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Rill erosion in burned and salvage logged western montane forests: Effects of logging equipment type, traffic level, and slash treatment

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ABSTRACT

Following wildfires, forest managers often consider salvage logging burned trees to recover monetary value of timber, reduce fuel loads, or to meet other objectives. Relatively little is known about the cumulative hydrologic effects of wildfire and subsequent timber harvest using logging equipment. We used controlled rill experiments in logged and unlogged (control) forests burned at high severity in northern Montana, eastern Washington, and southern British Columbia to quantify rill overland flow and sediment production rates (fluxes) after ground-based salvage logging. We tested different types of logging equipment—feller-bunchers, tracked and wheeled skidders, and wheeled forwarders—as well as traffic levels and the addition of slash to skid trails as a best management practice. Rill experiments were done at each location in the first year after the fire and repeated in subsequent years. Logging was completed in the first or second post-fire year. We found that ground-based logging using heavy equipment compacted soil, reduced soil water repellency, and reduced vegetation cover. Vegetation recovery rates were slower in most logged areas than the controls. Runoff rates were higher in the skidder and forwarder plots than their respective controls in the Montana and Washington sites in the year that logging occurred, and the difference in runoff between the skidder and control plots at the British Columbia site was nearly significant ($p = 0.089$). Most of the significant increases in runoff in the logged plots persisted for subsequent years. The type of skidder, the addition of slash, and the amount of forwarder traffic did not significantly affect the runoff rates. Across the three sites, rill sediment fluxes were 5–1900% greater in logged plots than the controls in the year of logging, and the increases were significant for all logging treatments except the low use forwarder trails. There was no difference in the first-year sediment fluxes between the feller-buncher and tracked skidder plots, but the feller-buncher fluxes were lower than the values from the wheeled skidder plots. Manually adding slash after logging did not affect sediment flux rates. There were no significant changes in the control sediment fluxes over time, and none of the logging equipment impacted plots produced greater sediment fluxes than the controls in the second or third year after logging. Our results indicate that salvage logging increases the risk of sedimentation regardless of equipment type and amount of traffic, and that specific best management practices are needed to mitigate the hydrologic impacts of post-fire salvage logging.

1. Introduction

Following wildfires, land managers often consider salvage logging burned trees to recover the monetary value of the timber and to meet other objectives (Peterson et al., 2009). Although the effects of both wildfire and logging have been studied, there is relatively little known of the cumulative impacts of these forest disturbances on forest hydrologic and geomorphologic processes. Recently, research has been more focused on post-fire logging effects on the biotic components of the ecosystem, such as habitat loss, altered community composition or forest structure, delayed vegetation recovery, and increased colonization of non-native species (Beschta et al., 2004; D'Amato et al., 2011; Karr et al., 2004; Lindenmayer and Noss, 2006; McIver and Starr, 2000), than on the impacts to runoff, peak flows, erosion, and sedimentation.

The assessment of post-fire logging is particularly complex, as there are several logging techniques and the effects of a given technique may vary by equipment operator, time since fire, post-fire and/or post-logging weather, and other site conditions (Chase, 2006). Some studies have reported little or no difference in the sediment loss from comparable burned areas and burned and logged

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areas (Fernández et al., 2007; Marques and Mora, 1998; Marston and Haire, 1990; Spanos et al., 2005; Stabenow et al., 2006). Smith et al. (2011) compared the sediment exported from two adjacent burned eucalypt catchments and one pine catchment that was subsequently logged. The sediment exported from the logged pine catchment was 1–2 orders of magnitude greater than the sediment exported from the unlogged eucalypt catchments. However, given that the pine catchment was burned at higher severity than either of the eucalypt catchments, the differences in exported sediment cannot be solely attributed to the logging operation. As part of the Southern Rockies Watershed Project, total suspended sediment concentrations from five watersheds burned at high severity were compared (Silins et al., 2009). Two of the five watersheds were logged one year after the fire; during a very wet second post-fire year, the mean concentrations were greater from the burned and logged watersheds than from the burned only watersheds. During later, drier years, there were no significant differences in mean concentration, yet turbidity from the salvage logged watersheds remained higher than unlogged controls for four years after the fire (Emelko et al., 2011). A study in southwest Oregon found higher sediment production rates in salvage logged areas compared to unlogged burned areas, but other management activities or site differences may have affected the results (Slesak et al., 2015). In another study in the interior western US, sediment production from burned and logged hillslope plots were up to two orders of magnitude larger than the sediment production from burned controls (Wagenbrenner et al., 2015).

Rill formation and extension are dominant erosion processes on steep hillslopes with exposed mineral soil, especially in burned areas where decreases in soil organic matter, litter and vegetation cover led to highly erodible bare soil (Moody and Kinner, 2006; Robichaud et al., 2010; Shakesby et al., 2007). A study in the Colorado Front Range found that 60–80% of the post-fire erosion at the hillslope scale was associated with rill erosion (Pietraszek, 2006). In one study in the Sierra Nevada in California, rill formation was directly related to the amount of bare soil and rills were observed in burned plots with >60% bare soil (Berg and Azuma, 2010). In several other studies bare soil has been indicated as a significant controlling factor in post-fire sediment yields (e.g., Inbar et al., 1998; Benavides-Solorio and MacDonald, 2005; Larsen et al., 2009).

Studies of logging effects in unburned areas have reported that log skidding over bare ground can cause severe soil disturbance over more than a third of the logged area (Klock, 1975; Page-Dumroese et al., 2006; Steinbrenner and Gessel, 1955) and erosion can be from 5 to 100 times greater on skid trails as compared to undisturbed areas (Croke et al., 2001, 1999; MacDonald et al., 2004; Robichaud et al., 1993). Increased pressure from logging equipment was measured at depths of 20 cm in experiments in Germany (Horn et al., 2004). The impacts of disturbance by logging equipment such as compaction, rutting, and loss of macropores, can affect coarse soils for decades after logging operations (Cambi et al., 2015). A runoff modeling exercise showed that the log drag lines act as an extension to the drainage network, thereby increasing the potential of hillslopes to be hydrologically connected to the stream network (Smith et al., 2011). Reduced infiltration and the somewhat linear shape of skid trails suggest erosion from bare skid trails is likely to be dominated by rilling.

Simulated rill experiments have been used in laboratory and field experiments to compare different soil conditions and to develop the rill erodibility parameters needed to model erosion rates (Bryan, 2000; Elliot et al., 1989; Govers et al., 2007; Knapen et al., 2007; Merz and Bryan, 1993; Wirtz et al., 2012). Similarly, rill experiments on burned soils have helped improve our understanding and ability to model post-fire erosion rates (Al-Hamdan et al., 2012; Pierson et al., 2009; Robichaud et al., 2010; Wagenbrenner et al., 2010) and show that the amount and type of soil cover can affect erosion rates (Foltz and Wagenbrenner, 2010; Pannkuk and Robichaud, 2003; Robichaud et al., 2013). Simulated rill experiments have also shown that initial rill erosion rates are much greater than steady state erosion rates that occur just a few minutes into the simulations (Foltz et al., 2008; Pierson et al., 2008; Robichaud et al., 2010). Rill experiments in burned areas conducted over multiple years suggest that the pattern of high initial erosion rates followed quickly by lower steady state erosion rates is repeated, but the overall rill erosion rates decrease over the time scale of years (Pierson et al., 2008; Sheridan et al., 2007).

Previous studies have related the effects of bare soil, water repellency, time since burning, and soil compaction to increases in runoff and/or sediment yield in burned and logged areas (Chase, 2006; Slesak et al., 2015; Wagenbrenner et al., 2015), although post-fire logging does not always result in significant increases in sediment yields (Fernández et al., 2007; McIver and McNeil, 2006; Silins et al., 2009). Our objective was to determine the effects of different ground-based equipment and operational practices used in post-fire salvage logging on soil properties, runoff, and rill erosion rates. We used simulated rill experiments following earlier research methods (Robichaud et al., 2010) at three burned sites for two years after logging to determine if different site conditions, logging equipment, traffic levels, or the addition of wood slash resulted in: (1) differences in soil bulk density, soil water repellency, surface cover, or vegetation; and (2) changes in runoff rates, runoff velocities, or sediment flux rates during the first two–three years after logging.

2. Methods

2.1. Site descriptions and experimental design

We used simulated rill experiments to compare areas recently burned at high severity (controls) to areas that were recently burned at high severity and salvage logged using ground-based logging equipment. Three high-severity burned areas classified according to burned area reflectance (White et al., 1996) or field assessments (Parsons et al., 2010) in forested mountainous areas were selected for rill experiments. All sites had coarse soils (Table 1), elevations between 1100 and 1800 m, annual precipitation between 545 and 1221 mm and pre-fire forests of firs and pines (Table 1). Hillslope gradients at the study sites were between 11 and 46%. Differences in logging equipment and practices among the three sites allowed us to compare some of the effects of these operations (Table 2).

The 2006 Red Eagle Fire burned 14,000 ha in northern Montana (Fig. 1). Sandy loam soil derived from argillite and mean annual precipitation of 1221 mm (1979–2009) supported a forest predominated by lodgepole pine (*Pinus contorta*) (Table 1) before the fire. Part of the burned area was logged in summer 2007 using feller-bunchers and whole-tree skidding. The grapple skidders had either steel tracks ("tracked") or rubber tires ("wheeled"). We compared runoff and erosion rates from unlogged controls to runoff and erosion from trails made by feller-bunchers, trails made by tracked skidders, and trails made by wheeled skidders (Table 2). We also measured the effect of adding logging slash to skid trails on runoff and erosion rates by manually adding wood ("slash") after skidding to achieve at least 50% wood cover on one track of each of the skid trail plots (Table 2). Five rill experiments were completed in the controls and treated plots in 2007, 2008, and 2009 (Table 2).

The 2005 School Fire burned 21,000 ha in southeastern Washington (Fig. 1). The study sites were located in volcanic ashy silt loam soils derived from basalt in an area with mean annual precipitation of 924 mm (2001–2012) (Table 1). Pre-fire vegetation was dominated by Douglas-fir (*Pseudotsuga menziesii*) and grand fir