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A review of available literature regarding forest fires and salvage logging

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Introduction

Wildfires typically trigger proposals for post-fire salvage logging operations. Regardless of whether or not post-fire salvage logging is the appropriate response, this review assumes that some amount of burned timber will continue to be harvested until federal forest policies dictate otherwise. Operating under this assumption, there is a need to have a thorough understanding of the effects of such proposals and best management practices that may be used to avoid or mitigate their effects. The objective of this review is to summarize (1) natural effects of forest fires, (2) effects of salvage logging operations, (3) the efficacy of fire rehabilitation practices, and (4) recommendations designed to limit the environmental impacts of salvage logging activities.

Natural effects of forest fires

Erosion, runoff, and sediment yields

While erosion, runoff and sediment yields in burned landscapes depend on a variety of factors, they are primarily a function of burn severity[1] and subsequent hydrologic events (Robichaud 2005). Published results indicate that increases in sediment yields range from 0.01 to 110 Mg per hectare per year in the first year after a fire (Robichaud et al. 2000). In the second year after a fire, sediment yields tend to decline by an order of magnitude and return to pre-fire levels by the fourth year (Robichaud and Brown 2000, Silins et al. 2009).

The potential for increased erosion, runoff, and sediment transport is higher on severely burned sites. This phenomenon can be explained by the fact that high-severity fires consume more organic matter than moderate- and low-severity fires. For example, DeBano et al. (1998) determined that when severe fires consume more than 90% of the plants and organic matter on the surface of the ground, surface runoff can increase by more than 70%, and erosion can increase by three orders of magnitude compared to pre-fire conditions. To the degree that organic matter remains in the immediate post-fire environment, it protects soils against water erosion by decreasing the area that is susceptible to raindrop impact (Foster 1982). Organic matter also reduces overland flow velocities and aids in the retention of sediment (Laflen 1983). Consequently, when severe fires consume the protective organic layer, the potential for increased surface runoff and erosion is higher.

However, severe fires alone will not necessarily result in increased surface runoff, erosion, and sediment transport. The amount of surface runoff and erosion that occurs in a post-fire environment also depend on subsequent hydrologic events. Several studies (DeBano et al. 1998, Neary et al. 1999, Moody and

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[1] This is an appropriate time to make a distinction between fire severity and fire intensity, which are often mistakenly used interchangeably. Fire severity is indicated by the amount of biomass consumed. Fire intensity, on the other hand, is measured by the amount of heat generated by a fire.

Martin 2001) have documented an association between high-intensity, short duration rainfall events, high peak stream flows, and significant erosion events after fires. Forests burned by medium- to low-severity fires are comparatively less prone to increased surface runoff and erosion.

Aquatic organisms

Fires may lead to a cascading series of ecohydrological effects. These effects are documented in numerous studies. However, most studies tend to focus on only one or two pieces of the puzzle. While it is possible to piece these studies together in order to construct a more complete picture, more comprehensive studies, such as Silins et al. (2014) can be illuminating. They investigated the effects of fire and post-fire salvage logging in the Oldman River Basin, Alberta at different trophic levels. In their five-year study, they compared seven adjacent tributaries, consisting of two unburned reference watersheds, three burned watersheds, and two burned and salvage-logged watersheds.

Measurement of phosphorus taken by Silins et al. (2014) revealed significantly higher levels of all forms of phosphorus in the disturbed watersheds. Moreover, they suggest that mobilization of phosphorus appears to be coupled with sediment production and transport. Consequently, they suggest that higher levels of disturbance are likely to mobilize greater quantities sediment and hence, phosphorus. Because the availability of phosphorus limits primary production in freshwater environment (Elwood et al. 1981, Hart and Robinson, 1990), it's mobilization has implications at numerous trophic levels.

For example, Silins et al. (2014) found that algal production increased significantly in burned watersheds. They attributed increased levels of primary production to higher levels of bioavailable phosphorus. Bioavailable forms of phosphorus were 70% higher in the disturbed watersheds than the reference watersheds. Increased light exposure as a result of the loss of riparian vegetation also contributed to the increase in primary production. The duration of these effects vary in the literature anywhere from five (Minshall et al. 2001b) to ten years (Mihuc and Minshall 2005). However, the bioavailability of phosphorus in the wake of fires (and thus primary productivity) depends on the severity of the fire, the underlying geology, the topography, and subsequent hydrologic events.

The increased algal production observed by Silins et al. (2014) also likely contributed to an increased abundance of macroinvertebrates in their study. They noted higher levels of macroinvertebrate biomass and species richness, but they also found a decrease in species that are sensitive to disturbance. Their results are consistent with Albin (1979) who reported greater macroinvertebrate abundance and species richness in streams affected by fire in Yellowstone National Park and Minshall et al. (1997) who observed a shift in taxa favoring disturbance-adapted species.

In contrast, Minshall et al. (2001b) and Minshall (2003) reported decreases in macroinvertebrate abundance and species richness following fire as a result of direct mortality and indirect effects, such as high flow events and sedimentation. Similarly, several other studies (Rinne 1996, Minshall et al. 2001c, Earl and Blinn 2003) noted lower macroinvertebrate abundance and richness after fires, which were largely attributed to major stream channel alteration and inputs of ash. To further complicate the variability of available studies, Roby and Azuma (1995) documented greater macroinvertebrate abundance after wildfire in northern California, but they also observed lower species richness.

Perhaps the variability in the responses of macroinvertebrates to fire reflects the many factors that influence the results in available literature. Responses of macroinvertebrates to fire depend on the taxa, intensity of the fire, the extent of the watershed that burned, stream size and gradient, subsequent hydrologic events, vegetative cover, geology, and topography (Minshall 2003). As a general rule, the potential for indirect effects of fire to macroinvertebrates increases with the extent of the watershed that burned (Minshall et al. 2001a). However, effects also tend to decline with increasing stream size. In fact, fires are unlikely to cause effects to macroinvertebrates in sixth order streams or larger (Mihuc et al. 1996, Minshall et al 2001b).

The taxonomic richness, abundance, and biomass of macroinvertebrate communities may return to pre-fire levels within one to two years, but wide variations may continue for five to ten years (Roby and Azuma 1995, Minshall et al. 2001a and 2001b). Fires may alter the availability of various food sources to macroinvertebrate communities, favor some species over others (Minshall et al. 1989). Opportunistic taxa appear to be well adapted to post-fire conditions (Anderson 1992, Mihuc et al. 1996, Minshall et al. 1997). On the other hand, taxa that require special habitats, such as stable riffles or slow water currents tend to decline in abundance and biomass following fires (Mihuc et al. 1996).

Fires may also affect fish populations. Howell (2006) reported that fire crews observed dead fish while engaging in fire suppression activities during the 1996 Tower Fire in the upper John Day River Basin of Oregon. Direct mortality occurred in areas of moderate- to high-intensity burns. While the cause of mortality is unknown, other authors made similar reports (Minshall and Brock 1991, Rieman et al. 1997). Post-fire floods, landslides, and debris flows may result in additional fish mortality (Howell 2006). In fact, most of the available studies that report wildfire-related fish mortality (Novak and White 1990, Propst et al. 1992, Bozek and Young 1994, Rinne 1996, Rieman et al. 1997) involved subsequent flooding and debris flows.

Fires may also benefit fish. For example, Silins et al. (2014) reported increases in the size and growth rate of cutthroat trout, which was associated with increased algal and macroinvertebrate production. The 2- and 3-year age class cutthroat trout that they sampled grew entirely in watersheds affected by fire in the Oldman River Basin of Alberta, Canada. Koetsier et al. (2007) found similar results twelve to fourteen years after a wildfire complex in the Boise River Basin of Idaho. They studied the density, biomass, and diets of rainbow trout inhabiting unburned reference watersheds, burned watersheds, and burned and scoured watersheds. Although Koetsier et al. found no significant differences in fish density between the three categories of stream conditions, the length and biomass of rainbow trout inhabiting the burned and burned and scoured watersheds were significantly greater. In addition, the larger trout were preying upon significantly more aquatic macroinvertebrates. They suggest that their results may be at least partially attributed to the rate of riparian recovery. The lack of overhanging riparian vegetation in the burned and burned and scoured watersheds likely increased the amount of solar radiation available to primary producers. Consequently, there was also likely an increase in the autotrophic energy available to the aquatic invertebrate community, upon which their rainbow trout were preying.

Fish populations may demonstrate remarkable resiliency in the face of wildfires. Where extirpation or high mortality of fish results from wildfires, recolonization or recovery can occur rapidly (Howell 2006, Rieman et al. 1997, Novak and White 1990). A variety of physical and biological factors control rates of recovery and recolonization. Predictably, responses of fish depend on the quantity and condition of habitat, fire severity, the extent of the watershed burned, timing, and subsequent hydrologic events. In addition, past land management practices can exacerbate the negative effects of fire to fish (Rieman et al. 2003).

Biological factors that control rates of recovery or recolonization include habitat connectivity, life history, and the presence of non-native species (Dunham et al. 2003). Howell (2006) note the importance of well-distributed and connected populations of fish to recovery and recolonization after the Tower Fire in the North Fork John Day watershed. In the Boise River Basin, Rieman et al. (1997) attributed the recovery of bull trout after fire to the presence of migratory life history forms. Resident fish populations appear to be more vulnerable to fire, particularly in small streams or reaches where they are isolated from other populations (Arno 1980, Swanson et al. 1990). In any event, the role of fire in creating and maintaining productive and diverse habitats should not be discounted.

Riparian areas

Riparian zones are broadly defined by Pettit and Naiman (2006) as the transitional zones between water bodies and the surrounding uplands. Unlike wetland and lacustrine ecosystems, riparian areas associated with stream corridors maintain large edge-to-surface ratios, making them highly susceptible to the effects of fire. This review focuses on the effects of fires to riparian areas located in stream corridors because they tend to comprise the bulk of the hydrologic features where forestry is practiced in the intermountain west. Consequently, the conclusions drawn by studies cited in this synthesis about the effects of fires to streams may not hold up in wetland or lacustrine ecosystems.

Compared to adjacent uplands, fires tend to burn less frequently and less intensely in riparian areas (Agee 1988, Benda et al. 1998, Patten 1998, Dwire and Kauffman 2003). The ability of fires to penetrate riparian areas from the surrounding uplands appears to largely depend on the intensity of the fire and the width of the riparian area (Agee 1988). Similarly, Benda et al. (1998) and Minshall et al. (1989) suggest that riparian fire frequency decreases with increasing stream size. Consequently, riparian areas associated with low-order headwater streams tend to burn with more regularity and intensity than high-order streams and rivers (Pettit and Naiman 2006). Other factors that control fire regimes in riparian areas include climatic conditions, the size and distribution of fuels, vegetation types, topography, and aspect.

Although riparian areas tend to burn less frequently, they may burn more severely than surrounding upland areas (Pettit and Naiman 2006). Fire effects in riparian areas depend on stream size and include changes to nutrient cycles, inputs of sediment, cobble, litter, and large woody debris, and consequently the general ecology of aquatic organisms (Minshall et al. 1989). Riparian fires increase the potential for erosion, landslides, debris flows and stream channel alteration by removing vegetative biomass (Shakesby and Doerr 2006). Fires can also reduce water infiltration and create hydrophobic soil conditions (Shakeby and Doerr 2006). Through the removal of vegetative cover and canopy, riparian fires may also reduce stream shading and consequently, lead to elevated stream temperatures (Moore et al. 2005).

Riparian fire effects may also extend far downstream, particularly when fires burn through riparian areas associated with headwater streams (Pettit and Naiman 2006). Fires can create pulses of nutrients, sediment, cobble, large woody debris, and plant propagules, which have the potential to be translocated anywhere downstream from a burn.

The recovery of riparian areas following fire may depend in large part on subsequent hydrologic events (Minshall et al. 1989). The potential for erosion, mass wasting events, and significant stream channel alteration is higher after riparian fires due to the loss of vegetative biomass that would otherwise help armor and protect stream banks and riparian areas against flood events. However, riparian vegetation is pre-adapted to frequent flooding, which may help ameliorate the effects of fires to riparian vegetation (Pettit and Naiman 2006). Species with an ability to resprout are favored in environments subject to frequent disturbances, such as flooding (Bellingham and Sparrow 2000) and fire (Bond and Midgley 2003). In fact, willows, cottonwoods, alders, hawthorns, grasses, and sedges may even resprout soon after a fire and may even resprout prior to spring floods. To the degree that recovery begins before subsequent hydrologic events, the potential for significant effects decreases.

Unburned riparian areas surrounded by adjacent burned uplands may serve a “life boat” role. Fire-sensitive species may find refuge in riparian areas due to the fact that they are less likely to burn than surrounding upland areas (Meave et al. 1991). When the embers have died out, plants and animals may leave riparian areas to recolonize adjacent burned areas.

Birds

A variety of bird species benefit almost immediately in the wake of forest fires. For example, Kotliar et al. (2002) reviewed all of the studies available at that time about the benefits of fire to bird species of western North America. They found that nine bird species are more abundant in burned than unburned forests. When taking into account the number of species described in fewer than three studies, the number increases to fourteen, and Smucker et al. (2005) determined that number more than doubles in severely burned forests.

Wood- and bark-boring species found in recently burned forests include black-backed woodpeckers, hairy woodpeckers, northern flickers (Saab et al. 2006). The wood-boring beetles that these bird species prey on have a life cycle of two to three years, so the window of opportunity for foraging in a post-fire environment is extremely narrow (Hutto 2006). Populations of timber-drilling woodpeckers peak at about four years after a forest fire and then decline to nearly zero another six years after that (Taylor and Barmore 1980, Hoyt and Hannon 2002, Kotliar et al. 2002). Therefore, it should come as no surprise that this trajectory reflects the availability of their primary food source.

Aerial insectivores also forage in burned forests. However, not only do their populations peak later in time than the wood- and bark-boring species, but aerial insectivores also persist in burned forests for a longer period of time. For example, Lewis’s woodpecker will forage in burned forests for as long as 25 years after a fire (Bock and Lynch 1970, Linder and Anderson 1998, Saab and Vierling 2001). Similarly, other aerial insectivores and open-space foragers, such as bluebirds, flycatchers, and swallows will persist in burned forests 10 to 20 years after fires. Several studies (Lowe et al. 1978, Hobson and Schieck 1999, Hannon and Drapeau 2005) suggest that conditions for aerial foragers likely improve in the post-fire environment as canopy cover decreases (as the needles, branches, and boles of burned trees fall to the ground). They cite the growth of shrubs and the associated increase in flying arthropods, upon which aerial insectivores and open-space foragers feed.

In addition to foraging in burned forests, birds also use burned trees for nesting. In particular, many cavity-nesting birds are attracted to post-fire environments (McIver and Starr 2001). Hutto (1995) found that in severely burned coniferous forests, approximately 60% of all bird species use snags as nest sites, and nearly all of them nest only in snags. Furthermore, nests tend to be located in and near large diameter trees and also near high densities of foraging trees (Caton 1996, Saab and Dudley 1998, Hejl and McFadzen 1998).

Effects of salvage logging

Effects to soil and water

The potential for damage to soil and water quality as a result of post-fire salvage logging is significantly higher where ground-based machinery is used (Beschta et al. 2004, Karr et al. 2004). For example, in a study of five post-fire salvage logging operations, Klock (1975) found that tractor skidding over bare ground caused the greatest percentage of area with severe soil disturbance (36%), followed by cable skidding (32%), tractor skidding over snow (9.9%), skyline (2.8%), and helicopter (0.7%). The amount of erosion closely paralleled the amount of soil disturbance. In the cable skidding units, surface erosion occurred over 41% of the total surface area, followed by tractor skidding over bare ground (31%), tractor skidding over snow (13%), and helicopter (3.4%).

Wagenbrenner et al. (2015) studied the effects of skid trails, skid trails with slash mats, and feller-buncher trails used to implement four other post-fire salvage logging operations. They measured rates of sediment production from skidder plots that were 10 to 100 times greater than their control plots. Skid trails with slash mats produced 5 to 50 times more sediment than the control sites. Sediment production rates from feller-buncher plots were intermediate between the skidder and control plots. The relative differences in sediment production between the disturbed plots and the control plots tended to increase over time as the control plots exhibited more rapid regrowth and recovery. They concluded that in a given location with a given rainfall intensity, the amount of sediment produced was primarily a function of soil compaction and loss of surface cover.

In comparison, McIver and McNeil (2006) observed relatively lower rates of erosion as a result of three post-fire salvage logging treatments on severely burned sites in northeast Oregon. The three treatments in their study included unlogged controls, commercial harvest (two-thirds of all dead trees removed, leaving 17 snags per hectare), and fuels reduction (removal of all dead merchantable trees, leaving six snags per hectare). They found that post-fire logging operations caused a significant increase in the percentage of soil area disturbed, ranging from 17 to 22% in the commercial units and from 12 to 32% in the fuel reduction units. However, differences in erosion rates between the mechanical treatments and the unlogged controls were insignificant. They attributed their results to (1) the absence of extreme weather events during the two years after logging occurred, (2) that operations did not commence until two years after the fire burned, (3) that no new roads were constructed to access the units, (4) trees were felled by hand, and (5) with the exception of two units, logging was limited to dry or frozen ground. They concluded that their results are likely representative of the low end of the range of effects of post-fire salvage logging operations.

Although Karr et al. (2004) and Beschta et al. (2006) questioned the motive for post-fire salvage logging, they recommend using helicopters or full-suspension cable systems to protect soils when land managers do decide to salvage burned trees. Where ground-based salvage logging methods are used, Wagenbrenner et al. (2015) recommend limiting operations to times when the soil is dry or when there is enough snow cover to prevent machines from disturbing the soil. They also noted that the addition of surface cover, such as logging slash may reduce expected rates of sediment production. Burned logs may trap fine sediment in riparian zones before it reaches stream channels (Wondsell and King 2003), so salvaging logging should be avoided in these areas. When salvage logging operations occur, land managers should expect slower rates of recovery, even where mitigation practices are employed (Wagenbrenner et al. 2015).

Roads

The availability of studies about the effects of existing or newly constructed roads in post-fire environmental are limited, but studies from unburned sites are revealing. For example, Megahan and Kidd (1972) compared the relative influence of roads versus logging on erosion rates in unburned forests. They estimated that roads alone caused erosion rates to increase 100- to 200-fold compared to control sites, while logging caused erosion rates to increase two- to seven-fold. Megahan (1971), Beschta (1978), and McIver and McNeil (2006) suggest that roads will contribute more to sediment production in post-fire environments, just as they do in unburned forests.

Two available studies about the effects of roads in post-fire environments include Helvey (1980) and McIver and McNeil (2006). After the Entiat Fire in central Washington, Helvey (1980) observed that road construction associated with salvage logging appeared to contribute to the sediment loads in experimental watersheds. McIver and McNeil (2006) investigated soil disturbance and hill-slope sediment transport in an experimental study of post-fire salvage logging operations in northeastern Oregon. They placed silt fences below the treatment units in their study in order to measure sediment production. No new roads were constructed in the units where salvage logging operations occurred. However, existing roads were utilized to access some of the treatment units. They observed that the existing road system influenced the locations where the most sediment was generated. These sites included situations where a road left a unit, where a road formed the lower boundary of a unit, and cases where culverts above units concentrated surface flow that failed to completely infiltrate before reaching the catchments located at the bottom of their units.

Silins et al. (2009) conducted a watershed-scale investigation about the effects of wildfire and post-fire salvage logging in the Oldman River Basin of Alberta, Canada. During a four-year study period, they measured stream flow and water quality indicators in seven adjacent catchments following the Lost Creek wildfire. Instruments were installed in three burned watersheds, two burned and subsequently salvage logged watersheds, and two unburned control watersheds. They concluded that linear features in the salvage logged watersheds, such as skid trails and roads acted as conduits for overland flow and sediment transport. These features exacerbated sediment concentrations in affected stream courses compared to watersheds that were burned but not salvage logged.

Road construction should be avoided in post-fire environments in order to prevent additional runoff and erosion (Minshall 2003). Given the relative contribution of roads to erosion and sediment production, land managers should also consider reclamation of existing roads (i.e. removing roads and restoring natural drainage features and vegetation) where they are no longer needed for access.

Effects to wildlife and fish

Experimental studies about the effects of post-fire salvage logging to fish and wildlife are extremely limited. For example, Silins et al. (2014) authored the only available study that reports, among other things, the effects of post-fire salvage logging operations to fish. During a five-year study, they investigated the effects of fire and post-fire salvage logging at multiple trophic levels. They compared the growth rates and sizes of cutthroat trout inhabiting reference watersheds, burned watersheds, and watersheds that were burned and subsequently salvage logged. They reported significantly higher growth rates and sizes of cutthroat trout in both the burned and burned and salvage logged watersheds than the reference watersheds. However, there were no significant differences between the trout inhabiting the burned and burned and salvage logged watersheds. Unfortunately, the authors did not describe the design and implementation of the salvage logging activities that occurred in the study, which may have influenced the results.

While additional research on this topic is needed, conservatism is warranted with respect to riparian areas. Fish and other aquatic organisms are unlikely to benefit from post-fire salvage logging in riparian areas. Removing burnt trees and logs from riparian areas could reduce the recruitment of large woody debris to stream channels, where it would otherwise contribute to the creation and maintenance of diverse aquatic habitats (Reeves et al. 2006). Moreover, in many cases, burnt trees and logs are the primary sources of wood for streams until post-fire stands reach maturity, which may take decades (Beechie 2000). Removing post-fire sources of wood from riparian areas may exacerbate the negative effects of fires and delay the recovery of aquatic habitats (Reeves et al. 2000). Therefore, land managers should avoid post-fire salvage logging in these sensitive areas.

In addition, Minshall (2003) recommends removing no more than 25% of the merchantable timber. Post-fire salvage logging units should also be appropriately spaced across the landscape, and removal of burnt trees should be in proportion to the size classes of trees present on the site at the time of the fire (Beschta et al. 1995). Proportional harvesting is necessary in order to ensure that a mix of large woody debris size classes are available to be recruited to riparian and aquatic habitats during recovery (Minshall et al. 1989). The input of large woody debris is critical to the creation of habitat, nutrient cycling, soil formation, and to retard runoff and channel alteration.

A greater body of research has been developed about the effects of post-fire salvage logging to birds. For example, Saab et al. (2007) examined trends in nest densities of cavity nesting birds over an 11-year period after two forest fires in Idaho. They compared nest densities in unlogged controls with nest densities in partially logged sites. In the partially logged sites, more than half the snags greater than 23 cm dbh were retained. Despite retention of such sangs, Saab et al. found that black-backed woodpecker, hairy woodpecker, northern flicker, and mountain bluebird nest densities were significantly higher in the control sites compared to partially logged areas. Black-backed woodpeckers (a post-forest fire habitat obligate) appear to be especially vulnerable to post-fire salvage logging and fire suppression (Hutto 1995, Dixon and Saab 2000, Hoyt and Hannon 2002). In contrast, Lewis's woodpecker, American kestrels, and western bluebirds (all neotropical migrants) persisted in the partially logged sites. Their results resembled the observations reported by others (Raphael et al. 1987, Imbeau et al. 1999, Haggard and Gaines 2001, Morissette et al. 2002, Smucker et al. 2005).

Unfortunately, meaningful snag management and tree retention guidelines for birds inhabiting post-fire environments are currently lacking (Hutto 2006). There is not enough available data to establish a precise relationship between snag density and bird or nest density under a range post-fire salvage logging prescriptions. In the absence of such information, Hutto suggests that land managers have made unfounded conclusions about the effects of partial salvage logging prescriptions. Land managers often conclude that retaining some of the burned trees is better than removing them all. However, the extent and severity of wildfire that is necessary to enable populations of fire-dependent bird species to expand and survive until the next fire is unknown.

Regeneration of new trees and vegetation

Most post-fire salvage logging operations commence before the establishment of new seedlings. However, even the most immediate post-fire salvage logging operations can affect the regeneration of new trees and vegetation. For example, Perry et al. (1989) found that the regeneration of new trees and vegetation is limited by removal of burned trees, which provide shade and favorable microclimates for reestablishment.

In fact, even when special mitigation practices are employed to limit ground disturbance, the regeneration of new trees and vegetation may still be retarded. Sexton (1998) studied a post-fire salvage logging operation conducted over snow cover in ponderosa pine stands in central Oregon. The amount of vegetative biomass produced one and two years after post-fire salvage logging was just 38 and 27% of that in the unlogged control sites. The decreased canopy cover led to greater temperature extremes and drier soil conditions in the salvage logged stands. Sexton postulated that these conditions limited the regeneration of new trees and vegetation. He also observed more exotic plants species in the salvage logged sites and lower native plant species richness, relative to the unlogged controls.

Post-fire salvage logging operations are also often coupled with efforts to replant burned sites with fast-growing conifers and reseed native and non-native plant species. These practices can truncate the biologically rich stages of early succession that follow forest fires (Odian et al. 2004). Seeding burned sites with nonnative vegetation can create competition with desirable native species and impede their establishment (Amaranthus et al. 1993, Beyers 2004). Planting and reseeding should only be considered when natural regeneration is unlikely (Karr et al. 2004). Otherwise, the ecological benefits of the early successional ecosystems that develop in the aftermath of wildfire may not be fully realized.

Subsequent insect and disease outbreaks and fires

The responses of forest insects to fire depend on a variety of factors, but fire severity, the timing of the fire, forest composition, and the proximity to existing insect populations appear to be important factors. For example, severe fires may result in high levels of tree mortality. Only wood wasps and wood borers generally infest trees killed by fire in the interior west (McCullough et al. 1998, DeNitto et al. 2000). These insects rarely build up and attack neighboring green trees (DeNitto et al. 2000).

On the other hand, less tree mortality occurs as result of low severity fires. Instead, individual trees may be weakened but not killed. Several studies suggest that bark beetles commonly attack trees weakened but not killed by fire (Amman and Ryan 1991, McCullough et al. 1998, Bradley and Tueller 2001, Conklin and Armstrong 2001, Thies et al. 2001, Fowler and Sieg 2004). However, trees must be sufficiently scorched in order to weaken their defenses (Parker et al. 2006). Trees with thick bark (e.g. ponderosa pine and western larch) are less likely to be damaged and weakened by fire (Ryan and Reinhardt 1988, Reinhardt and Ryan 1989, Ryan and Frandsen 1991) than trees with comparatively thinner bark.

Following a fire, a population of beetles must also be within flight distance in order to infest trees weakened by the fire (DeNitto at al. 2000). Moreover, the timing of the fire must occur close enough to when adult beetles are flying and searching for host trees. If burned trees are not colonized soon after a fire, the phloem may become too dry before the next flight season. Finally, in order to survive, beetle larvae must have access to a sufficient supply of undamaged inner bark to feed on (Parker et al. 2006).

Responses of forest pathogens to fire vary. Root decaying pathogens may increase in stands where fire weakens the roots of trees (Parker et al. 2006). On the other hand, fires may consume fuels that harbor laminated root rot (Dickman and Cook 1989, Dickman 1992). Similarly, fires may consume dwarf-mistletoes and their hosts. However, mixed-severity fires may spare some trees infected with mistletoe, which may later serve to infect regenerated stands (Jones 1974, Baranyay 1975, Hawksworth 1975, Hreha and Weber 1979, Hawksworth and Johnson 1989).

Finally, post-fire salvage logging has been suggested as a tool to reduce the potential for a catastrophic "reburn" (Brown et al. 2003). However, the reburn hypothesis is an untested theory (Reeves et al. 2006). Beschta et al. (1995), Everett (1995), and McIver and Starr (2001) could not find any studies that documented a reduction in fire severity in a stand that had been burned and then salvage logged. Similarly, Reeves et al. (2006) could not find any studies that determined whether or not post-fire salvage logging in riparian areas reduces the spread of invasive species, lowers the vulnerability of upland forests to insect and disease outbreaks, or lessens the frequency and severity of future fires.

Effectiveness of rehabilitation practices

Common post-fire rehabilitation practices employed to reduce erosion include seeding, mulching, and sediment barriers (e.g. fences, straw bales, straw wattles, and contour-felled logs). Indeed, the highest erosion rates are generally observed during the first year after a fire and often decrease by an order of magnitude in the second year (Robichaud 2005). Consequently, effectively applied rehabilitation treatments have the potential to reduce erosion and runoff.

Broadcast seeding (particularly of grasses) is one of the most common post-fire rehabilitation practices. Approximately 60 to 70% ground cover must be established in order to effectively reduce erosion (Robichaud et al. 2000, Pannkuk and Robichaud 2003). After reviewing nine available studies about this topic, Robichaud et al. (2000) suggests that seeding is rarely an effective post-fire rehabilitation practice. About half the studies reported less than 30% ground cover in the first year after a fire. Only two studies reported at least 60% ground cover in the first year. While increased ground cover in the second and third years can reduce erosion, several studies (e.g. Roby 1989, Van de Water 1998, Wohlgemuth et al. 1998) reported that even second-, third-, and even fourth-year erosion rates were not affected by seeding. In another review of seeding effectiveness, Beyers (2004) noted that non-native seed sources could lead to the establishment of vegetation that competes with desirable native species. Where seeding occurs, land managers should select native seed sources in order to avoid the introduction of non-native species.

Another common post-fire treatment is the application of mulch. Typically, land managers apply straw, which has been shown to be effective. For example, Bautista et al. (1996) and Faust (1998) observed reductions in erosion rates of 50 to 94%. Straw mulch reduces erosion rates by lessening the impact of precipitation when it falls upon the ground. Mulch is often combined with a seed mix and improves germination by increasing soil moisture retention. However, a drawback to straw mulch is the potential for introduction of straw species, noxious weeds, and other non-native plants.

Contour-felled logs are often used to create barriers to overland flow, increase infiltration, and trap sediment. The effectiveness of these treatments varies in the literature. For example, Miles et al. (1989) observed low efficacy of contour-felled logs after the 1987 South Fork Trinity Fire in California. In contrast, Dean (2001) found that contour-felled logs, paired with the application of straw mulch reduced erosion rates by 77% in the first year after a fire and 96% in the second year. Robichaud (2000) suggests that contour-felled logs can be effective against low- to moderate-intensity rainfall events, but he also noted that effectiveness decreases over time as the barriers become filled with sediment and lose their storage capacity. Other mechanical barriers include straw wattles, straw bales, and other engineered structures.

Land managers should evaluate the need to apply rehabilitation treatments in conifer forests where burn severity ranges from low to moderate. Lightly charred and partially consumed trees often shed needles on the forest floor where they are naturally effective at limiting erosion. A 50% ground cover of dead needles may naturally reduce interrill erosion by 60 to 80% and rill erosion by 20 to 40% (Pannkuk and Robichaud 2003). Areas with sufficient needle cover should, therefore, be excluded from post-fire rehabilitation treatments. Instead, priority should be given to severely or intensely burned sites where crowns and duff layers were consumed.

Monitoring, research, and adaptive management

Not surprisingly, a number of sources recommended additional research, monitoring, and the use of adaptive management practices (McIver and Starr 2001, Lindemayer and Noss 2006, Reeves et al. 2006, Pettit and Naiman 2006). In particular, Lindemayer and Noss (2006) stressed the importance of pairing treatments with unlogged controls in experimental design. Due to the fact that research in post-fire environments tends to be highly opportunistic, very few studies have been undertaken where the effects of salvage logging treatments are compared to control sites (McIver and Starr 2001). Additional research is needed to more precisely determine the relationship between a range of post-fire salvage logging prescriptions and response variables, such as nesting densities of fire-dependent birds, soil compaction, sediment production, etc. Without further research, land managers are faced with making decisions with limited or no information.

Recommendations

- The potential for post-fire salvage logging to exacerbate ground disturbance, erosion and water quality degradation is significantly higher when ground-based machinery is used. Helicopter logging results in the least disturbance, followed in order by skyline, tractor skidding over snow, cable skidding, and tractor skidding over bare ground. To the extent practical, land managers should select logging systems that result in the least disturbance and consider limiting operations to periods of time when the soil is dry, covered with a significant snow layer, frozen, or a combination of snow and frozen soil.

- Land managers should avoid new or temporary road construction in post-fire salvage logging operations. In fact, because past land management practices may accentuate the effects of fire, land managers should consider decommissioning unnecessary roads in burned areas.

- Riparian areas should be excluded from post-fire salvage logging operations. Land managers should also consider applying greater buffers to riparian corridors than they do during green timber sales.

- Until a greater body of research is developed to provide guidance about what post-fire harvest prescriptions should be applied or avoided in wildlife habitat, land managers should limit the harvesting of burnt trees to no more than 25% of the merchantable volume. The harvest of burnt trees should also be in proportion to the size classes present on the site at the time of the fire. Proportional harvesting ensures that a mix of snags and large woody debris size classes are available on the site. In addition, post-fire salvage logging units should be appropriately spaced.

- Land managers should avoid applying seed mixes or mulches that may introduce non-native vegetation. Non-native species may compete with and impede the establishment of desirable native species.

- Post-fire salvage logging operations are often followed by aggressive efforts to replant burned areas with fast-growing conifers. These practices truncate the biologically rich stages of early succession. Planting and reseeding should only be considered when natural regeneration is unlikely.

- Land managers that feel a sense of urgency to implement post-fire salvage logging operations often overlook opportunities for monitoring, adaptive management, and research. Unless land managers make a commitment to monitoring and research, they will continue to make decisions about post-fire salvage logging with limited information.

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