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California Forestry Report No. 7

February 2023

Mitigating Potential Sediment Delivery from Post-Fire Salvage Logging

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Rubber-tired skidder operating after the 2015 Valley Fire on the Boggs Mountain Demonstration State Forest in Lake County, California.

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1 Introduction

Post-fire salvage logging using ground-based heavy equipment can impact soils and vegetation, and lead to various effects that can increase or decrease post-fire runoff and erosion (removal of soil or sediment from its initial position). This document briefly outlines the current understanding of these effects and provides an overview of best management practices (BMPs) designed to mitigate the negative effects related to sediment delivery to streams and other aquatic resources. It is based on the best available scientific information regarding BMPs that may be used to reduce sediment delivery from post-fire salvage logging activities as well as the authors' knowledge on this topic. The document is intended to complement state, regional, and national regulations and/or guidance for timber harvest activities in unburned and burned forests (California Department of Forestry and Fire Protection (CAL FIRE), 2023; U.S. Environmental Protection Agency, 2005; USDA Forest Service, 2000, 2012). This document focuses on implementation on lands subject to California's Forest Practice Rules (FPRs), although the process-based approach allows more broad application of this guidance with appropriate caution, including consideration for climate, landscape setting, and operational conditions or constraints. The primary audience for this document is forestry and watershed professionals. Abbreviated operational guidance will be provided for licensed timber operators in a subsequent product. Research results informing the various effects and guidance are provided in reference materials. No attempt is made to address the ecological aspects of post-fire salvage logging, which are covered elsewhere. Site preparation for reforestation can occur with or without salvage logging, but few studies have addressed the effects of those practices on runoff and erosion (Cole et al., 2020). Similarly, this document does not address best management practices for fire suppression repair, although some of the practices presented herein may apply to suppression repair activities.

2 Fire effects on soils, runoff, erosion

Fire consumes organic matter in the forest canopy, understory, litter layer, and soil (Certini, 2005; Keeley, 2009). These direct effects lead to changes in interception, snow accumulation and melt rates, and evapotranspiration (Harpold et al., 2014; Moody et al., 2013). The heat conducted through soils also changes some of the chemical properties of the soil. The changes in soil organic matter can change the structure, texture, strength, and porosity of soils, which can reduce infiltration rates through increased water repellency and/or soil sealing, lead to increased overland flow rates, and increase the erosion hazard (Larsen et al., 2009; Moody et al., 2013). Connectivity, the ability for surface water to flow from a point on a hillslope to a point downstream, is generally thought to increase because of fire (Cawson et al., 2013; Olsen et al., 2021), but there are no widely accepted measures of connectivity and there are few data available on post-fire surface-water connectivity.

The effects on these fundamental hydrologic processes can lead to increases in surface runoff on the order of 1000 times or more relative to pre-fire conditions on hillslopes and in channels draining small watersheds (Moody et al., 2013). The changes in soil conditions and increased surface runoff also can lead to increases in soil erosion and downstream sediment delivery by surface runoff (**Figure 1**), or as debris flows given specific geologic and precipitation conditions (Kean et al., 2011). Soil erosion by surface runoff can be many times greater after wildfire than the soil erosion rates in undisturbed forests (Moody & Martin, 2009), and post-fire debris flows can scour upland channels and deliver thousands of tons of sediment to valley bottoms (Kean et al., 2011).

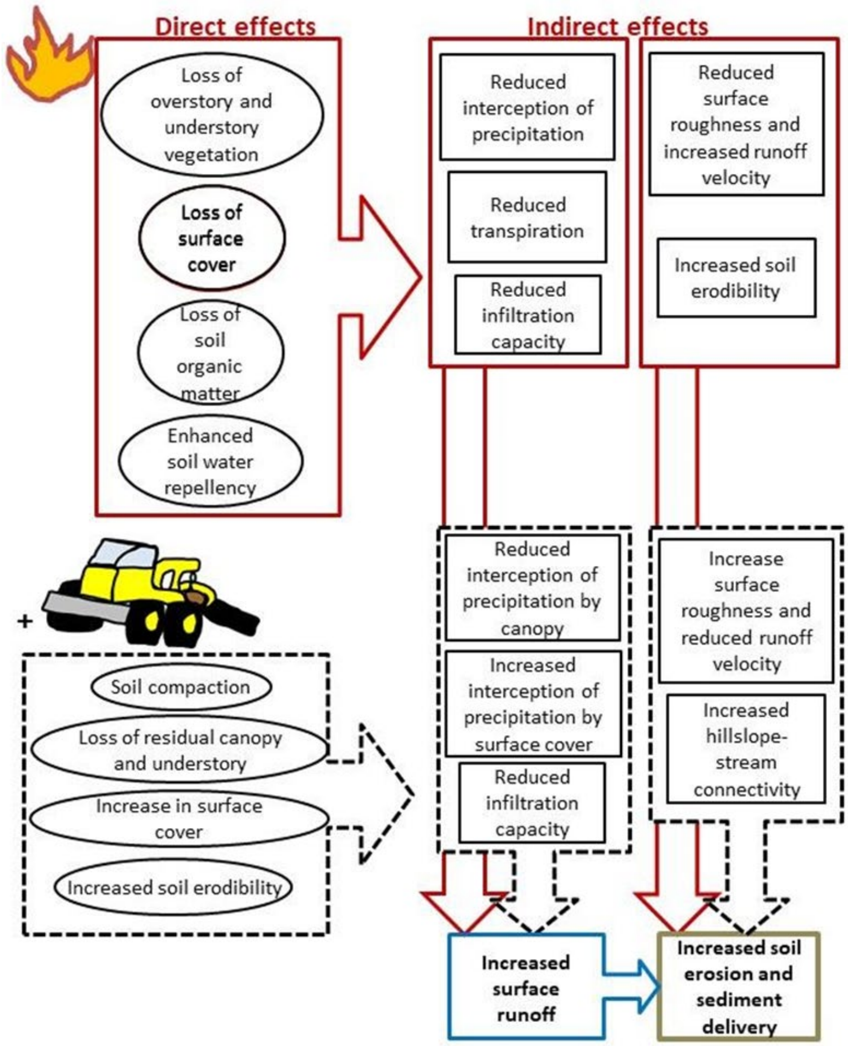

Figure 1. Some of the relevant direct and indirect effects of fires (upper portion, solid red outline) and ground-based post-fire salvage logging (lower portion, dashed black outline) on soils and hydrologic processes that lead to increased runoff, erosion, and sediment delivery. Not all changes are represented and some of the effects interact with others. Adapted from Wagenbrenner et al. (2015).

2.1 Soil burn severity: A key concept in post-fire management

Post-fire runoff and erosional responses are strongly dependent upon the degree of soil damage caused by the fire (represented by "direct effects" in **Figure 1**). The magnitude of the potential changes is affected by the amount of heat released by the fire and imparted on the vegetation and soils (fire intensity) (Keeley, 2009), and the effects are normally categorized into a four-level soil burn severity classification system (Keeley, 2009). The patch size and continuity of soil burn severity are other important factors dictating the magnitude and timing of runoff and erosional responses following wildfire (Ebel et al., 2012; Olsen et al., 2021) (**Figure 2**).

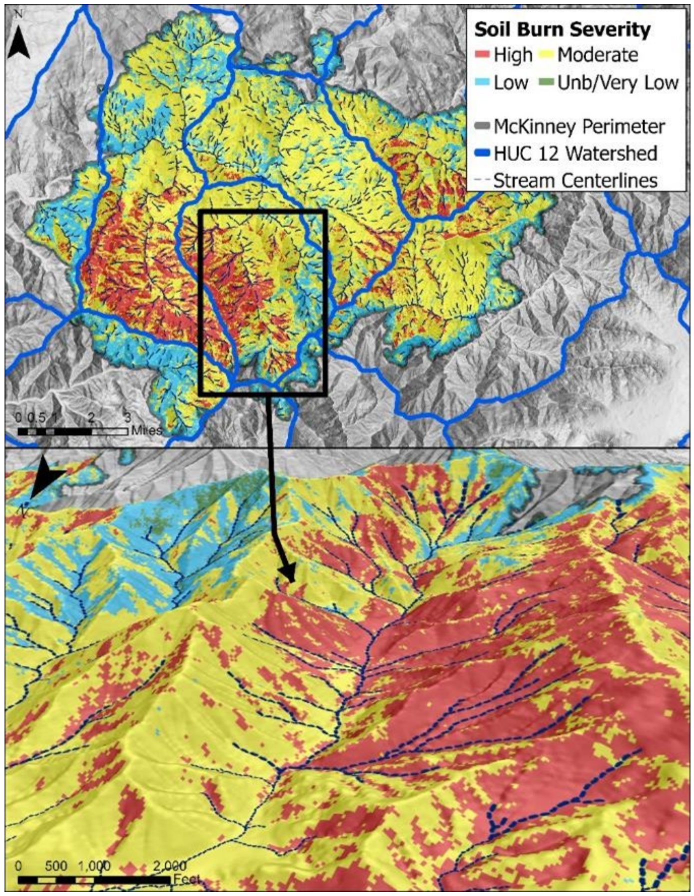

Figure 2. Map showing soil burn severity for the 2022 McKinney Fire in Siskiyou County, California. Top is the entire fire and the bottom is a magnified view of the inset box, looking upstream in a small watershed. The highest degree of post-fire response will generally be in areas affected by moderate (yellow) and high (red) soil burn severities.

Soil burn severity is generally determined through a combination of remote sensing and field observations. Remotely sensed products like the Burned Area Reflectance Classification (BARC) map are derived by comparing pre- and post-fire satellite images using spectral bands that are sensitive to changes in vegetation and soil characteristics. The BARC maps show an initial prediction of soil burn severity, but they must be field verified using diagnostic characteristics such as those shown in **Table 1** to accurately show the spatial arrangement of fire-induced soil damage. Soil burn severity (SBS) maps are created by field observations and modifications of the BARC map. BARC maps are often requested, and SBS maps are often created, by federal Burned Area Emergency Response (BAER) teams or California State Watershed Emergency Response Teams (WERT). Areas burned at moderate to high soil burn severity are most likely to result in erodible soils, low infiltration capacity, and low surface cover, resulting in much higher erosion potential (i.e., increased erosion hazard rating (EHR)), and higher sensitivity to salvage logging.

Table 1. Changes in diagnostic soil characteristics by relative soil burn severity (adapted from Parson et al., 2010, where additional information and photos are available).

Soil Burn Severity	Ground Cover: Amount and Condition	Ash Cover and Depth	Soil Structure	Rooting Strength	Soil Water Repellency
Very Low/ Unburned	Little or no change from pre-fire condition.	Patchy with little consumption of litter.	Structure unchanged. Granular aggregates are not weakened by consumption of organic matter.	Fine roots (0.1 inches in diameter and larger) intact and unchanged.	No fire-induced water repellency. Water infiltrates immediately; however, some soils exhibit water repellency even when unburned.
Low	Little or no change from pre-fire condition. Less than 50% consumption of litter, some char. Needles and leaves mostly intact.	Ground surface may be black with recognizable fine fuels (needles, grass, and leaves) remaining on surface.	Structure unchanged. Granular aggregates are not weakened by consumption of organic matter.	Fine roots (0.1 inches in diameter and larger) intact and unchanged.	No fire-induced water repellency. Water infiltrates immediately; however, some soils exhibit water repellency even when unburned.
Moderate	Up to 80% consumption of litter and duff, but generally incomplete. Recognizable leaves and needles remain. If tree mortality occurred, the potential for needle cast may be a mitigating factor.	Thin layer of black to gray ash with recognizable litter beneath it. Ash layer may be patchy as it is highly moveable by wind and water. Soil heating may have been significant.	Structure slightly or not altered. Some consumption of organic matter in the top 0.5 inch of soil profile.	Fine roots (0.25 inches in diameter and larger) near surface may be charred or scorched; large roots intact.	Weak to medium fire-induced water repellency often found at or just below soil surface. Water infiltrates slowly.
High	Little to no effective ground cover remaining (< 20%). All or most litter and duff has been consumed, only ash or bare soil remain. Little or no potential for leaf-or needle cast.	Thick, 1- to 3-inch plus layer of powdery gray or white ash can cover the ground. Greater than 90% surface organics consumed; significant soil heating occurred. Localized red (oxidized) soil may underlie a thick powder layer of gray and white ash.	Structural aggregate stability reduced or destroyed. Loose- and single-grained soil dominates and is exposed or under ash. Consumption of organic matter in the top 2 inches of the soil profile.	Many or most fine roots near surface consumed or charred. Some charring may occur on very large roots (3 inches in diameter or larger).	Strong fire-induced water repellency may be found at surface or deeper. Water does not immediately infiltrate. In case of extreme soil heating, soil water repellency may exist at very deep soil depths (6 inches).

2.2 Rainfall as a determinant of post-fire response

While intense fire can decrease infiltration capacity, decrease surface roughness, and increase sediment supply, sufficient rainfall is generally needed to generate overland flow and initiate erosion[4]. The minimum rainfall intensity needed to trigger post fire runoff is generally around 0.2 inches per hour (5 millimeters per hour) for a 60-minute duration (Moody, 2012; Wilson et al., 2018), which is far less than a 1-year recurrence interval rainfall event in most forested locations. Post-fire erosion is highly dependent on the size, number, intensity of runoff generating events (e.g., high intensity rainfall, rapid snowmelt), especially during the first one to two years after an intense wildfire. Debris flows in forested areas are often triggered by short duration rainfall intensities near the 1 to 2-year recurrence interval (Staley et al., 2020).

3 Effects of post-fire salvage logging on runoff and erosion

3.1 Roads and landings

Roads are critical for moving salvage-logged timber to processing facilities, and landings facilitate the loading of forest products from logged areas onto trucks. With exceptions, most of the road and landing network is usually established prior to salvage logging. As such, roads are a preexisting land use feature subject to increases in runoff and erosion following wildfire. Road networks are different from skid trails in that, because they are wider, they have a much larger disturbance footprint per unit length. The linear nature of road networks as well as the tendency of roads to cross potential surface and subsurface flowpaths means that they can affect runoff and erosional pathways much more significantly than other land use features (Luce and Wemple, 2001). The hydrologic alterations forced by road networks have the potential to be much more severe following wildfire, due to the much higher rates of runoff and sediment intercepted from burned slopes (Sosa-Pérez and MacDonald, 2017). Watercourse crossings are unique in that they provide conveyance of runoff, sediment, and debris at the intersections of the road and stream networks. However, the design capacity of drainage structures at watercourse crossings can be overwhelmed by the combination of excess runoff, sediment, and debris following severe wildfire (Foltz et al., 2009; Foltz and Robichaud, 2013; Cafferata et al., 2017).

[4] Dry ravel is an erosion process that increases on steep slopes after fires and, since it is driven by gravity, does not need rainfall to occur. It occurs due to loss of structural support by burned vegetation.

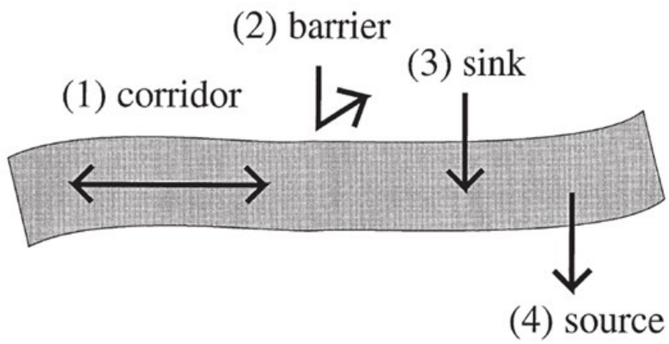

Figure 3. Four basic types of flow interactions with a road segment (Jones et al., 2000). These same interactions can also occur on skid trails.

Roads can respond to fire-induced changes in runoff and sediment in several ways, largely dictated by the slope position, road and hillslope gradients, road surfacing, amount of traffic, and underlying hillslope and fill properties (**Figure 3**):

- Roads can act as corridors, collecting surface and subsurface runoff and concentrating runoff to a single concentrated drainage point. This phenomenon can be repeated across multiple drainage points across the entire road network affected by the burned area.
- Roads can be barriers to flowpaths. An example of this may be an elevated road prism on gentle terrain, where the road acts as an embankment that blocks a potential flowpath. Drainage structures (e.g., culverts) at watercourse crossings can often become barriers when excess debris and sediment plugs the structure (**Figure 4**).
- Roads can be runoff and sediment sinks. This is typical of flatter road segments (i.e., ≤ 5%), which have shown a tendency to preferentially capture runoff and sediment eroded from upslope burned areas (Sosa-Pérez and MacDonald, 2017; Cao et al., 2021).
- Roads can be a source of runoff and erosion following wildfire. This is common at road drainage points, where excess concentrated runoff can trigger rill, gully, and landslide erosion. High intensity runoff generation on the road tread or overtopped or blocked watercourse crossings might lead to erosion of portions of the tread and fill by excess runoff. In some cases, the entire crossing fill may be removed by post-fire runoff and/or debris flows.

The descriptions above are not mutually exclusive, as a barrier can also become a sink for runoff or sediment. Depending upon the intensity and duration of the storm, the capacity of the sink can be overwhelmed, resulting in the road becoming a corridor or source of runoff, sediment, and/or debris. These types of interactions can become progressively linked across multiple down-gradient road segments resulting in extensive erosion from gullies and landslides, a phenomenon known as a “disturbance cascade” (Nakamura et al., 2000; Wemple et al., 2001; Sosa-Pérez and MacDonald, 2017). A similar phenomenon can occur on skid trail networks, where skid trail or road drainage can be intercepted and rerouted by downslope roads/skid trails, resulting in accumulated runoff with resultant increases in erosion herein referred to as “stacking.”

Figure 4. A culvert partially blocked by burned wood and debris in the 2020 North Complex Fire in Butte County, California. In this picture, the road is acting as a partial barrier and a sink for runoff, sediment, and debris.

3.2 Ground-based yarding

Modern post-fire salvage logging often uses ground-based heavy equipment such as feller-bunchers, skidders, tractors, forwarders, or processors to cut the timber, process the timber in place, or yard the timber to a landing for further operations. The main physical considerations of the heavy equipment occur where the machines move through the burned forest, and include compaction of soils which is often measured by rutting or increases in soil bulk density (**Figure 5**), killing or reducing the vigor of understory vegetation, and creation or extension of a network of connected machine pathways (e.g., skid trails) (**Figure 6, Figure 7**). The compaction also reduces soil water repellency, but the net effect of these two countering mechanisms is a decrease in infiltration capacity (Demirtas, 2017; Prats et al., 2021; Wagenbrenner et al., 2015, 2016), with a resultant increase in local runoff generation.

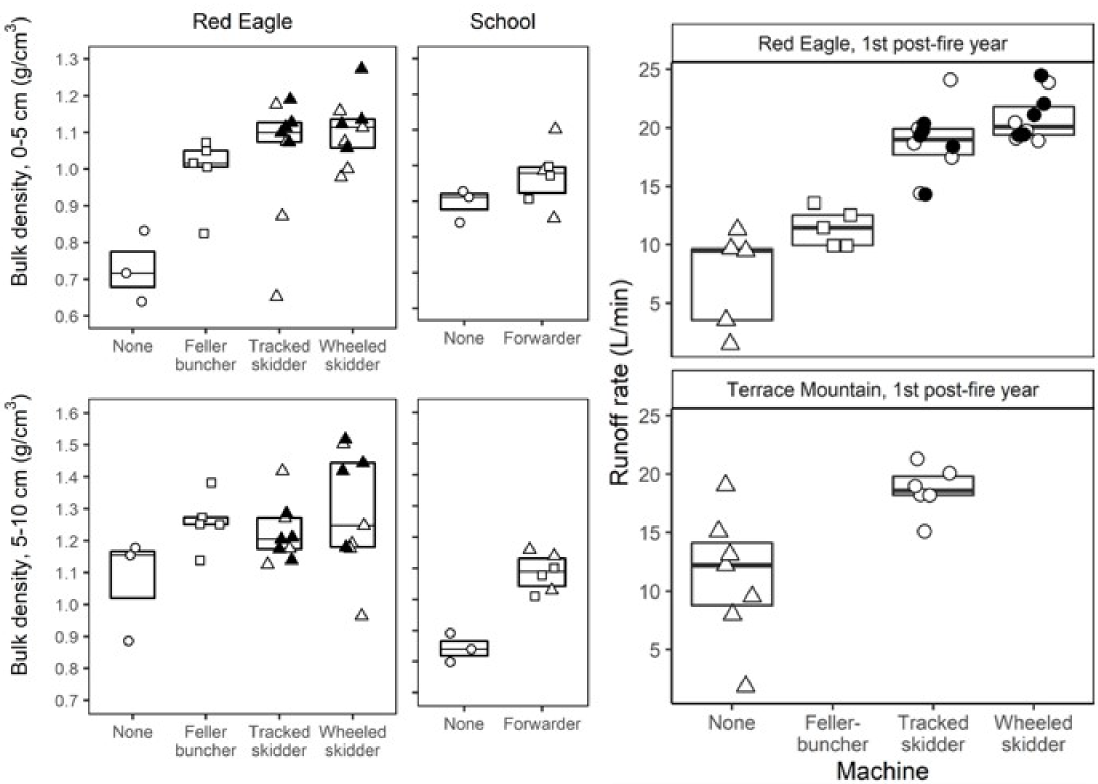

Figure 5. Bulk density, a measure of soil compaction (left) and runoff rate during a controlled runoff experiment in areas of high soil burn severity with different types of machine traffic (right). Not all types of machines were tested at each of the study sites (modified from Wagenbrenner et al., 2016). "None" represents high soil burn severity with no salvage logging equipment traffic.

In addition to the effects of the machines, removal of the residual overstory canopy can reduce the interception of precipitation, and this generally leads to more precipitation reaching the soil surface and greater erosion rates (Prats et al., 2021). Removal of residual canopy can also lead to increased snow accumulation and melt rates in salvage logged areas (Leverkus et al., 2021). Conversely, in some precipitation regimes, such as in the Northern Coast Ranges or foothills of the southern Cascades in California where long-duration, relatively low-intensity rainfall is common, when the residual canopy is tall enough it can also lead to increased throughfall drop sizes by aggregation of the droplets intercepted by the canopy, and this can lead to increased energy for erosion as the larger drops hit the soil surface (Cole et al., 2020; James & Krumland, 2018). In these conditions, removal of the residual canopy may decrease the local erosion rates relative to unharvested area, and this difference would persist until the erosion rates in the unharvested areas decrease as the surface cover increases by recovery of understory vegetation and litter and the falling of fire-killed trees.

In the short term (~3-7 years post-fire, prior to when most unharvested fire-killed trees fall to the ground) salvage logging can increase the amount of wood surface cover (Cole et al., 2020; James & Krumland, 2018; Olsen et al., 2021; Wagenbrenner et al., 2015), particularly in cut-to-length operations that leave limbs and tops on the hillslopes. In some operations, such as biomass removal for fuel reduction, the amount of wood cover may decrease (James & Krumland, 2018). Whole tree yarding to a landing may also result in less soil cover than if trees are processed on the hillslope. The amount of soil erosion is strongly and inversely related to the amount of surface cover by wood or other non-soil component such as litter (Larsen et al., 2009).

Traffic by heavy machines used for post-fire salvage logging can reduce the vegetation component of ground surface cover (Cole et al., 2020; James & Krumland, 2018; Wagenbrenner et al., 2015). The reduced amount of vegetation, combined with the compaction of soil which changes soil water availability for vegetation use, can also lead to delayed recovery of understory vegetation (Wagenbrenner et al., 2015).

3.3 Skid trails

The soil compaction, soil churning/displacement by heavy equipment and log skidding, and disturbance of vegetation through the act of ground-based yarding during post-fire salvage logging operations can lead to a complicated skid trail network (**Figure 6**). These networks may be new, on previously harvested hillslopes, or machines may use existing networks. Roads and landings may be re-opened or added to increase operational efficiency. Like road segments, skid trails may run across or down topographic gradients, and their orientation may determine whether these features act as barriers, sources, sinks, or corridors of runoff and erosion (Chase, 2006; Jones et al., 2000) (**Figure 3**).

However, the result of these networks in the burned area generally is an increase in connectivity between the hillslopes and stream network (Olsen et al., 2021), with the increase in connectivity related to both the length of stream per unit area (stream density) and the road or skid trail length per unit area (road/trail density) (Jones et al., 2000)(**Figure 7**). Hillslope-stream connectivity increases after fires in general, but the controls on that connectivity are not well understood and the effects of skid trails on hillslope-stream connectivity are also relatively unknown. Observations suggest that decreased waterbar spacing and appropriate placement of these waterbars can result in lower levels of connectivity (**Figure 8**). Skidding down or within convergent topography (i.e., swales) can increase connectivity. In contrast to drainage of skid trails delivered to unburned forests, where surface runoff typically infiltrates, drainage of skid trails or other sloped, compacted areas that flows into burned areas with lower infiltration capacity and less surface cover is less likely to infiltrate and can increase erosion and sediment delivery (**Figure 8**, **Figure 9**).

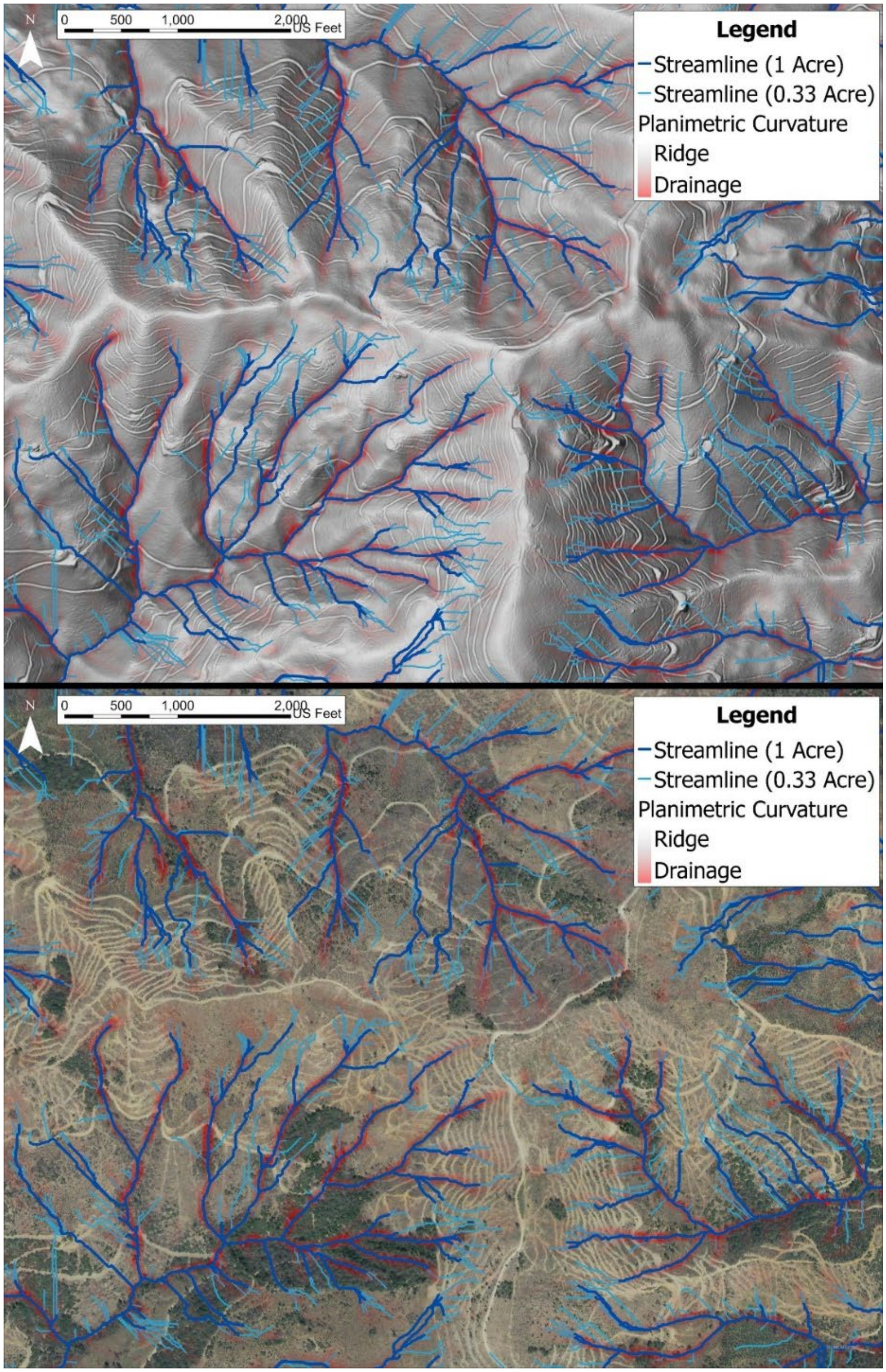

Figure 6. Hillshade (upper) and National Agriculture Imagery Program (NAIP) imagery (lower) showing skid trail layout in salvage logged area of the 2018 Carr Fire in Shasta County, California. Flowlines were determined using a 1-m digital elevation model (DEM) and an accumulation area of one acre. Areas of concentration (red shading) were derived from a 1-m DEM.

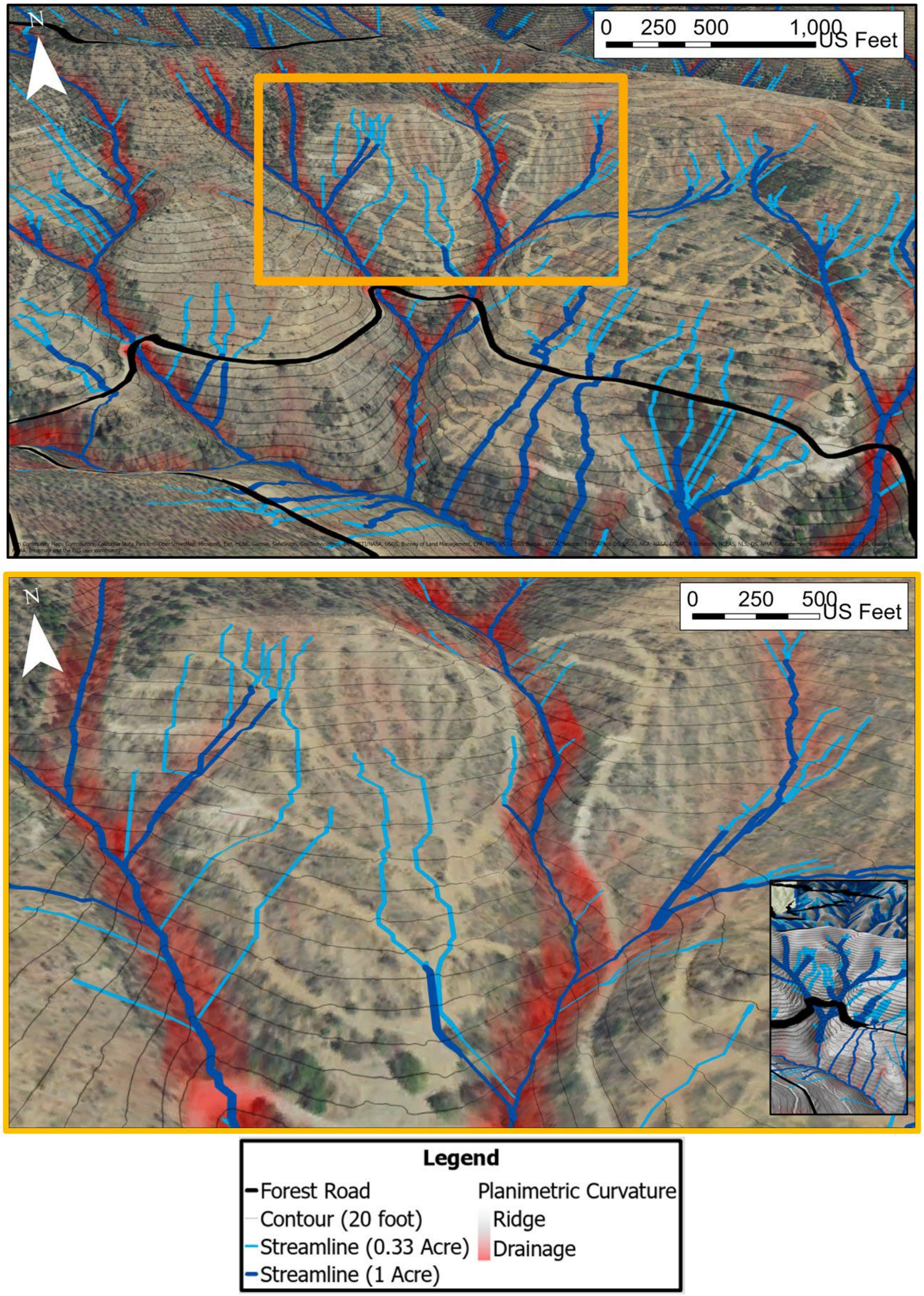

Figure 7. An example of a skid trail network with high potential connectivity to the stream network. Hillshade (upper) and NAIP imagery (center) with magnified inset (lower) with NAIP imagery of the 2018 Carr Fire in Shasta County, California. Contour interval for upper panel is 20-feet. Flowlines routed using 1-m DEM and accumulation areas of 0.3 acre (light blue lines) and 1 acre (dark blue lines). Areas of flow concentration (red shading) derived from a 1-m DEM.

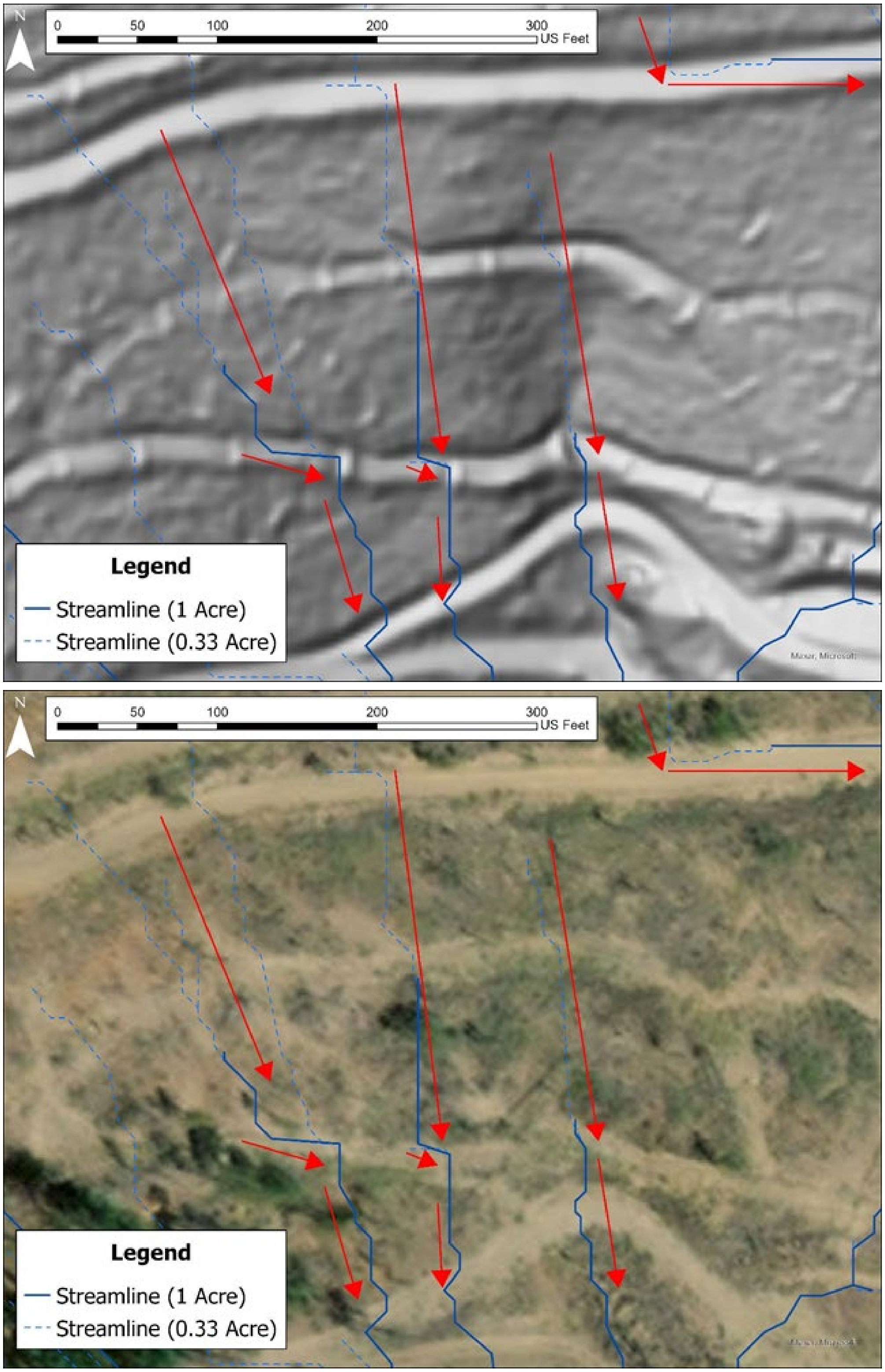

Figure 8. Hillshade (upper) and NAIP imagery (lower) showing flow paths in a salvage logged area of the 2018 Carr Fire in Shasta County, California. Waterbars deflecting flow are more visible in upper panel but present in both images. Flowlines routed using 1-m DEM and accumulation areas of 0.3 acre (dashed lines) and 1 acre (solid lines).

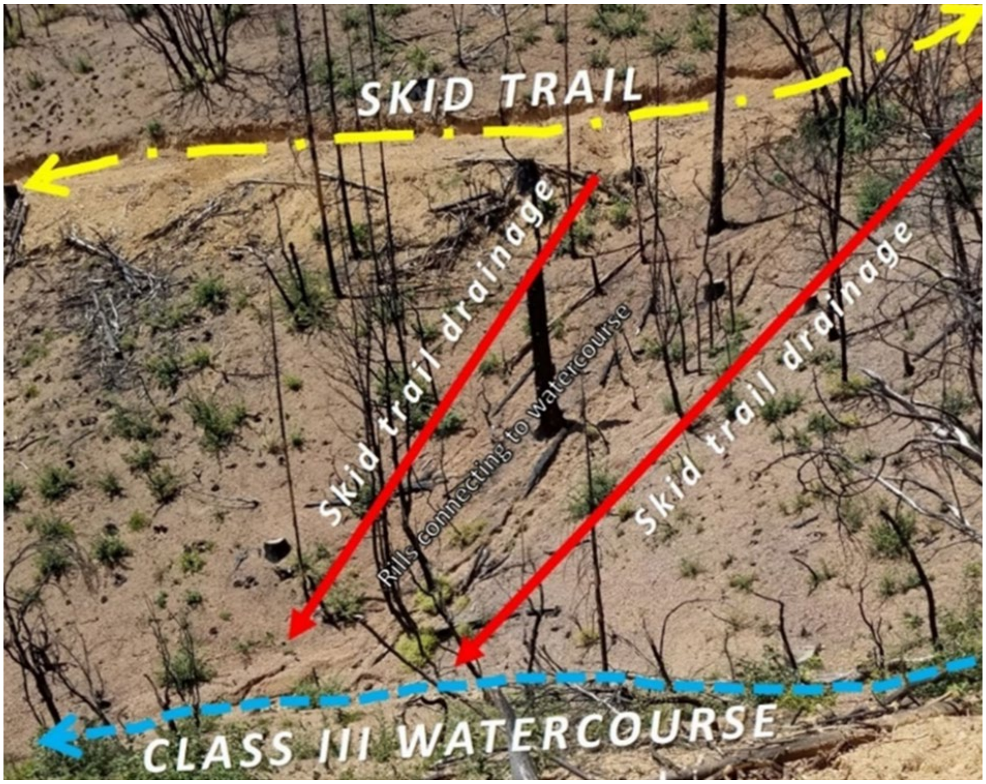

Figure 9. Connectivity from a skid trail to a Class III (ephemeral) watercourse following salvage logging after the 2018 Carr Fire in Shasta County, California. Also note soil displaced downslope from skid trail (sidecast) which can provide additional sediment availability for transport to watercourse.

Increased connectivity between hillslopes and streams alone does not increase sediment delivery, as sufficient overland flow must occur to transport sediment from the source area to the stream channel, and sufficient sediment must be readily available for transport (**Figure 9**). However, given the lower infiltration capacity of burned soil and areas compacted by heavy equipment in salvage-logged areas, the amount of surface runoff will be much greater than in comparable unburned areas. The runoff source strength is a term used to describe the ability of a particular land surface to generate overland flow and the probability of this runoff reaching the stream network, and is a function of rainfall intensity, the extent of area used by heavy equipment and design of the skid trail network, and size of the contributing drainage area (Croke & Hairsine, 2006). In addition to the fire's effect on soil erodibility, sediment availability may also be increased by ground-based logging operations due to the churning of soil during traffic and the displacement of readily moved earthen material such as sidecast and berms.

4 Best management practices for post-fire salvage logging

Together, the knowledge of the physical effects of fire on watersheds and post-fire salvage logging, bolstered by recent California-specific field studies, inform the customization of existing BMPs and development of new BMPs that forestry and watershed professionals can implement during post-fire salvage logging. These practices can reduce the runoff source strength, hillslope to stream connectivity, or both and thereby reduce the sediment delivery to streams (**Figure 10**). These BMPs generally fall into two broad categories: 1) planning and design; and 2) mitigation of yarding/hauling operations through BMP implementation, which are addressed in the following sections. Mitigating the effects of yarding/hauling operations includes addressing soil compaction; increasing surface cover; managing drainage from skid trails and road networks; hardening and/or roughening flowpaths with a high likelihood of concentrated surface runoff; and reducing connectivity between hillslopes, skid trail and road networks, and streams. Each of these mitigations has a unique set of costs and benefits.

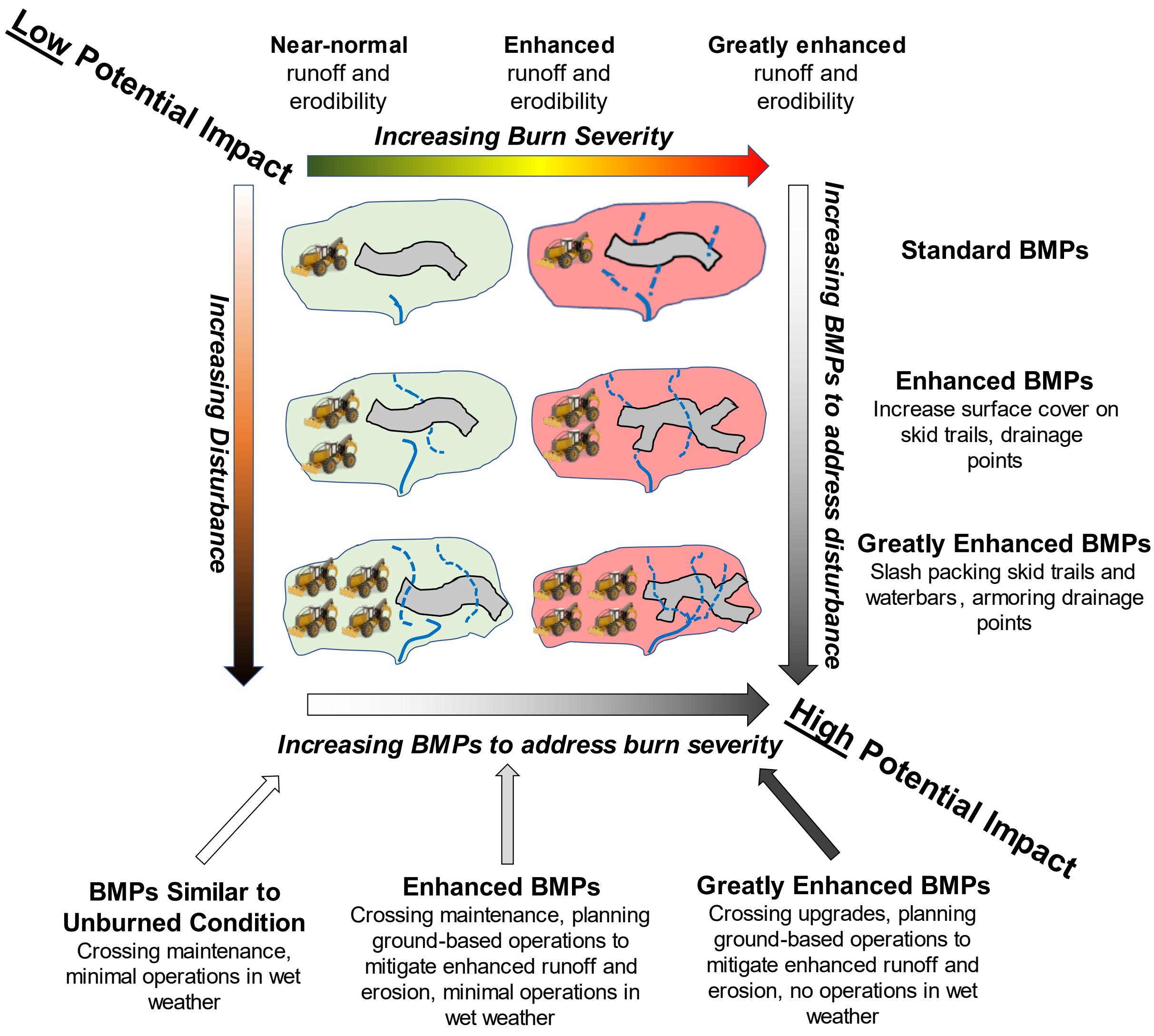

Figure 10. Conceptualization of the amount of potential impact of post-fire salvage logging as soil burn severity (Table 1) and/or ground disturbance increase. In this figure, the number of skidders represents the intensity of ground disturbance, the amount of grey-shaded area represents the spatial extent of the compacted skid trail network (see Section 3.3), burn severity (low or high) is represented by the colored background shading, and flow paths are shown as blue lines. The amount of sediment delivered to the stream network, depicted here as “impact”, will increase when the runoff source strength, soil erodibility, and/or hillslope-stream connectivity increase. Example BMPs for each disturbance scale can reduce potential sediment delivery.

As the burn severity or the amount of soil disturbed by post-fire salvage logging activities of a given site increases, the potential for elevated runoff source strength, increased soil erodibility, and increased connectivity between hillslopes and the stream network also increases (**Figure 10**). Each site has unique combinations of fire and disturbance impacts, and different regions have different precipitation regimes which can affect the runoff source strength. It is therefore important to consider the local risk factors when selecting the type and number of BMPs to mitigate sediment delivery from post-fire salvage logging. A greater level of mitigation and post-implementation monitoring is generally recommended in areas of higher burn severity and/or greater extent of soil disturbance (**Figure 10**).

The time it takes burned areas to recover to pre-fire conditions depends on factors such as burn severity and extent and post-fire weather patterns which affect vegetation regrowth (Wagenbrenner et al., 2021). Because of the complexity of the recovery process, no conceptual or empirical model predicts recovery rate well. For planning purposes, the period of highest hazard typically is about three years, though large post-fire floods have been reported for up to seven years after burning in the western U.S. (e.g., Robichaud et al., 2013). The effects of salvage logging may be present for much longer periods. For example, soil compaction has been detected decades after timber harvest in unburned forests in the western U.S. (Miller et al., 2004).

The following BMPs for post-fire salvage logging have either been tested in areas subject to post-fire salvage logging or are supported by assessment of the physical processes that cause increases in runoff, erosion, and sediment delivery. Combinations of these practices would likely lead to greater effectiveness.

4.1 Planning and design

Use of soil burn severity in planning

If available, SBS or BARC maps should be obtained to provide a spatial overview of soil burn severity for the burned area. The products might be available from BAER or WERT teams. In the absence of these products, practitioners can coarsely map soil burn severity using the diagnostic criteria of **Table 1**.

Erosion hazard rating (EHR) assessment

Following state or federal guidelines, an erosion hazard rating assessment can provide information about the potential erosion risk and the need to mitigate that risk. Generalized erosion hazard can increase dramatically after wildfire. However, post-fire conditions are not directly accounted for in the erosion hazard rating worksheet for California (see Technical Rule Addendum #1 of the CA FPRs, CAL FIRE, 2022).[5] Several adjustments to the rating can accommodate post-fire soil conditions:

- The detachability of the soil is the most sensitive factor in the EHR assessment, and the detachability of the soil can be modified to a more erodible condition. Maximum soil temperature reached during the wildfire affects the erodibility of

[5] A digital version of TRA #1 is available for rapid use over large wildfire areas.

soil, and this change in detachability is reflected in the soil burn severity maps (Moody et al., 2005). Practitioners may use values between 19-30 if soil burn severity is moderate or high and/or if the surface soil has a high ash content relative to soils in unburned areas.
- The effects of fire on infiltration capacity in moderate and high burn severity soils can be accounted for by reducing the permeability. Practitioners may use values for low permeability in the EHR worksheet.
- The depth to restrictive layer can be used to reflect fire-induced changes in soil water repellency. Practitioners may use values reflecting shallow depth to restrictive layer (e.g., values from 9-15).
- The soil cover factor accounts for changes in total organic cover (e.g., dead leaves and needles) as well as shrub or tree cover. Moderate and high soil burn severity will generally result in low soil cover. Practitioners may use a soil cover that reflects the post-fire cover condition.

Specific planning or mitigation activities can reduce the sediment delivery, particularly in areas rated at high or extreme soil erosion hazard. Furthermore, the calculated erosion hazard rating drives some of the prescriptive requirements of the CA FPRs, including slope prohibitions for ground-based logging and erosion mitigation requirements for roads and skid trails. Where available, high resolution (e.g., 1-m resolution) DEMs may be used in GIS to identify headwall swales or drainage routes that may develop post-fire channelized flow, resulting in potential Class III (ephemeral) watercourses where they were not present before the fire or first large post-fire storm or snow melt. Standard resolution DEMs (10 m) may be used to identify areas where moderate and high soil burn severity intersect steeper slopes. Many large wildfires will have a post-fire debris flow probability map from the USGS that may be used to identify areas of increased peak flow, hyper-concentrated flow, or debris flows within a project area. While the accuracy of the absolute predictions of the USGS debris flow models can be variable for different parts of California, the model predictions generally offer a reasonable prediction of areas with a relatively higher likelihood and magnitude of post-fire hydrologic and sedimentary response (Cafferata et al., 2021).

Road, skid trail, cable row, and landing placement and utilization

Existing documents and the CA FPRs provide guidance and regulations related to the appropriate harvesting practices (i.e., logging system) and associated BMPs relevant for accessing and yarding timber (i.e., erosion mitigation for skid trails and cable rows). Yarding by fully suspending logs via cable yarding or helicopter are low-impact alternatives and may be operationally and economically feasible. However, ground-based yarding is the most common logging system implemented in fire-prone areas of California.

Key considerations when implementing ground-based logging in burned areas include much higher rates of hillslope surface runoff than under unburned conditions, runoff production that will vary considerably under different soil burn severities (**Figure 11**), and the linear nature of logging disturbance that can concentrate and enhance the ability of this runoff to erode soil. Practices for avoiding impacts associated with ground-based yarding include reducing the total area impacted by ground-based felling or yarding equipment; reusing existing skid trails; avoiding placement of new trails near watercourses, aquatic resources, directly down steep slopes, or in a manner that concentrates runoff; and implementing erosion mitigation treatments.

Consideration of the potential runoff generation and runoff flowpaths into logging design and BMP implementation can be used to mitigate the sediment delivery related to post-fire salvage logging operations. For instance, skid trails should be placed in a manner that interrupts or disperses flowpaths rather than concentrating them. Waterbar installation on skid trails or cable corridors should take into consideration the excess runoff from burned hillslopes compared to unburned hillslopes in addition to runoff generated from the logging-impacted soil. Skidding down or up convergent topography (swales) should be avoided.

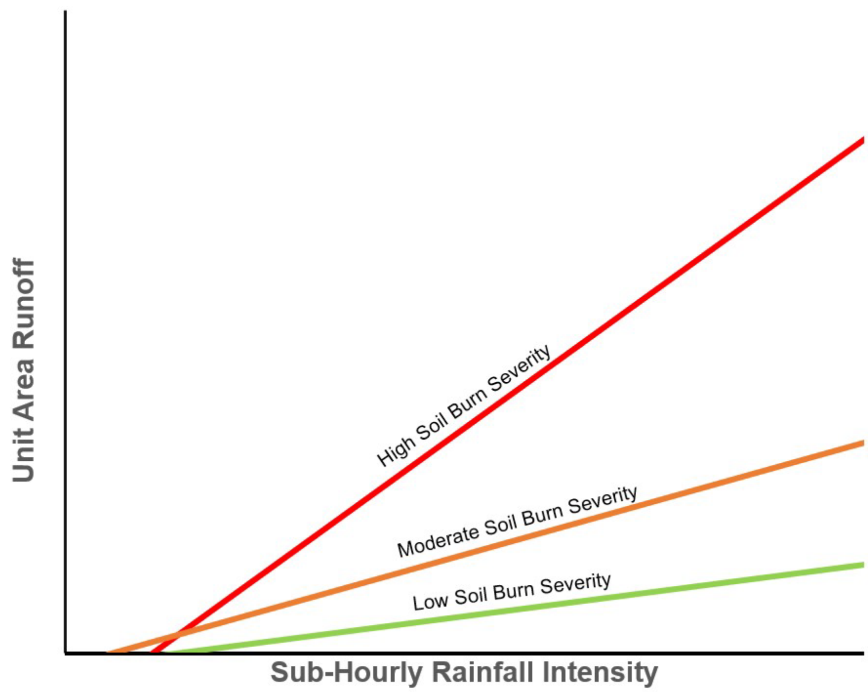

Figure 11. Peak stream flow rates in areas of different soil burn severities in the northern part of the California Coast Ranges. Lines reflect the difference in the runoff and rainfall intensity relationship among catchments burned at different soil burn severities for the first winter (2015-2016) following the 2015 Valley Fire at Boggs Mountain Demonstration State Forest.

4.2 Mitigation of yarding operations

Addressing soil compaction

Heavy equipment traffic increases compaction, rutting, and soil displacement. Even a single pass of a machine like a tracked skidder or feller-buncher can compact soil (Wagenbrenner et al., 2016), and compaction is an important factor in runoff generation after salvage logging (Prats et al., 2021).

Operating period

Operations during wet periods will lead to even more severe impacts on runoff and sediment delivery and should be avoided. In areas that receive sufficient snowfall, over-the-snow yarding can reduce soil compaction if the packed snow layer is at least 12-18 inches deep (Nash et al., 2020).

Decompaction

Ripping or subsoiling, which is ripping with winged tines, of compacted areas can increase infiltration rates and reduce surface runoff and sediment delivery (James and Krumland, 2018). However, applying these techniques along slopes greater than about 5% (i.e., ripping along skid trails that follow a slope rather than the contour) can increase concentration of flow in the furrows and lead to high rates of erosion and sediment delivery (Demirtas, 2017; Olsen et al., 2021).

Increasing surface cover

Vegetative regrowth following fire and post-fire salvage logging increases canopy cover by increasing leaf area and ground surface cover through the contribution of dead leaves and stems to the forest floor. However, vegetative recovery can take years, and during that period bare soil is vulnerable to erosion. Increasing surface cover is the most effective way at mitigating the risk of increased soil erosion in areas impacted by heavy equipment.

Adding slash

Cut-to-length harvesting methods increase surface cover by adding logging slash. Redistribution (scattering) of slash from landings or piles to harvested hillslopes can also reduce erosion and sediment delivery and increasing the slash contact with the ground surface makes the slash more effective at reducing sediment delivery (Robichaud et al., 2020). “Walking-in” the slash increases the slash contact with the soil surface, making these practices more effective on skid trails. However, using heavy equipment to distribute slash on untrafficked slopes or increase slash to soil contact can also increase compaction, reducing the benefit of these practices. Adding slash can also increase residual fuel loads, and this aspect should be considered during planning. Targeted slash placement, such as on or adjacent to compacted areas, can reduce hillslope-stream connectivity and may reduce fuel continuity.

Mulching

Adding straw, hydromulch, wood shreds, shredded bark, or other similarly elongated and interlocking material at coverage rates greater than 60-70% has been shown to reduce erosion and sediment delivery rates in burned areas and can be used to reduce erosion after post-fire salvage logging (e.g., Prats et al. 2019). This is particularly important near watercourses, such as at crossing approaches, where potential connectivity can be high. These materials should not be placed close enough to the watercourse where they may be transported by high post-fire flood flows. In general, grass seeding has been shown to be ineffective in post-fire applications (Cafferata et al., 2021).

Managing drainage from skid trails

Increase drainage frequency

Reducing the distance between waterbars or other drainage structures on skid trails as compared to the standard spacing identified from the erosion hazard rating assessment will lead to smaller relative flows exiting the skid trail. Theoretically the smaller flows from the smaller areas of compacted soil should produce less erosion and sediment delivery as compared to the larger flows related to standard waterbar spacing, at least during low to moderate intensity storms. However, initial test results using a high intensity rainstorm did not show any reduction in sediment delivery when the waterbar spacing was halved (Wagenbrenner, unpublished data) (**Figure 12**; see "double drainage").

Placement of drainage structures

Multiple skid trails and drainage structures in close proximity to one another can lead to a "stacking" of runoff and erosion (**Figure 8**). Drainage structures should be placed in a manner that minimizes runoff concentration and connectivity due to this "stacking" effect. For example, for multiple skid trails that follow contours, the drainage outlets can be separated or spaced so that runoff does not combine in the same flow path to avoid "stacking". Alternating the direction of the drainage or draining to convex or planar surfaces may also help to minimize runoff concentration and connectivity.

Hardening and/or roughening skid trail or waterbar outlets

This practice can increase the roughness of the concentrated flow path, which can lead to greater deposition and reduced sediment delivery over the times scale of post-fire recovery (approximately 3-7 years). Initial results suggest that adding slash cover to skid trails to achieve 50% surface cover or increasing slash cover at the outlets of waterbars or other drainage structures to 70% surface cover can reduce sediment delivery rates (**Figure 12**; Wagenbrenner, unpublished data). Adding other heavy cover elements, such as large rocks (~6 inches), would likely have similar effects as slash (Cafferata et al., 2017).

4.3 Reducing connectivity between hillslopes, road networks, and streams

Increase patchiness

Sediment has an opportunity to deposit in areas of higher surface cover or low slope that are downslope of equipment-impacted areas. Planning operations in small patches provides more edge length per unit area of impact, and this may reduce the connectivity between hillslopes and streams as compared to larger patches. For instance, patch sizes of ground disturbance can be minimized by more frequent use of end-lining logs.

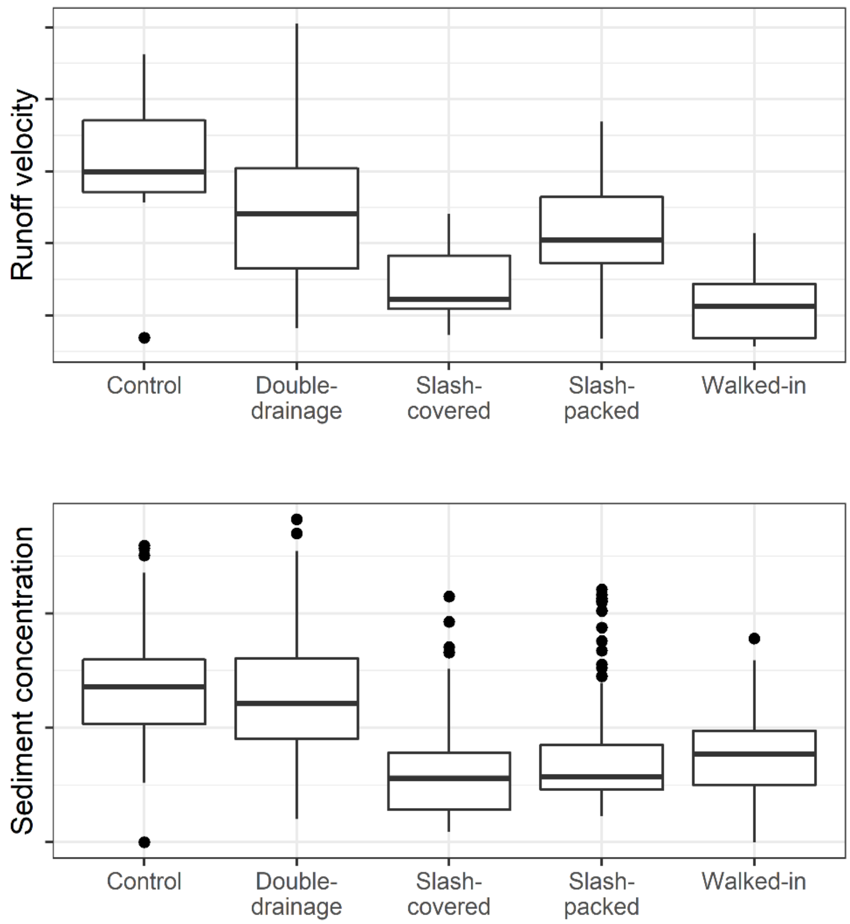

Figure 12. Initial results from a controlled runoff experiment in a post-fire salvage logging environment. “Control” plots were skid trails with waterbars spaced as directed using the CA Forest Practice Rules and soil erosion hazard rating worksheet (100 ft between drainage features) and no added surface cover on the skid trail or waterbar outlet. “Double-drainage” was a skid trail with half the waterbar spacing (50 ft between drainage features) and no extra surface cover on the skid trail or waterbar outlet. “Slash covered” had waterbars at the regular spacing (100 ft) with 50% cover of slash on the skid trail and 70% cover of slash on the waterbar outlet. “Slash-packed” had waterbars at the regular spacing (100 ft) with no extra cover on the skid trail and 70% cover of slash on the waterbar outlet, and the slash was driven over by heavy equipment to increase ground-wood contact. “Walked-in” had waterbars at the regular spacing (100 ft) with 50% slash cover on the skid trail and 70% cover of slash on the waterbar outlet and the slash was driven over by heavy equipment to increase ground-wood contact. Upper panel: runoff velocity along the skid trail flow path. Lower panel: sediment concentration in water samples collected below the waterbar outlet. (Wagenbrenner, unpublished data).

Adding cover downslope of compacted areas

Surface cover, such as slash, can also be added to areas immediately downslope of equipment-impacted patches, where it would increase roughness and facilitate sediment deposition and decrease connectivity between hillslopes and streams.

Reduce convergent linear features

Orienting skid trails and feller-buncher tracks along the contour would reduce convergence and help distribute runoff generated from the compacted areas. Similarly, positioning landings or haul roads along ridges would lead to less downslope convergence and hillslope-stream connectivity. However, upslope yarding (e.g., “adverse skidding”) can result in increased soil churning and rutting and may cause additional disturbance on steeper slopes and may need to be further mitigated. Skidding down or up convergent topography (swales) should be avoided.

Contour subsoiling or ripping

Contour subsoiling or ripping can reduce surface runoff from hillslopes and allow sediment to deposit in the furrows. This reduces the hillslope-stream connectivity when the storage capacity of the furrows is sufficient to store the runoff and sediment delivered within the recovery period (Cole et al., 2020). The storage capacity of the contoured furrows can be exceeded by high runoff, high sediment deposition rates, erosion of the ridges and filling of the furrows over time, or a combination of these factors. This BMP has not been rigorously tested in areas where high-intensity rainfall is common, post-fire recovery is slow because of extreme burn severity, or recovery after the fire or salvage logging is delayed because of site-preparation. Cases of runoff and sediment breaking through the ridge/furrow microtopography have been observed, and site factors such as the soil properties and slope which may affect the likelihood of this occurring should be considered before implementing this practice.

Streamside management zone (SMZ), aquatic management zone, and watercourse and lake protection zones (WLPZ)

State and federal regulations set standards for the protection of aquatic resources. Additional protection can be implemented such as extending the no-entry buffer zone along streams. A recent study compared travel distance and sediment concentration of surface runoff conditions in different burn severities and time since burning (Robichaud et al., 2021). **Figure 13** shows sediment travel distance as a function of soil burn severity and time since fire. This figure suggests that ground-based logging in areas of high soil burn severity soon after the fire have the potential for generating much longer sediment travel distances than areas of lower soil burn severity or unburned areas. These results can be used to guide protection of aquatic resources in burned areas during the operational planning, BMP design, and BMP implementation and monitoring phases.

Reducing diversion potential at watercourse crossings

After severe wildfire, increased runoff, sediment, and debris loads should be anticipated at watercourse crossings (Cafferata et al., 2017). Because roads can act as barriers or sinks, these watershed products can cause blockages at the inlets of drainage structures (**Figure 4**). Crossing structures can be easily overwhelmed by runoff during relatively high frequency storms (e.g., <2-year recurrence interval), placing the crossing structure, road surface, and fill at risk of failure. When runoff is diverted down road surfaces, it can potentially create a cascade of erosion features (e.g., gullies or runoff-initiated landslides) on previously undisturbed hillslopes. Drainage capacity can be increased or protected by upsizing culverts, or installing emergency overflow pipes, slotted culvert risers, and flared metal end sections. Undersized culverts can be replaced by rock-armored crossings designed to accommodate much higher flows and debris loads. Dips (critical dips, diversion prevention dips, rolling dips, or culvert relief dips) placed adjacent to culverts or other watercourse crossing structures can allow runoff to remain in the watercourse even when the crossing structure is blocked. Designing and hardening the dip for overtopping flows will reduce the potential for erosion of the road fill. Additionally, protecting culverts from deposition of wood and sediment would help reduce the risk for blockage and mitigate impacts from potential increases in flows, sediment, and wood loads. Significant runoff and sediment delivery can occur during relatively small, high-frequency storms (e.g., well below the 1-year recurrence interval). Establishing appropriate rainfall thresholds that trigger monitoring activities for high-risk crossings (Cafferata et al.,2017) would help maintain watercourse crossing protections throughout the recovery period.

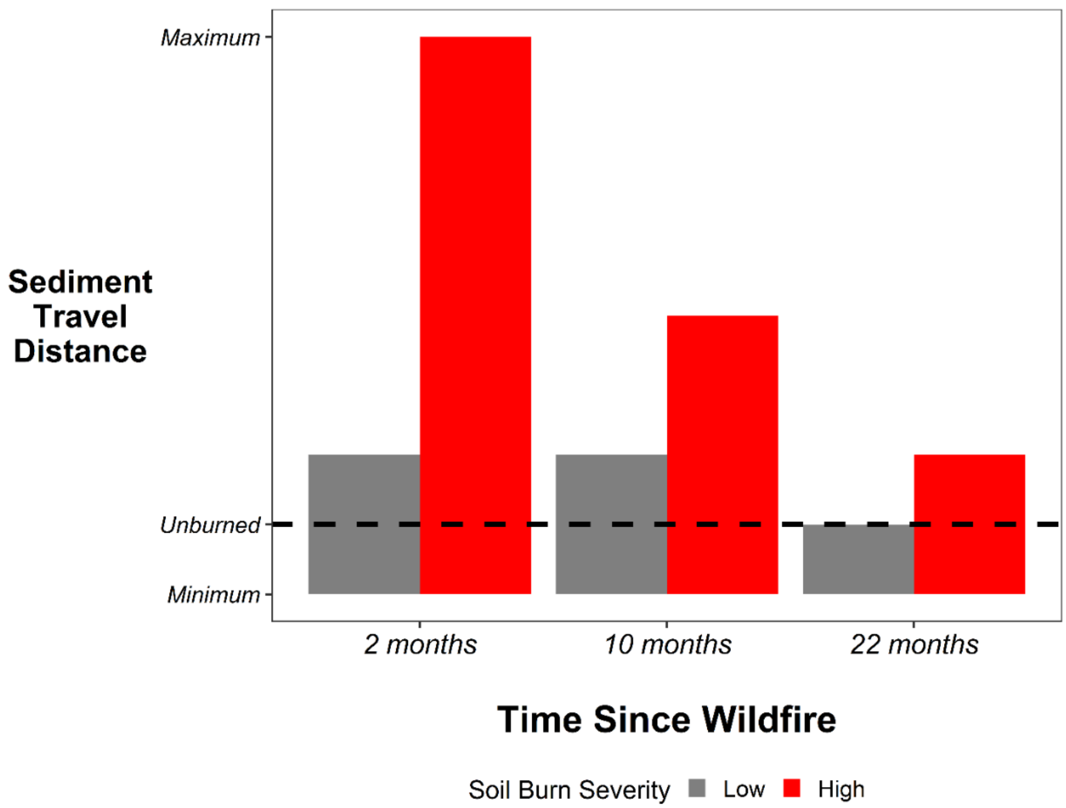

Figure 13. Sediment travel distance as a function of soil burn severity and time since wildfire. Figure created using data on the travel distance of applied runoff versus time since burning under different burn severity conditions after the 2015 North Star Fire and 2016 Cayuse Mountain Fire in eastern Washington (Robichaud et al., 2021). For these experiments, sediment-laden runoff was applied to a hillslope of the burn condition, and the distance the runoff traveled before it completely infiltrated was measured. Original data were scaled to the unburned condition to determine the travel distance multiplier. While the data used to make this figure come from burned coniferous forests in eastern Washington, we expect soil burn severity and time since fire to have the same relative effect on sediment travel distances in burned California forests.

Managing drainage from road network

Forest roads are a source of runoff and sediment, which can be partly mitigated by road specific BMPs (e.g., drainage, surfacing, design). After severe wildfire, increased road-stream connectivity can be expected because of increased surface runoff and the reduction of infiltration capacity on burned areas downslope of roads (Sosa-Pérez & MacDonald, 2017, Benda et al., 2019). Post-fire BMPs for roads can be used to mitigate these hazards (Foltz et al., 2009). In addition, roads can intercept and concentrate runoff generated from burned and logged hillslopes, which can further increase erosion from roads and hillslopes located downstream of the road drainage outlets. BMPs to mitigate increased runoff and sediment delivery from roads that are specific to post-fire salvage logging have not been developed. Protecting the tread surface via rocking, outsloping roads where feasible, increasing drainage capacity by upsizing or installing more road drainage structures (e.g., rolling dips), and maintaining the road and drainage structures after hauling and storm events would help mitigate potential road-related increases in runoff and sediment. Connectivity between road drainage features and streams can be reduced via practices described earlier for skid trail drainage (e.g., by adding slash or rock armor to drainage outlets; Section 4.2).

Summary of operational BMPs

None of the practices described herein will completely eliminate sediment delivery from areas affected by post-fire salvage logging during very high intensity runoff-generating events. However, the practices described above can mitigate the runoff, erosion, and hillslope-stream connectivity, and their effectiveness is related to the physical processes they affect, their design, and their implementation (**Figure 14**). Their effectiveness can also be influenced by site conditions such as soil or parent material, burn severity, slope, extent of machine-disturbed area, and rainfall or snow melt characteristics. No study has tested the relative effects of all of the BMPs. Benefits may be additive, and in areas of higher risk of sediment delivery (**Figure 10**), multiple mitigations should be considered.

Practice	Runoff	Erosion	Connectivity
Addressing soil compaction			
Avoid wet periods	○	◉	◉
Decompaction by ripping/subsoiling skid trails or landings	●	◉	◉
Increasing surface cover			
Increase slash cover	◉	●	●
Apply mulch to compacted areas with bare soil	◉	●	◉
Managing drainage from skid trails			
Increase drainage frequency	○	○	◉
Placement of drainage to avoid “stacking”	○	◉	◉
Harden or roughen skid trail surface	○	◉	○
Harden or roughen waterbar outlets	○	◉	○
Reducing connectivity between hillslopes, skid trail and road networks, and streams			
Increase patchiness	○	○	◉
Add cover downslope of compacted areas	○	○	◉
Reduce convergent linear features	○	○	◉
Contour subsoiling or ripping	●	◉	●
Extend streamside management zone	○	○	●
Reducing diversion potential at watercourse crossings	○	◉	◉
Managing drainage from road network	○	◉	◉

Figure 14. Authors’ perspective of the relative effect of each of the operational BMPs on runoff, erosion, and connectivity between the hillslope and stream. Full circles indicate the largest mitigative potential, partly filled circles represent a mid-level mitigative potential, and empty circles represent relatively small mitigative potential. Site conditions, operational practices, and runoff-generating events may change the relative effects for any BMP. Although the effects across BMPs are not directly additive, sites with higher potential impacts (e.g., higher burn severity, more extensive compaction, or greater soil disturbance by logging machinery), may benefit from using several BMPs.

4.4 Monitoring

Post-fire hydrologic recovery depends on the amount of area burned, the burn severity, and the post-fire revegetation rates, which are affected by climate and post-fire weather conditions (Wagenbrenner et al., 2021). Post-fire salvage logging and other management activities may affect the recovery period and the period of elevated runoff and sediment delivery responses (Ebel et al., 2022). Because most post-fire salvage logging occurs early in the post-fire recovery period, there may be several years of increased risk of elevated surface runoff and sediment delivery following the logging. Results from monitoring efforts can therefore be useful in repairing and adjusting BMPs, providing for adaptive management on operational timescales, and to ensure the effectiveness and maximize the mitigation potential of BMPs throughout the recovery period. Making monitoring findings publicly available can help improve site specific implementation and effectiveness of the proposed measures presented herein in future post-fire salvage operations. Monitoring activities might include:

- Monitoring the implementation of BMPs prior to rainfall to determine if BMPs were implemented as designed, including, proper placement and construction (i.e., implementation monitoring).
- Assessing BMPs for damage or plugging after rain or wind events and determining if they were effective in preventing sediment delivery (i.e., effectiveness monitoring). Rainfall rates above 0.2 inches per hour can create some surface runoff and erosion and may provide useful feedback about BMP effectiveness with low risk of BMP failure. Rainfall rates closer to the 1-2 year recurrence interval can result in significant runoff and sediment delivery, and would test well-designed and implemented BMPs.
- Since surface cover is an important determinant of post-fire erosion (Larsen et al., 2009), it is important to monitor vegetative recovery over time following post-fire salvage logging using field observations or remote sensing. This can help determine if the logged area will be less susceptible to increased runoff and erosion during future precipitation events.

4.5 Research or technology development needs

There are few studies that have assessed the effectiveness of BMPs used to mitigate runoff, erosion, or sediment delivery after post-fire salvage logging. For example, the relative effects on sediment delivery rates of increased cover and increased compaction caused by using heavy machines to place slash on otherwise untrafficked hillslopes are not well known. Recent results from small rainfall simulation plots show that the surface cover has a greater impact on erosion than compaction (Prats et al., 2019, 2021). Similar comparisons at hillslope scales would be useful in assessing the individual and cumulative effects of adding cover and compacting soils.

The timing of salvage logging after the fire may have an impact on the runoff and sediment delivery rates but has not been tested. Logging soon after the fire may result in less impact on recovering vegetation, since the amount of vegetation will be lower. However, the runoff and erosion rates may be higher during the early post-fire period, and this may lead to a greater overall effect in absolute terms. Logging later may result in more impact on the recovering vegetation, but since the disturbance occurs later in the post-fire recovery period, the risk of sediment delivery may be lower.

Most post-fire salvage logging studies have been done at scales small enough to isolate individual impacts or processes (Cole et al., 2020; Lucas-Borja et al., 2019; Robichaud et al., 2021; Slesak et al., 2015; Wagenbrenner et al., 2015, 2016) or in small drainages or watersheds (James & Krumland, 2018; Olsen et al., 2021; Wagenbrenner et al., 2015). Effects of post-fire salvage logging and BMPs at larger spatial scales are relatively unknown.

Studies that assess whether specific skid trail layout patterns affect sediment delivery are also needed. For example, a herringbone-patterned layout with main travel routes leading to short, low-traffic side trails may increase total disturbed area but may also reduce skid trail to stream connectivity and overall sediment delivery. Similarly, branching dendritic-patterned skid trail networks made up of heavily used main travel routes leading to successively lower traffic skid trails may increase connectivity and sediment delivery despite their smaller extent of disturbed soil.

There is a need for studies that measure the relative and absolute sediment delivery rates from harvests conducted with alternative forwarding techniques such as slash mats using a harvester or shovel logging. Observations suggest that these techniques in unburned forests result in less impact than whole-tree skidding and would likely reduce runoff and sediment delivery rates in burned areas when compared to post-fire salvage logging using traditional ground-based equipment. Similarly, equipment for timber harvesting in wet or sensitive soils, such as skidders with balloon tires, has been developed for unburned harvests (Stokes & Schilling, 1997) and might reduce the impact on burned soils during salvage logging. The rise of winch-assisted (tethered) ground-based yarding shows potential for use in post-fire salvage logging, but little is known about the benefits and/or trade-offs of using this logging system in fire-impacted areas. These or other technological developments might reduce the extent of the skid trail network and/or the ground-pressure of heavy equipment and the relative advantages and disadvantages of their use on burned soils should be assessed.

Excavator-mounted subsoiling equipment has been developed and used on roads and skid trails in unburned forests (Monk, 2009). This technology may have the capacity to de-compact skid trails used for post-fire salvage logging without additional disturbance to the areas outside of the skid trails.

Site preparation using mechanical or herbicide treatments is often done to increase the conifer seedling regeneration rate relative to natural regeneration in burned areas. This can be done following post-fire salvage logging (Cole et al., 2020; James & Krumland, 2018) or without logging as an intermediary step. Site preparation treatments can potentially affect ground cover and soil properties (e.g., bulk density and soil strength). The relative effects of site preparation have not been widely tested (Cole et al., 2020), and have not been individually assessed at spatial scales greater than a few hundred square feet. Questions remain about the erosional responses to different site preparation techniques following post-fire salvage logging.

5 Summary and Conclusions

Wildfire can increase surface runoff, soil erosion, and sediment delivery, and ground disturbance from post-fire salvage logging can further impact these processes. Various resources are usually available for large fires that can be used to identify areas with greater fire impacts and greater potential sediment delivery, including maps of soil burn severity or burned area reflectance classification, potential debris flow areas, and potential flood areas. Compacted areas like skid trails, roads, and landings are the most susceptible to increased runoff and erosion, and reduced connectivity between compacted areas and streams can reduce sediment delivery at larger spatial scales. Best management practices (BMPs) can be implemented at different stages of post-fire salvage logging to reduce the potential for increased sediment delivery: planning and design, during and after yarding operations, and during road maintenance. This document describes BMPs that can reduce runoff, erosion, and hillslope to stream connectivity, and the planning and implementation of specific practices will depend upon site conditions and constraints. Frequent monitoring of post-fire salvaged logged areas and the performance of implemented BMPs after substantial rainfall events can be used to refine management plans. This rapid type of adaptive management can help reduce the risk of increased sediment delivery caused by sequential runoff generating events during the post-fire recovery period as the effects of wildfire and ground disturbance on soils, surface runoff, erosion, and sediment delivery return to pre-fire conditions.

Acknowledgements

We thank Lee MacDonald, Pete Robichaud, Sergio Prats Alegre, Maruxa Malvar Cortizo, Chris Faubion, Bob Brown, Don Lindsay, Kevin Bladon, Ryan Cole, Javier González-Romero, Manuel Lucas-Borja, John Deane, Ellyn Rickels, Megan Arnold, Jayme Seehafer, Diane Sutherland, John Whiting, and Iskender Demirtaş for their contributions to studies that we relied on for this report as well as many insightful discussions on the topic. We appreciate the assistance of the Boggs Mountain Demonstration State Forest staff and access to the BMDSF lands that allowed us to implement studies after the Valley Fire that have informed this document. Similarly, we thank the Stanislaus National Forest staff for their cooperation and assistance in a series of studies conducted after the Rim Fire. We thank Chris Anthony, Pete Cafferata, George Gentry, Bill Short, Mathew Boone, Ronna Bowers, Kelly Hickcox, Debra Hallis, and Jonathan Warmerdam for detailed reviews of earlier drafts of this report. Partial financial support was provided by the Timber Regulation and Forest Restoration Fund (administered by the California State Water Resources Control Board), CAL FIRE's California Climate Investments Forest Health Grant Program, USDA Forest Service Pacific Southwest Research Station, and Michigan Technological University.

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