

Partial Harvest in Watercourse and Lake Protection Zones Using Low Ground Pressure Equipment to Support Fire Resilient, Ecologically Diverse Stands and Associated Ecosystem Services

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Introduction

The Board of Forestry and Fire Protection (Board) has received several comments expressing concerns that restrictions in riparian corridors may be contributing to the size and severity of recent wildfires. It has been hypothesized that California's history of fire suppression and policy of limited management in Watercourse and Lake Protection Zones (WLPZs) is resulting in increased fire severity in riparian corridors. When considering timber harvest in WLPZs concerns arise with respect to aquatic and riparian habitat conditions, appropriate stand structure, and essential functions related to soil and water quality. However, recent conditions indicate that fire severity in riparian corridors located in the interior part of California may already be resulting in significant adverse effects on many of these critical functions. Moving forward, these management strategies require re-assessment and trade-offs must be considered. In some cases, the development of resilient forests may warrant the use of timber harvesting strategies that utilize low pressure ground equipment in WLPZs to prevent extreme fire conditions and subsequent soil, water quality, and species composition impacts.

Limited ground-based timber harvest activities in WLPZs are currently supported under the California Forest Practice Rules (FPRs) if explained and justified by a Registered Professional Forester (RPF) as an in-lieu practice and approved by the Department of Forestry and Fire Protection. This white paper uses information from scientific studies to inform resource professionals where and when use of certain low ground pressure equipment in WLPZs may be appropriate to reduce wildfire severity without producing significant adverse impacts, while considering site-specific conditions and utilizing Best Management Practices (BMPs).

Historic and Current Conditions of Riparian Forests

Historic Fire Return Intervals

Many studies have illustrated that modern fire return intervals have deviated significantly from historic fire return intervals, with associated changes in intensity and severity. Van de Water and North (2010) present a model-based comparison of present

and reconstructed fire histories and stand structures. Using three regions of the northern Sierra Nevada, dead trees with long fire histories were sampled in riparian and upland areas. Tree samples were analyzed to develop fire return intervals before and after 1850 as well as to determine the seasonality of burns. The study found that fire histories between upland and riparian areas were very similar, indicating that “riparian forests bordering many montane streams might be managed for fuel loads and fire return intervals similar to adjacent upland forests.”

Several other studies indicate that historic fire regimes were often composed of frequent, low-intensity fires and highlight the importance of heterogeneity on the landscape. This heterogeneity tends to produce a patchwork of fire severities, creating a more diverse landscape that is better able to slow high-intensity fires while maintaining smaller areas of high-severity fire that can encourage stand diversity (Kilgore & Taylor, 1979).

High Stand Density and Resulting Fire Regimes in Riparian Areas

Anecdotal evidence is noted in several studies, and the York & Roughton, 2019 presentation suggests that stand densities in riparian forests are higher than they have been historically and may be linked to increased fire behavior across the interior forests of California. For example, Dr. York provided images in his presentation showing the difference between managed upland stands and riparian stands, with the riparian stands having significantly higher vegetation densities. Additionally, he noted that the El Dorado National Forest experienced the King Fire in 2014, which burned across riparian and upland areas near Blodgett Forest Research Station. A visual assessment of the land post-fire showed some live trees in upland regions and mostly dead trees in riparian corridors, indicating that the fire may have burned more severely in riparian areas.

Several empirical studies support this notion, indicating that stand densities are higher and stand composition dynamics are making these areas more fire-prone (Jurgensen et al., 1997; van de Water and North, 2011). Van de Water and North (2011) suggest that California’s history of fire suppression, limited management areas, and higher moisture content in riparian corridors have resulted in high stem densities and fuel loads in these areas. It has been proposed that the difference in spatial severity seen in the 2014 King Fire and in other recent fires may subsequently be the result of over-stocked riparian corridors.

In their 2011 study, van de Water and North’s model reconstructed historic stand conditions for riparian and upland forests. They then compared these reconstructed models to current stand conditions to approximate departure from historical stand conditions and fire regimes. They found that both riparian and upland forests have significantly greater basal area, stand density, snag volume, canopy bulk density, duff, and total fuel load when compared with the reconstructed stands. Also noted were significantly lower torching and crowning indices. A comparison between current upland and riparian stands indicates that riparian forests have lower quadratic mean diameter,

canopy bulk density, and proportion of fire-tolerant species; higher stem density, probability of torching, and greater predicted mortality than upland stands. Indeed, van de Water and North state that “denser riparian stands composed of primarily fire-intolerant species with more vertical continuity of canopy fuels may result in higher riparian fire severity,” and cite “observations of greater occurrence of crown fire near stream channels.” In contrast, reconstructed riparian and upland forests appeared to have no significant difference in fire intensity indices, consistent with their earlier findings (van de Water & North, 2010).

The departure from historic stand conditions in both upland and riparian stands may be contributing to the extreme fire regimes California has been experiencing in the Sierra Nevada. More importantly, riparian stands are more divergent from historical structures than upland stands, putting these areas at greater risk for high-severity fires and changes in ecosystem function. As linear landscape features, this increase in fire severity in riparian areas may also contribute to larger fires; over-stocked riparian areas have been hypothesized to act as “wicking” agents along their length, sometimes carrying fire into unaffected upland areas (Pettit & Naiman, 2007; van de Water & North, 2011). Riparian areas historically served as moist areas that could lessen the intensity of fires or stop their spread upon approach, and while this still occurs in some places, this function has decreased in recent years and in some instances inverted.

[Impacts of High-Severity Fire on Water Quality and Site Productivity](#)

In addition to anthropogenic impacts on stand density and composition in riparian areas, changes in climatic conditions are resulting in significant increases in tree mortality across the landscape. Longer and more intense droughts have become a common occurrence in California, resulting in increased drought-related mortality and susceptibility to pests and diseases. This increase in mortality contributes to fuel loads in riparian corridors and is likely to drive more frequent and more severe fires in the future (Pettit & Naiman, 2007; van Mantgem et al., 2013, 2009). The implications of these changes in fuel loading are wide-reaching, particularly in riparian areas where downstream effects can span miles of river.

Ice, Neary, and Adams (2004) summarize a variety of effects that may result from severe wildfires and highlight the importance of these impacts for riparian areas. As more severe fires burn closer to watercourses, impacts are more likely to affect watershed processes. Specifically, soil can be impacted by increased fire temperatures resulting in the exposure of mineral soil as the fire consumes organic layers. A layer of negatively charged, hydrophobic soil can also develop on the surface. Poor soil cover and a hydrophobic layer can result in dry ravel, reduced infiltration and percolation, increased surface flows and subsequent surface erosion, slope failures and debris torrents, stream in-fill, changes in nutrient cycling, changes in annual and peak flow, and related impacts to wildlife. For example, sediment yields and annual flow measurements have been shown to double or triple following wildfire, resulting in higher turbidity, increased channel scouring, changes in primary productivity in streams, and

extreme water flows that may produce further bank failures or overloading of woody debris in streams (Dahm, Candelaria-Ley, Reale, Reale, & van Horn, 2015; Ice et al., 2004).

Soil health issues are compounded by reduced vegetation and canopy cover on riparian banks post-fire, which can result in severe increases in stream temperature and reduced bank stability. Additionally, Dahm et al. (2015) note changes in stream pH, conductivity, and dissolved oxygen, which may strongly affect macroinvertebrate community structure and could produce hypoxic conditions.

As severe wildfire impacts on riparian and aquatic ecosystem processes and wildlife become more apparent, it is important to consider that fire severity and location are much stronger determinates for soil and watershed responses to fire than the presence of fire itself (Ice et al., 2004). Restoration of historic fire regimes and stand densities will be an important component of fire prevention in future years, and careful management of riparian areas to prevent adverse effects to water quality as well as riparian and aquatic wildlife will be essential.

Restoring Pre-Colonization Stand Dynamics

In an environment that has evolved with fire serving as an integral part of the life cycle, it is not surprising that anthropogenic exclusionary practices have been associated with structural and compositional changes in forests (Messier, Shatford, & Hibbs, 2012). Several studies have cited increased stand densities and increased fire severity in historically fire-prone areas, both of which have implications for stand complexity (Agee, 1993; Kilgore & Taylor, 1979; North, 2012).

Messier, Shatford, and Hibbs (2012) look specifically at fire exclusion effects on riparian forests, the impacts of reserve systems, and public policy related to forestry and prescribed burning in riparian corridors. They ask: do separate management strategies for riparian and upland forests with similar fire histories make sense; and how does fire exclusion in combination with these different management strategies affect riparian stand dynamics? Study results reveal that historic riparian forests were maintained by a mixed-severity fire regime which resulted in “complex, multi-aged stands with large, old fire-resistant trees” and a heterogeneous nature that included gap creation and unburned areas for fire-sensitive species (Messier et al., 2012). Changes in this dynamic are resulting in higher retention rates in riparian corridors and subsequently higher stand density. This increased stand density favors more shade-tolerant species and prevents the gap creation that historically allowed for the establishment of new shade-intolerant conifer species, resulting in reduced heterogeneity in stand density and age structure. Additionally, the preference for shade-tolerant species creates issues for wildlife as large stream-side conifers are often important for woody debris in streams and snag creation; with predicted lower future recruitment of these trees to replace the dominant canopy trees, these critical habitat features may decline. Messier, Shatford, and Hibbs (2012) conclude that current riparian management policies may be “detrimental to the long-term health of riparian forests in regions shaped by fire.”

Keane et al. (2002) reference similar conclusions; namely, that fire suppression and limited management are resulting in higher stand densities which may be having detrimental effects on riparian ecosystems. These effects can include: decreased biodiversity, increased crown and surface fuels, increased instances of fire-sensitive invasive species, increased pest infestations, changes in soil absorption, and changes in stand and landscape level composition and structure. Keane et al. (2002) cite many of the compositional and structural changes documented by Messier, Shatford, and Hibbs (2012), such as a shift to shade tolerant species, increased density, and changes in retention rates and successional patterns. However, Keane et al. (2002) also note the invasion and overgrowth of brush and shrubs into grasslands and shrublands because regular disturbance is no longer regulating the size and number of these fuels. This may also hold true in some forested lands with adequate light penetration to allow the growth of brush and shrubs, increasing surface fuels in these areas.

Keane et al. (2002) and Messier et al. (2012) both assert that neither thinning nor prescribed burning is independently sufficient to restore historical fire regimes. For the restoration of historical stand dynamics that are more conducive to lower severity fires, Keane et al. (2002) suggest the inclusion of thinning treatments as well as prescribed fire to restore ecosystem processes and prevent large, severe fires that kill more plants and alter more ecosystem processes. Messier, Shatford, and Hibbs (2012) echo these sentiments for riparian areas. They suggest that “large canopy gaps, un-treated ‘islands’, clumps and irregularly spaced trees” may be appropriate methods of thinning riparian areas to mimic historical disturbances, and that these treatments in addition to prescribed fire will “promote the recruitment of shade-intolerant, fire-resistant tree species, increase overall tree vigor, increase structural diversity, and create a more discontinuous forest canopy, restricting the spread of high-severity crown fires” (Messier et al., 2012).

Potentially Improved Habitat Conditions Resulting from Riparian Treatment

As detailed in previously referenced studies, wildfire has significant impacts on riparian areas and the wildlife that depend on them. This is particularly true in the case of high-severity fires, which are becoming more common in California following an era of fire exclusion and limited management policies in riparian corridors (Dwire, Meyer, Riegel, & Burton, 2016). Changes to soil structure can result in declines in water quality and water infiltration, negatively impacting aquatic species and downstream habitat; changes in tree vigor, stand composition, and age structure due to overstocking can result in declines in woody debris recruitment and inadequate habitat for some riparian species; increased susceptibility to pest infestations due to limited management and environmental stress can increase surface fuels and result in increases in invasive plant species. The list of potential habitat degradations that can result from severe riparian fires is endless. Indeed, these impacts have the potential to cascade through the ecosystem and downstream to many locations and species. Efforts to more closely mimic historic stand and fire dynamics in riparian corridors to shape a more frequent, less severe fire regime are essential for establishing fire resilience and restoring habitat

value, which in turn support healthy water, soil, and wildlife. While thinning operations can have significant impacts, several studies have stated that thinning efforts and prescribed burning may be a more controlled and less impactful method of management than the current fire regime, particularly when BMPs are employed (Keane et al., 2002; Messier et al., 2012; Scott, James, & Ralph, 2012).

[Ponderosa Fire \(2012\): A Case Study](#)

TO BE COMPLETED

Environmental Concerns Related to Heavy Equipment Use in WLPZs

Given California's historic use of riparian areas and the associated impacts of less advanced logging equipment, it is imperative that environmental considerations be included in any discussion of heavy equipment use in WLPZs. As discussed previously in the context of fire spread, watercourses serve as a key feature that links the landscape together. As such, any impacts to watercourses or surrounding riparian zones can result in impacts that reach far from the point of entry. This section is not intended to be an all-inclusive discussion of environmental concerns, as many concerns related to timber harvest are extremely site specific. Rather, this section covers many of the most common concerns.

Soils

[Soil Compaction, Runoff and Changes in Site Productivity](#)

Soil compaction and the associated implications for site productivity and water quality are some of the most commonly identified impacts of harvesting in riparian areas. As heavy equipment moves into these areas for harvesting, soils are put under pressure and the porous space between particles of soil becomes smaller. As these pores shrink in size and number, less water can percolate through them (Grigal, 2000). The results are 1) water is more prone to flow over the landscape, potentially carrying increased sediment loads into adjacent watercourses; 2) it is more difficult for new vegetation to establish roots, and more difficult for existing vegetation to adapt to changes in water availability resulting in depressed growth; and 3) residual vegetation becomes more stressed and may die, resulting in increased fuel loads (B. Poff, Koestner, Neary, & Henderson, 2011). Grigal (2000) echoes these findings and further asserts that the impacts of compaction can be compounded in areas with rutting by funneling runoff and sediment into waterways.

Froehlich and McNabb (1983) discuss these impacts at length, indicating that soils in the Pacific Northwest are particularly vulnerable to compaction due to low soil strength. Their paper describes the relationship between machine trips and increases in bulk density, indicating that most compaction occurs during the first few passes. They document that increases in bulk density have negative impacts on soil processes such as soil aeration and water movement and can result in subsequent impacts on site productivity. Reductions in shoot growth have been observed following compaction, and Froehlich and McNabb (1983) found that "soil compaction affects volume growth more

than it does height growth.” Further, their paper indicates that these impacts are long-lasting and can be expected to persist for decades. The ecological implications for reduced site productivity are particularly important in riparian areas that depend on canopy cover for temperature regulation and wildlife habitat.

Surface erosion and stream sedimentation

Soil compaction can result in many site impacts, as discussed above. Specifically, as an impermeable surface is imposed on the landscape, water is concentrated and forced to flow over land, picking up sediment as it flows (Sidle, Sasaki, Otsuki, Noguchi, & Abdul Rahim, 2004). Compaction accompanied by reductions in surface litter and vegetation cover can result in large amounts of surface erosion as natural barriers to erosive forces are removed from the system. These changes in the hydrology of a site can carry excess sediment to waterways, having subsequent negative effects on aquatic habitat.

Studies by Rice, Rothacher, and Megahan (1972), Sidle et al. (2004), and McCashion and Rice (1983) indicate that the most significant contributor to surface erosion in most logging systems is from road construction, where adequate soil compaction is required. McCashion and Rice estimate in their 1983 study that approximately 40% of sediment from surface erosion originates from road systems. In fact, Rice, Rothacher, and Megahan (1972) assert that the action of logging itself contributes very little to these erosive processes. Instead, focus for preventative measures should be shifted to roads and yarding methods.

Sidle et al. (2004) specifically looked at the impact of connectivity on stream sedimentation in logging systems by using a sediment budget to compare “temporal and spatial management effects on erosion and sediment delivery.” They assert that when considering the impacts of surface erosion on aquatic systems, it is imperative to consider the links between the disturbed location and the watercourse being affected. In other words, how is the sediment getting from the disturbed area to the watercourse and are there management strategies to mitigate erosion at this stage? Sidle et al. (2004) found that while total erosion values were similar, roads were 64% connected to watercourses while only 26% of skid trails were connected. Due to differences in connectivity, 112 major (greater than or equal to 0.05 m³) and 115 minor sediment deposits resulted from roads, with just 36 major and 26 minor deposits resulting from skid trails. Their findings indicate that while skid trails appeared to have slightly more total erosion, the level of connectivity between roads and watercourses was much higher, indicating a greater impact from road systems than from skid trails. Connectivity between skid trails and roads can exacerbate this problem, but management strategies to control connectivity with roads may help mitigate sediment contributions from both roads and skid trails. Connectivity between skid trails and roads is also a significant problem that may enable increased stream sedimentation, but management of road connectivity to streams may alleviate much of the total sediment reaching streams.

Lewis 1998 examined the impacts of logging on suspended sediment transport in the Caspar Creek Experimental watersheds. Suspended sediment has been sampled from both the North and South Forks since 1962 with fluctuations in suspended sediment recorded following logging operations in the early 1970's and in the 1990's under the modern FPRs. The results indicated that suspended sediment increased by 212% over a 6-year period following tractor logging operations in the 1970's without modern FPRs and 89% following logging in the 1990's with modern practices and primary cable yarding. Lewis (1998) asserts that the difference in impact is the result of "differences in road alignment, yarding methods, and stream protection zones." Improved management had a significant effect on reducing erosion inputs to waterways from timber harvesting. In addition to these reductions in potential impacts, a study by Nitschke (2005) indicates that sedimentation is increased more by severe wildfire than by harvesting because wildfire tends to disturb larger areas, reduces surface cover, and may create a layer of hydrophobic soil, further reducing permeability in the affected areas. The only exception that was found echoes the idea that roads are the greatest source of total and continuous sediment and enforces the concept that careful management and maintenance of roads and skid trails is one of the most important components for reducing surface erosion.

Nutrient Input and Cycling

Nutrient leaching that can be exacerbated by increases in surface erosion is a concern following timber harvesting because there are fewer plants taking up the available nutrients. The organic and inorganic nutrients that remain in the soils can be vulnerable to erosive forces, resulting in less productive soils, increased susceptibility to insect pests and fungal infections, and changes in water quality in adjacent water bodies (Jurgensen et al., 1997). The literature indicates some disagreement about the severity of impacts to watercourses and soil productivity. Nutrient leaching and other soil and water chemistry impacts are site specific and depend on a wide variety of factors including soil type and structure, tree type(s), existing soil chemistries, and climate (Dahlgren, 1998; Feller, Lehmann, & Olanski, 2000; Jurgensen et al., 1997; Nitschke, 2005).

Changes to levels of organic forms of nitrogen, phosphorus, and carbon are of particular concern with relation to nutrient leaching because studies indicate that they may take longer to recover (>50 years), can be more severe, and can have great impacts on key watershed processes (Jurgensen et al., 1997; Nitschke, 2005). Jurgensen et al. (1997) and Dahlgren (1998) assert that much of organic matter losses are associated with soil mixing during harvest and increased microbial activity post-harvest. This organic layer of soil is important for insulating lower layers from changes in moisture and temperature as well as preventing erosion. Increased erosion following decomposition can carry organic carbon, nitrogen, and phosphorus into watercourses, resulting in increased aquatic primary productivity. Nitschke (2005) states that fluctuations in dissolved organic carbon in waterways can increase post-harvest and may have some of the most detrimental effects on streams. Some of the effects of

additional organic inputs to streams do not seem to carry too far downstream – Dahlgren’s 1998 study at North Fork Caspar Creek showed that “nitrate concentrations were near those of the nonperturbed reference watersheds” by the time the stream left the experimental watershed (approximately 1,000 m in length). However, some papers state that the losses of organic matter from the harvesting site can have long-lasting impacts on site productivity (Nitschke, 2005). Nitrogen serves as the limiting nutrient in many Pacific Northwest forests and is of particular concern (Dahlgren, 1998).

Inorganic nutrients are also subject to leaching and may impact site productivity and water quality. Nitschke (2005), based largely in the Pacific Northwest and Western Canada, states that harvesting can impact water quality by decreasing total SO_4^{2-} and increasing total phosphorus, Ca^{2+} , Mg^{2+} , Na^+ , NO_3 , and NH_3 . However, Feller, Lehmann and Olanski (2000) found that in Southwestern British Columbia, fluctuations from mineral soils were relatively low, with the only significant changes occurring in potassium and NO_3^- , indicating instead that fluctuations in organic nutrients were more significant. Contrary to Nitschke (2005), Feller, Lehmann and Olanski (2000) concluded that harvesting, regardless of methods or percentage removed, are “unlikely to influence the sustainability of forest management in the study area.”

Changes in nutrient cycling are of particular concern when considering timber harvesting near watercourses because the impacts of harvest do not mirror the impacts of fire. Site differences further complicate management for this attribute, as many factors can impact how much nutrient leaching occurs. For example, Dahlgren (1998) found minimal impacts in the Caspar Creek Watershed and attributed much of these differences to the ability of California coast redwoods to sprout from stumps, thus increasing the nutrient sink on-site and preventing leaching. Additionally, in regions of Washington, Oregon, Idaho, Montana, and Wyoming, Jurgensen et al. (1997) suggests leaving some woody debris on-site to help maintain biodiversity and nutrient content in soils by mitigating erosion. However, this study also recognizes the difficulty in determining how much woody debris is enough, and concludes that this management tool is extremely site-specific and depends on a number of factors, including fire hazard.

Mass wasting and stream sedimentation

Mass wasting events – the process by which large amounts of sediment are moved and may enter waterways rapidly – such as landslides, are another significant source of stream sedimentation that may be of concern when conducting timber operations close to watercourses. Studies have shown that timber operations and associated road construction can result in reductions in site stability as vegetation is removed or killed and the remaining roots begin to decay (Dhakal & Sidle, 2003; Rice et al., 1972; Swanson et al., 1987). Additionally, steeper slopes and higher harvest percentages can increase the number of mass wasting events and the total volume of soil movement.

The 2003 study by Dhakal and Sidle examined numbers and volume of landslides associated with clearcutting, partial cutting (90%), and partial cutting (75%)

over 50% or 100% of an area. Their results indicated that 75% partial cutting “did not produce significant landslide volumes compared to other harvesting practices.” Dhakal and Sidle also studied the effects of different harvesting intervals in British Columbia and found that increasing the interval between clear-cut and partial harvesting (e.g. 10, 20, 30, 40 years between harvests) resulted in fewer mass movement events for clearcutting and partial cutting. Finally, they investigated the impacts of “leave areas” on slopes $>40^\circ$ and the impacts of understory vegetation and found that the use of leave areas resulted in 1.8-2.9 fold decreases in landslide events and that the maintenance of appropriate understory vegetation resulted in 3.8-4.8 fold reductions in landslide events (Dhakal & Sidle, 2003).

However, several studies also indicate that the main cause of most post-harvest mass wasting events is poor road construction or road construction on inherently unstable areas (Nitschke, 2005; Rice et al., 1972; Swanson et al., 1987). Indeed, available literature seems to indicate that the dominant source for most sediment production in timber harvesting systems is roads. For the purposes of this paper, soil specific impacts can best be addressed through skid trail designs and tree selection techniques. Additionally, heavy equipment use should only be proposed on limited sites after full consideration of slopes, soil type, and soil moisture.

Flow and Energy Characteristics

Summer Stream Flows

Several studies by Keppeler (1998), Keppeler and Ziemer (1990), and Lewis et al. (2011) look at the impacts of logging activity on stream flows in the Caspar Creek Experimental Watershed. Keppeler (1998) indicates that evapotranspiration in the Caspar Creek watershed is estimated to consume half of the annual rainfall. This portion of the area’s water budget is then returned to the atmosphere and does not reach the stream. Timber harvesting, fire, and other disturbances can alter this trend by reducing the amount of water taken up by plants, and allowing that water to penetrate the soil to be released in the dry summer months. Their study saw increases in total annual flow and summer flow, explained by the additional retention of 100 mm (of 660mm estimated to be lost to evapotranspiration) following 50% harvest. However, this number is not closer to the 50% additional retention proportional with the 50% harvest in part because soil moisture conditions can impact how much additional water can be absorbed post-harvest. Particularly these increases in summer stream flow may result in positive outcomes for aquatic species by maintaining connectivity in streams and helping to moderate water temperatures (Keppeler, 1998).

However, Keppeler and Ziemer (1990) found increases in annual flow that they largely attributed to increases in flow during the wet season in Caspar Creek, indicating a lack of predictability regarding when this increased flow will occur. In British Columbia, Nitschke (2005) also cites decreased summer flows resulting from low infiltration rates and high runoff in the wet months, indicating that the soil type and local hydrology are important for determining the possible impacts of timber harvesting on stream flows.

Keppeler and Ziemer (1990) also express concerns about the tradeoffs between increases in annual flow and the potential for increased sediment inputs and impacts to water quality. Lewis et al. (2011) sites annual sediment load increase of 123-269% in tributaries for total or partial clear-cut systems in the Caspar Creek Experimental Watershed, but with minimal impacts in the main stem.

Light Availability and Energy Dynamics

Reductions in canopy cover can have serious impacts on the energy dynamics of aquatic habitat. Canopy cover serves as one of the limiting factors for primary productivity in streams, often resulting in some dependence on terrestrial sources of carbon (Kaylor, Warren, & Kiffney, 2016). As more light reaches streams, aquatic primary productivity can spike, resulting in associated trophic cascades with unknown consequences. The effects are extremely site dependent and can fluctuate based on available nitrogen and mineral nutrients, but positive implications for macroinvertebrates and salmonids due to increased food production are possible and have been found in a number of streams in coastal Northern California (Warren et al., 2016; Wilzbach, Harvey, White, & Nakamoto, 2005).

Kaylor, Warren, and Kiffney (2016) and Warren et al. (2016) both indicate that light and energy dynamics in forested riparian areas are more complicated when considering long-term stand dynamics. These studies suggest that many Pacific Northwest riparian forests may be in stem-exclusion phases where canopy closure is complete and new seedling growth is stunted. They also show that previously logged areas when compared with old-growth stands differ significantly in light penetration –old-growth stands have significantly higher penetration that results from more heterogeneity and gap creation. Warren et al. (2016) depicts several conceptual diagrams showing stand succession, all of which end in a mature gap dynamic that allows for heterogeneity in canopy cover, species composition, age structure, and light availability (discussed further under Treating slash is important because it serves as a source of debris that may enter watercourses and presents a serious fire hazard. Indeed, Fahnestock (1960) conducted a thorough study surrounding the flammability, rate of spread, and fire severity associated with various slash characteristics and opened with the statement that “over much of the West logging slash is now the most hazardous forest fuel, and it threatens to remain so for an indefinite period.” When handling slash disposal, consideration of site specific conditions such as relative humidity, species composition, amount of sunlight reaching the ground, fire seasons, and age of slash is imperative. These characteristics may inform when slash is treated, how much is treated, and how it is treated. Planning for slash disposal early in the harvesting process will support the overall management goal of reducing fire hazard in riparian areas.

Appropriate Post-Treatment Stand Dynamics”). Regardless of harvest intervention, Warren et al. (2016) anticipates significant changes in light availability and canopy closure in the next 50-100 years.

Stream Temperatures

Water temperature is an important physical characteristic for aquatic biota in many streams and rivers, and changes to the temperature regime can have far-reaching and long-lasting impacts on these systems (Davies & Nelson, 1994; Kaylor et al., 2016; Moore, Spittlehouse, & Story, 2005; Nitschke, 2005; B. Poff et al., 2011). Moore, Spittlehouse, and Story (2005) discuss the impacts of timber harvesting on riparian microclimates and, by extension, impacts on aquatic thermal regimes. Riparian microclimates are typically more humid and have narrower temperature ranges as a result. Removal of timber in these areas can result in higher wind speeds which can increase evaporation and reduce humidity, contributing to greater air temperature ranges. This outcome, coupled with decreased shading can result in significant increases in stream temperature. In fact, Moore, Spittlehouse, and Story (2005) cite a study by Tyler Scott Ledwith (1996 Masters Thesis at Humboldt State University) which showed decreases in air temperatures above streams of 1.6 °C per 10m of buffer width up to 30m.

This 30m buffer width is generally accepted as the threshold for protecting riparian areas from serious microclimatic and thermal impacts (Davies & Nelson, 1994; Moore et al., 2005). However, Nitschke (2005) suggests that retention harvesting may allow for more adequate shading and maintenance of riparian microclimates and would more closely mimic a lower intensity fire regime. Additionally, the impacts on thermal regimes seem to be short-lived in many cases (recovery within five to ten years) and are “unlikely to produce substantial changes in the temperatures of larger streams into which they flow” (Moore et al., 2005).

Post-Harvest Forest Conditions

Exotic and Invasive Species

Concerns related to invasive species are two-fold for timber harvesting activities. First, with heavy equipment entering work sites and materials being brought in from external sites, there are many opportunities to spread invasive plants from other locations (Ledoux & Martin, 2013). Second, harvesting often disturbs soils and creates canopy openings that can result in more favorable conditions for invasive species to establish themselves. The introduction of invasive species into new areas and the spread of invasive species in infested areas may by extension have serious implications for local wildlife, vegetation composition, and overall forest health. However, Ledoux and Martin (2013) indicate with a series of BMPs that this issue can be managed if planning of operations includes considerations to prevent the spread of invasive plants.

Residual stand damage

Anytime heavy equipment is used in a forested landscape concerns regarding residual stand damage should be considered. As large equipment moves through stands that are seldom evenly spaced and often on uneven terrain, there is high probability that the equipment or the logs in tow may strike a tree that hasn't been harvested, and negatively impact stand health as well as the economic value of the

remaining trees (Akay, Yilmaz, & Tonguc, 2006). Damage can occur anywhere on the tree (crown damage, trunk scarring, or root damage) based on harvesting and yarding techniques, and can therefore carry different implications for overall stand health and individual tree impacts.

Several studies have compared relative impacts on residual stands that result from different harvesting and yarding techniques, and have found that harvesters and forwarders can be viable tools that help minimize stand damage under certain conditions (Akay et al., 2006; Han & Kellogg, 2000; Limbeck-lilienau, 2003). However, not all impacts can be avoided using these logging systems, and attention should be paid to the use of BMPs to minimize impacts which will be discussed under “Best Management Practices (BMPs) Identified in the Literature”.

Adequate Slash Disposal and Fuel Loading

Treating slash is important because it serves as a source of debris that may enter watercourses and presents a serious fire hazard. Indeed, Fahnestock (1960) conducted a thorough study surrounding the flammability, rate of spread, and fire severity associated with various slash characteristics and opened with the statement that “over much of the West logging slash is now the most hazardous forest fuel, and it threatens to remain so for an indefinite period.” When handling slash disposal, consideration of site specific conditions such as relative humidity, species composition, amount of sunlight reaching the ground, fire seasons, and age of slash is imperative. These characteristics may inform when slash is treated, how much is treated, and how it is treated. Planning for slash disposal early in the harvesting process will support the overall management goal of reducing fire hazard in riparian areas.

Appropriate Post-Treatment Stand Dynamics

As an ecosystem altering process, timber harvesting can inspire significant concerns with stand structure, species composition, and the general successional characteristics of riparian forests. Particularly, in selection harvesting methods potential long-term implications for fundamental ecosystem functions can result based on the species that colonize the empty spaces, at what rate, and how those outcomes shape canopy diversity. As previously discussed, levels of heterogeneity in stand age and species dynamics were historically high (Messier et al., 2012). Riparian areas were dominated by multi-age stands with some even-aged patches, some unburned patches, and a mix of hardwood and softwood species that were periodically thinned by fire or other disturbances. The frequent disturbances in this regime allowed for shade-intolerant species like large, commercial conifers to recruit in canopy gaps and these species offer a variety of ecological benefits including terrestrial wildlife habitat, large woody debris inputs, and stream shading. Limited management in riparian areas has resulted in more shade-tolerant hardwood species recruitment due to decreases in the levels of disturbance necessary to create sufficient gaps for the historically dominant softwoods and may have long-term implications for wildlife as the current dominant canopy softwoods begin to die and cannot be replaced (Messier et al., 2012).

As a result, Messier et al. (2012) suggest that timber harvest via gap creation may mimic historic disturbances enough to encourage more historic forest succession and associated levels of diversity. However, conducting these operations appropriately to maintain the right levels of diversity and minimize impacts will be crucial to adequate management. Several studies indicate significant changes in diversity for species and age classes in stands logged with selection harvesting (Ferry Slik, Verburg, & Kebler, 2002; Hall, Harris, Medjibe, & Ashton, 2003; Saiful & Latiff, 2014). There are relatively mixed reviews of the specific impacts on stand diversity measures, but these three studies agree that the most significant impacts occur immediately after harvesting and that recovery can take 10-20 years, with one study citing reduced basal area 18 years after logging that was attributed to “the physiological stress associated with sudden crown exposure, and damage to the residual stand” (Hall et al., 2003). Also noted for extremely selective practices were increases in shade-tolerant species from one quarter of the original basal area to almost half (Hall et al., 2003) and increases in the percentage of rarity, but decreases in the total number of rare species (Saiful & Latiff, 2014). It is worth noting that two of these studies do not specify the equipment used for harvesting, and the study noting significant residual stand damage was performed using a heavy bulldozer.

It is without doubt that harvesting has the potential to have significant impacts on stand diversity, but a comparison between heavily burnt stands and harvested stands indicates that management decisions in landscapes with historical fire suppression may not be easy (Ferry Slik et al., 2002). Ferry Slik et al. (2002) investigated a variety of diversity measures following harvesting and burning and found that the Fisher's- α Index (a species evenness measurement) was within the range for primary forest one year after disturbance and increased to pre-harvest levels about 20 years after harvesting, but not after burning. Further, the Fisher's- α Index regression mimics a classic decay curve, leveling off after 20 years at an approximate value of 25, with the primary forest value estimated at approximately 80. Ferry Slik et al. (2002) does, however, caveat these findings by indicating that the studied forests were heavily burned, and that stands with stocking levels and fuel loads that can achieve a lower burn intensity may change the outcome of species diversity indices. Hall et al. (2003) concludes by proposing that carefully executed increased canopy disturbance may be the best solution for managing forests for economic and ecological resiliency by creating opportunities for shade-intolerant and high quality timber species to recruit. Mimicking historical disturbances through regular harvesting and maintenance of ground fuels may be an avenue for multi-purpose management of California's forests and may help restore certain riparian sites that are determined to require management.

Botanical Resources

Timber harvesting is fundamentally a disturbance on the landscape, and sensitive plant species may be impacted by the landscape alterations such as those detailed in previous sections (Golec, LaBanca, & Leppig, 2004; Halpern & Spies, 1995). Indeed, these changes in composition may persist for years following harvest (Gross,

2009). However, our understanding of sensitive and rare plants and their responses to specific timber harvesting practices is still very limited (Golec et al., 2004; Halpern & Spies, 1995).

Halpern and Spies (1995) discuss plant diversity in commercially managed landscapes in the Pacific Northwest and the relationships between plant diversity and forest succession following harvest. They generally noted a decrease in diversity following harvest that began to recover quickly to exceed old-growth levels, but the recovery rate of specific plots depended largely on the intensity and frequency of disturbance. In more intensely harvested systems, resource availability and habitat fragmentation become serious concerns. For species that need shade or very specific microclimatic conditions, for example, harvesting of large numbers of trees may not leave adequate habitat and fragmentation may not enable these species to colonize adjacent areas as readily. Harvesting has the potential to eliminate species if these kinds of alterations are not considered during planning. However, their study also indicates that the maintenance of heterogeneity on the landscape through less intensive harvesting techniques may help to ameliorate some of these impacts by providing diverse habitat for a variety of species. For the limited scope of this paper and the harvesting methods being considered, significant long-term impacts to botanical resources are expected to be lower than in commercially harvested stands.

This assertion is supported by the Heavenly Creek Demonstration Project in the Lake Tahoe Basin Management Unit of the United States Forest Service (Gross, 2009). For this project, low-pressure ground equipment entered Stream Environment Zones (SEZs) to perform limited removal of fuels to reduce fire hazard. A monitoring effort accompanied this project which measured plant abundance and diversity before treatment and, most recently, 9 years post-treatment. Results show that for native herbaceous cover (including graminoids and forbs), native shrubs, and non-native invasive species, total cover did not differ significantly from pre-treatment values. Additionally, no significant changes in a variety of diversity indicators were detected from this study. However, decreases were measured in each of these categories in the first 1-3 years, followed by a recovery period.

It is also important to consider that while overall trends may not be concerning, changes at smaller scales were significant in some cases and may result in site-specific impacts. For example, while invasive plants did not increase as a group, two species increased significantly in some plots and may be of concern. Halpern and Spies (1995) echo this trend, indicating that site-specific impacts may differ significantly from overarching trends with regard to changes in abundance, diversity, and recovery time. Generally, the Heavenly Creek Demonstration Project is considered a success with minimal impacts on botanical resources, but prevention measures for invasive species and harvest plans that consider habitat retention will be important for any level of management to maintain diversity of sensitive and rare plants in forested landscapes.

Riparian and Aquatic Wildlife

To manage multi-use areas, it is important that habitat quality for riparian and aquatic wildlife be maintained. The culmination of previously discussed impacts can have positive or detrimental effects on wildlife and disrupt food webs, often with mixed results. Fuchs, Hinch, and Mellina (2003) and Kreutzweiser, Capell, and Good (2005) both studied the impacts of selection harvesting on aquatic macroinvertebrate communities in British Columbia and Ontario, respectively, and generally found minimal impacts on species diversity, with some slight changes in single species abundance. Increased primary productivity due to increased fine organic sediment (Kreutzweiser et al., 2005) and increased light availability (Fuchs et al., 2003) may be resulting in increased macroinvertebrate biomass. However, no significant differences in the relative abundance of specific feeding guilds were seen. Significant declines are described from other studies by Kreutzweiser, Capell, and Good (2005), but these previous studies were largely in areas of clear-cut or intensive logging. These findings are further echoed by Bottorff and Knight (1996) in the Caspar Creek Experimental Watershed. Specifically, they found increases in abundance and diversity of macroinvertebrate species related to increases in algae from increased solar radiation, nutrient input, and temperatures post-harvest.

Similarly, a study by Burns (1972) suggests that “logging is compatible with anadromous fish production if adequate attention is given to stream and watershed protection and channel clearance.” He further states that harvesting, in certain circumstances and when managed under BMPs, can have positive impacts on salmonid communities by increasing the available biomass of macroinvertebrates that these fish feed on and increasing summer stream flows. However, he also cites several activities that may negatively impact salmonids including: removing too much canopy, use of bulldozers on steep slopes or in stream channels that can result in sedimentation and pool infill or channel compaction, woody debris entering streams, and repetitive activity on a single site without adequate recovery time between harvesting. Of greatest importance is the consideration of the life cycles of species of concern in riparian areas such as spawning season for salmonids, because the time of harvest can also influence the general trend of logging impacts in an area.

More mixed results were identified for bird, mammal, and amphibian communities in studies by Pottier (2002), Fredericksen and Fredericksen (2004), and Raffael (2006). Pottier’s study (2002) addressed the impacts of selection logging on macroinvertebrate, fish, and bird communities and found generally that selection logging “appears to cause less disruption than clearcutting and/or stand conversion,” but that impacts that are present can remain for decades.

Fredericksen and Fredericksen (2004) studied the diversity of amphibian communities following partial harvest and observed a trend for increased abundance in disturbed areas, but it was not significant. They also noted no significant difference in species richness between treatments. However, they did note increased abundances

for certain species and reduced numbers of frogs compared to toads in disturbed areas. Understory cover did not differ significantly between treatments and large woody debris cover was greater in disturbed areas which may have habitat benefits for species that are more dependent on snags and forest floor composition. In general, they argue that limited harvesting (23-30%) may not have significant negative impacts for amphibian communities.

Raffael (2006) echoes this sentiment to some extent, stating that disturbances can have positive and negative impacts on amphibian species. However, Raffael (2006) agrees with Burns (1972) and highlights the importance of considering multiple life stages of a given species or group of species. Impacts to adult frogs, for example, may be very different than the impacts to juveniles or embryos of the same species. Raffael (2006) and Pottier (2002) also highlight the important point that while the overarching measure of diversity may not be troubling, finer scale inspections often reveal benefits for some species and negative impacts for others and depending on management goals the negative impacts may out-weigh the benefits. Indeed, Raffael (2006) discusses the importance of functional diversity and looking closer at the species level impacts. Large-scale, generalized measures of diversity may not be sufficient to capture the true impacts of anthropogenic disturbances and instead may hide significant differences in functionality at the species level. Older disturbances have shown some recovery in amphibian functional diversity, but the short-term implications of these changes are important for things like invasive species establishment. Studies have shown that “communities with higher functional group diversity have been shown to be more resistant to invasion by exotic species” as functional groups decline and provide niche space for invasive species.

Finally, Braithwaite and Mallik (2012) highlight the edge effects produced by buffer zones around watercourses, and argue that a more “feathered” approach that creates a more gradual shift between habitat types and encourages heterogeneity in the edge zone may benefit wildlife. They also assert that this kind of management may more closely resemble the patchiness of edges created by wildfire.

TO BE COMPLETED:

Approaches for Riparian Stand Management

Management approaches possible with feller-buncher logging - thin from below; improve spacing, vigor, tree size; ladder and surface fuel treatment; possible gap creation

- (R. A. York, Battles, Wenk, & Saah, 2012)
- (Agee & Skinner, 2005)
- (Bolding, Lanford, & Kellogg, 2003)
- (Christopherson, 1992)
- (Resources, 2010)

Best Management Practices (BMPs) Identified in the Literature

Maintain adequate canopy cover, particularly on south side of stream for stream shading

- (R. J. Poff, 1996)

Do not store or use chemicals in riparian zones; no refueling or servicing equipment in WLPZs.

- (Broadmeadow & Nisbet, 2004)

Employ directional felling away from the watercourse channel

- (Akay et al., 2006)
- (Kreutzweiser & Capell, 2002)

Minimize equipment passes on a single track

- (Contreras, Parrott, & Chung, 2015)
- (Broadmeadow & Nisbet, 2004)

Utilize zero-swing equipment and skid trails without severe turns to minimize residual stand damage

- (Resources, 2003)
- (Akay et al., 2006)
- (Broadmeadow & Nisbet, 2004)

Equipment exclusion on areas that are unnecessarily steep (>35%), on unstable areas, or where saturated conditions are present; pre-flag boundaries

- (Resources, 2003)
- (R. J. Poff, 1996)
- (Sidle et al., 2004)

Log yarding should not alter natural drainage or flow patterns; no connectivity between the site disturbance and the watercourse

- (Kreutzweiser & Capell, 2002)
- (Sidle et al., 2004)
- (Lewis, 1998)

Place slash on the equipment pathway to reduce soil compaction; when possible utilize mechanized harvesting equipment which delimb harvested trees on the pathway over which equipment will travel

- (Rone, 2011)
- (R. J. Poff, 1996)
- (Akay et al., 2006)

Do not place slash into the watercourse or in areas where it is likely to enter the watercourse; treat logging slash appropriately (e.g., pile burning)

- (Resources, 2003)
- (Broadmeadow & Nisbet, 2004)

Avoid disturbance to flood prone areas

- (Cafferata et al., 2005)

Create a planned skid route with attention to minimizing soil impacts, clearly flag the skid route, and include the operator in the planning process to ensure understanding of management objectives

- (Kreutzweiser & Capell, 2002)
- (Contreras et al., 2015)
- (Mattson, Baumgras, Blinn, & Thompson, n.d.)
- (Sidle et al., 2004)
- (Lewis, 1998)

- (Nitschke, 2005)
- (Froehlich & McNabb, 1983)

Conduct operations only in dry soil conditions

- (Resources, 2003)
- (R. J. Poff, 1996)

Use tracked feller-bunchers as they exert less pressure on soil, or alternatively using high-flotation rubber tire designs

- (Mattson et al., n.d.)
- (Akay et al., 2006)
- (R. J. Poff, 1996)

Prevent residual stand damage by using a cut-to-length harvester and forwarder system or straight skid trails when possible

- (Mattson et al., n.d.)
- (Akay et al., 2006)

Discussion of How Utilization of These BMPs Addresses the Concerns with Utilization of Feller-Bunchers in WLPZs

Case study: York study on Blodgett Forest Research Station and Preliminary Results

Conclusion

Reiteration of the Board's support for this use in appropriate site-specific locations, provided that BMPs are followed and appropriate analysis pursuant to the FPA and CA FPRs are completed.

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