash with poor and irregular ground contact affected its performance. However, slash treatment of skid trails was effective in reducing sediment yield at the Tripod site. The untreated skid trails produced 0.7 Mg ha⁻¹, and this was about 5 times the sediment production from the treated skid trails and 16 times the yield from the unlogged control plots.
- Assessment of the water bars on skid trails indicated a failure rate of 19% at Red Eagle, 14% at Hayman, and 33% at Tripod. Water bar data revealed that water bars perpendicular to a skid trail are more likely to fail (overtop) than those crossing the skid trail at 45 degrees which divert the flow off the skid trail. Slash treatment of skid trails

improved water bar effectiveness at all three sites.

- Although post-fire salvage logging affects soil hydrologic properties at the plot scale, the effects were not consistent across years and study areas at the scale of swales (0.5-3 ha).

3) Objective: Directly measure the impacts of specific post-fire salvage logging practices, both with and without erosion mitigation treatments on rill erodibility.

- Ground-based logging operations remove virtually all live vegetation in the skidder, feller-buncher and forwarder trails. This set back vegetative recovery in the logged plots by at least 2-3years.
- The runoff and sediment flux rates were greater in all of the plots disturbed by post-fire salvage logging equipment as compared to the unlogged, burned control plots.
- Despite the reducing effects of ground cover on runoff rate and sediment flux, the addition of slash by hand to half of the skid trail plots in the Red Eagle site did not reduce the runoff or sediment flux in these plots. The results may have been different had the slash been applied during the logging process increasing surface roughness and ground contact.
- The number of passes (few or many) of the forwarder in the School site did not have an effect on the runoff rates or sediment flux rates, and both levels of forwarder traffic produced runoff and sediment flux rates that were greater than the controls. From these results and the lack of difference in runoff rate and sediment flux rate between the rubber-tired skidder, tracked skidder and feller-buncher at the Red Eagle site, we conclude that the passage of any equipment on the burned hillslopes compacted the soil, removed protective ground cover, delayed vegetative regrowth, and increased runoff and sediment flux rates.

4) Objective: Develop specific results for several key eco-regions and develop regional BMP guidelines.

- Use logging systems and machinery that minimize the percent area disturbed and percent bare soil. Efforts to break up or physically disturb soil water repellency should not be used, as the necessary depth of disturbance, increase in surface erodibility, and greater propensity for soil sealing will all result in a greater negative effect than any possible benefit from reducing the soil water repellency by physical disturbance.
- Maximize ground cover by lopping and scattering logging slash on site; do not skid the whole tree to the landing. Efforts to crush the slash with heavy machinery in order to increase ground contact generally should be avoided, as the benefit of increasing ground contact is likely to be counterbalanced by potential longer-term adverse effects of disturbing the natural regeneration, compaction, and increasing the amount of exposed mineral soil.
- Minimize the compacted area and the potential to compact soils. If ground-based machinery is used, operations should be conducted when the soils are as dry as possible

to minimize the potential for compaction, and the machines should disperse their weight over as large an area as possible (e.g., use tracks or wide, low pressure tires).

- All compacted areas (i.e. log landings) generally should be treated by ripping and mulching to prevent them from generating overland flow and surface erosion, and maximizing their infiltration rate. Since the ripping will increase the soil erodibility and susceptibility to soil sealing, this must be immediately followed by mulching with straw or other materials to provide at least 65% soil cover. Ripping without mulching may be counterproductive, at least in the short term, while mulching without ripping is not likely to be effective as the mulch is likely to be washed away by the overland flow. This combination of treatments is particularly important in areas burned at high severity, as these have the greatest potential for generating overland flow that can then be intercepted and concentrated by skid trails, feller-buncher trails, and cable draglines.
- Any linear feature created by logging operations, such as skid trails and cable rows, should be oriented across slope to the maximum extent possible, and laid out to prevent any convergence in the downslope direction. Waterbars must be installed to minimize the accumulation of overland flow and disperse the water onto downslope areas. These waterbars need to be both more frequent and larger than normal to account for the greater amounts of overland flow and the greatly reduced capacity of downslope areas to infiltrate overland flow and trap sediment. They should be installed diagonally to the skid trail to ensure that there is minimal risk at accumulating water and overtopping.
- The optimal timing of salvage logging will depend in part on the logging methods to be used and the site characteristics. Salvage logging increases the amount of bare soil, therefore salvage logging in the first few months after burning will result in a smaller absolute increase in the amount of bare soil as compared to salvage logging in subsequent years. However, the first year is when a site is most likely to generate large amounts of surface runoff, so salvage logging in the first year after burning should have as little impact as possible (e.g., skyline, over-the-snow, or helicopter logging) whereas in subsequent years salvage logging will cause more disturbance to the initial regrowth and any protective litter layer, and thereby result in a larger absolute increase in the amount of exposed mineral soil.
- Skid trails and landings should be laid out prior to the sale in a location that minimizes the delivery of surface runoff and sediment to the nearest stream channel, especially in areas burned at high and moderate severity. To the extent possible, harvest units should be located upslope of unburned areas or areas burned at lower severity.
- Riparian management and buffer zones should be at least as large as for green sales, as there is an even greater potential for upslope surface runoff and erosion. Even if the riparian area is itself burned, any additional disturbance to the buffer zone has the potential to increase surface runoff and sediment delivery to the stream.

5) Objective: Collect field data from salvage operations to eventually be used in developing

an erosion prediction tool for salvage logging that will tie in to our other web-based erosion prediction tools.

- Rill erodibility and soil shear stress, two parameters related to how easily the soil is detached were measured at three sites: Red Eagle, School, and Terrace Mountain.
- The rill erodibility parameter, K_r , varied from 3.2×10^{-7} to $2.0 \times 10^{-5} \text{ s m}^{-1}$ in control plots in the first post-fire year. In the year of the logging, the K_r values in the feller-buncher ($2.6 \times 10^{-4} \text{ s m}^{-1}$) and skid trail plots (1.9×10^{-5} to $6.2 \times 10^{-4} \text{ s m}^{-1}$) were an order of magnitude greater than the values in their respective controls. The K_r parameters in the year of logging were always one to two orders of magnitude greater regardless of the logging traffic amounts or type of equipment used than the corresponding controls indicating the soil was more easily detached when it had been disturbed by logging operations.
- The rill erodibility parameter, K_r , generally decreased with respect to time at 7 of the 10 site/treatment combinations due to consolidation of the soil and increased cover effects, while 2 of the site/treatment combinations had an increase or no consistent trend in K_r .
- The calculated shear stress, τ_c ranged from 2.3 to 22.5 Pa and it was not possible to calculate in 20 of the 28 possible combinations, and there was no trend with disturbance, thus indicating the highly variable site conditions. The τ_c values also showed no consistent trend over time.
- Modeling the effects of post-fire salvage logging will require dividing the total hillslope area into classes--the burned only portion and the portion that is affected by burning and logging equipment traffic. The further division of the logging traffic into types of equipment and number of passes is less than expected because the K_r values, despite a wide range, were similar. The number of designated hillslope areas can probably be reduced to three: burned but no logging traffic; feller-buncher traffic only; and skidder or forwarder traffic. The relevant K_r and τ_c values, along with interrill erodibility, and infiltration/runoff parameters such as hydraulic conductivity could then be applied to each hillslope fraction.
- We added a component to this project when some remote sensing imagery became available. We analyzed this imagery (1-m NAIP -National Agriculture Imagery Program or Quickbird imagery) at two sites, Red Eagle and School to determine the aerial extent of bare soil exposed and ground disturbance from the salvage logging.
- Imagery analysis at the Red Eagle site indicates 29 % of the area (8 ha) within 15-m of any equipment trail was classified as having no disturbance due to the salvage operation, 44% (12 ha) was classified as low disturbance and 27 % (7 ha) was classified as highly disturbed by the logging operations. These areas were likely exposed, disturbed soil immediately after the logging operation. The sum of this area is nearly three-quarters of the area closest to where the logging equipment operated; therefore, it can be reasonably assumed that most of the rest of the surrounding area is also undisturbed or lightly

disturbed, with the likely exception of roads going to and from the area.

- A chance detection approach using pre-and post-salvage logged QuickBird imagery at the School Fire site indicates that one year after the fire, there was an average of 40-45% exposed soil on all units, regardless if they were eventually logged or not. In 2009, there was an average of 71% exposed soil on the logged units, and only 47% on the unlogged units ($p < 0.05$). When burn severity was taken into account, we observed a greater percent change in soil exposure on the high severity logged sites than on the low severity logged sites. In 2009 after salvage logging, low severity logged units averaged ~60% exposed soil (a 50% increase), whereas the high severity logged units averaged ~80% exposed soil (nearly a 100% increase) ($p < 0.05$). Thus both of these imageries were able to detect the ground disturbance by salvage logging.

V. Management Implications

- At the plot scale, salvage logging reduces cover by litter and vegetative cover, and on skid trails recovery of such vegetation recovery and subsequent ground cover may lag behind unlogged controls by three years or more.
- Skidding of logs breaks up the post-fire water repellent layer, which may have the effect of locally increasing infiltration. But skidding of logs also increases soil strength and bulk density (soil compaction), especially in the surface 5 cm, and this may locally decrease infiltration to a greater extent than the reduced water repellency. The impact on soil bulk density is relatively persistent over time, compared to the impact of equipment operation on water repellency.
- Infiltration rates following fire and post-fire salvage logging increased over time. The infiltration rate was inversely related to water repellency and soil strength, and directly related to ground cover plus vegetative cover. Local site differences as well as the countervailing influences of reduced water repellency and increased bulk density may explain the lack of strong effects of log skidding on infiltration rate.
- Post-fire salvage logging may increase sediment production at both the plot and swale scales by 1-2 orders of magnitude, as compared to burned-only controls, although the results were not consistent across years and study areas at the swale scale. Sediment production in general is positively related to maximum 10-min rainfall intensity, percent bare soil, slope and negatively correlated with vegetative cover.
- The effects of logging by forwarder, feller-buncher without skidding, few pass skid traffic on water repellency, soil compaction, and sediment production are not as great as log skidding that often requires multiple trips along the same route.

- Hand application of slash treatment of skid trails was effective in reducing sediment yield at some sites but not others. The differences may be related to intrinsic site variables such as soil erodibility. Other research results have clearly shown the benefits of ground cover. However the presence of slash on skid trails improved water bar effectiveness.
- The success of water bars on skid trails is related to the angle of the bar across the trail. Angled water bars providing drainage were more effective than water bars that were perpendicular to the trail but were frequently unable to store the accumulated runoff

VI. Relationship to other findings and ongoing work on this topic

This JFSP project has very strong support and interest from local and regional Forest Service managers, timber companies, and Native American Tribes throughout the United States and Canada. Many National Forests, timber companies and Native American Tribes provided financial and logistical support to help expand this project.

- Alternative wood shred mulch products made from fire killed trees for post-fire erosion control are being evaluated in pilot phase studies. This includes simulated rainfall in a laboratory setting, hillslope plots and small paired watersheds of wood shred mulch areas and controls. This work is funded under JFSP # 07-1-1-01.
- Post-fire road treatments are often prescribed after fires. The fire does not affect the road itself but the increased runoff and sediment from the burn area can impact the road infrastructure. We have completed a current, yet limited, knowledge assessment of road treatments in an easy to use GTR reference (Fotlz et al., 2009) funded by JFSP # 06-3-4-03. Since this publication became available, three fires have been selected to monitor road improvement treatments with short-term funding (3 years) by regional funds.
- Improvement to the watershed scale modeling for fuel and fire effects and the subsequent impacts on fisheries habitat are be developed using various WEPP model interfaces that we have developed including the ERMiT interface . The project PI is G. Reeves under JFSP # 09-1-08-26 in collaboration with W. Elliot.
- Several study sites are still producing sediment 5 to 8 year post-fire. For example, the Hayman Fire and the Cedar Fire study sites continue to have significant runoff and erosion events. Various Forest Service Regional offices have helped to funds to some of continue monitoring these sites.

VII. Future work needed

- Additional knowledge on the longer term effects of post-fire logging techniques and erosion mitigation treatments on erosion (such as water bars and slash distribution) is needed. These studies should be 7 to 10 years post-fire to compare with longer term recovery measured on burned but not logged areas.

- As new logging practices are developed, salvage logging becomes increasingly more diverse. There are many aspects of post-fire logging that need to be studied. This project only addressed ground-based logging systems after high burn severity fires.
- The parameters measured in these studies need to be incorporated into an erosion prediction tool for salvage logging that will tie into other web-based forest disturbance erosion prediction tools.
- A study is needed to incorporate remote sensing imagery to better determine the aerial extent of various types of salvage logging operations on bare soil exposure and ground disturbance.
- It would be useful to study salvage logging effects in various regions: different rainfall regimes and soil types (silt soils vs sandy soils), harvesting methods (ground-based, cable logging with drag lines, skyline systems, and helicopter logging), different burn severities (e.g., is it better to salvage in low or moderate burn severity sites rather than high burn severity sites?), and timing (e.g., salvage log immediately after the fire or wait until the area has stabilized, 1-2 years later).

VIII. Deliverables

The information gained from this study has been integrated into publications, presentations, and training activities. The dissemination of newly obtained results and data comes through the publication of peer-reviewed journals and presentations to post-fire assessment teams and land managers at workshops and conferences. All proposed products are complete, unless stated otherwise as *in review* at the end of the citation.

Proposed	Delivered/status
Annual progress reports and final report	<ul style="list-style-type: none"> • Progress reports were completed for 2008, 2009. • Final Report was completed in 2011.
Data Collection Collect data at salvage sites throughout the western US.	<ul style="list-style-type: none"> • We have actively and continuously collected sediment yield data, rainfall characteristics and ground cover for five post-fire and post-salvage sites (Red Eagle, Tripod, School, Kraft Springs and Hayman) through October 2010. That data are included in these analyses. • We have performed rill experiments on three salvage logging sites, two in the US (Red Eagle, School) and one in British Columbia, Canada (Terrance Mountain), collecting runoff and sediment yield, rainfall characteristics, water repellency, and ground cover data. Data from these rill experiments are included in these analyses.
National and Regional Meetings 1. We proposed to	2007: <ul style="list-style-type: none"> • Robichaud, P.R. (2007) Postfire erosion mitigation: tools, treatment and effectiveness: The Hayman fire: 5 years later. Sustaining Colorado's

conduct workshops at national and regional BAER meetings for Forest Service and Dept. of Interior agencies on post-fire treatment effectiveness. These presentations included salvage logging results, as appropriate and available.

Watersheds Conference: Making the Water Quality Connections by Colorado Water Protection Project, Breckenridge, CO. October 2007.

- Elliot, W. J., P. R. Robichaud, S. Lewis and C. Busskohl. (2007) Erosion following wildfire: Prediction, mitigation and monitoring. Presented at the Fall Meeting of the Inland Empire Chapter of the Soil and Water Conservation Soc of America. 19 October, Dayton, WA.
- Elliot, B. and P. R. Robichaud. (2007) ERMiT: Introduction, summary, development (and a bit of GeoWEPP). Presented at the Workshop on Adopting ICWater for Postfire Sediment Transport. 2 October, 2007, Missoula, MT
- Robichaud, P.R. (2007) Postfire erosion mitigation: tools, treatments and effectiveness. Treated and Endangered Species: Plants, Invasive Plants, Native Plants and Range Program Managers Meeting, US Forest Service Region 6, Bonneville, OR. November 2007.

2008:

- Elliot, W. J., P. Robichaud and D. Hall. (2008) Erosion risk management tool (ERMiT) – A probability-based postfire erosion prediction model. Presented at Fire in the Southwest: Integrating fire into management of changing ecosystems. 28-31 January, Tucson, AZ.
- Robichaud, P.R. (2008) Latest Findings on Effectiveness of Various Postfire Rehabilitation Treatments and Salvage Logging. Technical Fire Management – Fire Effects Module, Bothel, WA. May 2008.
- Robichaud, P.R. (2008) BAER Treatment Effectiveness. Region 1, 4 and 6 BAER Team Leader Training, Spokane, WA, Sept 2008.
- Robichaud, P.R. (2008) New Tools for Post-fire Assessment. Region 1, 4 and 6 BAER Team Leader Training, Spokane, WA, Sept 2008.
- Robichaud, P.R. (2008) Update on BAER treatment effectiveness and salvage logging effects. US Forest Service Region 1, 4 and 6 BAER Team Leader Training, Spokane, WA. 18 September 2008.
- Robichaud, P.R. (2008) Update on New Tools and Treatment Effectiveness. Forest Service National BAER Coordinator’s Annual Meeting, Denver, CO. May 2008
- Robichaud, P.R., Lewis, S., Lentile, L., Morgan, P. (2008) Vegetation response to post-fire treatments. Fire in the Southwest – Integrating Fire into Management of Changing Ecosystems, Association for Fire

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2009:

- Robichaud, P.R. (2009) Update on New Tools and Treatment Effectiveness. Forest Service National BAER Coordinator's Annual Meeting, Orlando, FL. January 2009.
- Elliot, B., P. Robichaud, F. Pierson and C. Moffet. (2009) New technologies for modeling fire and disturbed conditions in forests and rangelands. Presented at the Symposium: Rangeland Hydrology and Erosion Technology Advancements as part of the Annual Meeting of the Society of Range Management. 10 February, Albuquerque, NM.
- Robichaud, P.R. (2009) Latest Findings on Effectiveness of Various Post-fire Rehabilitation Treatments. Presented at USFS Region 2 BAER Assessment Team Training, Denver, Colorado. 19 May 2009.
- Robichaud, P.R. (2009) Latest Findings on Effectiveness of Various Postfire Rehabilitation Treatments and Salvage Logging. Technical Fire Management – Fire Effects Module, Bothel, WA. 14 May 2009.
- Dobre, M., W.J. Elliot, S. Miller and G. Bitelli. (2009) Spatial distribution of fire effects in forest using GIS tools. Proceedings of the IUFRO Workshop forestry utilization in Mediterranean countries with particular respect to sloping areas. Annual International Conference of the Commission Internationale de l'Organisation Scientifique du Travail en Agriculture. 17-19 June, Reggio Calabria, Italy. 2185-2189
- Lewis, S., Robichaud, P.R., Morgan, P., Hudak, A., Lentile, L. (2009) Assessing soil and vegetation recovery following the 2005 School Fire – 4 years post-fire. School Fire area, Pomeroy Ranger District, Umatilla National Forest, Pomeroy, WA. June and July 2009.
- Robichaud, P.R. (2009) New Tools and Treatment Effectiveness. Forest Service Region 5 Soils Meeting, Redding, CA. October 2009
- Robichaud, P.R. (2009) Advances in Treatment Effectiveness presented for Graduate Level Fire Ecology course, University of Idaho, Moscow, Idaho. 20 Nov 2009.

2010:

- Robichaud, P.R. (2010) Update on New Tools and Treatment Effectiveness. Forest Service National BAER Coordinator's Annual Meeting, Albuquerque, NM. January 2010.
- Robichaud, P.R. (2010) New Tools and Treatment Effectiveness. Forest Service Region 4 BAER Training Meeting, Ogden, UT. April 2010.
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- Elliot, W.J., P.R. Robichaud and R.B. Foltz. (2010) Monitoring for Modeling. Poster presented at the Seventh National Modeling Conference. April 25-29, Denver, CO.
- Robichaud, P.R. (2010) New Tools and Treatment Effectiveness. Forest Service Region 6 Watershed and Soils Training Meeting, Vancouver, WA. May 2010.
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- MacDonald, L.H. (2010) Effects of different post-fire treatments on watershed functions. Pre- and Post-fire Wildfire Conference, University of California Extension, Sacramento, CA, 9-11 March.
- MacDonald, L.H. (2010) Effects of fires on soils, runoff, and erosion: processes and rehabilitation. Training course in Post-fire Forest Management in Southern Europe, Valencia, Spain, 13-16 April.
- Elliot, W.J., R.B. Foltz and I.S. Miller. (2010) Sources of Sediment in Forested Watersheds in the Clearwater and Lower Snake River Basins. Presented at the Snake River Local Sediment Management Group Summer 2010 Workshop. 12 August, 2010, Clarkston, WA.

2011:

- Robichaud, P.R., Lewis, S., Morgan, P., Droske, C. (2011) Vegetation Response to Fire, Rehabilitation Treatments and Salvage Logging. Umatilla National Forest Leadership Team, Pendleton, OR. 23 February 2011.

Refereed Publications

1. Effects and Mitigation of Post-fire Salvage Logging on Physical Soil Properties and Sediment Production
 - Submitting to *Forest Ecology and Management*
2. Rill erosion in burned and logged forests.
 - Submitting to *Journal of Hydrology*
3. Best Management Practices for Post-fire Salvage Logging
 - Submitting to Forest Service Research as a *General Technical Report* to be used as a desk reference for post-fire management.

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