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Environmental Effects of Postfire Logging: An Updated Literature Review and Annotated Bibliography

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Cover: King Fire, El Dorado National Forest, California. Photo by Morris Johnson.

Abstract

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The practice of removing fire-killed trees from burned forests (or "postfire salvage logging") has sparked public controversy and scientific debate when conducted on public lands in the United States. This review synthesizes the current scientific literature on the subject, providing an update to a 2000 literature review (PNW GTR-486) and subsequent synthesis (PNW-GTR-776). Forty-three published studies are reviewed, summarizing ecological effects on wildlife, vegetation, fuels, soils, and other environmental variables. Several key themes emerge from the review and specific research topics for future study are suggested. An annotated bibliography is provided at the conclusion of the document.

Keywords: Ecological effects, fire, fuel dynamics, wildlife, salvage, soil erosion, wildfire.

Contents

Introduction

The harvesting of merchantable timber from forests and woodlands following stand-replacing wildfires (commonly referred to as "salvage logging") on federal lands has been the subject of considerable controversy, both in the public sphere and the scientific literature. The Society of American Foresters (Helms 1998) defines salvage logging as "the removal of dead trees or trees damaged or dying because of injurious agents other than competition, to recover economic value that would otherwise be lost." As such, this practice is often driven by economic concerns, as land managers are motivated to recover the value of fire-killed trees and to support local timber economies in rural areas (Gorton and Kays 1996, McIver and Starr 2000). Promoting future forest development and reducing future fire hazard are additional benefits cited from the harvest of fire-killed trees from burned forests. The use of these latter arguments by managers and policymakers has prompted debate in the scientific literature regarding the validity of these claims. In the past several decades, researchers attempting to assess the ecological effects of postfire logging have published dozens of studies evaluating effects of salvage logging on myriad aspects of forest ecosystems. These studies have been synthesized in several documents in an attempt to provide a cohesive source of information useful to managers and decisionmakers. Relevant research on this topic continues, such that it is occasionally necessary to include the most recent studies in new literature reviews. The purpose of this report is to provide an annotated bibliography of the relevant peer-reviewed literature published in the time since a previous review of the scientific literature on postfire logging (McIver and Starr 2000). As such, it is not intended to be a meta-analysis, or a synthetic review of the state of knowledge on the topic of salvage logging.

The review produced by McIver and Starr (2000) was written in response to a debate that was taking place both in the public arena and the scientific literature over the environmental costs and ecological justifications associated with postfire logging on public forest lands. This debate has a long history. Reacting to pressure from constituents in timber-dependent communities, U.S. Senator Slade Gorton (R-Wash.) attached a salvage rider to the Fiscal Year 1995 Rescissions Act.[1] The stated objective of the rider was to promote forest health and restore timber jobs in rural communities of the Pacific Northwest (Gorton and Kays 1996). The rider led to an open debate among scientists and managers in the region (Beschta et

[1] Oklahoma City Disaster Assistance and Rescissions Act: Emergency Supplemental Appropriations for Additional Disaster Assistance, for Anti-Terrorism Initiatives, for Assistance in the Recovery from the Tragedy that Occurred at Oklahoma City, and Rescissions Act, 1995. Pub. L. No. 104-19.

al. 1995, Everett 1995, McIver and Starr 2000). Beschta et al. (1995) posited that salvage logging had strong negative ecological consequences, arguing that the only value of such action is economic, and they offered a set of recommendations for management of postfire forests. Everett (1995) refuted the conclusions of Beschta et al., arguing for more active management of postfire landscapes, including timber harvest.

The 2000 literature review (McIver and Starr 2000) was an attempt to synthesize the current state of scientific understanding in the field, evaluate knowledge gaps, and provide managers with the basis from which to make informed decisions when applying postfire management practices. Using what they described as "scanty" information, they summarized the findings of 21 studies into several categories and predicted "likely" ecological effects based on the results of these studies. One of the better studied topics, the impacts of salvage logging on wildlife, was well documented, with variable effects on different clades depending on their habitat requirements. In particular, largely negative outcomes were documented for cavity-nesting birds. Additionally, the reviewers found that substantial changes in wildlife habitat, resulting from the removal of structural and functional elements in the form of large-diameter snags and their associated insect communities, were likely following harvest. A predicted result of postfire logging was that the removal of these attractants for forest insect pests may reduce the likelihood of infestation of nearby healthy stands. Although longer term studies were lacking at the time, there was evidence that impacts of logging-related disturbance to understory communities included declines in species richness and diversity, an increase in nonnative plant species cover, and a reduction in vegetative biomass. Negative effects on tree regeneration were predicted if salvage operations are not designed to reduce seedling mortality. The reviewers did not find studies that documented increased soil erosion following postfire logging, but posited that road-building and the use of skid trails might increase its incidence in already compromised burned watersheds. Conversely, one study included in the review found that logging slash remaining from salvage activities might reduce postfire erosion. Little research had been done on the impacts of salvage logging on postfire fuel dynamics, a deficit highlighted in the review. In their conclusions, the authors recommended further study of this and several other subjects. Many of these topics continue to be explored in current research, and more broadly applicable knowledge has been made available in the years since the 2000 review was completed.

In many ways, the 1995 debate continues in the present moment. Although more scientific study has been conducted on this topic (as detailed in this review), both supporters and detractors of the practice can point to evidence in the literature to support their arguments. Since 2000, many of the scientific questions surrounding the practice of postfire logging have been explored at greater depth and in more detail, but these issues are by no means resolved.

Interpretations of the ecological effects of salvage logging are mutable, as observations depend on the scope, spatial and temporal scales, and class of metric studied. Some effects are initially quite dramatic, but dissipate over time. Other effects may vary based on the attributes of the studied ecosystem. Owing to the structural and functional impacts of severe wildfire on forested ecosystems (e.g., widespread tree mortality, depletion of soil organic matter, consumption of woody fuels), effects of postfire logging can be difficult to distinguish from the effects of the fire itself. All these concerns complicate attempts to synthesize the current state of knowledge in this field. This review seeks to present the last 18 years of published data on this topic in a way that is relevant to managers and scientists while acknowledging the limitations in interpreting the research.

In this report, we reviewed 43 scientific studies published since 2000, and confine our geographic scope to Western United States and Canada, in keeping with the focus of the 2000 review. As with the standards set by McIver and Starr (2000), we adhere to the same definitions to classify published scientific work. If treatments were not imposed by the researchers, the study is classified as **observational**, as opposed to a **replicated** study.

Only peer-reviewed studies reviewed for this paper are annotated in the bibliography; other citations mentioned are presented without additional text.

Ecological Effects of Postfire Logging

Wildlife

When the ecological effects of postfire timber harvest are examined, negative impacts to wildlife are frequently cited in arguments against this type of postfire management. Upon thorough review of the published literature on the subject, it is clear that negative consequences of postfire harvest exist for many species. However, it would not be accurate to apply these results universally to all wildlife species. The response of an individual species to the removal of fire-killed trees is often determined by its unique qualities and the habitat features on which it depends. Although many species experience a loss of habitat when dead trees are removed following a stand-replacing fire, others benefit from the resulting alteration of stand structure, reduction in stand density, increases in understory plant diversity, and changes to surface fuel loads.

Birds

The response of avian species to the removal of fire-killed trees is highly dependent on the habitat requirements of the studied species. In their review, McIver and Starr (2000) noted that birds that depend on snags for forage and nesting structures are the most affected by the removal of dead trees following stand-replacing wildfire, while those that favor open habitats appear to benefit from logging. Cavity-nesting birds, such as the black-backed woodpecker (*Picoides arcticus*), are the archetypal fire-dependent wildlife guild, and their response to postfire harvest has been the focus of much research since the 2000 review. Owing to their dependence on standing dead trees, cavity nesters are often strongly associated with severely burned forests. These species have been found to be more abundant following fire in unmanaged stands than in harvested stands (Cahall and Hayes 2009, Hutto and Gallo 2006, Kronland and Restani 2012, Morissette et al. 2002, Rost et al. 2013, Saab et al. 2007). One contradictory study (notably with low replication) found higher abundance and richness of cavity-nesting birds following salvage (Haggard and Gaines 2001). Other birds species, such as the federally threatened northern spotted owl (*Strix occidentalis caurina*), also appear to be negatively affected by salvage logging (Clark et al. 2013), but this effect is blurred by the impacts on owl site occupancy of high-severity fire. Another study of the related California spotted owl (*S. o. occidentalis*) did not find significant declines in owl populations resulting from either fire or postfire logging, but did emphasize the small yet potentially meaningful compounded effect of fire and logging, which marginally increased the probability of site extinction (Lee et al. 2013). Bird species that use more open habitats generally have positive or neutral responses to salvage logging (Cahall and Hayes 2009, Morissette et al. 2002, Rost et al. 2013, Saab at al. 2007). As studies of this topic have largely focused on the impact of postfire snag removal on birds species that are dependent on them, information is lacking on the influence of salvage logging on the avian community as a whole, as well as on the longer term effects of these postfire management activities.

Mammals

McIver and Starr (2000) observed that, as for bird species, mammal populations tend to shift toward those that prefer more open habitat in response to salvage logging. Few studies have examined the impacts of postfire logging on mammals since 2000, and findings have not been conclusive. In one study, populations of deer mice increased in density following salvage logging, likely owing to the temporary increase in downed woody debris that was the result of harvest (Kronland and Restani 2012). Another study that compared abundance of small terrestrial mammals across three levels of harvest intensity (unlogged, moderate, and high) found no significant difference among treatments (Brown 2009). In this same study, bat densities were observed to be higher in harvested stands; however, this may have been a consequence of the availability of open habitat for feeding, and not an indication of increased population size resulting from logging. In a study of salvage logging's impacts on trophic relationships, Hebblewhite et al. (2009) found that elk avoided areas logged after fire, largely because of increased predation risk from wolves in these open sites. The authors pointed to the increased road construction associated with postfire harvest as major factors in this disruption of ecosystem dynamics, and recommended that it be minimized. Published studies on this topic are scarce, and as a consequence, little specific information is available on the effects of postfire tree harvest on mammal populations.

Invertebrates

Insects are often abundant following stand-replacing wildfires, and are a critical element of postfire landscapes, providing forage for insectivorous birds, advancing the decay of fire-killed trees, and influencing soil nutrient cycling. Postfire timber harvest has been found to be deleterious to populations of wood-boring beetles, negatively affecting both abundance and species richness (Cobb et al. 2010, Thorn et al. 2018). Cobb et al. (2010) noted that this decrease in populations of saproxylic insects can have cascading impacts on soil nutrients. In contrast, species richness, abundance, and biomass of benthic macroinvertebrates increased in salvage-logged watersheds, though only incrementally, above unharvested burned sites when compared with unburned controls (Silins et al. 2014). Studies of invertebrate response to salvage logging are few and narrow in focus; as such, this field would benefit from further investigation, particularly including a greater diversity of species and over greater time scales following harvests.

Vegetation

Tree Regeneration

Post-wildfire tree regeneration is of great concern to land managers, resulting in the common practice of postfire planting of timber species following stand-replacing fire. McIver and Starr (2000) noted that in the majority of the studies they reviewed, salvage logging operations occurred prior to the establishment of seedlings, avoiding the high mortality (75 percent in one study) that can be caused by logging equipment. In the intervening years, the effect of harvest of fire-killed trees on natural regeneration has been examined by several authors, but results are somewhat equivocal between studies. Two studies found that natural regeneration of tree species was negatively affected by salvage logging operations (Donato et al. 2006, Keyser et al. 2009), which caused injury to establishing seedlings. Another study found no significant effect of postfire harvest (Peterson and Dodson 2016). Interestingly, these results do not appear to depend on the interval between wildfire and harvest, as at least one of each of the former and latter groups of studies was logged at a point where seedling establishment could be expected to have occurred (2 to 3 years postfire). It is important to note that the former group of studies were conducted within 5 years of wildfire occurrence, and the latter studies examined the longer term (15 and 10 years, respectively) impacts of salvage logging on regeneration. Additionally, although natural regeneration is a concern in many postfire environments, salvage logging prescriptions typically call for post-harvest tree planting. Although species selected for replanting may not accurately reflect local assemblages, the practice reduces the reliance on natural regeneration for forest restoration in salvage-logged stands, rendering any negative impacts to preexisting seedlings less consequential.

Understory

Postfire logging effects on understory vegetation are dependent on temporal scale and site-specific factors. Numerous studies have documented a convergence in understory development between logged and unlogged stands over time (Campbell et al. 2016, Keyser et al. 2009, McGinnis et al. 2010, Peterson and Dodson 2016). In one study, repeated measurements of species richness and community composition similarly demonstrated an initial effect of logging that dissipated over several decades and was overtaken by the influence of canopy structure in the long term (Kurulok and Macdonald 2007). This was not the conclusion of another long-term study, which documented significant changes to plant communities in salvaged sites, particularly along forest edges (Hanson and Stuart 2005). Several researchers have found that other factors, such as burn severity and postfire planting, had greater influence on understory vegetative development than salvage logging (Macdonald 2007, Morgan et al. 2015). Kurulok and Macdonald (2007) found greater short-term species richness and higher shrub abundance in salvaged stands, results that are in stark contrast to Knapp and Richie (2016), who found that shrub cover decreased with salvage intensity. These discrepancies are likely due to differences in the regenerative strategies of the prefire vegetation of the studied sites, as well as the timing of salvage operations, as described by Peterson et al. (2009). Most of these studies found no increase in nonnative plant species abundance resulting from salvage logging (Keyser et al. 2009, Knapp and Ritchie 2016, McGinnis et al. 2010, Peterson and Dodson 2016), though one did find a short-term increase that dissipated over time (Kurulok and Macdonald 2007). Although most research on the topic has concluded that understory vegetation is resilient to postfire logging over intermediate time periods, this subject would benefit from longer term study, as well as the variable effects on plants with different fire-adaptive strategies (e.g., sprouting vs. reseeding species).

Fuels

Owing to the regular use of the "reburn hypothesis" (which posits that removing dead trees from a burned stand will reduce future wildfire risk and severity) as an ecological justification by managers for removing fire-killed timber, postfire fuel dynamics are an important element of study in the realm of salvage logging research. McIver and Starr (2000) emphasized the paucity of evidence for these claims, and since that time, substantial research has been conducted on this subject. Results of recent studies suggest divergent trajectories for coarse and fine fuels in logged and unmanaged postfire stands, as well as significant changes in fuel conditions through time. The dynamics of fine fuel (fuels < 7.6 cm in diameter; 1-, 10-, and 100-hr timelag fuels) loading are critical to understand in this context, as they are the primary driver of fire spread in wildland fires (Rothermel 1972). However, coarse fuels (fuels > 7.6 cm; 1,000-hr timelag fuels) can contribute to fire behavior as well, via increased local intensity, crown ignition potential to residual surviving trees, and as a source of long-range spotting (Brown et al. 2003). Coarse fuels can also substantially increase burn severity by means of long-term smoldering and local soil heating, which can exceed lethal temperatures for long periods, affecting nutrient cycling (Brown et al. 2003, McIver and Ottmar 2018, Reinhardt et al. 1997).

Many researchers have found that, in the short term, postfire logging increases fine fuel loading when compared with unmanaged stands (Donato et al. 2006, 2013; McGinnis et al. 2010; McIver and Ottmar 2007; Peterson et al. 2015). However, longer term measurements often reveal that this effect is short lived, leading to the convergence of logged and unlogged stands within a decade (Campbell et al. 2016, McGinnis et al. 2010, McIver and Ottmar 2018, Peterson et al. 2015). The temporal variation of fine fuel loads in severely burned sites is particularly compelling in studies that remeasured prior field sites, as in the latter three studies. Note that although some authors posit that increased fine fuel loading will increase fire risk, at least in the short term (Donato et al. 2006, 2013; Thompson et al. 2007), others contend that fire hazard is unaffected by these additional fuels, largely because of the characteristics of postfire fuelbeds (Newton et al. 2006, Ritchie et al. 2013). Empirical evidence that could substantiate either position is lacking on this subject, as opportunities to observe this phenomenon are limited.

Dynamics of coarse surface fuel loading, which are dependent on snag retention in postfire environments, often exhibit the opposite trend. As would be expected, logged stands contain fewer standing snags following harvest than untreated stands. The transition of these aerial fuels to surface fuels is highly dependent on the decomposition rates (which vary by species and local climate) and diameter of remaining dead trees (Campbell et al. 2016, Ritchie and Knapp 2014). A number of studies have found high accumulation of surface coarse woody fuels over time in unharvested stands when compared with logged sites (Dunn and Bailey 2015, Keyser et al. 2009, McIver and Ottmar 2018, Peterson et al. 2015, Ritchie and Knapp 2014, Ritchie et al. 2013) as snags begin to fall. Conversely, a single study (McGinnis et al. 2010) found that large woody debris increased following postfire logging in the Sierra Nevada, although the authors noted that this effect was not significant in older (19 to 21 years since harvest) study sites. Ritchie et al. (2013) observed that, regardless of treatment, the majority of standing dead material remaining following harvest was on the ground 10 years following fire and salvage logging in the Lassen National Forest in California, and suggested that the habitat provided for cavity-nesting wildlife was therefore transient.

Owing to the very small proportion of the forested landscape that has undergone postfire salvage harvesting in the Western United States and Canada, reburn of these areas is unlikely to occur within the timespan covered by this review or its predecessors. Thus, it has been difficult for researchers to design a study that tests the reburn hypothesis in the field. Instead, many studies of postfire salvage impacts on forest fuels use fire behavior and fuels consumption models to simulate a reburn event. Several of these studies, which often pair empirical fuel measurements with modeled fire behavior, have found that models do not project elevated fire behavior or increased fire effects in unlogged stands when compared to salvaged sites (McGinnis et al. 2010, McIver and Ottmar 2007). Researchers in this field note, however, that current fire behavior and consumption models do not accurately represent the influence of large logs and other heavy fuels, which could contribute to additional fire severity via longer residence times and subsequent soil heating (McIver and Ottmar 2018, Peterson et al. 2015). Others cite high postfire shrub cover as having a substantial effect on future fire behavior, potentially overwhelming any influence of post-burn tree harvest (Campbell et al. 2016, Donato et al. 2013, McGinnis et al. 2010). In a study of reburn severity that did not evaluate the impact of postfire salvage logging, Coppoletta et al. (2016) found that postfire shrub cover and snag basal area following an initial fire contributed significantly to fire severity in reburns, but the effect of these variables (particularly snag basal area) was dwarfed by weather conditions during reburn events.

The reburn hypothesis did not receive substantiation from the sole study we found that quantified the impact of postfire logging on reburn severity (Thompson et al. 2007). Although the authors were unable to separate the effects of postfire planting from salvage logging, they found that fire severity increased in harvested areas when compared with unmanaged sites, potentially refuting the validity of the reburn hypothesis. However, it is important to note that determination of burn severity was based solely on remote sensing data (delta Normalized Burn Ratio, dNBR) and was not verified in the field. This method of measuring burn severity raises concerns about the accuracy of the data (Miller and Thode 2007) and adds an additional level of uncertainty to the study's results. Although it is difficult to arrange the necessary treatments in the field, the limitations of current models make it imperative for researchers to continue to pursue opportunities to examine the relationship of postfire logging and reburn severity when they occur on the landscape.

Soils

An important area of study has been the contribution of postfire logging to soils and watersheds, particularly its effect on erosion and sedimentation in streams. Noting the scarcity of published research on this topic, McIver and Starr (2000) posited that road building and subsequent use would have the greatest influence on post-salvage logging erosion. Since then, several studies have found that salvage logging operations can be a major contributor to soil disturbance and compaction (McIver and McNeil 2006; Slesak et al. 2015; Wagenbrenner et al. 2015, 2016), and the majority of these studies document increased erosion in burned watersheds that were subsequently logged (Slesak et al. 2015; Wagenbrenner et al. 2015, 2016). In contrast to these studies, McIver and McNeil (2006) noted that despite increased soil disturbance, erosion from harvested sites was not significantly greater than untreated stands, and that roads were the greatest contributor to movement of soil. Additionally, these researchers found that some of the impact to soils caused by machinery during postfire harvest can be mitigated by adjusting the employed techniques and the timing of operations (McIver and McNeil 2006). Note that the influence of postfire logging on erosion, when present, does appear to be short lived, as the observed effect can diminish over time (Slesak et al. 2015, Wagenbrenner et al. 2016).

Other effects on soils from postfire logging, such as effects on soil nutrients, soil microbial and fungal communities, and cation exchange capacity, can be difficult to distinguish from the often greater influence of the initial wildfire. However, some studies have noted lasting effects of salvage logging on certain soil parameters, most notably reduction in soil organic carbon (Jennings et al. 2012, Kishchuk et al. 2014). Another study documented changes in soil biogeochemistry, but only in certain horizons (Poirier et al. 2014). Bacterial and fungal communities in soils appeared to be resilient to the disturbance caused by postfire logging (Jennings et al. 2012). Similarly, the influence of postfire harvest on water quality and stream biota can be difficult to distinguish from the signal of wildfire; however, certain parameters show detectable differences (Emelko et al. 2011, Silins et al. 2014).

Abiotic Variables

Effects of postfire logging on abiotic variables are just beginning to receive attention. Recent studies have examined microclimatic changes following salvage logging, as well as the impact of the practice on carbon sequestration and storage. One study observed that surface air temperatures did not increase in logged stands, but noted other small microclimatic changes (such as earlier daytime heating and lower nighttime minimum temperatures) attributed to postfire harvest (Fontaine et al. 2010). Researchers documented a marked decrease in the amount of carbon stored in salvaged sites, particularly those that received intensive management (Powers et al. 2013). The authors of this study emphasized the competing interests of managers, who are likely to include carbon sequestration in an already complex analysis of how best to manage forests. Although more research has been conducted in the period since 2000, results are not conclusive, and much remains to be learned about salvage logging impacts on soils and the abiotic environment, both within salvaged sites and at the landscape level.

Conclusions

Limitations

In their 2000 review, McIver and Starr lamented the fact that little research had been conducted on the effects of postfire logging. Since that time, more than 40 additional studies have been conducted on this topic, but some important scientific questions remain unresolved. One topic of particular interest to researchers, managers, and decisionmakers is the scientific validation or rejection of the reburn hypothesis. Although most studies have documented greater long-term fuel loading in unmanaged stands when compared with logged ones, the majority of studies that attempt to evaluate the reburn hypothesis use simulation models to predict fire behavior and effects, as few opportunities for empirical study have presented themselves. The only empirical study of which we are aware (Thompson et al. 2007) refuted the premise: salvage-logged stands burned at higher severities than comparable unlogged stands, though the authors noted that the high live fuel loading resulting from postfire planting in logged stands was the most likely driver of fire severity, and were not able to separate this variable from the effect of logging alone. Research based on field experiments and modeled analyses using physics-based fire behavior models (such as the Wildland-Urban Fire Dynamics Simulator) presents a potential avenue for improved evaluation of the reburn hypothesis in the future.

Shortcomings with experimental study design mentioned by McIver and Starr (2000) have not been fully addressed in the research conducted since the publication of that review. Of particular concern to those authors was the lack of replicated experiments. In the study of postfire logging effects, researchers are rarely allowed the opportunity to determine the locations of treatments or their distribution on the landscape, with the result that the majority of studies are observational in nature. This is largely a result of the logistics involved in planning these projects: managers tend to locate harvest units based on proximity to existing road networks, distance from sensitive areas, and operable slope location. As a result, replication is often limited, sites are not randomly distributed, and spatial autocorrelation and pseudoreplication are concerns in the analysis of results. Beyond these, the use of unsalvaged sites as proxies for prefire conditions brings up issues with space-for-time or chronosequence approaches that have been highlighted in other ecological research (Johnson and Miyanishi 2008). The implementation of long-term experiments employing repeated measures over time are necessary to avoid these pitfalls and produce widely applicable, meaningful conclusions.

We found that the geographic diversity of the region is not well represented in the literature: 37 percent of the studies reviewed here were conducted in one U.S. state (Oregon), and 23 percent of published studies focused on only two wildfires (Biscuit Fire and Summit Fire, both in Oregon) (fig. 1). This lack of replication to relevant ecosystems may lead to conclusions derived from the study of one area being broadly applied to other regions where ecosystems are quite distinct. Researchers

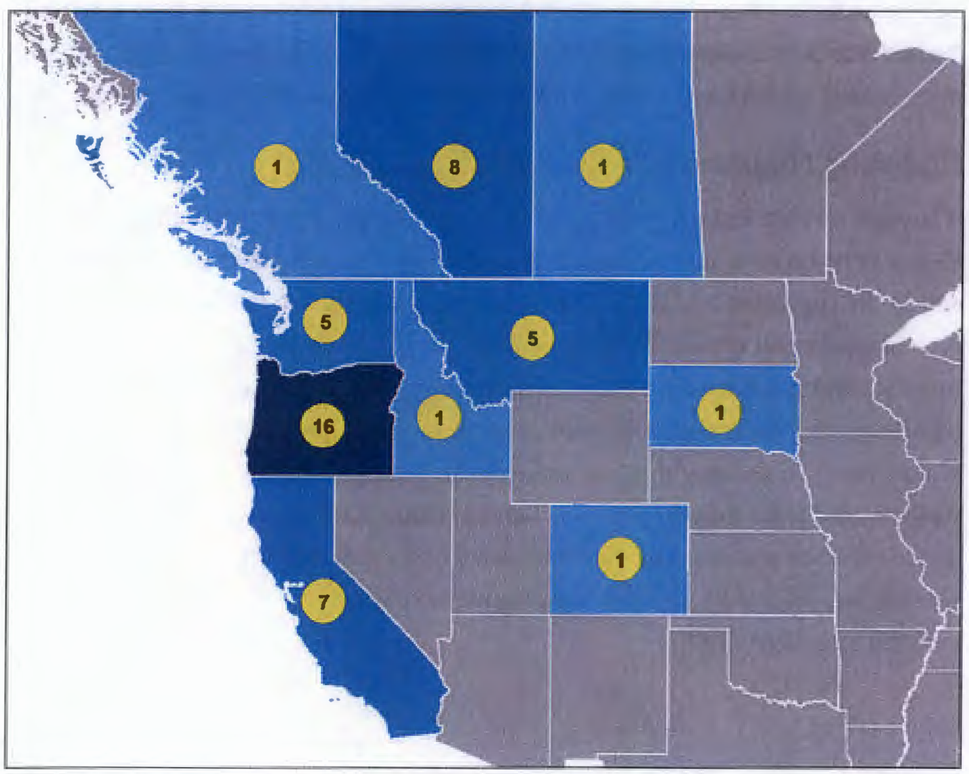


Figure 1—Salvage research locations by U.S. state and Canadian province in focus region. Most field sites featured in published studies between 2000 and 2018 were located in Oregon, particularly the Biscuit and Summit Fires.

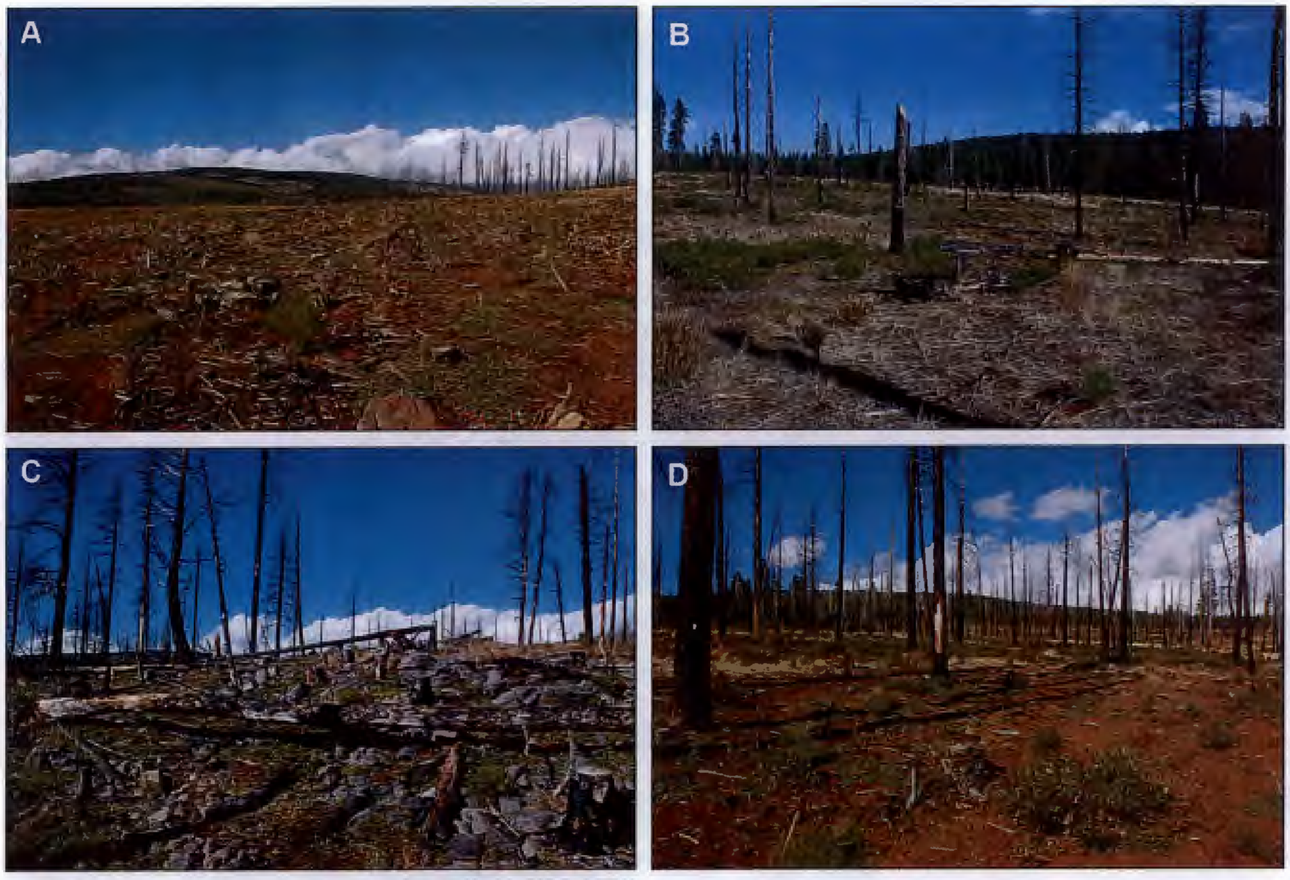
are limited by access to sites, communication with local managers, funding, and other logistical concerns when conducting field research, and these limitations are reflected in the number of fires that have received attention from scientists.

Another concern voiced by McIver and Starr (2000) is the frequent lack of unburned controls: this continues to be a common problem in salvage-logging research. Of the 43 studies reviewed here, only 14 (about a third) included unburned controls in their study design. This design shortcoming creates analytical problems for many studies. Many researchers were unable to tease out the confounding variables that affected their results. Often, the signal of a severe wildfire in the data overwhelmed the effect of postfire logging. In some cases, comparison with data from unburned controls may have aided in the clarification of these effects.

Typical of wildfire research, many of the studies reviewed here suffer from minimal knowledge of prefire conditions. Thus, confounding factors such as prefire vegetative characteristics are impossible to control in data analysis. Compounding these issues, many studies are short term in nature, which can lead to findings that are not representative of relevant ecological outcomes that occur over longer time scales. Researchers have begun to address these concerns by revisiting prior study sites, yielding valuable data on long-term trends. This practice should be continued and expanded to other previous research, as the information produced from long-term studies is critical to understanding the future trajectories of landscapes under differing management regimes and will be far more relevant to managers and policymakers.

Reducing Negative Effects of Postfire Logging

Although salvage logging is injurious to certain species guilds and habitat elements, steps can be taken to minimize these negative impacts in some situations (figs. 2 and 3). As suggested by McIver (2003), alterations to harvest methods (particularly type of equipment used and timing of operations) can substantially reduce soil disturbance and subsequent mortality of understory vegetation. Additionally, changing harvest prescriptions such that more of the large snags preferred by cavity-nesting birds remain on site may mitigate some of the effects of logging on these species, as well as provide for longevity of snag habitat (Hutto 2006, McIver and Ottmar 2007). These methods provide managers with avenues for reducing the negative effects of postfire logging, while maintaining a source of revenue for local timber economies affected by severe wildfire.



M. Ritchie, U.S. Forest Service Pacific Southwest Research Station

Figure 2—Photos of variable-retention salvage treatments from a multiyear study at the Blacks Mountain Experimental Forest, California, in fall 2006. Images were taken 4 years after the Cone Fire and 3 years after salvage operations: (A) 0 percent retention; (B) 25 percent; (C) 50 percent; (D) 75 percent; and (E) 100 percent.

D. Nemens, University of Washington

Figure 3—Fifteen years after the Storrie Fire, and 3 years after the Chips Fire, Lassen National Forest, California. The foreground shows an area where no action was taken, while postfire logging (on private timber holdings) is visible in the distance.

Directions for Future Research

Investigators in this field should consider the limitations of the current body of research and attempt to address these concerns in their work. Specifically, future research efforts should attempt to incorporate these elements:

1. Replicated study design using appropriate controls
2. Long-term experiments with repeated measurements
3. Expanded geographic diversity into understudied regions and ecosystems
4. Use of improved models, or seizing opportunities to directly measure fire behavior and severity
5. Integrated studies in which many variables are measured, in order to capture a more complete picture of impacts on the entire ecosystem.

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Appendix: Literature Cited and Annotations

Note: Citations without annotation are for text reference only and were not reviewed in this document.

Beschta, R.L.; Frissell, C.A.; Gresswell, R.; Hauer, R.; Karr, J.R.; Minshall, G.W.; Perry, D.A.; Rhodes, J.J. 1995. Wildfire and salvage logging: recommendations for ecologically sound post-fire salvage management and other post-fire treatments on federal lands in the west. Corvallis, OR: Oregon State University. 16 p.

Brown, J.K.; Reinhardt, E.D.; Kramer, K.A. 2003. Coarse woody debris: managing benefits and fire hazard in the recovering forest. Gen. Tech. Rep. RMRS-GTR-105. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p.

Brown, M. 2009. Post-fire salvage logging in central Oregon: short-term response in bats, birds and small mammals. Fire Science Brief 76. Boise, ID: Joint Fire Science Program. https://www.firescience.gov/projects/briefs/04-2-1-95_FSBrief76.pdf. (12 December 2018).

Location: Davis Lake Fire, central Oregon.
Type of study: Observational.
Variables: Breeding bird population density, bat activity, and small mammal abundance.
Treatments: Burned/unlogged, burned/moderate salvage, burned/intensive salvage.
Results:

- Reducing the intensity of harvest did not reduce impacts to species that responded negatively to postfire logging.
- Small mammal populations did not demonstrate a response to harvest, or varied with harvest intensity.
- Negative effects of salvage logging on some bird species may be mitigated by maintaining islands of unlogged snags within larger harvest units.
- Bat activity was higher in open areas created by intensive salvage harvest.

Cahall, R.E.; Hayes, J.P. 2009. Influences of postfire salvage logging on forest birds in the eastern Cascades, Oregon, USA. Forest Ecology and Management. 257: 1119–1128.

Location: Davis Lake Fire, central Oregon.
Type of study: Observational.
Variables: Density and abundance of bird populations.
Treatments: Burned/unlogged, burned/moderate salvage, burned/intensive salvage.
Results:

- Reducing the intensity of harvest did not reduce impacts to species that responded negatively to postfire logging.
- Negative effects of salvage logging on some bird species may be mitigated by maintaining islands of unlogged snags within larger harvest units.

Keywords: Birds, fire, salvage logging, ponderosa pine–Douglas-fir forest.

Campbell, J.L.; Donato, D.C.; Fontaine, J.B. 2016. Effects of post-fire logging on fuel dynamics in a mixed-conifer forest, Oregon, USA: a 10-year assessment. International Journal of Wildland Fire. 25: 646–656.

Location: Biscuit Fire, southwest Oregon.
Type of study: Observational (remeasure).
Variables: Surface fuel mass, decay rates, shrub cover.
Treatments: Unburned control, burned/unlogged, burned/moderate logging, burned/heavy logging.
Results:

- Fine surface woody fuel loads were initially higher in salvaged stands, but loadings converged with unsalvaged stands within a decade.
- Snags decayed at a significant rate while standing, indicating that some surface fuels did not fall to the forest floor.
- Cover of resprouting shrubs was high 10 years following fire regardless of treatment, representing a high fire danger not mitigated by postfire harvest.

Keywords: Biomass, coarse woody debris, dead wood, decay, decomposition, fuel succession, Klamath-Siskiyou, salvage logging, snag, wildfire.

Clark, D.A.; Anthony, R.G.; Andrews, L.S. 2013. Relationship between wildfire, salvage logging, and occupancy of nesting territories by northern spotted owls. Journal of Wildlife Management. 77: 672–688.

Location: Timbered Rock, Biscuit, and Quartz Fires, southwest Oregon.
Type of study: Observational.
Variables: Site occupancy of northern spotted owls.
Treatments: Unburned, moderate burn/unlogged, high-severity burn/unlogged, high-severity burn/logged.
Results:

- Site occupancy of spotted owls showed short-term declines subsequent to wildfire, and postfire disturbance may have contributed to these declines.

Keywords: Colonization, extinction, northern spotted owl, occupancy, salvage logging, site occupancy, southwest Oregon, *Strix occidentalis caurina*, wildfire.

Cobb, T.P.; Hannam, K.D.; Kishchuk, B.E.; Langor, D.W.; Quideau, S.A.; Spence, J.R. 2010. Wood-feeding beetles and soil nutrient cycling in burned forests: implications of post-fire salvage logging. Agricultural and Forest Entomology. 12: 9–18.

Location: Chisholm Fire, Alberta, Canada.
Type of study: Observational.
Variables: Abundance of saproxylic beetles.
Treatments: Unburned, burned, unburned/logged, burned/logged.
Results:

- Beetles were not present in burned stands subjected to salvage logging.

Keywords: Beetle frass, boreal forest, coarse woody debris, IPDM, *Monochamus s. scutellatus* (Say), nitrogen cycling, saproxylic beetles, soil microbial activity, wildfire.

Coppoletta, M.; Merriam, K.E.; Collins, B.M. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications. 26: 686–699.

Donato, D.; Fontaine, J.B.; Campbell, J.; Robinson, W.; Kauffman, J.; Law, B.E. 2006. Post-wildfire logging hinders regeneration and increases fire risk. Science. 311(5759): 352.

Location: Biscuit Fire, southwest Oregon.
Type of study: Observational.
Variables: Surface fuel loads, tree regeneration density.
Treatments: Unburned, burned/unlogged, burned/logged.
Results:

- Salvage logging resulted in higher fine dead surface fuel loads than unlogged stands.
- Postfire tree regeneration was reduced by 71 percent in logged sites.
- Short-term fire risk was increased following salvage operations.

Donato, D.C.; Fontaine, J.B.; Kauffman, J.B.; Robinson, W.D.; Law, B.E. 2013. Fuel mass and forest structure following stand-replacement fire and post-fire logging in a mixed-evergreen forest. International Journal of Wildland Fire. 22: 652–666.

Location: Biscuit Fire, southwest Oregon.
Type of study: Observational.
Variables: Surface and aerial fuel mass, shrub cover.
Treatments: Burned/unlogged, burned/moderate, and burned/intensity harvest.
Results:

- Standing dead biomass was significantly reduced by salvage logging.
- Activity fuels remaining on site were greater following high-intensity (28 percent of felled material) than moderate intensity-harvest (14 percent of felled material).
- Cover of downed wood was three to five times greater in harvested stands.
- High-intensity salvage logging resulted in surface fuels that may require additional treatment to reduce fire risk.

Keywords: Biomass, Biscuit Fire, coarse woody debris, dead wood, fuel succession, Klamath–Siskiyou, legacy, logging intensity, postfire management, salvage logging, snag.

Dunn, C.J.; Bailey, J.D. 2015. Modeling the direct effects of salvage logging on long-term temporal fuel dynamics in dry-mixed conifer forests. Forest Ecology and Management. 341: 93–109.

Location: Multiple fires, central Oregon Cascade Range.
Type of study: Modelling.
Variables: Surface fuel loads, understory woody biomass.
Treatments: Burned/unlogged, burned/logged.
Results:

- In salvage harvest scenarios, fine woody fuel loads were greatest 17 to 18 years after high-severity fire.
- Postfire logging resulted in an increase in fine fuel loadings of 160 to 237 percent that persisted for 22 years after fire.
- 1,000-hr fuels loadings peaked 24 to 31 years following fire in untreated stands.
- 1,000-hr fuels were significantly reduced 7 years following postfire harvest.

Keywords: Fuel succession, reburn, salvage logging, hazardous fuels, snag dynamics, decomposition.

Emelko, M.B.; Silins, U.; Bladon, K.D.; Stone, M. 2011. Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for "source water supply and protection" strategies. Water Research. 45: 461–472.

Location: Lost Creek Fire, Alberta, Canada.
Type of study: Observational.
Variables: Water quality.
Treatments: Unburned, burned, burned/logged.
Results:

- Wildfire and salvage logging contributed to increased turbidity and dissolved organic carbon in studied watersheds.
- Additional measures are needed to assure clean drinking water for downstream communities following large-scale wildfire.

Keywords: Source water supply and protection, treatability, adaptation, wildfire, climate change, integrated water management, drinking water treatment.

Everett, R. 1995. Review of recommendations for post-fire management (Beschta et al.). August 16 letter to John Lowe, regional forester. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 1133 N Western Avenue, Wenatchee, WA 98801.

Fontaine, J.B.; Donato, D.C.; Campbell, J.L.; Martin, J.G.; Law, B.E. 2010. Effects of post-fire logging on forest surface air temperatures in the Siskiyou Mountains, Oregon, USA. Forestry. 83: 477–482.

Location: Biscuit Fire, southwest Oregon.
Type of study: Observational.
Variables: Surface air temperature.
Treatments: Burned, burned/logged.
Results:

- Maximum daily surface air temperature was not affected by postfire logging.
- Salvage logging caused slight increase in nightly minimum temperatures and earlier daytime heating.

Gorton, S.; Kays, J. 1996. Legislative history of the timber and salvage amendments enacted in the 104th Congress: a small victory for timber communities in the Pacific Northwest. Environmental Law. 26: 641.

Haggard, M.; Gaines, W.L. 2001. Effects of stand-replacement fire and salvage logging on a cavity-nesting bird community in eastern Cascades, Washington. Northwest Science. 75: 387–396.

Location: Rat Creek Fire, Washington.
Type of study: Observational.
Variables: Abundance, species richness, and nesting populations of cavity-nesting birds.
Treatments: Burned/low, burned/medium, and burned/high-intensity salvage.
Results:

- Medium-intensity salvage sites had highest bird abundance, richness, and nesting population of the three treatments.
- Large-diameter snags (>48 cm) provided nesting habitat for greater number of bird species.

Hanson, J.J.; Stuart, J.D. 2005. Vegetation responses to natural and salvage logged fire edges in Douglas-fir/hardwood forests. Forest Ecology and Management. 214: 266–278.

Location: northwestern California.
Type of study: Observational.
Variables: Understory species composition and structure.
Treatments: Unburned, burned, burned/logged.
Results:

- Salvage logging resulted in significant changes to plant community along forest edges.
- Edge effects on intact forest patches were greater on salvaged sites than unsalvaged ones

Keywords: Edge effects, edge, fire, salvage logging, understory, old-growth, Douglas-fir.

Hebblewhite, M.; Munro, R.H.; Merrill, E.H. 2009. Trophic consequences of postfire logging in a wolf–ungulate system. Forest Ecology and Management. 257(3): 1053–1062.

Location: Alberta, Canada.
Type of study: Observational.
Variables: Forage (understory) biomass, spatial distribution of wolves and ungulate prey.
Treatments: Burned, burned/logged postfire, burned/logged prefire.
Results:

- Reductions in herbaceous biomass in logged units immediately post-harvest dissipated by the third year of the study.
- Elk avoided logged areas, despite increased forage abundance.
- Wolves selected open sites near roads and logged areas, increasing predation risk, and influencing elk movement and resource use.
- Postfire logging caused a top-down increase in predation risk for elk, affecting trophic interactions between elk and wolves.

Keywords: Edge effects, edge, fire, salvage logging, understory, old-growth, Douglas-fir.

Helms, J.A. 1998. The dictionary of forestry. Bethesda, MD: Society of American Foresters. 210 p.

Hutto, R.L. 2006. Toward meaningful snag-management guidelines for postfire salvage logging in North American conifer forests. Conservation Biology. 20: 984–993.

Hutto, R.L.; Gallo, S.M. 2006. The effects of postfire salvage logging on cavity-nesting birds. The Condor. 108: 817–831.

Location: Blackfoot-Clearwater Wildlife Management Area, Montana.
Type of study: Observational.
Variables: Nest abundance and density of cavity-nesting birds.
Treatments: Burned, burned/logged.
Results:

- Nest density was lower in sites subjected to postfire harvest.
- Sites which were unlogged had higher bird species richness.
- 50 percent of studied species were more abundant in unharvested areas.
- Six postfire specialist bird species were absent from logged sites.
- Nest abundance may be dependent on available foraging habitat.

Keywords: Black-backed woodpecker, cavity-nesting birds, fire, healthy forests, salvage logging.

Jennings, T.N.; Smith, J.E.; Cromack, K.; Sulzman, E.W.; McKay, D.; Caldwell, B.A.; Beldin, S.I. 2012. Impact of postfire logging on soil bacterial and fungal communities and soil biogeochemistry in a mixed-conifer forest in central Oregon. Plant and Soil. 350: 393–411.

Location: B&B Fire, central Oregon.
Type of study: Observational.
Variables: Soil nutrients, microbial and fungal species richness and community composition.
Treatments: Unburned, burned, burned/logged.
Results:

- Soil compaction resulting from postfire timber harvest decreased plant-available nitrogen.
- Subsoiling following harvest-related compaction decreased plant-available phosphorus.
- Bacterial and fungal richness did not vary between treatments.

Keywords: Soil microbial and fungal communities, nutrient cycling.

Johnson, E.A.; Miyanishi, K. 2008. Testing the assumptions of chronosequences in succession. Ecology Letters. 11: 419–431.

Keyser, T.L.; Smith, F.W.; Shepperd, W.D. 2009. Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understory development in ponderosa pine forests of the Black Hills, SD, USA. International Journal of Wildland Fire. 18: 451–458.

Location: Jasper Fire, South Dakota.
Type of study: Observational.
Variables: Surface fuel loading, understory cover, tree regeneration density.
Treatments: Burned, burned/logged.
Results:

- Fine and coarse woody debris were greatly increased in unharvested sites.
- Tree regeneration was reduced by 75 percent in salvage-logged sites because of low seed-tree retention.
- Understory vegetation did not vary between treatments.

Keywords: Exotic species, fuel load, mixed-severity, *Pinus ponderosa*, wildfire.

Kishchuk, B.; Thiffault, E.; Lorente, M.; Quideau, S.; Keddy, T.; Sidders, D. 2014. Decadal soil and stand response to fire, harvest, and salvage-logging disturbances in the western boreal mixed-wood forest of Alberta, Canada. Canadian Journal of Forest Research. 45: 141–152.

Location: Chisholm Fire, Alberta, Canada.
Type of study: Observational.
Variables: Soil nutrients, forest floor properties, foliar nutrition, understory.
Treatments: Unburned, burned, unburned clearcut, burned/logged.
Results:

- Postfire logging caused changes in soil nutrition that remain evident 10 years after harvest.
- After 10 years, forest floor properties were comparable between harvested and control sites.
- Soil and foliar nutritional differences did not affect regeneration vigor.

Keywords: Compound disturbance, salvage logging, soil carbon, soil nutrients, boreal plains ecozone, boreal mixed-wood forest.

Knapp, E.E.; Ritchie, M.W. 2016. Response of understory vegetation to salvage logging following a high-severity wildfire. Ecosphere. 7(11): e01550. https://doi.org/10.1002/ecs2.1550.

Location: Cone Fire, California.
Type of study: Replicated experiment.
Variables: Understory species richness and cover.
Treatments: Burned/logged at five levels of intensity (control to 100 percent removal)
Results:

- Postfire logging at highest intensity significantly reduced shrub cover.
- Salvage intensity did not affect understory plant species richness.
- Factors unrelated to postfire logging may have a stronger influence on changes in postfire plant communities.

Keywords: High-severity wildfire, nonnative species, *Pinus ponderosa*, postfire management, salvage logging, species diversity, species richness, variable-retention salvage.

Kronland, W.J.; Restani, M. 2012. Effects of post-fire salvage logging on cavity-nesting birds and small mammals in southeastern Montana. Canadian Field-Naturalist. 125: 316–326.

Location: Kraft Springs, Montana.
Type of study: Observational.
Variables: Density of small mammals and cavity-nesting birds.
Treatments: Burned, burned/logged.
Results:

- Deer mouse density showed a positive relationship with postfire harvest.
- Postfire logging resulted in lower densities of cavity-nesting birds, particularly hairy woodpeckers.

Keywords: Cavity-nesting birds, downed woody debris, forest management, nest survival, salvage logging, wildfire, hairy woodpecker, *Picoides villosus*, deer mouse, *Peromyscus maniculatus*, Custer National Forest, Montana.

Kurulok, S.E.; Macdonald, S.E. 2007. Impacts of postfire salvage logging on understory plant communities of the boreal mixedwood forest 2 and 34 years after disturbance. Canadian Journal of Forest Research. 37: 2637–2651.

Location: Various fires, Alberta, Canada.
Type of study: Observational.
Variables: Understory species composition, shrub abundance.
Treatments: Burned, burned/logged.
Results:

- Salvage logging increased species richness, presence of weedy species, and shrub abundance, and reduced fire specialists in the short term.
- Older salvaged stands showed minimal effects of logging.

Lee, D.E.; Bond, M.L.; Borchert, M.I.; Tanner, R. 2013. Influence of fire and salvage logging on site occupancy of spotted owls in the San Bernardino and San Jacinto Mountains of southern California. Journal of Wildlife Management. 77: 1327–1341.

Location: Various fires, California.
Type of study: Observational.
Variables: Owl extinction and colonization probabilities.
Treatments: Unburned, burned, burned/logged.
Results:

- Effects of salvage logging on occupancy dynamics were not statistically significant, but may be biologically meaningful.
- A slight decrease in the probability of owl occupancy was observed in burned sites that were subsequently logged.

Keywords: California spotted owl, fire severity, forest structure, occupancy modeling, population dynamics, *Strix occidentalis*.

Macdonald, S.E. 2007. Effects of partial post-fire salvage harvesting on vegetation communities in the boreal mixedwood forest region of northeastern Alberta, Canada. Forest Ecology and Management. 239: 21–31.

Location: House River Fire, Alberta, Canada.
Type of study: Replicated experiment.
Variables: Understory species richness and composition; tree regeneration.
Treatments: Burned, burned/single-tree retention harvest, burned/patch retention harvest.
Results:

- Aspen regeneration was greater in harvested stands.
- Understory species richness and diversity were unaffected by salvage.

- Salvage logging affected plant community composition, but prefire composition and burn severity may have greater effects.
- Variation in harvest intensity had little effect on variables studied.

Keywords: Boreal forest, mixed wood forest, vascular plants, richness, composition, fire, salvage logging, salvage harvest.

McGinnis, T.W.; Keeley, J.E.; Stephens, S.L.; Roller, G.B. 2010. Fuel buildup and potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide shrub removal in Sierra Nevada forests. Forest Ecology and Management. 260: 22–35.

Location: McNally, Star, Cleveland and Stanislaus Fires, California.
Type of study: Observational.
Variables: Surface fuel loading, understory species richness and cover.
Treatments: Burned, burned/logged, burned/herbicide treatment.
Results:

- Short-term fuel loading was greater in logged stands.
- Modelling did not predict differences in fire behavior between logged and control stands.
- Postfire salvage did not affect understory cover or species richness.

Keywords: Salvage logging, conifer plantations, fuel, fire behavior, cheatgrass.

McIver, J.D. 2003. Sediment transport and soil disturbance after postfire logging. Hydrological Science and Technology. 19: 335–348.

McIver, J.D.; McNeil, R. 2006. Soil disturbance and hill-slope sediment transport after logging of a severely burned site in northeastern Oregon. Western Journal of Applied Forestry. 21: 123–133.

Location: Summit Fire, Oregon.
Type of study: Replicated experiment.
Variables: Soil disturbance, sediment transportation.
Treatments: Burned, burned/partial harvest, burned/full harvest.
Results:

- Soil compaction, displacement, and erosion were greater in harvested stands.
- Sediment transport out of salvaged units was minimal.
- Favorable site conditions and logging practices designed to reduce soil impacts likely limited effects of postfire harvest.

McIver, J.D.; Ottmar, R. 2007. Fuel mass and stand structure after post-fire logging of a severely burned ponderosa pine forest in northeastern Oregon. Forest Ecology and Management. 238: 268–279.

Location: Summit Fire, Oregon.
Type of study: Replicated experiment.
Variables: Surface fuel loading.
Treatments: Burned, burned/logged commercial, burned/fuel reduction.
Results:

- Ladder tree height and tree species composition were not affected by logging.
- Surface fuel mass was greatest in fuel reduction stands, particularly in slash component.
- Modelling of fuel bed predicted a 15-year duration of dissimilarity in slash fuels.
- Projections of 1,000-hr fuel dynamics predicted heavier accumulations in unlogged stands.
- Fire effects models did not predict a difference in tree mortality between treatments, partly because of reliance on flame length as cause of tree death.

Keywords: Salvage logging, reburn hypothesis, restoration.

McIver, J.D.; Ottmar, R. 2018. Fuel mass and stand structure 13 years after logging of a severely burned ponderosa pine forest in northeastern Oregon, U.S.A. Forest Ecology and Management. 424: 505–518.

Location: Summit Fire, Oregon.
Type of study: Replicated experiment.
Variables: Surface fuel loading, tree regeneration.
Treatments: Burned, burned/logged commercial, burned/fuel reduction.
Results:

- 13 years after harvest, discrepancies in slash fuel loading dissipated.
- Logged stands continued to lack snags and coarse woody debris after 13 years.
- Regeneration density was highly variable, but higher on average in unlogged stands.

Keywords: Salvage logging, postfire logging, reburn hypothesis, restoration logging, disturbance, wildfire.

McIver, J.D.; Starr, L. 2000. Environmental effects of postfire logging: literature review and annotated bibliography. Gen. Tech. Rep. PNW-GTR-486. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p.

Miller, J.D.; Thode, A.E. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment. 109: 66–80.

Morgan, P.; Moy, M.; Droske, C.A.; Lewis, S.A.; Lentile, L.B.; Robichaud, P.R.; Hudak, A.T.; Williams, C.J. 2015. Vegetation response to burn severity, native grass seeding, and salvage logging. Fire Ecology. 11(2): 32–58. doi: 10.4996/fireecology.1102031.

Location: School Fire, Washington.
Type of study: Observational.
Variables: Understory species richness and abundance.
Treatments: Unburned, burned/logged, burned/seeded, burned/seeded/logged; replicated with three burn-severity classes.
Results:

- Species richness and diversity were reduced by salvage logging.
- Burn severity and postfire seeding had a greater effect on vegetation response than logging.
- Differences between treatments were initially substantial, but declined after 6 years.

Keywords: Fire effects, mixed-conifer forests, plant succession, post-fire rehabilitation, salvage logging.

Morissette, J.; Cobb, T.; Brigham, R.; James, P. 2002. The response of boreal forest songbird communities to fire and post-fire harvesting. Canadian Journal of Forest Research. 32: 2169–2183.

Location: Hawk Fire, Saskatchewan, Canada.
Type of study: Observational.
Variables: Songbird abundance, species richness and diversity.
Treatments: Unburned, burned, burned/logged.
Results:

- Songbird community composition was distinct in all three treatments.
- Differences in bird species assemblage were greatest between burned

and salvaged sites.

- Generalists and species associated with open habitats were more abundant in logged areas.
- Cavity and canopy nesters, insectivores, and resident species abundance were negatively affected by salvage logging.
- Postfire salvage may be a greater disturbance to songbird communities than fire.

Newton, M.; Fitzgerald, S.; Rose, R.R.; Adams, P.W.; Tesch, S.D.; Sessions, J.; Atzet, T.; Powers, R.F.; Skinner, C. 2006. Comment on "Post-wildfire logging hinders regeneration and increases fire risk." Science. 313: 615–615.

Peterson, D.L.; Agee, J.K.; Aplet, G.H.; Dykstra, D.P.; Graham, R.T.; Lehmkuhl, J.F.; Pilliod, D.S.; Potts, D.F.; Powers, R.F.; Stuart, J.D. 2009. Effects of timber harvest following wildfire in western North America. Gen. Tech. Rep. PNW-GTR-776. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 51 p.

Peterson, D.W.; Dodson, E.K. 2016. Post-fire logging produces minimal persistent impacts on understory vegetation in northeastern Oregon, USA. Forest Ecology and Management. 370: 56–64.

Location: Summit Fire, Oregon.
Type of study: Replicated experiment.
Variables: Understory plant cover, species richness, diversity, community composition.
Treatments: Burned, burned/logged commercial, burned/logged fuel reduction.
Results:

- No significant effect of postfire logging was observed 15 years following treatments.
- Understory species appear resilient to disturbance.
- Low-impact harvest methods may have minimized negative effects on understory.

Keywords: Postfire logging, salvage logging, understory vegetation, species richness, biodiversity, postfire forest management.

Peterson, D.W.; Dodson, E.K.; Harrod, R.J. 2015. Post-fire logging reduces surface woody fuels up to four decades following wildfire. Forest Ecology and Management. 338: 84–91.

Location: Various fires, Oregon and Washington.
Type of study: Observational.
Variables: Surface fuel loading.
Treatments: Burned, burned/logged.
Results:

- Postfire logging created a temporary pulse of increased fine and medium fuels that lasted 5 to 7 years following harvest.
- In the long term, all woody fuel loadings were lower in salvage-logged stands.
- Coarse woody fuels were reduced by logging for nearly 40 years.

Keywords: Ponderosa pine, Douglas-fir, post-fire logging, salvage logging, fuel succession, forest restoration.

Poirier, V.; Paré, D.; Boiffin, J.; Munson, A.D. 2014. Combined influence of fire and salvage logging on carbon and nitrogen storage in boreal forest soil profiles. Forest Ecology and Management. 326: 133–141.

Location: Various fires, Quebec, Canada.
Type of study: Observational.
Variables: Soil organic carbon (SOC), total soil nitrogen (N), soil structure.
Treatments: Unburned, burned, burned/logged.
Results:

- SOC was lower in organic layer in logged stands compared with burned only.
- Logging increased SOC and N in mineral horizons.
- Whole-soil SOC and N stocks of burned soils were unchanged by salvage logging.

Keywords: Soil organic carbon, total soil nitrogen, soil horizons, wildfire, salvage logging, black spruce forest.

Powers, E.M.; Marshall, J.D.; Zhang, J.; Wei, L. 2013. Post-fire management regimes affect carbon sequestration and storage in a Sierra Nevada mixed conifer forest. Forest Ecology and Management. 291: 268–277.

Location: Storrie Fire, California.
Type of study: Observational.
Variables: Carbon storage and sequestration.
Treatments: Low-severity burn, burned, burned/logged/planted, burned/logged/planted/intensive management.

Results:

- Postfire salvage logging reduced total ecosystem carbon storage.
- Belowground carbon storage in mineral soil was lowest in intensively managed treatment.
- Total carbon sequestration did not vary significantly among treatments.

Keywords: Carbon flux, carbon storage, forest management, fire, climate change.

Ritchie, M.W.; Knapp. E.E. 2014. Establishment of a long-term fire salvage study in an interior ponderosa pine forest. Journal of Forestry. 112: 395–400.

Location: Cone Fire, California.
Type of study: Replicated experiment.
Variables: Snag dynamics, surface fuel loading, tree regeneration.
Treatments: Burned/logged at five levels of intensity, including unlogged control.
Results:

- Transition of snags to surface fuels was rapid.
- Stands with higher snag retention levels (basal area > 60 ft²/acre) exceeded historical surface fuel loads after 10 years.
- White fir and incense-cedar snags had greater longevity than pine snags.
- Regeneration was minimal, and seedling density appeared unrelated to treatment.

Keywords: Snag dynamics, biomass, regeneration.

Ritchie, M.W.; Knapp, E.E.; Skinner, C.N. 2013. Snag longevity and surface fuel accumulation following post-fire logging in a ponderosa pine dominated forest. Forest Ecology and Management. 287: 113–122.

Location: Cone Fire, California.
Type of study: Replicated experiment.
Variables: Snag dynamics, surface fuel loading.
Treatments: burned/logged at five levels of intensity, including unlogged control.
Results:

- Fuel loading of coarse materials increased with snag retention level.
- Greatest loading of 1,000-hr fuels occurred in control units.
- More than 80 percent retained snag biomass had transitioned to surface fuel by year 8.
- Pine snags were more susceptible to breakage and decay than white fir or incense-cedar.

Keywords: Coarse woody debris, snag dynamics, salvage logging.

Rost, J.; Hutto, R.L.; Brotons, L.; Pons, P. 2013. Comparing the effect of salvage logging on birds in the Mediterranean Basin and the Rocky Mountains: common patterns, different conservation implications. Biological Conservation. 158: 7–13.

Location: Various fires, Montana and Catalonia, Spain.
Type of study: Observational.
Variables: Species richness and abundance of birds.
Treatments: Burned, burned/logged.
Results:

- Species that are dependent on snags were negatively affected by salvage logging.
- Logging had positive effect on open-habitat species in Mediterranean sites.

Keywords: Catalonia, conifer forests, fire specialists, forest management, Montana, wood harvesting.

Rothermel, R. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Saab, V.A.; Russell, R.E.; Dudley, J.G. 2007. Nest densities of cavity-nesting birds in relation to postfire salvage logging and time since wildfire. The Condor. 109: 97–108.

Location: Foothills Fire and Star Gulch Fire, Idaho.
Type of study: Observational.
Variables: Nest density and success of open space and cavity-nesting (bark-foraging) birds.
Treatments: Burned, burned/partially logged.
Results:

- Nest densities of cavity nesting (bark foraging) were higher in unlogged than logged burn.
- Logged burn had higher nest density of two open-space-foraging species vs. unlogged burn.
- Mountain bluebird nest density was higher in unlogged than logged burn, while western bluebirds did not show an effect of treatment.
- Hairy woodpecker nest survival was reduced in logged burn vs. unlogged during early postfire period.

Keywords: Cavity-nesting birds, nest densities, nest survival, ponderosa pine forests, postfire salvage logging, wildfire.

Silins, U.; Bladon, K.D.; Kelly, E.N.; Esch, E.; Spence, J.R.; Stone, M.; Emelko, M.B.; Boon, S.; Wagner, M.J.; Williams, C.H. 2014. Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. Ecohydrology. 7: 1508–1523.

Location: Lost Creek Fire, Alberta, Canada.
Type of study: Observational.
Variables: Water chemistry, algal production.
Treatments: Unburned, burned, burned/logged.
Results:

- Phosphorous concentrations were highest in logged watersheds.
- Although wildfire had a greater effect on measured variables, salvage logging added incremental impacts.
- Wildfire and salvage logging caused a cascading series of effects on the ecohydrology of studied watersheds.

Keywords: Forest fire, natural disturbance, hydrologic recovery, stream ecology, phosphorus, sediment, algae macroinvertebrates.

Slesak, R.A.; Schoenholtz, S.H.; Evans, D. 2015. Hillslope erosion two and three years after wildfire, skyline salvage logging, and site preparation in southern Oregon, USA. Forest Ecology and Management. 342: 1–7.

Location: Timbered Rock Fire, Oregon.
Type of study: Observational.
Variables: Sediment transport, vegetative cover.
Treatments: Burned, burned/logged.
Results:

- Erosion was more pronounced in salvage-logged sites in year following harvest.
- In second year, no differences in erosion were detected.
- As little soil disturbance was observed, increased erosion in harvested sites was most likely due to vegetation control prior to replanting salvaged areas.

Keywords: Vegetation control, plot scale measurements, postfire erosion, Pacific Northwest.

Thompson, J.R.; Spies, T.A.; Ganio, L.M. 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. Proceedings of the National Academy of Sciences of the United States of America. 104: 10743–10748.

Location: Biscuit Fire and Silver Fire, Oregon.
Type of study: Observational.
Variables: Burn severity (differenced normalized burn ratio (dNBR) from remote sensing data).
Treatments: Burned, burned/logged/planted, replicated across continuous dNBR indices of burn severity of both fires.
Results:

- Sites that burned at high severity in Silver Fire tended to burn again at high severity in Biscuit Fire.
- Harvest of fire-killed trees reduced large fuels but did not decrease reburn severity.
- Replanting of conifers in harvested areas may have increased burn severity in salvaged-logged stands.

Keywords: Public land management, salvage logging, Biscuit Fire, landsat, landscape ecology.

Thorn, S.; Bässler, C.; Brandl, R.; Burton, P.J.; Cahall, R.; Campbell, J.L.; Castro, J.; Choi, C.-Y.; Cobb, T.; Donato, D.C.; Durska, E.; Fontaine, J.B.; Gauthier, S.; Hebert, C.; Hothorn, T.; Hutto, R.L.; Lee, E.-J.; Leverkus, A.B.; Lindenmayer, D.B.; Obrist, M.K.; Rost, J.; Seibold, S.; Seidl, R.; Thom, D.; Waldron, K.; Wermelinger, B.; Winter, M.-B.; Zmihorski, M.; Müller, J. 2018. Impacts of salvage logging on biodiversity: a meta-analysis. Journal of Applied Ecology. 55: 279–289.

Location: Various fires, worldwide.
Type of study: Meta-analysis.
Variables: Species richness and community composition of 24 taxonomic groups.
Treatments: Disturbed, disturbed/logged (including fire).
Results:

- Salvage logging negatively affected richness in eight taxonomic groups.
- Post-disturbance harvest had disproportionally negative impacts on saproxylic organisms.
- Species that use open habitats had generally positive responses to logging.

Keywords: Bark beetle, climate change, dead wood, disturbed forest, fire, natural disturbance, post-disturbance logging, salvage logging, saproxylic taxa, windstorm.

Wagenbrenner, J.W.; MacDonald, L.H.; Coats, R.N.; Robichaud, P.R.; Brown R.E. 2015. Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States. Forest Ecology and Management. 335: 176–193.

Location: Tripod, Kraft Springs, Red Eagle, and Hayman Fires, Washington, Montana, and Colorado.
Type of study: Observational.
Variables: Ground cover, soil disturbance, runoff, sediment production.
Treatments: Burned, burned/logged replicated across various harvest methods.
Results:

- Soil compaction increased in salvage-logged sites.
- Harvested stands in areas with greater disturbance produced more sediment.
- Vegetative cover was negatively associated with salvage, and vegetation recovery was delayed in these sites.
- Sediment production did not increase with logging in larger swales.
- Treatment of skid trails with logging slash resulted in decreased sediment yields but did not affect soil properties.

Keywords: Erosion, wildfire, water repellency, soil compaction, salvage logging, mitigation.

Wagenbrenner, J.W.; Robichaud, P.R.; Brown, R.E. 2016. Rill erosion in burned and salvage logged western montane forests: effects of logging equipment type, traffic level, and slash treatment. Journal of Hydrology. 541: 889–901.

Location: Red Eagle, School, and Terrace Mountain Fires, Montana, Washington, and British Columbia, Canada.
Type of study: Observational.
Variables: Vegetative cover, runoff, sediment production, soil disturbance.
Treatments: Burned, burned/logged, replicated across various harvest methods.
Results:

- Erosion was more pronounced in logged stands, but effects diminished over time.
- Runoff rates were higher in logged sites.
- Equipment used for harvest did not have measureable effects.
- Using logging slash to cover skid trails did not affect runoff or sedimentation.

Keywords: Salvage logging, wildfire, runoff, soil compaction, soil water repellency, sediment.

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