Effects of Salvage Logging on Riparian Zones in Coniferous Forests of Eastern Washington and Adjacent Regions

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Washington State Forest Practices Adaptive Management Program

The Washington State Forest Practices Board (FPB) has established an Adaptive Management Program (AMP) by rule in accordance with the Forests & Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> *Provide science-based recommendations and technical information to assist the FPB in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. The board may also use this program to adjust other rules and guidance.* (Forest Practices Rules, WAC 222-12-045(1)).

To help provide the information needed to support adaptive management, the FPB established and empowered the Cooperative Monitoring, Evaluation and Research (CMER) committee to conduct effectiveness and validation monitoring in accordance with WAC 222-12-045 and Board Manual Section 22.

Report Type and Disclaimer

This technical report contains scientific information from research and monitoring studies designed to evaluate the effectiveness of the forest practices rules in achieving Forest and Fish performance goals, resource objectives, and/or performance targets. The document was prepared for the Cooperative Monitoring, Evaluation and Research Committee (CMER) and was intended to inform the Forest and Fish Adaptive Management program. The project was conducted under the oversight of the Scientific Advisory Group Eastside (SAGE).

This document was reviewed by CMER and was approved for distribution as an official CMER document. As a CMER document, CMER is in consensus on the scientific merit of the document. However, any conclusions, interpretations, or recommendations contained within this document are those of the authors and may not reflect the views of all CMER members.

Historical Background

During the summer of 2015 there were extensive wildfires that spanned across several counties in Eastern Washington, and fire salvage logging has been the main focus for affected landowners in the region. In response to the recent fires, SAGE members expressed a need to understand fire salvage logging practices that should be used when harvesting adjacent to public resources such as riparian management zones. This literature review was intended to help CMER and SAGE identify research gaps in fire salvage harvest practices in order to inform the development of future research projects.

Proprietary Statement

This review was developed with public funding. As such, it is within the public use domain. However, the concept of this work originated with the Washington State Forest Practices Adaptive Management Program and the editors. As a public resource document, this review should be cited as:

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Synthesis Report

Literature Review:

Effects of Salvage Logging on Riparian Zones in Coniferous Forests of Eastern Washington and Adjacent Regions

Submitted in fulfillment of

Washington State Department of Natural Resources

Contract No. PSC 93-095317

October 2017

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Executive Summary

This Synthesis Report represents the contract final report for Washington State Department of Natural Resources [DNR] contract number PSC 93-095317, titled *Literature Review and Synthesis Related to Salvage of Fire Damaged Timber*. For this literature review project, contemporary research information was requested by the Scientific Advisory Group Eastside (SAGE) to help support the work of the Cooperative Monitoring, Evaluation, and Research (CMER) committee of the DNR Forest Practices Board.

This report provides an overview of the goals, objectives, methods, and results of the project. We reviewed 75 relatively recent publications that provide information about potential effects of salvage logging on riparian areas for eastside forests and comparable forests elsewhere in the Pacific Northwest. A major finding from the review is that the literature provides relatively little specific information about the effects of salvage logging in riparian areas. This lack of data applies not only to Washington eastside forests, but for riparian forests elsewhere in the western U.S. The lack of riparian-specific research is likely related to the fact that most modern-day fires have occurred on federal lands, where salvage logging and salvage-related research have been largely absent. Otherwise, the literature contains a wide range of information about the possible effects of salvage logging on adjacent upland forests, which can be useful for developing riparian management strategies. Examples of recent salvage-related research include studies investigating possible effects on soils (e.g., erosion, compaction, hydrophobicity), and studies documenting the effects of various management practices such as differing harvesting methods and equipment, erosion mitigation practices, and varying silvicultural prescriptions. A considerable amount of literature also describes research on post-salvage regeneration issues, and on fuels management practices. Conversely, less information exists about potential effects of salvage logging on riparian ecosystem structure and function, such as stream temperature regimes, water quality issues, aquatic biota, and the effectiveness of forest buffer retention zones. Topics such as salvage effects on soil processes (e.g., nutrient cycling, soil biota), riparian wildlife habitat, riparian restoration, and modern-day riparian fire regimes are also less well represented in the literature. Therefore, after describing the state of relatively recent research on salvage logging in relation to riparian areas, this report concludes by listing some current research gaps that have been identified by various study authors and other professionals.

In addition to this Synthesis Report, the literature review project produced the following products: 1) an *Excel* database housing key data elements for the literature (e.g., authors, publication years, summaries), 2) a User Guide that explains how to efficiently locate and summarize information in the *Excel* database, and 3) a literature collection composed of downloadable digital copies (pdf files) of each piece of literature reviewed during the project.

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Introduction

Riparian area management has been identified as an important priority for the Washington Department of Natural Resources (DNR), particularly in western Washington's heavily timbered forests containing critical freshwater salmonid habitats. In recent decades, fire's ecological role in riparian areas of eastern Washington has been identified as an important management consideration. For example, in 2002 the agency initiated a contract to document historical fire regimes for forests in eastern Washington, titled *A Review and Synthesis of Available Information on Riparian Disturbance Regimes in Eastern Washington* (Concurrent Technologies Corporation. 2002).

The current eastside rules that apply to commercial forestlands were established through the Forests and Fish Agreement in 1999 (Washington State DNR 1999). That document, compiled by multiple forest stakeholders, provided broad management directives aimed at protecting water quality and riparian habitat and associated dependent species. In response, a major management goal has been to restore and maintain riparian areas to emulate the historical range of conditions that existed in fire-dependent landscapes. In addition, a 2006 update to the 1992 state forest management plan, titled *Policy for Sustainable Forests* (Washington State DNR 2006), highlights the importance of conserving riparian areas on state-owned lands in eastern Washington, as well as statewide:

> In Eastern Washington, the protection of riparian and wetland acreage and function is critical. Although these ecosystems are only a small portion of the Eastern Washington landscape, they are disproportionately important as habitat. Riparian and wetland areas in Eastern Washington are more strongly differentiated from surrounding uplands than the same areas in Western Washington and therefore, provide a more specialized habitat for rare plant and animal species. (Washington State DNR 2006: p. 38)

Several severe wildland fire years and predictions that global climate change may increase their frequency has raised concerns among forest managers in eastern Washington over how to best manage riparian areas after wildfire. The goal of this literature review is to provide managers with information to support the development of best management practices that can be used in association with salvage harvests to protect riparian resources. Scientific Advisory Group Eastside (SAGE) members elevated this issue within the forest practices adaptive management program. In discussing potential research projects, the Cooperative Monitoring, Evaluation, and Research (CMER) committee recognized the need to first document the best available scientific information about riparian disturbance ecology, including data on the effects of post-fire salvage logging. The purpose of this literature review project is to document the current Best Available Science on Best Management Practices for use with fire salvage operations in support of the work of CMER.

Methods

The methods used during this project can be subdivided into several phases, as described below.

Analysis Area. The literature search focused on studies that have occurred in a large region encompassing the Inland Northwest and adjacent areas. Specifically, our analysis area includes eastern Washington, Oregon, Idaho, western Montana, northern California, northern Nevada, southeastern British Columbia, and southwestern Alberta (Fig. 1). (In addition, a few applicable studies were conducted in Colorado and South Dakota.) Major forest cover types (Eyre 1980; Franklin and Johnson 2012) in the analysis area include relatively dry coniferous forests, such as those dominated by interior ponderosa pine (*Pinus ponderosa*) and interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), and relatively mesic mixed-conifer forests containing various admixtures of the above species and others such as grand fir (*Abies grandis*), lodgepole pine (*P. contorta*), western larch (*Larix occidentalis*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*A. lasiocarpa*).

Literature Searches. Several techniques were used to locate potentially informative literature. First, we sought the most up-to-date (e.g., post-2000) research that was directly or indirectly related to the topics of post-fire riparian forests and salvage logging. Personal communications with researchers, authors, and other subject matter experts helped us identify relevant research and obtain copies of research papers. Those initial publications also were useful for identifying other articles that might be informative—that is, we scrutinized the Literature Cited sections for further publications. Next, we conducted web-based searches, using such applications as Google Scholar and ResearchGate, using potentially applicable keywords and phrases, such as "post-fire salvage logging in coniferous forested riparian zones in eastern Washington." In addition, we consulted online databases, such as those maintained by the Joint Fire Science Program, to identify potentially useful research documents.

We sought the following types of documents, with the first type representing the highest-value sources: 1) peer reviewed and published documents such as journal articles, and 2) unpublished work, such as research progress reports, symposia proceedings, and so-called white papers and grey literature. Note, however, that peer reviewed publications were the highest priority sources, whereas unpublished material would only be reviewed if sufficient contract time allowed.

Literature Evaluation. After compiling an initial list of potentially informative literature and obtaining digital copies, each piece of literature was evaluated as to its potential usefulness and relevance to the key theme of post-fire salvage logging in and near RMZs. In addition to reviewing research reports for individual studies, we also examined review publications that summarize research to date, such as Reeves et al's (2006) Conservation Biology article titled *Post-fire logging in riparian areas*. Similarly, Wagenbrenner et al's (2015) Forest Ecology and Management article titled *Effects of post-fire salvage logging and a skid treatment on ground cover, soils, and sediment production in the interior western United States* provided pertinent information. Although review articles typically cover very large geographic areas, such as the western U.S. or western North America, the reports often cite information from studies in

Figure 1. General geographic extent of analysis area. The literature review excluded studies occurring on the west side of the Cascade Mountains (black hatching), and included some data from applicable forest types in Colorado and South Dakota.

our analysis area that could then be consulted for region-specific information. That is, such reviews provide up-to-date summaries of the state the knowledge. Also note that, because relatively little research has been conducted on salvage logging in riparian zones *per se*, our literature search necessarily included salvage-related and other publications that provide useful background information to enable interpretations about potential effects of salvage logging in riparian zones. For instance, information from studies evaluating the effects of salvage logging on upland forests can often be used to make interpretations about possible effects on adjacent riparian zones. (Caution must always be used, however, when evaluating a given study's findings; that is, users are necessarily limited to drawing inferences from studies in upland terrain, and in doing so, must recognize that caveats and limitations can apply to riparian zones.)

Data Extraction. After locating potentially useful research, we reviewed each piece of literature and extracted key descriptive information for entry into a database (described below), such as author name(s), publication year, major biophysical attributes of each study area, major research findings, and author recommendations. DNR personnel and other SAGE members also provided a list of data to extract from each report, as shown below:

- **Type of item** (e.g., Peer reviewed publication; white paper)
- **Author(s).**
- **Publication date.**
- **Topics addressed** (e.g., keywords from report).
- **Location**: (e.g., State, National Forest, etc.)
- **Forest Types** (i.e., SAF cover type)
- **Forest practices examined**.

- **Analysis methods**.

To facilitate data analysis and enable efficient long-term storage, the extracted data were entered into an *Excel* database, using the above information to guide our spreadsheet design (Appendix A). In addition to creating data fields for each of the DNR-defined descriptors above, we included several data fields to help future users analyze data according to some common research themes. For instance, we created a field named *Primary Research Theme* to classify each report according to one or more major topics (Table 1). (Secondary and tertiary research themes also were assigned to each report, when possible.) In addition, we included several data fields that document whether a given publication directly addresses the major questions posed by SAGE about riparian salvage logging (discussed later in this report).

Table 1. The five general research themes used during the literature review project.

Research Theme	***Description***
Riparian/Aquatic	Research examining the structure and function of riparian systems, especially in relation to salvage logging
Silviculture/Forest Practices	Research examining specific harvesting practices and their effects on riparian areas
Erosion/Soils	Research examining the effects of fire and salvage logging on geomorphic and soil processes including erosion
Fuels/Fire	Research examining interactions between fuels and salvage logging and effects on the behavior, severity, and ecological effects of fire
Biodiversity/Ecosystems	Research examining the effects of fire and salvage logging on ecosystem services (e.g. drinking water) and function including nutrient cycling and productivity as well as components of biodiversity such as wildlife habitat

We also created a database worksheet called the Keywords Matrix (Fig. 2) which is a table that shows all publications in relation to a list of applicable keywords that we developed after reviewing the literature. By displaying which keywords apply to a given piece of literature, the matrix can serve as a convenient search tool for quickly locating reports on topics of interest. We also developed a user guide that describes various ways of efficiently searching and analyzing the database.

Citation	Review	Riparian	Fire History	Harvest Methods	Aquatic Resources	Erosion
Reeves et al. 2006	Yes	Yes	Yes	Yes	Yes	Yes
Olson and Agee 2005	No	Yes	Yes	No	No	No
Kobziar and McBride 2006	No	Yes	No	Yes	No	No
Berg et al. 2002	Yes	Yes	No	No	No	Yes
Skinner 2003	No	Yes	Yes	No	No	No
Silins et al. 2009	No	Yes	No	No	Yes	Yes
Karr et al. 2004	Yes	Yes	No	Yes	Yes	Yes
Wagenbrenner et al. 2015	No	No	No	Yes	No	Yes
McIver and McNeil 2006	No	No	No	Yes	No	Yes
Slesak et al. 2015	No	No	No	Yes	No	Yes
Larsen et al. 2009	No	No	No	No	No	Yes
Robichaud et al. 2013	No	No	No	No	No	Yes
Ice et al. 2004	Yes	No	No	No	No	Yes
Moody and Martin 2009	Yes	No	No	No	No	Yes
Wondzell and King 2003	Yes	No	No	No	Yes	Yes
Wondzell 2001	Yes	Yes	No	Yes	No	Yes
Silins et al. 2014	No	Yes	No	No	Yes	No

Figure 2. Truncated example of the Keywords Matrix. A "Yes" entry in the column for a given keyword (top of table) signifies that the keyword applies to a given publication (left side of table).

Analysis and Reporting. The analysis and reporting phase began after the database was finalized. First, we produced short (1-page) summary reports for each piece of literature in the database. Each summary report contains the following elements extracted from the database. First, we present an overview, using abstracts and other information from within the body of each article. The overview describes the research objectives, study locations, research methods, major findings, and any conclusions and recommendations that may have been provided by the article author(s). Next, the bottom of each summary report contains a bulleted list of additional SAGE-requested information for quick reference purposes. Therefore, the summary reports compendium can serve as a supplemental or alternative reference source for users who prefer to read narrative summaries instead of *Excel* spreadsheets. (Note, however, that the *Excel* database contains additional information that is not contained in the summary reports, such as a keywords matrix and other data.)

After compiling the individual summary reports, we analyzed the entire literature collection to provide an overview of project results. Specifically, the analysis summarized the literature collection in terms of number of published versus unpublished papers, study completion years, associated geographic descriptors, research according to the five general research themes mentioned above, and so on. In addition, the analysis helped us address key research questions that were developed for this project by SAGE members (described near the end of this report).

Results and Discussion

Salvage Logging and RMZs: Research Status. Relatively few studies to date have focused on salvage logging in riparian zones *per se*, not only in the Pacific Northwest but elsewhere in western North America. However, our findings suggest that the state of science on salvage logging in general has improved considerably over the past 2 decades. For example, McIver and Starr's (2001) article, *A literature review on the environmental effects of postfire logging*, discussed the circa 2000 state of research on post-fire salvage logging. The authors indicated that early understanding of post-fire salvage logging was hindered not only by a lack of research, but also by poor experimental design, replication, and controls. Specifically, the authors located only 21 studies worldwide (including six from our assessment area), of which only seven studies had conducted experimental treatments. In contrast, results from our literature review suggest a steadily increasing body of research—although the literature still lacks information about salvage logging in riparian areas *per se*.

As part of a broader review on the topic of salvage logging, Peterson et al. (2009a) briefly addressed and summarized the state of knowledge as of 2009 regarding the possible effects of timber harvesting on riparian forests. The researchers stated that, "Few data exist on the effects of postfire logging on aquatic ecosystems, although effects can be inferred from the literature on riparian fire, fire effects, and logging effects" (Peterson et al. 2009a: 22). In other words, most studies to date have occurred in adjacent uplands and have provided broad guiding principles rather than quantifiable guidelines specifically for salvage logging. Since about 2000, however, increasing amounts of research have been devoted to studying the potential effects of post-fire salvage logging in many areas of the Pacific Northwest. Although the literature lacks specific information on salvage logging in riparian areas, many studies have provided potentially useful information about salvage logging in upland areas that are adjacent to and/or encompass riparian forests. Therefore, although we have obtained a substantial number of publications that post-date Peterson et al.'s (2009a) overview, our results support their earlier contention that research on salvage logging and other post-fire studies provides largely *inferential* information that can be useful for RMZ management planning.

Literature Overview. After searching for and reviewing potential literature for this project, we obtained the following results. The literature collection consists of 75 publications that can have potential to inform managers about the effects of salvaging logging on riparian zones and adjacent upland terrain (*Note*: Appendix B contains the literature review bibliography). Because the research topics ranged widely, we grouped the publications according to the five major research themes described earlier in this report (and discussed in detail below). As for literature types, most (96%) of the 75 pieces of literature in our collection consist of peer-reviewed journal articles, with only 3 exceptions (2 USDA Forest Service General Technical Reports and one conference proceedings article). Of these, most (99%) of the articles were published after 2000, with one article published in 1999.

Time limitations prevented us from including earlier literature and searching for non-peer reviewed material, such as agency white papers. We do not know therefore what literature exists or if it would more directly inform our study questions, but we assume that the most relevant and novel white papers were subsequently published in peer reviewed journals.

The studies in our database occurred in numerous locations (Figs. 3 and 4; Table 2), but often are clustered geographically—especially around recent large fires that received considerable management- and research focus. For example, much work occurred on the east

Figure 3. General locations of individual studies in the literature review database. The number of mapped sites (n=48) is less than the number of literature pieces in the database (n=75) because of the following factors: 1) some studies shared similar general locations 2) the database contains 20 review articles that cover broad geographic areas, and 3) some study locations lie beyond the map boundaries (i.e., Colorado, S. Dakota).

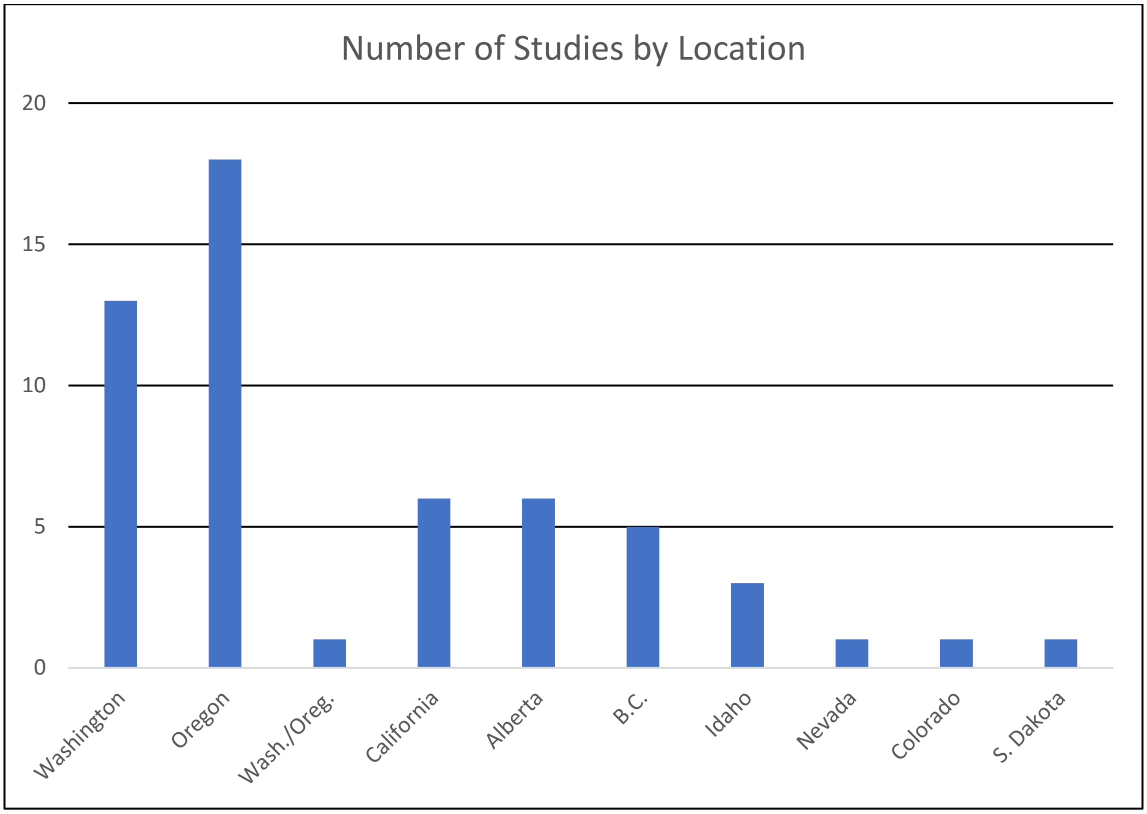

Figure 4. Number and state/region locations of database publications that document site-specific studies (n=55 total). (Twenty review articles are not represented in this graph because they cover multi-state or larger regions.)

Table 2. Database publications that describe a single study each (n=54). The publications are listed according to location, with Washington and Oregon studies listed first, and according to the five primary research themes used by this literature review project.

(*Note*: Complete bibliographic citations appear in Appendix B).

Publication	*Location*	*Research Theme*
Peterson et al. (2015)	Wash./Oregon	Fuels/Fire
Morgan et al. (2015)	Washington	Silviculture/Forest Practices
Wagenbrenner et al. (2015)	Washington	Erosion/Soils
Wagenbrenner et al. (2016)	Washington	Erosion/Soils
Robichaud et al. (2013)	Washington	Erosion/Soils
Peterson et al. (2009b)	Washington	Silviculture/Forest Practices
Monsanto and Agee (2008)	Washington	Fuels/Fire
Mellon et al. (2008)	Washington	Riparian/Aquatic
Robichaud et al. (2006)	Washington	Silviculture/Forest Practices
Everett et al. (2003)	Washington	Riparian/Aquatic
Lehmkuhl et al. (2003)	Washington	Biodiversity/Ecosystems
Haggard and Gaines (2001)	Washington	Biodiversity/Ecosystems
Everett et al. (1999)	Washington	Fuels/Fire
Flitcroft et al. (2016)	Washington	Riparian/Aquatic
Keyser et al. (2009)	S.Dakota	Silviculture/Forest Practices
Campbell et al. (2016)	Oregon	Fuels/Fire
Peterson and Dodson (2016)	Oregon	Biodiversity/Ecosystems
Donato et al. (2013)	Oregon	Fuels/Fire
Dunn and Bailey (2015a)	Oregon	Fuels/Fire
Dunn and Bailey (2015b)	Oregon	Fuels/Fire
Slesak et al. (2015)	Oregon	Erosion/Soils
Clark et al. (2013)	Oregon	Biodiversity/Ecosystems
Dodson and Root (2013)	Oregon	Biodiversity/Ecosystems

Jennings et al. (2012)	Oregon	Biodiversity/Ecosystems
Halofsky and Hibbs (2009)	Oregon	Riparian/Aquatic
Cahall and Hayes (2009)	Oregon	Biodiversity/Ecosystems
Halofsky and Hibbs (2008)	Oregon	Riparian/Aquatic
Thompson et al. (2007)	Oregon	Silviculture/Forest Practices
McIver and Ottmar (2007)	Oregon	Fuels/Fire
Donato et al. (2006)	Oregon	Fuels/Fire
McIver and McNeil (2006)	Oregon	Erosion/Soils
Olson and Agee (2005)	Oregon	Riparian/Aquatic
Sessions et al. (2004)	Oregon	Silviculture/Forest Practices
Johnson et al. (2005)	Nevada	Biodiversity/Ecosystems
Isaak et al. (2010)	Idaho	Riparian/Aquatic
Dunham et al. (2007)	Idaho	Riparian/Aquatic
Russell et al. (2006)	Idaho	Fuels/Fire
Larsen et al. (2009)	Colorado	Erosion/Soils
Knapp and Ritchie (2016)	California	Biodiversity/Ecosystems
Ritchie and Knapp (2014)	California	Silviculture/Forest Practices
Ritchie et al. (2013)	California	Fuels/Fire
Kobziar and McBride (2006)	California	Fuels/Fire
Skinner (2003)	California	Riparian/Aquatic
Berg et al. (2002)	California	Riparian/Aquatic
Leach and Moore (2010)	British Columbia	Riparian/Aquatic
Eaton et al. (2010)	British Columbia	Erosion/Soils
Moore and Scott (2005)	British Columbia	Silviculture/Forest Practices
MacDonald et al. (2003)	British Columbia	Riparian/Aquatic
Story et al. (2003)	British Columbia	Riparian/Aquatic
Emelko et al. (2015)	Alberta	Erosion/Soils

Silins et al. (2014)	Alberta	Riparian/Aquatic
Wagner et al. (2014)	Alberta	Riparian/Aquatic
Emelko et al. (2011)	Alberta	Erosion/Soils
Silins et al. (2009)	Alberta	Erosion/Soils
Bladon et al. (2008)	Alberta	Erosion/Soils

slope of the Cascades, and in the large area burned by the 2002 Biscuit Fire in southwest Oregon. Among the various states and provinces, studies in Oregon comprise the largest amount (n=18 [33%]) of the 55 site-specific studies. (The database contains 75 articles, but 20 of them are review publications rather than individual, site-specific studies). In addition, 13 (24%) of the 55 studies occurred in eastern Washington (Tables 2, 3), and one study had sample sites in both Washington and Oregon. Therefore, the 32 studies that were conducted in Oregon or Washington represent 58 percent of the site-specific publications.

As for study designs, the unpredictable nature of wildfire makes studying the effects of post-fire salvage difficult (McIver and Starr 2001; Reeves et al. 2006; Peterson et al. 2009a). The most powerful experimental approach to studying the effects of salvage logging are paired watershed experiments that can match forest composition and structure, and environmental conditions including watershed size and topography. Further hampering the implementation of riparian-related salvage studies is the fact that most of the large fires have occurred on public lands such as National Forests, which generally lack riparian salvage logging activity. Therefore, most studies were initiated *after* ecological disturbances, such as by fire or upland salvage logging, had occurred. These studies primarily compare salvage logging with burned-only or unburned forests, and few leverage some of the more powerful experimental designs (e.g. Before-After-Control-Impact statistical design (BACI; Stewart-Oaten et al. 1986) that are capable of isolating specific effects of salvage and how they differ from those produced by fire alone.

We also included review articles in the collection to provide broader geographic context and to address subject matter gaps. Reviews draw upon studies addressing local management concerns from across large multi-state regions such as the western U.S. and present the current state of knowledge. These publications provide a synthesis of what is known, identify knowledge gaps, and often provide generalizable guidance for areas that lack geographically specific studies based on knowledge from similar biophysical settings. Specifically, 20 (27%) of the 74 total articles in our collection are review-type publications (Table 4). Below are some examples, which will be discussed later in this report:

- Reeves et al.'s (2006) article, *Postfire logging in riparian areas.* (i.e., in the western U.S.);
- Peterson et al.'s (2009a) General Technical Report, *Effects of timber harvest following wildfire in western North America*;

Table 3. Database publications for eastern Washington (n=16). Table includes one study (Peterson et al. 2015) that occurred in both Washington and Oregon, and two review articles (Wondzell 2001; Wagenbrenner and Robichaud 2014). Associated keywords show a wide array of topics in relation to riparian- and upland forest management, such as salvage logging, wildfire, fire regimes, fuels, and wildlife habitat issues.

(*Note*: Complete bibliographic citations appear in Appendix B).

Publication	*Article Title*	*Keywords*
Morgan et al. (2015)	*Vegetation response to burn severity, native grass seeding, and salvage logging.*	Wildfire, fire behavior, fire severity, timber harvest, salvage logging, vegetation recovery, grass seeding, mitigation.
Peterson et al. (2015)	*Post-fire logging reduces surface woody fuels up to four decades following wildfire.*	Fuel dynamics, Ponderosa pine, Douglas-fir, post-fire salvage logging, fuel succession
Wagenbrenner et al. (2015)	*Effects of post-fire salvage logging and a skid treatment on ground cover, soils, and sediment production in the interior western United States.*	Post-fire salvage logging, soil erosion, hydrophobic soils, forest regeneration
Wagenbrenner et al. (2016)	*Rill erosion in burned and salvage logged western montane forests: Effects of logging equipment type, traffic level, and slash treatment.*	Post-fire salvage logging, soil erosion, hydrophobic soils, soil compaction
Robichaud et al. (2013)	*Post-fire mulching for runoff and erosion mitigation Part I: effectiveness at reducing hillslope erosion rates.*	Hillslope erosion, post-fire mulching (wheat straw, wood strands, hydromulch)
Wagenbrenner and Robichaud (2014)	*Post-fire bedload sediment delivery across spatial scales in the interior western United States.*	Post-fire erosion; hillslope; catchment; sedimentation; rainfall intensity
Peterson et al. (2009b)	*Fertilization and seeding effects on vegetative cover after a wildfire in north-central Washington state.*	Post-fire seeding; fertilization; mulching; erosion control;
Mellon et al. (2008)	*Effects of forest fire on headwater stream macro-invertebrate communities in eastern Washington, USA.*	Headwater stream, macroinvertebrates, wildfire effects
Monsanto and Agee (2008)	*Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington.*	Fuels, salvage logging, soil heating; wildfire, Ponderosa pine, coarse woody debris
Robichaud et al. (2006)	*Effects of postfire seeding and fertilizing on hillslope erosion in north-central Washington, USA.*	Wildfire, hillslope erosion, mitigation practices, post-fire seeding, post-fire fertilizer application
Everett et al. (2003)	*Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests.*	Historical fire regimes, wildfire, riparian forest, upland forest, ponderosa pine, Douglas-fir
Lehmkuhl et al. (2003)	*Cavities in snags along a wildfire chronosequence in Eastern Washington.*	Post-fire snags, bird habitat, Douglas-fir, lodgepole pine, ponderosa pine, subalpine fir

Haggard and Gaines (2001)	*Effects of stand-replacement fire and salvage logging on a cavity-nesting bird community in Eastern Cascades, Washington.*	Post-fire snags, cavity nesting birds, wildfire, salvage logging
Wondzell (2001)	*The influence of forest health and protection treatments on erosion and stream sedimentation in forested watersheds of eastern Oregon and Washington.*	Erosion; fire; sediment; overland flow; debris slides; debris flows; forest health/protection treatments, grazing
Everett et al. (1999)	*Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA.*	Post-fire snags, snag longevity, wildlife habitat, Douglas-fir, lodgepole pine, ponderosa pine, Engelmann spruce, subalpine fir
Flitcroft et al. (2016)	*Wildfire may increase habitat quality for spring Chinook salmon in the Wenatchee River subbasin, WA, USA.*	Wildfire effects, watershed responses, riparian habitat, Chinook salmon, restoration

Table 4. Database publications that are review articles (n=20). The publications summarize closely related research that occurred within five large geographic regions.

(*Note*: Complete bibliographic citations appear in Appendix B).

Publication	***Region***	***Research Theme***
Dwire and Kauffman (2003)	western U.S.	Riparian/Aquatic
Karr et al. (2004)	western U.S.	Silviculture/Forest Practices
Moore et al. (2005)	Pacific Northwest	Riparian/Aquatic
Moore and Wondzell (2005)	Pacific Northwest	Riparian/Aquatic
Reeves et al. (2006)	western U.S.	Silviculture/Forest Practices
Peterson et al. (2009a)	western U.S.	Silviculture/Forest Practices
Moore and Richardson (2012)	N. America	Riparian/Aquatic
Bladon et al. (2014)	western U.S.	Riparian/Aquatic
Bixby et al. (2015)	Global	Riparian/Aquatic
Wondzell (2001)	Washington State	Erosion/Soils
Wondzell and King (2003)	Pacific Northwest	Erosion/Soils
Ice et al. (2004)	western U.S.	Erosion/Soils
Gomi et al. (2005)	Pacific Northwest	Erosion/Soils
Moody and Martin (2009)	western U.S.	Erosion/Soils
Robichaud and Ashmun (2013)	western U.S.	Erosion/Soils

Wagenbrenner and Robichaud (2014)	western U.S.[3]	Erosion/Soils
Beyers (2004)	western U.S.	Silviculture/Forest Practices
Peppin et al. (2011)	western U.S.	Silviculture/Forest Practices
Peppin et al. (2014)	western U.S.	Silviculture/Forest Practices
Bisson et al. (2003)	western U.S.	Riparian/Aquatic

- Bisson et al.'s (2003) article, *Fire and aquatic systems of the western USA: Current knowledge and key questions*;
- Moore et al.'s (2005) article, *Riparian microclimate and stream temperature response to forest harvesting: A review*. (i.e., Pacific Northwest);
- Moore and Wondzell's (2005) article, *Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review*.
- Wagenbrenner et al.'s (2015) article, *Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States*.

[3] This article reviews results from six locations in the western U.S., including one in Washington (i.e., North 25 Fire).

Publications by Subject Matter. As described earlier in this report, we organized the literature according to five general research themes (Silviculture/Forest Practices, Fuels/Fire, Erosion/Soils, Riparian/Aquatic, Biodiversity/Ecosystems). For instance, much research to date has focused on soil erosion processes after fires and/or after salvage logging (Fig. 5). The literature since about 2000 also reflects increasingly informative long-term research (e.g., longitudinal studies) that documents stand-to-landscape-level ecosystem processes in relation to fires. For example, a number of long-term studies were initiated in Oregon and Washington after so-called mega-fires like the 2002 Biscuit Fire.

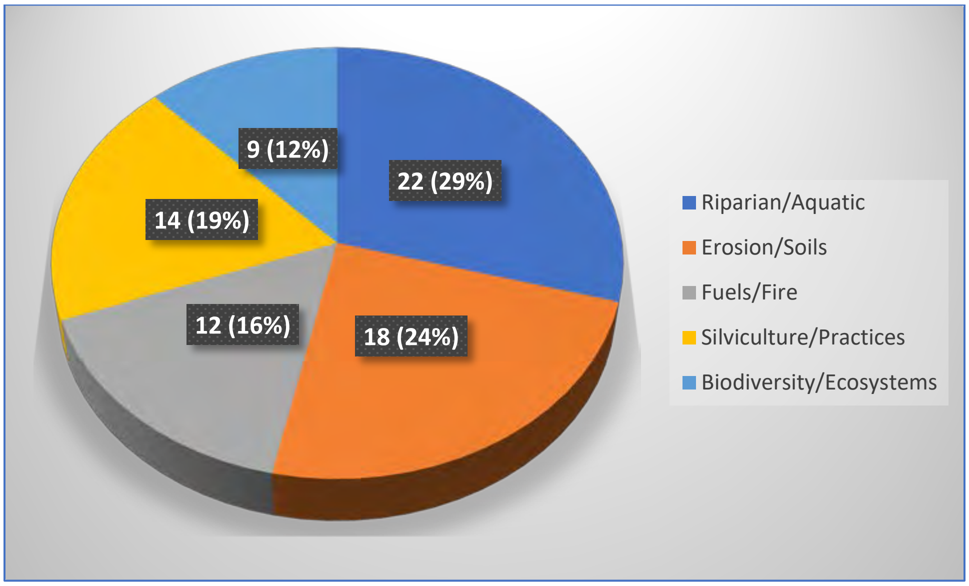

Figure 5. Number and percent of database publications according to the five general research themes used by this literature review project. Results include both site-specific and general review articles (n=75).

In the following sections, we provide a brief synthesis and some highlights from prominent studies to date, presented according to the five major research themes. The purpose of this overview is to synthesize recent literature published on post-fire salvage logging and related themes for riparian- and upland forests. Each section begins with a synthesis overview to provide context about a given body of research, followed by highlights from individual studies. Also note that the *Excel* database and individual summary reports provide highly detailed information about a given study's objectives, methods, findings, research limitations, and other data. And finally, please note that the *Responses to SAGE Questions* section near the end of this report provides study-specific information in relation to some current management issues raised by SAGE team members.

Silviculture/Forest Practices. We classified 14 publications, or about 20 percent of the database, according to the Silviculture/Forest Practices category. (Also note that we sometimes assigned secondary and tertiary research themes, such as the Biodiversity/Ecosystems or Fuels/Fire classes, to a given publication.) Eight of the publications describe individual studies. Examples include both observational and experimental studies that measured direct impacts from logging equipment on soils and regeneration, post-fire practices such as post-fire planting and seeding, and studies that had documented tree regeneration after fires and logging. The remaining six publications were reviews spanning large geographic regions.

Synthesis Overview. Salvage logging is primarily aimed at recouping economic losses to tree mortality from fire. Salvage differs from traditional forest harvesting of unburned forest in that salvaged sites are subject to the compound effects of two disturbances (i.e., severe fire followed by salvage logging). Peterson et al. (2009) provide a broad review of salvage logging and suggest the following as major factors affecting ecological outcomes after salvage logging: 1) the effects of harvesting equipment and roads on ground disturbance, 2) the abundance and spatial patterns of residual living and dead trees, 3) post-salvage fuel treatments, and 4) mitigation efforts such as re-seeding and placement of salvage residuals (e.g., slash). In addition to mitigating the effects of these factors, several silvicultural and other forest management practices are aimed at increasing future stand productivity through manipulation of composition and structure.

Harvesting equipment and associated road systems can have important ecological effects during salvage logging. Soil erosion is one of the main management concerns in this regard, and we will briefly highlight studies that have focused on such mitigation practices here (also note that other soil-related studies are discussed in depth in the Erosion/Soils section of this report). Wagenbrenner et al. (2016) examined salvage logged areas in eastern Washington and other locations to evaluate the effectiveness of best management practices on rill and overland flow as well as sediment production rates after ground-based salvage logging. The authors found that ground-based logging compacted soil, reduced soil water repellency, and promoted elevated erosion rates when compared to unlogged control sites. Vegetation recovery rates were also slower in most salvaged sites. Erosion mitigation practices such as strategic placement of slash (McIver and McNeil 2006, Wagenbrenner et al. 2015) and promotion of rapid recovery of understory vegetation (Reeves et al. 2006) can help mitigate the effects of salvage logging on soil disturbance. Also note that, although we found no studies examining the effects of salvage logging on snow or frozen ground, such mitigation measures evidently are considered to be best management practices for logging in general (Ziesak et al. 2015).

In terms of silviculture, the abundance and spatial pattern of residual live and dead trees have important implications for forest recovery and establishment (Thompson et al. 2007; Keyser et al. 2009; Peterson et al. 2009a). Residual trees play an important role in forest recovery by providing local seed sources in areas subject to non-stand replacing fire. Residual snags and dead downed wood can also buffer local temperature and moisture conditions by providing transitory shade for seedling establishment and for effective riparian functioning. Most salvage-related studies in our database focus on sites that have been impacted by high-severity fires that left few residual live trees. Research suggests that salvaging of dead wood can reduce fuel loads (Thompson et al. 2007), but can also have detrimental effects on wildlife habitat (Haggard and Gaines 2001; Russell et al. 2006, Cahall and Hayes 2009). For example, salvage prescriptions that do not retain substantial amounts of snags can have negative implications for species that require habitat conditions with a specific range of snag sizes and densities (Lehmkuhl et al. 2003).

Replanting after wildfire is a common practice thought to hasten the establishment of conifer forests, especially after high-severity fire heavily depletes residual canopy trees that can serve as seed sources (Sessions et al. 2004). Replanting after wildfire is a common practice thought to hasten the establishment of conifer forests after high-severity fire that kills most or all canopy trees that could serve as potential seed sources (Sessions et al. 2004). A major finding from such research is that, although natural post-fire regeneration often meets or exceeds silvicultural management objectives on mesic- and upper elevation sites, supplemental tree planting is often necessary for many severely burned xeric sites (Thompson et al. 2007; Keyser et al. 2009). Planting may be necessary at lower elevation sites where high temperatures and low precipitation can inhibit conifer regeneration (Dodson and Root 2013). However, replanting conifers at high densities can increase susceptibility to short-interval, high-severity reburns (Thompson et al. 2007). And, although applying pre-commercial thinning treatments can decrease fuel continuity in regenerating stands, we found no research to support the presumption that such practices can reduce reburn hazards.

Several studies have examined the effects of seeding for erosion control after salvaging. Although managers have routinely used seeding practices and often assume them to be effective (Peppin et al. 2014), most researchers agree that seeding has only limited ability to reduce erosion (Beyers 2004; Robichaud et al. 2006; Peterson et al. 2009b; Peppin et al. 2011; Peppin et al. 2014). In addition, this relatively expensive practice is often detrimental in terms of native species displacement when non-native species are used. Native seed may be difficult to obtain, especially after large-fire years (Beyers 2004). Furthermore, post-fire seeding has also been found to be detrimental to conifer regeneration and can delay the establishment of desired forest conditions.

Study Highlights. Below is more-detailed information from some of the most prominent studies in the Silviculture/Forest Practices category. For example, Karr et al. (2004) reviewed studies that documented the potential effects of post-fire salvage logging on aquatic ecosystems in the western U.S. Although this review article did not present detailed information about specific forest practices—in part because empirical evidence is often lacking for a given topic—the authors presented some general concepts that could help guide riparian zone management. The authors made 10 recommendations that feasibly could help mitigate impacts from salvage logging and that could help improve watershed conditions: 1) allow natural recovery to occur on its own, or intervene only in ways that promote natural recovery, 2) retain large old trees (live or dead), 3) protect soils, especially those that are shallow, severely burned, erosion prone and otherwise fragile, 4) protect ecologically sensitive areas including riparian and roadless areas, steep slopes, and watersheds with sensitive or imperiled aquatic species, 5) avoid creating new road and landings in burned landscapes, 6) limit reseeding and replanting (to foster the recovery of native vegetation), 7) do not place structures such as sediment traps, riprap, and check dams, or artificially-installed large wood in streams, 8) protect and restore watersheds before fire occurs, 9) continue research, monitoring, and assessment, 10) educate the public about riparian functioning and intrinsic value.

A review article by Beyers' (2004) discussed studies in the western U.S. that had examined the effectiveness of post-fire seeding for erosion control. Few such data existed in 2004, but less than half of the literature suggested that seeding was an effective erosion control measure. In cases where seeded grasses did help reduce erosion, native or naturalized species (including shrub and tree seedlings) were often displaced. Native species and sterile cereal grains have increasingly been used for seeding in recent years. Aerially applied straw mulch has also been used, but such treatments have increased the risk of weed introduction from contaminated bales. The author concluded that more research was needed to document both the effectiveness and the impacts from seeding practices.

In a 2004 Journal of Forestry article, Sessions et al. (2004) discussed some of the major silvicultural issues and management alternatives facing managers during the modern era of megafires in the West. For example, the authors examine the likely consequences and tradeoffs of allowing natural ecosystem recovery versus various management interventions. The article points out that often only a narrow window of opportunity exists to promote cost-effective restoration of burned conifer forests—while simultaneously reducing insect- and fire risks and salvaging some economic value to help offset restoration costs. Regarding Northwest mixed conifer forests, the review also mentions that "the lack of adverse impacts from salvage logging [in the Biscuit Fire area] is attributed to protection of riparian areas, improved road construction practices, and minimizing disturbance through the use of helicopter logging." (Sessions et al. 2004: 44).

Thompson et al. (2007) documented fuel dynamics in managed versus unmanaged Douglas-fir stands in the Biscuit Fire area of southwestern Oregon. The study area had been severely burned by a 1987 wildfire, and had reburned during the 2002 Biscuit Fire. The researchers found that upland areas that had been salvage-logged and planted after 1987 had reburned more severely during 2002 when compared to comparable unmanaged (i.e., unlogged or planted) areas. The results suggested that fuel conditions in conifer plantations can increase potential fire severity despite the removal of large woody material, because tree planting can promote a dense and/or continuous layer of fine-to-coarse fuels.

In South Dakota's Black Hills, Keyser et al. (2009) studied the effects of salvage logging on regeneration and fuels in ponderosa pine stands that had been moderately- to severely burned by a 2000 wildfire. On unsalvaged sites, post-fire tree mortality had promoted exponential increases in fine and coarse woody debris by post-fire year 5. In contrast, salvage logging had significantly reduced fuel accumulation rates. On sites that had experienced moderate-severity fire and salvaging, tree regeneration was 75 percent lower because of the reduction in potential seed-trees. However, the authors stated that the likelihood of substantial regeneration occurring on high severity burn sites was low on both salvaged and unsalvaged sites. The paper concluded by recommending more such research, while stating that "the effects of salvage logging may be dependent on when and how salvage logging is conducted as well as forest type rather than an invariant set of effects inherent to salvage logging." (Keyser et al. 2009: 457).

We also reviewed several studies that focused on the topic of post-fire tree regeneration (both natural and planted). Such research often discussed the need for planting on xeric upland sites and on other sites that lack potential seed trees. For example, in northeastern California, Ritchie and Knapp (2014) studied surface fuels and regeneration during a 10-year long period after a high-severity wildfire and salvage logging in ponderosa pine-dominated stands (Lassen National Forest). Surface fuel accumulations were rapid, corresponding with a high rate of snag decay and subsequent breakage or windthrow. Retained pine snags exhibited the fastest rates of breakage and transitioning to surface fuels, while white fir (*Abies concolor*) and incense-cedar (*Calocedrus decurrens*) were significantly more stable during the study period. Although the 2002 wildfire had provided a receptive seedbed, the fire destroyed most of the available seed sources. Consequently, post-fire natural regeneration was scarce irrespective of the salvage treatment. Similarly, growth and survival of artificial regeneration was highly variable and unrelated to the salvage treatment. The authors stated that natural regeneration cannot be relied on to re-establish such conifer stands in the foreseeable future. Regarding post-fire fuel dynamics, unsalvaged areas experienced rapid accumulations beyond characteristic amounts for interior ponderosa forests historically. The authors therefore concluded that salvage logging likely helped reduce the reburn risk in that severely burned ponderosa pine forest. (Note that the above interpretations about ponderosa pine regeneration potential likewise are supported by Dodson & Root [2013; discussed later in this report], who concluded that, without management intervention, xeric ponderosa pine/Douglas-fir stands often might fail to regenerate for extended periods after stand-replacing fire.)

After interviewing regional- to national level managers (e.g., fire management- and other specialists) in the western U.S., and conducting a literature review, Peppin et al. (2014) summarized expert opinions and perceptions about the effectiveness of post-fire seeding in conifer stands. The authors state that some researchers have questioned the effectiveness of post-fire grass seeding treatments, and have suggested that: 1) seeding has a low probability of success during the first and second critical erosion years after fire (Robichaud et al. 2000); 2) successful grass establishment often displaces native plant regeneration (Robichaud et al. 2000, Beyers 2004, Peppin et al. 2010); 3) seeded plots rarely reduce erosion compared to unseeded plots (Peppin et al. 2010); and 4) seeding has limited effectiveness in curtailing non-native species invasions (Peppin et al. 2010). Although interviews and telephone surveys of managers revealed widely varying perceptions regarding the potential effectiveness of seeding, most of the 23 respondents believed that information about the long-term effects of seeding was insufficient. The paper concludes by stating that more research, more long-term monitoring, and better communication and collaboration between managers and scientists would likely help managers make better-informed decisions about post-fire seeding practices.

Peterson and Dodson's (2016) study in northeastern Oregon documented the response of understory vegetation to two post-fire logging treatments in ponderosa pine/Douglas-fir stands that had been severely burned by the 1996 Summit Fire (Malheur National Forest). The treatments consisted of commercial salvage logging with and without additional fuel reduction measures. In the commercial treatment, two-thirds of dead merchantable trees were harvested while leaving at least 17 snags per hectare larger than 30 cm diameter (dbh). In contrast, the supplemental fuel reduction treatment also removed most non-merchantable small trees (10–29 cm dbh). Neither type of salvage produced significant effects on understory vegetation cover, diversity, or composition 15 years after treatment. The researchers emphasized that understory vegetation can be resilient to post-fire logging, particularly when best management practices, such as logging over snow, are used to limit damage to soils and understory vegetation. The authors also state that, "If further research confirms our findings, post-fire logging debates will be able to focus more on how to mitigate short-term disturbance impacts and manage fire-killed trees to meet wildlife habitat, fuel reduction, and economic objectives, and less on concerns over long-term ecosystem degradation." (Peterson and Dodson 2016: 63).

Fuels/Fire. Our database contains a number of studies that examined post-fire fuel dynamics and other fire management topics (with or without salvage logging). We classified 12 publications, or about 15 percent of the database, according to the Fuels/Fire category. (Also note that we occasionally assigned secondary and tertiary research themes, such as the Silviculture/Forest Practices or Biodiversity/Ecosystems classes, to a given publication).

All publications in this category describe individual studies that investigated such topics as fuel amounts, fuel succession, or fire behavior modeling in relation to severe fires or salvage logging.

Synthesis Overview. Post-fire fuel reduction is a frequent management objective associated with salvage logging, and the topic has received considerable attention in the literature. Fire affects fuel structure by altering the composition, amount, and vertical and horizontal arrangement of live and dead fuels. Although research in the early 2000s sometimes generated controversy about the role of salvage logging and its potential impact on fuels and tree regeneration (e.g., Donato et al. 2006; discussed below), such research projects tended to be limited in number and in geographic scope. In contrast, subsequent studies have not only been more numerous but have also begun to incorporate longitudinal data that include repeat experiments in salvaged logged stands. The growing body of literature has helped build the knowledge base about salvage logging and associated fuel dynamics (but note again the overall lack of data from riparian areas). On non-salvaged sites that recently experienced fires, the amount of residual live fuels depend largely on associated fire severity levels, and on post-fire recovery rates of understory and overstory vegetation. For example, shrub- and tree regeneration often recovers relatively rapidly after disturbances, but tree regeneration is often scarce on severely burned, low-elevation xeric sites (Dodson and Root 2013). Multiple studies have examined various aspects of fuel dynamics, such as residual woody fuel loads and fuel succession after fires and/or salvage logging (Donato et al. 2006; McIver and Ottmar 2007; Dunn and Bailey 2015b; Peterson et al. 2015; Campbell et al. 2016). In general, residual fuels immediately after severe fires contain a diverse mix of fuel classes, ranging from relatively fine fuels to large logs and snags. Snag densities vary with burn severity and pre-fire stand structure and composition traits, and snag longevities vary by size and among tree species and (Everett et al. 1999; Russell et al. 2006; Ritchie et al. 2013; Dunn and Bailey 2015a). In contrast, salvage-logged sites generally contain a deficit of large woody material for at least several decades, but promote relatively dense downed-fuel layers comprised of logging slash. As for short-term reburn potential, some researchers (Donato et al. 2006) have suggested that post-fire salvage logging might increase short-term reburn risk due to the intermingling of logging slash with developing tree- and shrub layers. However, Campbell et al.'s (2016) re-sampling of a previous study location (Donato et al. 2013) 10 years after salvaging found that both logged- and unlogged young stands would have high reburn potential for at least several decades after the initial stand replacement fire.

Study Highlights. Below is more-detailed information from some of the most prominent studies in the Fuels/Fire category. For example, Donato et al. (2006) sampled conifer regeneration and fuel loads in salvage-logged versus unlogged portions of the Biscuit Fire burned area in southwestern Oregon. Pacific Douglas-fir (*Pseudotsuga menziesii var. menziesii*) regeneration on severely burned, unlogged sites was variable but generally abundant. The researchers found that post-fire logging had subsequently reduced tree regeneration by about 70% because of soil disturbance and physical burial during logging operations. The post-fire logging also had significantly increased fine- and coarse downed woody fuels (i.e., slash), which elevated the short-term fire risk. The authors concluded that a re-burn in logged stands would likely have increased rates of fire spread, intensity, and soil heating. The researchers stated that, "Our data show that postfire logging, by removing naturally seeded conifers and increasing surface fuel loads, can be counter-productive to goals of forest regeneration and fuel reduction. In addition, forest regeneration is not necessarily in crisis across all burned forest landscapes." (Donato et al. 2006: 352). Note, however, that the study was controversial: Newton et al.'s

(2006) Technical Comment in the August 2006 issue of *Science* magazine countered that, “The research [by Donato et al. 2006] may make a valuable contribution, but the study lacks adequate context and supporting information to be clearly interpreted.” (Newton et al. 2006: 615a). Similarly, Baird (2006) took issue with the finding that postfire logging had significantly reduced seedling regeneration. He argued that “Analysis of [Donato et al.’s 2006] study methodology and raw data suggests that this estimate is statistically flawed and misleading and says nothing about the impacts of more prompt postfire harvest.” (Baird 2006: 615b). In the same issue of *Science*, Donato et al. (2006b) attempted to counter the above arguments by providing more details about their study design and data interpretations.

McIver and Ottmar (2007) modeled the effects of salvage logging on fuels and stand structures in ponderosa pine/Douglas-fir stands two years after the 1996 Summit fire in eastern Oregon (Malheur National Forest). The researchers used a forest vegetation simulation model to project changes in fuel beds for a 100-year-long post-fire period. Total woody fuel mass increased significantly in fuel reduction units when compared to unlogged control stands, with the slash fuel component exhibiting the greatest differences between treatment- and control stands. Regarding the potential efficacy of such modeling, the authors conclude by saying, “Until we know more about the mechanisms of fire-induced tree mortality, and incorporate this knowledge into fire-effects models, we will remain uncertain on the extent to which post-fire logging reduces re-burn severity, at least with respect to experimental studies that involve the use of fire behavior models.” (McIver and Ottmar 2007: 278).

In Washington’s eastern Cascades, Monsanto and Agee (2008) studied coarse woody debris dynamics 1 to 35 years after wildfires—with and without salvage logging—in multiple dry-conifer stands (Okanogan-Wenatchee National Forest). Total biomass (i.e., snags/logs/post-fire vegetation) averaged roughly 60 Mg/ha (66 tons/2.47 ac.) across all sites, with log-to-snag proportionality increasing over the chronosequence. However, salvaged units generally had the lowest log biomass. The researchers also studied soil heating and fine root mortality caused by experimental burning of logs. Moisture content of small and large diameter logs averaged 17.7 and 14.7 percent in early season to 11.9 and 12.5 percent in late season. The researchers found that prescribed burning for fuel reduction and stocking control can cause significant root damage, especially in young stands with substantial amounts of coarse woody debris. The authors state that, where prescribed fire is introduced to post-wildfire stands that are between 20 and 30 years old, the effects of root heating from smoldering coarse woody debris can be minimized by burning in spring. In salvaged and unsalvaged stands, spring burning can help mitigate soil heating because such fires typically are less intense and cover less area.

In southwestern Oregon, Donato et al. (2013) studied fuel mass and forest structure 3-4 years after post-fire salvage logging had occurred in an area burned by the 2002 Biscuit Fire. The researchers compared results among different logging intensities and climatic settings in Douglas-fir/mixed conifer stands. Results suggested that the effect of post-fire logging on fuel profiles (e.g., 10-1000+ hr. fuels) and stand structures varied significantly according to both harvest intensity and forest type. The authors state that moderate-intensity treatments resulted in surface fuel loads that were the most consistent with commonly prescribed levels (which are unspecified in the article), whereas fuel reduction measures such as pile burning likely would be necessary after high-intensity harvests. The researchers concluded that such results potentially reduce the need for follow-up fuel treatments such as slash piling and broadcast burning. The paper also states that moderate-intensity treatments tend to leave a greater proportion of snags, which can be highly compatible with wildlife habitat objectives.

Peterson et al. (2015) documented patterns of woody fuel succession following stand-replacing wildfires for logged and un-salvage-logged stands at 68 burned sites in eastern Washington and Oregon. Specifically, they sampled the effects of post-fire logging on mean woody fuel loads up to 39 years after wildfire, and assessed the influence of pre-fire stand basal area on post-fire woody fuel loads. In unlogged stands, woody fuel loads were low initially, but then increased and peaked 10–20 years post-fire. In logged stands, small and medium diameter woody fuel loads peaked immediately after logging, whereas large diameter woody fuel loads peaked after 10–20 years. The authors concluded that salvage logging can be used to significantly reduce surface woody fuels in relatively young regenerating stands, but outcomes depend on such factors as: 1) volume and sizes of wood removed, 2) logging methods, 3) post-logging fuel treatments, and 4) the amount of coarse woody debris left on-site to support wildlife habitat, erosion control, and other competing management objectives.

In dry mixed conifer forests of Oregon's eastern Cascades, Dunn and Bailey (2015b) studied fuel loadings, snag dynamics, and snag decomposition rates within severely burned areas based on a 24-year chronosequence of seven fires. The fires had occurred between 1984 and 2007 on the Deschutes and Fremont-Winema National Forests, and in Crater Lake National Park. Modeling suggested that surface fuels accumulate quickly after such high-severity fires, and that salvage logging has had mixed effects on reducing hazardous fuel conditions. That is, salvage logging increased the amount of fine woody fuels (10-100 hr. fuels [slash]) while simultaneously decreasing the coarsest woody fuels (e.g., 1000+-hr. fuels). The authors concluded that "Reducing hazardous fuel loadings and their contribution to re-burn hazard requires manipulation of residual and future fuel sources. However, treatment benefits should be evaluated against any negative effects to early seral forest structure and function if resilient forest ecosystems are the management goal." (Dunn and Bailey 2015b: 93).

Campbell et al. (2016) documented fuel dynamics 10 years after post-fire salvage logging had occurred in the Biscuit Fire area of southwestern Oregon. (This study was a re-sampling of Donato et al.'s [2013] original plots.) The researchers found that treatment effectiveness in reducing fine surface fuels in Douglas-fir stands lasted for up to 10 years. Coarse fuel loads were significantly higher in logged- versus unlogged plots, especially during the latter portion of the sample period. The authors also predicted that dense tree- and shrub regeneration after year 10 on logged and unlogged sites would make them increasingly vulnerable to stand replacing fires, possibly for decades.

Erosion/Soils. Literature documenting soil erosion after fires, on both logged and unlogged terrain, comprises a relatively large part of the database (Fig. 5). We classified 18 publications, or about 25 percent of the database, according to the Erosion/Soils category. (We also sometimes assigned secondary and tertiary research themes, such as the Silviculture/Forest Practices or Biodiversity/Ecosystems classes, to a given publication.) Eleven of the publications describe individual studies, including both observational and experimental research that focused on various soil processes such as erosion, compaction, and nutrient dynamics after salvage logging and severe fires. The seven remaining publications were reviews that span large geographic regions.

Synthesis Overview. Fires and salvage logging can substantially increase soil erosion, especially on steep, severely burned terrain (McIver and McNeil 2006; Larsen et al. 2009; Silins et al. 2009; Eaton et al. 2010; Slesak et al. 2015). Removal of vegetative cover, formation of rills, channels, and hydrophobic soils, and decreased bank stability in riparian areas, can all contribute to erosion potential after fires and/or salvage logging (Berg et al. 2002, Reeves et al. 2006, Silins et al. 2009, Moore and Richardson 2012, Slesak et al. 2015). During harvesting operations, soil compaction and channelization caused by heavy equipment traffic can further exacerbate erosion (Slesak et al. 2015). Erosion rates and amounts can be substantial and can promote soil nutrient losses, depending on soil- and vegetation types (Gomi et al. 2005). However, such impacts generally are short-lived because protective vegetative cover tends to recover rapidly after most disturbances and because hydrophobic soils are usually relatively short-lived (Larsen et al. 2009). Post-disturbance erosion potential can also vary according to seasonal precipitation patterns, especially during the first decade after disturbance, and can vary according to recent fire severity- and topographic variables. For example, the amount, timing, and intensity of rainfall events often play a major role in the occurrence of post-disturbance erosion processes (Moody and Martin 2009). High severity fires also are thought to increase erosion potential, but less is known about erosion after low- to moderate severity disturbances because most studies have examined severely burned stands (Wondzell and King 2003).

Recent studies (Robichaud et al. 2013; Wagenbrenner et al. 2015; Wagenbrenner et al. 2016) examined the effects of mechanical disturbance during logging, as well as mitigative practices aimed at reducing soil erosion. The highest-risk stands in terms of salvage-induced soil erosion and stream sedimentation are those that contain a substantial number of rills and/or drainage ditches (Slesak et al. 2015). For instance, most erosion potential stems from associated road systems rather than from actual tree harvesting on adjacent slopes, which tend to recover rapidly in the absence of large-scale mechanical disturbance (Gomi et al. 2005; Robichaud et al. 2013). Research also underscores the importance of enhancing and protecting soil cover after logging activity (e.g., mulching, slash bedding), since most erosion potential results from a lack of soil cover rather than from fire-induced soil water repellency (Larsen et al. 2009; Wagenbrenner et al. 2015). However, it is important to note that most salvage-related studies have occurred at relatively small spatial scales (e.g., <100 acres), and thus examine only local erosional processes (Gomi et al. 2005, Wagenbrenner and Robichaud 2014).

Despite the number of studies on post-fire erosion and soils, it is important to note that most salvage-related studies have occurred at relatively small spatial scales (e.g., <100 acres), and thus examine only local erosional processes within stands (Gomi et al. 2005, Wagenbrenner and Robichaud 2014). The effects of post-fire salvage are less well understood at larger spatial scales, particularly with respect to events such as debris flows and landslides (Wondzell and King 2003; Ice et al. 2004). More-recent studies support long distance transport of nutrients and document short-term pulses of nitrogen, phosphorus, and heavy metals that can affect drinking water (Bladon et al. 2008, Bladon et al. 2014, Emelko et al. 2015) and floral/faunal components of downstream aquatic ecosystems.

Study Highlights. Below is more-detailed information from some of the most prominent studies in the Erosion/Soils category. For example, Wondzell (2001) reviewed studies in eastern Oregon and Washington that had documented the effects of various forest practices on soil erosion- and stream sedimentation processes. The author discussed such practices as salvage logging, tree thinning, mechanical fuel reduction, and livestock grazing. The review suggests that that heavy ground-disturbing activities, such as road construction during salvage logging, pose some of the highest risks of causing accelerated erosion and sedimentation. The author also found that erosion/sedimentation risk can be reduced by maintaining dense riparian vegetation. For example, maintenance of substantial streamside buffers and undisturbed riparian vegetation can serve as effective mitigation measures. Wondzell also concluded that well designed small-scale salvage treatments often pose little risk to watershed health because treatment impacts usually diminish substantially with increasing distance from riparian zones. (*Note*: This general review article does not quantify terms like "dense vegetation" "substantial buffer," or “small scale.”)

Wondzell and King’s (2003) review of research documenting post-fire erosion processes in western U.S. forests found that major erosion events are often triggered by intense storms occurring within 10 years of a severe fire. However, the authors stated that substantial knowledge gaps existed, in part because studies tended to focus on the most severe disturbance events. Consequently, the effects of lower severity wildfires and careful salvage logging remained poorly understood as of 2003. In a subsequent review, Moody and Martin (2009) compiled data from multiple studies across the western U.S. and compared measurements of post-fire erosion, transport, and deposition during differing rainfall regimes within 2 years of burning. Mean sediment yield from channels was significantly greater than from hillslopes, suggesting that on the time scale of wildfire (10–100 years) channels were the primary sources of sedimentation. On many severely burned sites, sediment availability (i.e., erodibility plus on-site volume) may be more important than either slope steepness or soil erodibility alone. The review also suggests that, although wildfires can be important geomorphic agents, fire effects usually are limited to the immediate burned area and to downstream channel corridors. The authors conclude that such studies not only help guide post-fire management policies, but also can be used to develop predictive models of post-fire sediment yield.

Ice et al. (2004) reviewed soil and watershed responses to fire and salvage logging in western U.S. forests. They concluded that salvage logging that employs careful mitigation practices, such as hand felling, minimizing the construction of new roads, and logging over snow, can help minimize soil disturbance and sediment loss. One of their earliest reviewed studies was conducted by Helvey (1980) in the area burned by the 1970 Entiat Fire (Wenatchee National Forest). That study found that post-salvage sedimentation was less than on comparable unlogged burned sites, suggesting that erosion potential on had diminished markedly on salvaged sites within a decade after the fire.

McIver and McNeil (2006) examined soil erosion after salvage logging on severely burned terrain in northeastern Oregon (Malheur National Forest). The researchers found that soil disturbance during the logging operations exceeded that caused by the wildfire alone. However, hillslope sediment transport was minimal on areas that had low-to-moderate (<25%) slope steepness, and low-to-moderate-risk soil (i.e., rocky clay). Low levels of hillslope erosion also occurred in areas that lacked many new roads, and in areas that had experienced logging on snow or dry ground. Additional possible mitigating factors included allowing at least two years of ground cover recovery between the wildfire and the logging, and a lack of severe weather events during the two-year period after salvaging.

Robichaud et al. (2013) studied erosion mitigation practices at several post-burn sites in southeastern Washington, northern and central Idaho, and west-central Colorado. Specifically, the researchers examined the effectiveness of several mulching techniques (i.e., wheat straw, wood strands, and hydromulch), and evaluated the effectiveness of tree needle cast and seeding with native grass species. Although the applied mulches had similar protective potential in terms of erosion resistance, widely varying mulch longevity contributed to significant variation in overall effectiveness. Specifically, wood strand mulch persisted the longest during the 7-year monitoring period, while wheat straw mulch decomposed about twice as fast as the wood strands, and hydromulch decomposed within the first post-fire year. The researchers also found that tree needle cast and seeding treatments were generally ineffective for mitigating post-fire runoff and erosion.

In southwestern Oregon, Slesak et al. (2015) studied hillslope erosion potential after the 2002 Timbered Rock wildfire (BLM Medford District and other ownerships). They analyzed post-salvage erosion rates on private land and on unsalvaged (control) sites on nearby BLM land. In the salvaged area, the authors examined sites that had experienced skyline logging and site preparation work. Results suggested that erosion potential is often highest immediately after fire on both salvaged and non-salvaged terrain. The authors state that a frequently negative correlation between vegetation cover and erosion potential often exists on sites subject to wildfire, steep slopes, and frequent storms. The authors also state that promoting rapid regrowth of vegetation, along with protective measures such as strategic placement of slash and other erosion control techniques after salvaging is highly advisable—especially on highly erodible soils. However, site preparation methods that promote artificial tree regeneration at the expense of recovering understory vegetation can increase erosion potential, especially on steep erodible sites that are prone to heavy rainfall.

Wagenbrenner et al. (2015) reviewed studies in the Interior West that investigated the potential effects of post-fire salvage logging on soil erosional processes. The article discusses potential impacts of skid trails on ground cover, soils, and sediment production in riparian zones, swales, and adjacent hillslopes. The authors state that, because severely burned sites are often prone to increased surface runoff and erosion, ground-based salvaging should include mitigation measures to protect or restore ground cover (e.g., applying logging slash to skid trails). Otherwise, the effects of logging on ground cover, soil water repellency, runoff, and sediment at the swale scale are often minimal because the total area impacted by the logging equipment typically is limited. The authors conclude by stating, "The greater sensitivity of burned landscapes to surface runoff and erosion indicates that site-specific best management practices. . .are needed to minimize the adverse impacts of post-fire salvage logging." (Wagenbrenner et al. 2015: 192).

Riparian/Aquatic. Research documenting post-fire effects on riparian systems represents one of the dominant themes in the database. We classified 22 publications according to the Riparian/Aquatics theme. (Also note that we occasionally assigned secondary and tertiary research themes, such as the Biodiversity/Ecosystems or Fuels/Fire classes, to a given publication in the database). Fourteen of the articles described individual studies, whereas the remaining publications were reviews spanning large geographic regions.

Synthesis Overview. Riparian forests are critically important landscape components throughout the western United States (Reeves et al. 2006). These forests play an indispensable ecological role as the interface between aquatic systems and adjacent uplands. Although fire is generally thought to have been historically less frequent and more severe in riparian areas than adjacent uplands (Skinner 2003; Olson and Agee 2005; Everett et al. 2003), it played an essential role in creating and maintaining habitat for a number of aquatic organisms. Although relatively few studies have examined and compared the effects of contemporary wildfires between riparian areas and adjacent uplands there is evidence indicating that the effects of fire differ between these biophysical settings (Halofsky and Hibbs 2008; Halofsky and Hibbs 2009). Given the unique structure, composition, and function of riparian areas, such forests present specific challenges in terms of protection and maintenance (Dwire and Kauffamn 2003, Reeves et al. 2006, Peterson et al. 2009a).

Data on disturbance patterns and effects can contribute to effective riparian management and for devising salvage logging prescriptions for adjacent upland forests (Peterson et al. 2009a). For example, wildland fires play an important role in creating and maintaining habitat for several aquatic species. Several publications (Berg et al. 2002; Moore and Wondzell 2005; Reeves et al. 2006) describe the fire's role in contributing to the episodic recruitment of downed wood important for habitat maintenance and in-stream channelization and other hydrological processes. Populations and communities of aquatic species can be directly impacted by fires and salvage logging, by altering such processes as tree canopy influences on stream temperature. Fish, and especially salmonids, are of particular concern. For instance, Isaak et al. (2010) documented largely negative impacts from climate change and wildfires on stream temperatures and trout habitat in central Idaho. Dunham et al. (2007) also studied fire's effects on fish and amphibian populations in central Idaho and found that physical stream habitats can remain altered (e.g., increased temperature) for many years after fires. However, they also found that native aquatic vertebrates are often adapted and resilient to disturbance. Similarly, Leach and Moore (2010) and Wagner et al. (2014) studied potential effects of fire on stream temperatures, and found that, in addition to providing in-stream wood recruitment, mixed severity fires tend to leave partial tree canopies that provide shade for mitigating stream surface temperatures. Other research in the Riparian/Aquatic category described the effects of fire and salvage logging on nutrient cycling and responses of riparian and in-stream aquatic flora and fauna (Silins et al. 2014). After major disturbances, especially by fire, phosphorous input to streams is often initially heavy, followed by rapid declines and long recovery periods. However, Silins et al. (2014) state that disturbance effects on stream productivity are complex and are still not well understood.

Study Highlights. Below is more-detailed information from some of the most prominent studies in the Riparian/Aquatic category. For instance, studies in Washington (Everett et al. 2003) and Oregon (Olson and Agee 2005) have provided valuable information about riparian fire regimes, and about potential ecosystem changes during the fire exclusion era. Similarly, Dwire and Kauffman's (2003) overview of riparian fire regimes in the western U.S. discussed potential impacts from modern land use activities. Presettlement fires were often less frequent, less severe, and patchier than in surrounding upland forests. However, such factors as long-term fire exclusion, livestock grazing, logging, damming and flow regulation, agricultural diversions, channel modifications, and introduction of invasive species have impacted many riparian areas. Consequently, many riparian ecosystems have experienced changes in vegetation composition and stand structure, altered fuels and fire behavior, changes in microclimate, soil erosion and sedimentation, altered wildlife- and aquatic habitat, and other impacts that are often cumulative and difficult to reverse. Regarding fire, the authors state that, "Given the critical resource values of riparian zones. . . improved understanding of fire ecology and effects in riparian areas is needed to prescribe ecologically sound rehabilitation projects following fire." (Dwire and Kauffman 2003: 61). (Note again the 2002 Washington State DNR contract that provided a review of riparian fire regimes in eastern Washington [Concurrent Technologies Corporation 2002]).

Although some studies in the database do not specifically address post-fire salvaging, we included such publications because they provide potentially useful information about riparian responses to disturbances that might be somewhat similar to those after salvage logging. For example, Macdonald et al.'s (2003) study in spruce-fir forests of northwestern British Columbia investigated the influence of three variable-retention riparian harvesting prescriptions on temperatures of first-order streams. The treatment types were: 1) low retention (removal of all merchantable timber >15 cm dbh within 20-30 meters of the stream); 2) high retention (removal of merchantable timber >30 cm dbh within 20-30 meters of the stream); 3) patch cut (high tree retention along the lower 60% of the watershed and removal of all riparian vegetation in the upper 40%). Samples taken 5 years after harvesting (not salvaging) showed substantially warmer stream temperatures (+ 4-6 degrees C.) occurring after 3 different retention prescriptions. Although the high-retention prescription initially was the least impactful treatment, post-logging windthrow had reduced the mitigative effects of that prescription by year 5. The authors concluded that, although most biota likely could tolerate such temperature changes, the logging could negatively impact stream insects, and fish populations in terms of egg incubation, rearing, migration timing, and susceptibility to disease.

Flitcroft et al. (2016) studied wildfire effects on spring Chinook salmon habitat in Washington's Wenatchee River subbasin. Modeling suggested a largely positive relationship between fire and salmonid habitat, particularly for the juvenile-to-adult stages of development. Although the paper does not examine logging influences, the authors concluded that Pacific Northwest salmonids are well adapted to disturbance, and that the occurrence of characteristic wildfires would likely have an overall positive influence on salmon habitat.

In addition to site-specific literature for our analysis area, our literature database contains several highly informative articles that reviewed disturbance ecology research for riparian forests and aquatic resources. The reviews included studies from the Pacific Northwest and from elsewhere in western North America. For example, Moore et al. (2005) reviewed potential effects of forest harvesting on riparian microclimate and stream temperature in the Pacific Northwest. They found that stream temperature increases after forest harvesting are primarily controlled by changes in solar insolation, but also depend on stream hydrology and channel morphology. Therefore, although stream temperatures recovered to pre-harvest levels within 10 years in many studies, recovery periods were longer (e.g., >10 yrs.) in other locations. The authors state that retention of riparian buffers can decrease the magnitude of stream temperature increases and changes to riparian microclimate. However, substantial warming has been observed for streams within both unthinned and partial retention buffers, and some studies have documented that streams may or may not cool after flowing from clearings into shaded environments. The article concluded by stating that more research was needed to document the range of factors that can affect stream temperatures. The authors concluded that more research was needed to document: 1) riparian microclimate and its responses to harvesting, 2) the influences of surface/subsurface water exchange on stream and bed temperature regimes, 3) biological implications of temperature changes in headwater streams (both on site and downstream), and 4) methods for quantifying shade and its influence on radiation inputs to streams and riparian zones.

Moore and Wondzell (2005) conducted a review of literature documenting the potential effects of timber harvesting on hydrologic processes in Pacific Northwest ecosystems. Although the review does not focus on salvage logging *per se*, the article provides some potentially useful information. For example, most studies in the Northwest and elsewhere have found that annual water yields generally increase somewhat after harvesting. That is, harvesting can promote slightly more precipitation input as streamflow, can promote increased snowmelt, and can increase hillslope runoff into stream channels. Timber harvesting in headwater basins generally increases annual runoff and peak flows and reduces the severity of low flows by increasing water availability (i.e., reducing transpiration losses in riparian zones). Recovery to pre-harvest conditions appeared to occur within about 10 to 20 years in some coastal areas but may take many decades longer in less productive mountain terrain. The authors of the review also point out that separating the effects of harvesting versus associated road building on peak flows is difficult because both activities generally occur simultaneously. Otherwise, the effects of road construction did not appear to have a significant effect on peak flows in most of the studies that measured road treatments in the absence of logging.

Reeves et al.'s (2006) review of salvage logging effects on riparian forests in the western U.S. (which we also classified as occurring in the Silviculture/Forest Practices category) likewise was informative. The article points out that aquatic and riparian organisms often have natural adaptations that allow them to recover relatively rapidly after fire and other disturbances. The authors state that the potential effects of post-fire logging depend on the landscape context and site disturbance history, but that more research was needed to determine the effects of salvaging on riparian areas and adjacent upland terrain. In addition, the authors stated that studies were needed to determine if salvage logging could be incorporated into silvicultural prescriptions to help restore riparian forests and make them more resilient to uncharacteristic wildfires in dry forest types. The authors concluded that, without such data, protecting post-fire riparian zones may be the most advisable policy and that "Without a commitment to monitor management experiments, the effects of post-fire riparian logging will remain unknown and highly contentious." (Reeves et al. 2006: 994).

Mellon et al.'s (2008) study in northeastern Washington examined the effects of salvage logging on headwater-stream macroinvertebrates in areas burned by the 2003 Togo Fire (Colville National Forest). The logging in 2003 and 2004 had employed 45-meter-wide riparian buffers (i.e., INFISH guidelines). The researchers found that macroinvertebrate biomass was greater at salvaged sites than at unburned/unlogged controls. Conversely, species diversity was lower in the salvaged catchments. Macroinvertebrate biomass was greater at burned sites only from emergence samples; in benthic and drift samples there was no significant difference between burn and control sites. For all sample types, diversity was lower in the burned catchments, and the macroinvertebrate community was dominated by chironomid midges. The authors state that, "Landscape patterns were established to some extent by previous management history, but the streams post-fire can also be affected by management decisions that optimize for recovery, such as minimizing the probabilities of mass failure or flash flooding, and maximizing opportunities for riparian regrowth." (Mellon et al. 2008: 2341).

Halofsky and Hibbs (2009) studied severely burned portions of the 2002 Biscuit Fire and 2003 B & B Complex Fire (Rogue River-Siskiyou National Forest; Deschutes National Forest). The study focused on documenting riparian fire severity patterns and post-fire vegetation recovery in lower elevation mixed conifer-hardwood stands. Despite experiencing higher severity fire than occurred in adjacent uplands, the disturbance-adapted riparian stands were found to be highly resilient, with all sample plots exhibiting relatively rapid post-fire recovery in terms of tree regeneration. The authors concluded the article by stating:

> Results of this study suggest that maintenance of riparian function can be expected after fire in other fire-prone regions. The resilience of these riparian plant communities suggests that, unless there is extensive pre-fire degradation of riparian forests, little post-fire riparian rehabilitation is necessary to ensure the continued functioning of riparian forests after fire. (Halofsky and Hibbs 2009: 1357-1358)

Peterson et al.'s (2009a) General Technical Report, *Effects of timber harvest following wildfire in western North America* (which we also classified as occurring in the Silviculture/Forest Practices category), provided a brief overview of possible effects of salvage logging on riparian forests. Below are some key points from that publication:

> Intact riparian buffers reduce sediment delivery to streams, maintain cooler stream temperatures through shading, and minimize changes in aquatic habitat for fish and macroinvertebrates. . . Few data exist on the effects of postfire logging on aquatic ecosystems, although effects can be inferred from the literature on riparian fire, fire effects, and logging effects . . . potential [impacts] include loss of in-channel wood, loss of vegetation, reduced soil infiltration, increased erosion, changes in timing and amount of runoff, elevated stream temperature, and altered channel morphology. . . Mass wasting and debris flows, often associated with structural failure of roads or removal of trees near drainage headwalls are the most damaging to stream habitat. . . Conversely, management activities that complement ecosystem recovery processes [such as stand restoration treatments] may help minimize long-term damage to aquatic systems. (Peterson et al. 2009a: 21-23)

Moore and Richardson (2012) conducted an overview of natural and human-caused disturbances in riparian forests of North America. Regarding tree harvesting, the authors identified the following potential impacts (without specifying associated forest types or silvicultural systems): 1) shade reduction and increased stream temperatures, 2) reduced or accelerated recruitment of in-stream wood (e.g., post-logging windthrow events), 3) decreased root strength and bank stability, 4) decreased water quality and increased temperatures, 5) alteration of stream processes such as increased sedimentation. The researchers also state that maintaining undisturbed forested buffers does not necessarily provide effective protection for riparian zones:

> The presence of a riparian buffer typically has little effect on harvesting-related changes in stream flow and may not protect against increases in sediment input. . . removal of upland forest can increase windthrow in riparian zones, and thus, influence patterns of recruitment of in-stream wood . . . upland forest harvesting also increases light penetration in riparian forest and releases understory growth from shade limitation. (Moore and Richardson 2012: 240)

The authors concluded by stating that more research is needed to help document the effects of various disturbances on riparian zones, and such data would help provide a scientific basis for riparian-sensitive management plans.

In the Crowsnest Pass area of Alberta, Canada, Wagner et al. (2014) examined post-disturbance stream temperature dynamics in burned (no salvage), burned (salvaged), and unburned (control) drainages. During the 2004 to 2010 study period, mean daily minimum and maximum temperatures, and mean annual stream temperatures, were elevated significantly (i.e., 1 to 2 degrees C. mean ann. temp.) in both the burned (no salvage) and burned (salvaged) sites when compared to unburned stream drainages. The authors state that salvage logging likely contributed to the even higher stream temperatures that were found in burned-only drainages, but other catchment differences prevented a conclusive interpretation. This study illustrates the importance of obtaining baseline information about post-salvage effects on streams, and the authors state that ". . . the magnitude and duration of the impacts on [stream temperature] from salvage harvesting remain poorly understood." (Wagner et al. 2014: 329).

Bixby et al. (2015) reviewed studies that examined potential effects of wildfire and fire management practices on freshwater ecosystems in various regions of the U.S. The authors state the following: "Of particular interest are aquatic responses to the use of fire retardant to contain fire spread, construction and maintenance of in-stream structures (e.g., debris dams) to intercept post-fire sediment and debris, applications that stabilize hillslopes (e.g., hydromulch, reseeding), and pre- and post-fire vegetation removal (e.g., via prescribed burns, mechanical removal, salvage logging) . . . Most investigators have found muted and short-lived stream ecological responses to prescribed burns . . . and little investigation has been done of the effects of different prescribed fire severities, extent, and spatial configurations on aquatic ecosystems." (Bixby et al. 2015: 1347).

Biodiversity/Ecosystems. This broadly defined category includes literature for such topics as post-fire or post-salvage effects on wildlife habitat (e.g., for snag-nesting birds), ecosystem function processes, and other subjects. We classified 9 publications according to the Biodiversity/Ecosystems category. (Also note that we occasionally assigned secondary and tertiary research themes, such as the Silviculture/Forest Practices or Fuels/Fire classes). All publications in this category describe individual studies that investigated such topics as post-fire/post-logging snag dynamics relative to bird habitat, bird population monitoring, natural tree regeneration after severe fires, and recovery of understory vegetation after fires or salvage logging.

Synthesis Overview. Fire affects numerous aspects of forest ecosystem structure and function, many of which can also be affected by salvage logging. Although we found relatively little riparian-specific research during our literature review, we identified a number of studies that have addressed the effects of salvage logging on such ecosystem aspects as wildlife habitat (Haggard and Gaines 2001; Lehmkuhl et al. 2003; Cahall and Hayes 2009; Clark et al. 2013), understory vegetation Knapp and Ritchie 2016; Peterson et al. 2016, and microbial community dynamics and nutrient dynamics Johnson et al. 2005; Jennings et al. 2012.

Several studies examined the effects of fire and salvaging on various aspects of bird habitat, such as that used by cavity nesters (Haggard and Gaines 2001; Lehmkuhl et al. 2003; Cahall and Hayes 2009; Clark et al. 2013). The research to date has tended to focus on identifying preferred snag characteristics in terms of tree species, diameters, and longevity (decomposition rates). The above researchers suggest that salvage prescriptions that emulate the effects of mixed severity fires will likely promote the most effective bird habitat, since mixed severity fires provide optimal mixes of living and dead trees important to many bird species. There is less research on the effects of removal of dead and downed wood, although this may have negative impacts on communities of decomposers (e.g. saproxylic invertebrates) and species that rely on this habitat component for denning or sheltering purposes.

Another sub-theme in the Biodiversity category involved studies (Johnson et al. 2005; Jennings et al. 2012) that compared the effects of fires versus salvage logging on soil nutrient- and microbial processes. In general, compaction from post-fire salvaging temporarily reduced the availability of nitrogen and phosphorous and removed substantially more carbon from sites than fires, whereas both fires and salvaging had similarly minor effects on soil microbes, largely due to the rapid recovery of N-fixing vegetation.

Also in the Biodiversity/Ecosystems category are studies that documented the effects of salvage logging on understory vegetation (Keyser et al. 2009; Knapp and Ritchie 2016; Peterson et al. 2016). Understory vegetation is an important component of forest structure and biodiversity, and plays an important role in wildlife habitat and other ecosystem functions. Some studies (Knapp and Ritchie 2016; Peterson et al. 2016; Peterson and Dodson 2016) have found minimal impacts on understory vegetation after salvaging, and impacts may depend on such factors as forest type, amount of soil disturbance (e.g., from road systems and logging equipment), and associated weed invasions. Morgan et al. (2015) also found that, although salvage logging on severely burned dry-forest terrain had temporarily slowed understory recovery in terms of species coverage and diversity, understory vegetation still exhibited relatively high resiliency.

Study Highlights. Below is more-detailed information from some of the most prominent studies in the Biodiversity/Ecosystems category. For example, Haggard and Gaines (2001) monitored the response of cavity-nesting birds to three post-fire salvage treatments in ponderosa pine/Douglas-fir stands on the eastern slope of the Washington Cascades. The study occurred in areas burned by the high severity 1994 Rat Creek fire (Wenatchee National Forest) that were subsequently salvage logged with 3 different snag-retention prescriptions. The highest levels of cavity nester abundance, nesting populations, and species richness occurred in the medium-density treatments (i.e., 15-35 snags/ha.) and ponderosa pine was preferred for most nest sites. Large snags (>48 cm dbh) provided nesting habitat for more species than smaller snags, but small snags were used for nesting and foraging by some species (e.g., American kestrel [*Falco sparverius*]). The article concluded with the following:

> Future studies designed to look at the relationship between the availability of ponderosa pine and the breeding bird population would help to separate snag density effects and tree species effects. In addition, long-term monitoring is necessary to understand the dynamics between snag deterioration rates and changes in bird assemblages following stand-replacement fires and salvage logging. (Haggard and Gaines 2001: 395)

Lehmkuhl et al. (2003) studied bird-excavated snags in a chronosequence of 26 high-severity wildfires on the eastern slope of the Washington Cascades (Okanogan-Wenatchee National Forest). Cavities were found in about 5 percent of the nearly 2000 recorded snags, with about 70 percent occurring in burns that were less than 20 years old. The most commonly excavated tree species were ponderosa pine (~30%) and Douglas-fir (~10%), with only minor-to-negligible amounts in Engelmann spruce, western larch, subalpine fir, and lodgepole pine. Factors such as large diameter (>34 cm. dbh), burn age (e.g., >20 years), broken tops, and moderate heights (10-21 m.) were important predictors of cavities in ponderosa pine and Douglas-fir snags. The authors recommended that, to promote cavity-nesting bird habitat, post-fire salvage prescriptions should include the retention of snags with defects that were incurred before the fire (especially broken tops) and large-diameter snags of the most favored tree species.

In central Oregon, Cahill and Hayes (2009) analyzed changes in bird communities after the severe 2003 Davis Mountain fire (Deschutes National Forest). Sampling occurred in salvaged and unsalvaged ponderosa pine/Douglas-fir stands. The moderate salvage prescription had retained an average of 30 snags per ha, whereas the heavy prescription had retained 5–6 snags per ha. No significant differences were found among treatments in densities or relative abundances for eight species and one genus of birds. Conversely, the sampling documented significant differences among the treatments for seven species, but the response patterns were highly variable. For species that responded negatively to salvage logging, the moderate salvage intensity did not appear to mitigate the negative response. The authors concluded that areas of unlogged burned forest provide the highest quality habitat for many bird species, and that retaining even small patches of unsalvaged forest during logging operations may be beneficial.

Also in central Oregon, Jennings et al. (2012) studied soil processes in mixed conifer stands that had been severely burned and salvaged after the 2003 B&B fire (Deschutes National Forest). Bacterial and fungal communities in soils compacted and decompacted by mechanical equipment during salvaging were compared to those in soils that experienced no mechanical disturbance. The researchers found that soil compaction decreased plant-available nitrogen by an average of nearly 30 percent when compared to sites with no mechanical disturbance. Subsoiling (i.e., mechanical plowing/mixing) decreased plant-available phosphorus by an average of about 25 percent compared to both compacted and non-mechanically disturbed treatments. However, bacterial- and fungal richness did not differ significantly among treatments. The authors concluded that salvage impacts on sandy loam volcanic soils likely are more pronounced for soil nutrient processes than for microbial communities—and effects could be long-lasting because such ecosystems are already nutrient limited. However, the authors state that more research is needed on this subject, and that soil impacts from post-fire salvage logging need to be weighed against other values such as fire hazard reduction and commercial harvesting of trees.

Clark et al.'s (2013) study in southwestern Oregon modeled short-term impacts of wildfire and salvage logging on spotted owl occupancy of three large-scale burned areas (i.e., Biscuit, Quartz, and Timbered Rock fires). For example, an unburned control stand in the southern Oregon Cascades (i.e., the "South Cascades" site) had greater colonization probabilities than the paired Timbered Rock site both before and after wildfire. But colonization probabilities declined over time for both areas. Extinction probabilities were greater at South Cascades than at Timbered Rock prior to the burn, but Timbered Rock had greater extinction probabilities after the wildfire. The results suggested that the combined effects of habitat disturbances due to wildfire and subsequent salvage logging negatively affected site occupancy by spotted owls. The authors concluded that site occupancy of spotted owl nesting territories declined in the short-term after the wildfires, and habitat modification and loss due to past timber harvest, high severity fire, and salvage logging jointly contributed to declines in site occupancy.

In central Oregon, Dodson and Root (2013) sampled natural tree regeneration in ponderosa pine/Douglas-fir stands 10 years after the severe 2002 Eyerly Fire (Deschutes National Forest). Regeneration varied widely across a 700m elevation gradient, with the largest amounts occurring on relatively high-elevation mesic sites. Subsequent modeling predicted rapid increases in regeneration across the gradient for seedlings of all conifer species. However, predicted increases in temperature and drought in the coming century are likely to increase the importance of moisture stress on post-fire regeneration, particularly on xeric sites. The authors concluded that natural regeneration will likely be sparse or absent in many severely burned xeric ponderosa pine/Douglas-fir stands without management intervention (e.g., planting programs).

Responses to SAGE Questions. This literature review and synthesis project was initiated, in part, because forest managers wanted to understand how to best manage post-fire salvage logging in and adjacent to RMZs. For example, the SAGE team members provided a list of salvage-related questions that would be addressed during this project. The questions revolve around two major themes and associated sub-questions, as described below. Note that our responses will highlight only general findings that apply either directly or indirectly to each SAGE question; additional information can be obtained by consulting the literature review database or the individual summary reports for each piece of literature.

In general, the results from this literature review support Peterson et al.'s (2009a) caveat that, "Few data exist on the effects of postfire logging on aquatic ecosystems, although effects can be inferred from the literature on riparian fire, fire effects, and logging effects." (Peterson et al. 2009a: 22). However, new science has emerged since 2009 that furthers our understanding of the potential effects of salvage logging in RMZs. Regardless, most studies have produced only broad management implications rather than prescriptive guidelines, a caveat that especially applies to information gleaned from the various review articles.

Below are the SAGE questions along with relevant information from the literature review. Please note that, because earlier sections of this report have already reviewed some of the most informative studies in the database, some repetition necessarily occurs in the following responses. (Also note that the previously mentioned Keywords Matrix in our *Excel* database might be useful for answering future questions about salvage logging in and near RMZs; the matrix lists each piece of literature along with some applicable keywords, and can serve as a guide for quickly identifying the major research themes within each publication.)

Part A: Questions About Ecological Effects. The first major question posed by SAGE centers on the ecological effects of post-fire salvaging, and has two parts. Namely, "*What are the effects of salvage logging on riparian forest stands, and how can ecological damage to riparian functions from salvage logging be reduced?*" Below are a number of subtopics raised by SAGE in relation to this overarching theme, along with applicable results from our literature review.

Question A1: *Are there significant differences between harvest methods in burned areas that potentially pose a greater risk to aquatic resources?*

Literature Results: The literature provides relatively little information about potential impacts from specific salvage methods in riparian zones or adjacent uplands in our analysis area. Studies to date have tended to focus on post-salvage impacts rather than using experimental studies to test impacts from various logging methods. In one of the few experimental studies to date, McIver and McNeil's (2006) post-fire research in upland ponderosa pine/Douglas-fir stands (Blue Mountains, Oregon) did not find significant differences in soil disturbance and hillslope erosion between fuel reduction treatments (i.e., removal of most dead merchantable trees and most dead trees greater than 10 cm diameter) versus commercial harvest treatments (i.e., removal of most dead merchantable trees). Most of the research we have found has examined post-salvage impacts from ground-based logging operations (i.e., skidders, tractors, etc.) on upland terrain, and has focused on such major issues as soil erosion, fuels, and wildlife habitat.

Most publications that discuss potential effects of salvaging on adjacent RMZs often highlight the fact that most ecosystems in the West are well adapted to disturbance, and that using best management practices—such as erosion control measures on roads and skid trails—is the best way to avoid causing negative impacts (Wondzell 2001, Wondzell and King 2003, Moore and Wondzell 2005, McIver and McNeil 2006, Peterson et al. 2009a, Wagenbrenner et al. 2015, Peterson and Dodson 2016). Although non-ground based techniques such as skyline logging may still result in less disturbance, they may still elevate erosion rates above rates in unlogged stands (Slesak et al. 2015). Reeves et al. (2006) point out that, although there has been little research on salvage logging in general, most RMZs are disturbance adapted and potential impacts from salvaging depend on such factors as landscape context and disturbance history. The authors also state that more studies are needed in dry forest types to determine if salvage logging can help restore RMZs and make them more resilient to uncharacteristic wildfires. However, the authors conclude by saying that, without such data, protecting post-fire riparian zones may be the most advisable policy.

Question A2: *To what extent does application of logging slash on skid trails affect sediment delivery to streams?*

Literature Results: Soil erosion potential after fires and salvage logging is one of the most common research themes in the literature (Wondzell 2001, Wondzell and King 2003, Moore and Wondzell 2005, McIver and McNeil 2006, Peterson et al. 2009a, Robichaud et al. 2013, Wagenbrenner et al. 2015, Slesak et al. 2015). Results from several studies (Robichaud et al. 2013, Slesak et al. 2015, Wagenbrenner et al. 2015) agreed that applying ground covers such as logging slash or mulch immediately after salvaging can help to markedly reduce skid trail erosion. For example, data from 3 salvaged sites in Washington, Montana, and Colorado (Wagenbrenner et al. 2015) suggested that adding slash to skid trails increased total ground cover by 20–30 percent and reduced sediment yields by 5–50 times when compared to the untreated skidder plots. Conversely, Wagenbrenner et al. (2016) conducted rill experiments in severely burned montane forest terrain that was salvage logged in eastern Washington, northern Montana, and southern British Columbia. The study compared results from logged and unlogged forests to evaluate the effectiveness of best management practices in reducing overland flow and sediment production after ground-based salvage logging. Overall results suggested that ground-based logging with heavy equipment had significantly compacted soil, reduced soil water repellency, and reduced vegetation cover. Vegetation recovery rates also were about 30 percent slower in most logged areas compared to unlogged control sites (i.e., logged-plot vegetation coverage after three years was roughly equivalent to that during post-disturbance Year 2 on the control plots). Runoff rates were also higher in the skidder and forwarder plots than in their respective controls during the first year of logging, and persisted during the subsequent 2 years of the study. The type of skidder, the addition of slash, and the amount of forwarder traffic did not significantly affect runoff rates. The authors concluded that salvage logging increases sedimentation risks regardless of equipment type and the amount of traffic, and that best management practices need to be developed or improved to mitigate such impacts.

Question A3: *Is there a difference in sediment delivery between salvage logging on snow covered versus non-snow covered land?*

Literature Results: Although the literature provides relatively little information on this topic, logging on frozen soil that is covered by snow (or by other substances such as slash) appears to be a well-accepted method for reducing soil erosion. McIver and McNeil's (2006) study in the Blue Mountains of Oregon found that salvage logging on snow (or dry ground) posed less risk of promoting hillslope erosion than logging on wet soils. In addition, Peterson and Dodson (2016) state that, "understory vegetation can be resilient to post-fire logging, particularly when best management practices, like logging over snow, are used to limit damage to soils and understory vegetation. (Peterson and Dodson 2016: 56). Similarly, McIver and McNeil's (2006) study of post-salvage erosion potential on severely burned terrain in northeastern Oregon (Malheur National Forest) found that logging operations accounted for more soil disturbance than pre-logging fire severity. However, sediment transport was minimal on areas with low-to-moderate slope steepness, low-to-moderate-risk soils, and areas that had experienced logging over snow or dry ground, hand felling, and minimal new roads.

Question A4: *Does soil disturbance from logging in burned areas increase erosion and delivery of sediment to streams?*

Literature Results: As stated above, many studies have addressed such questions (Wondzell 2001, Wondzell and King 2003, Moore and Wondzell 2005, McIver and McNeil 2006, Peterson et al. 2009a, Robichaud et al. 2013, Wagenbrenner et al. 2015, Slesak et al. 2015). The research often concurs that: 1) soil erosion/sedimentation potential tends to be greater in salvaged versus unsalvaged stands, and 2) skid trails and logging roads pose a significantly greater erosion threat than the ground disturbance that occurs during tree harvesting on adjacent slopes. However, these studies also point out that erosional processes can be influenced by many factors, such as soil types, terrain steepness, rainfall regimes, vegetation types, disturbance history, and vegetation responses to disturbance. Wondzell (2001) reviewed forest practices in relation to erosion and sedimentation potential in eastern Oregon and Washington and adjacent areas suggested that:

> There is great concern over the risk of accelerated erosion following wildfire but actual erosion is highly dependent upon both rainfall intensity and infiltration rate. . . For example, in dry forest types of central Idaho, the coarse, unconsolidated soils are easily eroded once surface litter is removed. [Megahan et al.'s (1995) study in central Idaho found that] prescribed burning following helicopter logging greatly accelerated erosion. Further, because recovery of overstory vegetation on dry, south-facing slopes was slow, high erosion rates persisted for at least 10 years. . . In contrast, regrowth on nearby north-facing slopes was rapid and erosion returned to background rates within 3 years. (Wondzell 2001: 131)

In addition, Moore and Wondzell's (2005) review of soil hydrology in relation to harvesting practices in the Pacific Northwest found that, although ground-based equipment such as skidders and tractors can cause substantial amounts of soil compaction, soil infiltration capacities may remain high enough to preclude infiltration-excess overland flow. However, the authors state that:

> . . . excavated trails and constructed haul roads typically have compact surfaces with low permeability and can generate infiltration excess overland flow in even moderate rainstorms. . . [and potential impact] depends on how much of the catchment area is disturbed, as well as whether the skid trails and roads direct water to the natural drainage network. (Moore and Wondzell 2005: 766).

Question A5: *Do different logging methods change the above impacts?*

Literature Results: As stated in Question A1 above, most studies did not experimentally test among various harvesting methods, but instead examined ecological effects after ground-based harvesting (e.g., with tracked skidders) had occurred (Sessions et al. 2004; Moore and Wondzell 2005; McIver and O'Neil 2006; Donato et al. 2006; Cahall and Hayes 2009; Dodson and Root 2013; Donato et al. 2013; Silins et al. 2014; Peterson and Dodson 2016). Also note that, although some researchers (Sessions et al. 2004) have suggested that helicopter logging might be inherently less impactful, there has been little experimental research on that topic (Dunham 2006). (In fact, one study [Megahan et al. 1995] in central Idaho documented a substantial amount of soil erosion after prescribed burning on a helicopter-logged site underlain by highly erodible granitic soils, suggesting that some sites are inherently more susceptible to erosion.) As for silviculture, studies (Haggard and Gaines 2001; Wondzell 2001; Donato et al. 2006; Slesak et al. 2015) that examined the effects of different salvage prescriptions have found that moderate snag-retention prescriptions (e.g., fuel treatments) tend to produce less impact on soils and wildlife habitat than low-retention prescriptions (e.g., commercial harvests). On a related vein, McIver and McNeil's (2006) research on a severely burned and salvaged site on the Malheur National Forest found that allowing at least two years of post-fire ground cover recovery between the fire and the salvaging may have helped reduce salvage-related soil erosion.

Question A6: *What effects does hydrophobic soil have on erosion and sediment delivery?*

Literature Results: Regarding the potential relationship between hydrophobic soil and erosion/sedimentation processes, Moore and Wondzell's (2005) review article, *Physical hydrology and the effects of forest harvesting in the Pacific Northwest*, states:

> Hydrophobicity and reduced infiltration capacity can occur in situations in which mineral soil grains become coated with organic compounds. Many soils are naturally hydrophobic when dry, as has been documented for soils under interior ponderosa and lodgepole pine. . . [but] hydrophobicity was no longer apparent once moisture contents exceeded 12 percent to 25 percent. Forest fires may induce hydrophobicity by producing volatile organic gases that condense on mineral soil grains in cooler layers below the surface. . .These layers may persist

> for long periods in dry forest types, impeding infiltration and helping produce overland flow. . . (Moore and Wondzell 2005: 766)

In addition, Larsen et al.'s (2009) study on post-fire soils in Colorado found that: 1) sediment yields were primarily due to the loss of surface cover rather than fire-enhanced soil water repellency, 2) surface cover is important because it inhibits soil sealing, and 3) ash temporarily prevents soil sealing and reduced post-fire runoff. The authors concluded that the most effective post-fire rehabilitation treatments will be those that immediately increase the amount of soil surface cover. In addition to promoting the rapid recovery of understory vegetation, management practices such as application of mulch on skid roads can also represent effective soil cover mitigation measures.

Part B: Questions about Restoration. The second major question posed by SAGE members centers on restoration issues, namely: "*How can riparian forest stands and associated riparian functions be restored after fire?*" Below are a number of subtopics raised by SAGE in relation to this overarching theme, along with applicable results from our literature review.

Question B1: *To what extent does leaving standing and dead trees within the RMZ contribute to riparian function?*

Literature Results: Although there has been a lack of research on salvage logging in RMZs *per se*, major reviews of riparian literature to date (Reeves et al. 2006; Peterson et al. 2009a; Moore and Richardson 2012) seemingly agree that retention of streamside buffers is generally desirable from the standpoints of conserving riparian processes, aquatic ecosystems, and wildlife habitats. Reeves et al.'s (2006) overview of potential salvaging effects on RMZs provided the following recommendations in terms of conservation and restoration:

> We suggest that current ecological insights have two implications for salvage logging: (1) fire in riparian areas creates a set of conditions that may not need to be "fixed" in order to sustain the long-term productivity of aquatic ecosystems in a watershed and (2) ecological protection of burned riparian areas should consider foremost what is left rather than what is removed. (Reeves et al. 2006: 998)

In addition, Peterson et al. (2009) state that RMZs are:

> . . . often the least severely burned part of the landscape owing to topography and the cooler temperatures of canyon bottoms. Intact riparian buffers reduce sediment delivery to streams, maintain cooler stream temperatures through shading, and minimize changes in aquatic habitat for fish and macroinvertebrates. . . all of which are especially important following wildfire. Vegetation in riparian areas also mitigates the effects of denuded slopes on wildlife [by providing refugia] . . . Peterson et al. (2009a: 21-22)

Leach and Moore (2010) studied post-fire effects on riparian microclimate in montane forest types in central interior British Columbia. They conducted modeling based on 3 canopy cover scenarios: 1) post-fire with standing dead trees, 2) simulated pre-fire (green canopy), and 3) simulated complete tree removal (i.e., virtual clearcut). Results suggested that the standing dead tree scenario allowed twice as much net radiation to reach stream surfaces when compared to the simulated pre-fire (green canopy) model. However, the standing dead tree model was about 30 percent more effecting at reducing net radiation than occurred with the virtual clearcut scenario.

Moore and Richardson's (2012) overview of disturbances in North American riparian forests likewise emphasizes the beneficial effects of tree shade on stream temperatures. For instance, the authors state that retention of post-fire standing dead trees can provide shade levels that are similar to those remaining after partial-harvest treatments of green trees—but did not specify applicable forest types.

Question B2: *To what extent does down wood reduce erosion and sediment delivery to streams and wetlands?*

Literature Results: Research on hillslope erosion and sedimentation after fires or salvage logging (Wondzell 2001, Wondzell and King 2003, Moore and Wondzell 2005, McIver and McNeil 2006, Peterson et al. 2009a, Robichaud et al. 2013, Wagenbrenner et al. 2015, Slesak et al. 2015) suggests that down wood can be an important factor in helping to reduce soil erosion potential. However, erosion risk on most hillslopes is mitigated when ground cover vegetation recovers relatively quickly. On a related vein, applying slash (or wood mulch) to skid trails after salvage logging is often recommended because road systems generally pose the greatest erosion risk, especially during severe rainstorms (Robichaud et al. 2013, Slesak et al. 2015, Wagenbrenner et al. 2015). For example, Robichaud et al.'s (2013) study of post-fire mulching practices on a severely burned and salvaged site in southeastern Washington found that wood mulch provided relatively effective erosion resistance on skid trails.

Question B3: *To what extent does the risk of sediment delivery change with stream and side slope gradients, different soil types, or with the intensity of the burn?*

Literature Results: Regarding the potential vulnerability of hillslope soils to erosion, Wondzell's (2001) review of forest practices in the Pacific Northwest cited an example from dry forest types in central Idaho, where "coarse, unconsolidated soils are easily eroded once surface litter is removed, [and where] prescribed burning following helicopter logging greatly accelerated erosion." (Wondzell 2001: 129). Regarding slope steepness, Wondzell's (2001) review stated that, ". . . in steep V-shaped valleys, riparian vegetation is less likely to be effective in buffering streams. Conversely, where valley floors are wide, sediment may be trapped effectively, even without significant interaction with riparian vegetation (Wondzell (2001: 129). As for burn intensity, studies (as reviewed by Moore et al. 2006 and Peterson et al. 2009a) suggest that sedimentation risk tends to be related to various combinations of factors rather than any single factor like fire severity. That is, fire severity, vegetation type, soil erodibility, slope steepness, rainfall regime, severe storm events, disturbance history, management history, and other factors can interact in various combinations that ultimately influence erosional processes.

Question B4: *To what extent do live standing trees and dead standing trees immediately adjacent to or over the streambank contribute to bank stability?*

Literature Results: The literature is limited on this question. Although most researchers clearly support the concept of conserving streamside buffers (as described previously) research has yet to quantify the role of, or provide specific recommendations for, tree retention for enhancing streambank stability. One study (Eaton et al. 2010) of post-fire effects on sedimentation and stream morphology in southern interior British Columbia described the role of post-fire root systems in relation to bank stability. Although sediment processes were similar between burned and nearby unburned riparian stands during the 4-year study period, post-fire declines in bank strength as a result of root decay contributed significantly to accelerated morphological changes in the adjacent streambed.

Moore and Richardson's (2012) general overview of natural and human-caused disturbances in riparian forests of North America states that timber harvesting in RMZs can promote decreased root strength in leave trees and thus reduce bank stability—but does not cite any studies from our analysis area. Similarly, Wondzell's (2001) review of forest practices in eastern Washington and Oregon states that:

> Riparian vegetation is an important factor determining rates of bank erosion. Roots of riparian vegetation can stabilize stream banks and slow bank erosion. . . although it may be ineffective in stabilizing banks along some deep channels or along larger rivers. . . Consequently, protection and maintenance of riparian vegetation may be an important way to maintain or reduce stream sediment loads. (Wondzell 2001: 130)

The review also stated that, "If surface runoff were to occur, riparian vegetation could be an important factor regulating the amount of sediment transported in surface runoff that reaches streams. . . Dense vegetation slows surface runoff, allowing deposition of fine sediment before it reaches streams." (Wondzell (2001: 129). (Note, however, that the above statements do not mention post-fire scenarios or the specific roles that may be played by trees as opposed to understory plants.)

Question B5: *Are there any differences in bank stability benefits provided by standing trees vs. stumps?*

Literature Results: Our literature review did not find any studies comparing the potential ecological roles played by riparian snags versus stumps relative to bank stability. However, Reeves et al.'s (2006) paper, *Postfire Logging in Riparian Areas,* would seem to suggest that snags and stumps share few similarities in terms of riparian functioning:

> Wildfires typically leave large amounts of downed and standing trees that provide seed sources and substrate for future riparian forests, habitat for a variety of

> organisms (e.g., amphibians and cavity-nesting birds), and a source of large wood for streams. Wood is delivered to streams episodically, along with sediment, through landslides and streambank erosion, providing structural elements that promote pool formation, sediment terraces, and a diversity of aquatic habitats. Removal of large wood from riparian areas and adjacent unstable hillslopes limits the future recruitment of this material to stream channels. (Reeves et al. 2006: 998)

Presumably the ecological roles played by riparian stumps would be very different from those described above, but studies have not addressed such questions. (On a related vein, studies also have not documented the potential effects of heavy logging slash that might be retained in riparian zones.)

Question B6: *To what extent do standing trees provide levels of shade that will mitigate the warming of streams or wetlands?*

Literature Results: The literature provided only a limited amount of detailed information about tree shading in riparian zones, and study results to date have been variable. For example, Macdonald et al's (2003) study in spruce-fir forests of northwestern British Columbia investigated the influence of three variable-retention riparian harvesting prescriptions on temperatures of first-order streams. Samples taken 5 years after harvesting (not salvaging) showed substantially warmer stream temperatures (i.e., +4-6 degrees C.) after 3 different retention prescriptions. Although the high-retention prescription initially was the least impactful treatment, post-logging windthrow had reduced the mitigative effects of that prescription by year five. The article closed by suggesting that the potential effects of logging on stream temperatures were not well understood, which likely reflects an overall lack of experimental studies in the literature as of that point in time.

As previously noted for Question B1 above, Leach and Moore (2010) studied post-fire effects on riparian microclimate in montane forest types in central interior British Columbia. They conducted modeling based on 3 canopy cover scenarios: 1) post-fire with standing dead trees, 2) simulated pre-fire (green canopy), and 3) simulated complete vegetation removal (i.e., salvage treatment). Results suggested that the standing dead tree scenario allowed twice as much net radiation to reach the stream surface when compared to the simulated pre-fire (green canopy) model. However, the standing dead tree model yielded one-third less net radiation than did the complete vegetation removal scenario.

Moore et al.'s (2005) review of riparian studies in the Pacific Northwest suggested that retention of buffers can decrease the magnitude of stream temperature increases and changes to riparian microclimate. However, the authors state that substantial warming has been observed for streams within both unthinned and partial retention buffers, and that streams may or may not cool after flowing from clearings into shaded environments.

Other review articles in our collection provide only general statements about the effects of tree shading on stream/wetland temperatures (and little information about the post-fire roles of streamside snags). For example, the riparian section of Peterson et al.'s (2009a) General Technical Report, *Effects of timber harvest following wildfire in western North America*, states the following: "Intact riparian buffers reduce sediment delivery to streams, maintain cooler stream temperatures through shading, and minimize changes in aquatic habitat for fish and macroinvertebrates. . . all of which are especially important following wildfire." Peterson et al. (2009a: 21-22). Similarly, Moore and Richardson's (2012) overview of disturbance effects on riparian forests of North America includes broad statements such as "Harvesting in the riparian zone can reduce shade and increase stream temperature" (Moore and Richardson 2012: 239). Conversely, the authors emphasized the potentially beneficial effects of tree shade on stream temperatures, and included the conceptual statement that retention of post-fire snags can provide shade amounts that are similar to those remaining after partial-harvests in unburned forests. (Note, however, that the authors did not identify applicable forest types or specify what constitutes a partial harvest).

Question B7: *Is buffer width critical and does this vary by stream size?*

Literature Results: Our literature review did not find any information about buffer widths (or lengths) for eastside forests, since most research to date has occurred in mesic forests on the west side of the Cascades (e.g., Cole and Newton 2013). Researchers (Reeves et al. 2006; Peterson et al. 2009a; Moore and Richardson 2012) often provide only general recommendations, such as: ". . . protection of residual [stand] structures following fire in riparian areas, including smaller streams, is critical for minimizing deleterious effects." (Peterson et al. 2009a: 22). However, Moore and Richardson's (2012) general overview of natural and human-caused disturbances in riparian forests of North America cautions that maintaining undisturbed forested buffers does not necessarily provide full protection for riparian zones:

> The presence of a riparian buffer typically has little effect on harvesting-related changes in stream flow and may not protect against increases in sediment input. . . . removal of upland forest can increase windthrow in riparian zones, and thus, influence patterns of recruitment of in-stream wood . . . upland forest harvesting also increases light penetration in riparian forest and releases understory growth from shade limitation. (Moore and Richardson 2012: 240)

Similarly, Moore et al.'s (2005) review of riparian studies in the Pacific Northwest concluded that, although the retention of riparian buffers can decrease the magnitude of stream temperature increases and changes to riparian microclimate, substantial warming has been observed for streams within both unthinned and partial retention buffers. For example, streams may or may not cool after flowing from clearings into shaded environments. In addition to discussing the influence of vegetation management practices, the authors also stated that variation can result from such factors as varying stream morphology, and that more research was needed to document the wide range of factors that can influence stream temperatures.

In addition, a study in northeastern Washington examined the effects of salvage logging on headwater-stream macroinvertebrates in portions of the 2003 Togo Fire burned area. The salvage logging in 2003 and 2004 had employed 45-meter-wide riparian buffers (i.e., INFISH guidelines). The researchers found that macroinvertebrate biomass was greater at salvaged sites than at unburned/unlogged controls. Conversely, species diversity was lower in the salvaged catchments. The authors state that, "Landscape patterns were established to some extent by previous management history, but the streams post-fire can also be affected by management decisions that optimize for recovery, such as minimizing the probabilities of mass failure or flash flooding, and maximizing opportunities for riparian regrowth." (Mellon et al. 2008: 2341).

Question B8: *To what extent are there differences between the rates of large woody delivery over time to streams where the burned RMZ is left in place, compared to one that is harvested and then replanted or allowed to reseed naturally after fire?*

Literature Results: Our literature review did not find any studies specifically investigating such questions. However, a considerable amount research has documented the role of post-fire snags/down wood in stream dynamics and aquatic habitat. For example, Reeves et al.'s (2006) article on riparian disturbances in western U.S. forests provides the following overview:

> [Post-fire] wood is delivered to streams episodically, along with sediment, through landslides and streambank erosion, providing structural elements that promote pool formation, sediment terraces, and a diversity of aquatic habitats. Removal of large wood from riparian areas and adjacent unstable hillslopes limits the future recruitment of this material to stream channels. (Reeves et al. 2006: 998)

Similarly, Peterson et al.'s (2009a) review states that:

> Removal of snags following fire may affect macroinvertebrate, fish, and amphibian populations, because large wood recruitment into streams following fire alters channel morphology, sediment transport, and nutrient cycling. . . Erosion following fires and logging can provide wood and coarse sediment that maintain productive habitats, create heterogeneity in channel structure and complexity, and temporarily increase aquatic productivity through nutrient transfer. (Peterson et al. 2009a: 22)

As previously noted, Moore and Richardson (2012) conducted an overview of natural and human-caused disturbances in riparian forests of North America. The authors state that tree harvesting in riparian areas can either reduce or accelerate the recruitment of in-stream wood (but did not give specifics on associated forest types or logging practices). The authors also state that maintaining undisturbed forested buffers does not necessarily provide effective protection for riparian zones:

> The presence of a riparian buffer typically has little effect on harvesting-related changes in stream flow and may not protect against increases in sediment input. . . removal of upland forest can increase windthrow in riparian zones, and thus, influence patterns of recruitment of in-stream wood . . . upland forest harvesting also increases light penetration in riparian forest and releases understory growth from shade limitation. (Moore and Richardson 2012: 240)

Note that the above reviews did not identify applicable forest types; in addition, our literature review did not identify any studies that addressed the harvesting/planting/reseeding scenario posed by SAGE in Question B8.

Question B9: *Are there biogeographic areas that require or do not require replanting after salvage harvest?*

Literature Results: Based on the literature to date, only a few generalizations can be made about the possible need for tree planting after severe fires. For instance, studies support the general conclusion that the most severely burned xeric sites in dry coniferous forest types might require planting after salvaging. For example, Dodson and Root's (2003) study in severely burned ponderosa pine/Douglas-fir stands (Deschutes National Forest) concluded that, without management intervention like tree planting, many xeric sites might fail to regenerate adequately during future decades—especially during an increasingly warming climate. Conversely, the same study found that natural post-fire reproduction has been relatively abundant on mesic sites, particularly in mid-to-upper elevation terrain.

Ritchie and Knapp's (2014) study of severely burned and salvaged ponderosa pine stands on the Lassen National Forest found that natural regeneration was scarce on both salvaged and non-salvaged xeric sites due, in part, to the lack of seed sources. However, fire management- and other issues could be important considerations when planning for post-salvage tree reforestation. Although some authors have stated that salvage logging may be necessary to help reduce reburn hazards on severely burned terrain (Ice et al. 2004; Sessions et al. 2004; Dunn and Bailey 2015), studies in southwestern and northeastern Oregon (Donato et al. 2006; McIver and Ottmar 2007; Thompson et al. 2007; Donato et al. 2013), and in South Dakota's Black Hills (Keyser et al. 2009), found that high levels of fine fuels after salvage logging can increase reburn risks in dry conifer forests within the first few decades after a severe wildfire. For example, Thompson et al. (2007) found that a 1987 burned area that had been salvage-logged and then planted had reburned more severely than an adjacent unmanaged area during the subsequent Biscuit Fire in 2002. The researchers concluded that post-salvage tree planting (without subsequent thinning treatments) had promoted a denser and more continuous fuel layer than had occurred in the unmanaged control plots.

Question B10: *To what extent does excessive dead standing and/or down wood post-fire affect the reforestation of the upland forest stand and the riparian area?*

Literature Results: The literature provided no direct answers to this question (and scant information about riparian reforestation issues in particular). First, none of the studies discussed the concept of excess fire-killed wood, although the topic conceivably could apply to previously unlogged stands that had experienced uncharacteristic fuel accretion during the fire exclusion era. Otherwise, inferences might be drawn from studies that examined potential effects of post-fire salvaging on tree regeneration, or that examined regeneration in the absence of salvaging.

For example, Ritchie and Knapp (2014) studied surface fuels and regeneration during a 10-year long period after a high-severity wildfire and salvage logging in ponderosa pine-dominated stands (Lassen National Forest, California). Surface fuel accumulations were rapid, corresponding with a high rate of snag decay and subsequent breakage or windthrow. Retained pine snags exhibited the fastest rates of breakage and transitioning to surface fuels, while white fir (*Abies concolor*) and incense-cedar (*Calocedrus decurrens*) were significantly more stable during the study period. Although the 2002 wildfire had provided a receptive seedbed, the fire destroyed most of the available seed sources. Consequently, post-fire natural regeneration was scarce irrespective of the salvage treatment. Similarly, growth and survival of artificial regeneration was highly variable and unrelated to the salvage treatment. The authors stated that natural regeneration cannot be relied on to re-establish such conifer stands in the foreseeable future.

In South Dakota's Black Hills, Keyser et al. (2009) studied the effects of salvage logging on regeneration and fuels in ponderosa pine stands that had been moderately- to severely burned by a 2000 wildfire. On unsalvaged sites, post-fire tree mortality had promoted exponential increases in fine and coarse woody debris by post-fire year 5. In contrast, salvage logging had significantly reduced fuel accumulation rates. On sites that had experienced moderate-severity fire and salvaging, tree regeneration was 75 percent lower because of the reduction in potential seed-trees. However, the authors stated that the likelihood of substantial regeneration occurring on high severity burn sites was low on both salvaged and unsalvaged sites. The paper concluded by recommending more such research, while stating that "the effects of salvage logging may be dependent on when and how salvage logging is conducted as well as forest type rather than an invariant set of effects inherent to salvage logging." (Keyser et al. 2009: 457).

In addition, as stated in Question 9 above, the post-fire reburn issue could be an important consideration when contemplating whether to retain or remove standing and down wood for reforestation and other objectives (Donato et al. 2006; Thompson et al. 2007; Ritchie and Knapp 2014; Dunn and Bailey 2015). Dunn and Bailey's (2015a) study of high-severity portions of seven fires that occurred in dry mixed-conifer forests of the eastern Cascades (Oregon) concluded that "Reducing hazardous fuel loadings and their contribution to re-burn hazard requires manipulation of residual and future fuel sources." (Dunn and Bailey 2015a: 93). Conversely, studies (Donato et al. 2006; McIver and Ottmar 2007; Thompson et al. 2007; Keyser et al. 2009; Donato et al. 2013) found that logging had significantly increased both fine- and coarse downed woody fuels in dry conifer forests, thus contributing to an increase in short-term fire risk. (On a related vein, Donato et al's [2006] study in the Biscuit burned area found that post-fire salvaging had markedly reduced natural tree regeneration by causing direct impacts during logging operations.) Ritchie and Knapp's (2014) study in severely burned ponderosa pine stands on the Lassen National Forest found that unsalvaged areas experienced uncharacteristically high and rapid fuel accumulations, and that salvage logging likely helped reduce the reburn risk.

Question B11: *To what extent do standing dead or down trees help promote the establishment of new seedlings post-fire whether planted or naturally re-seeded)?*

Literature Results: Again, the literature provided no direct answers to this question (and scant information about RMZ reforestation issues in particular). Although a few researchers have recommended substantially reducing fire-killed wood to help reduce reburn potential, some studies support the practice of leaving at least moderate amounts to promote reforestation and other objectives. For instance, Dodson and Root (2013) studied post-fire regeneration in severely burned, non-salvaged stands in the ponderosa pine/Douglas-fir type (Deschutes National Forest). Results indicated that, whereas most mesic sites will likely regenerate successfully without management intervention, many low-to mid-elevation xeric sites would likely remain non-forested for long periods without intervention. Similarly, Ritchie and Knapp's (2014) study of severely burned and salvaged ponderosa pine stands on the Lassen National Forest found that natural regeneration was scarce on both salvaged and non-salvaged sites due, in part, to the lack of seed sources. Therefore, in addition to planting trees on xeric sites, retaining at least moderate amounts of standing and down wood would provide transitory shade and long-term soil nutrients for enhancing seedling establishment (Topik and Halverson 1988).

Research Gaps. In response to requests made by several SAGE and CMER members, following is a list of possible research needs that became apparent during this literature review project. Some research needs have been identified by article authors, whereas other gaps have been identified based on our interpretations. Also note that, because the list reiterates key points that were discussed in detail earlier in this report, only limited discussion will be devoted to a given issue below.

- The most conspicuous research gap to date centers on the fact that virtually no salvage-related research has occurred in riparian areas *per se* (Reeves et al. 2006; Peterson et al. 2009a). The lack of studies stems from at least two major factors: 1) most wildfire and post-fire salvage research occurs on federal lands, and 2) most federally-managed riparian areas are subject to "hands-off" protection policies where salvage logging is largely prohibited.

- Regarding fire's ecological role in riparian areas, Dwire and Kauffman (2003) state that, "*Given the critical resource values of riparian zones. . . improved understanding of fire ecology and effects in riparian areas is needed to prescribe ecologically sound rehabilitation projects following fire*." (Dwire and Kauffman 2003: 61). Similarly, Moore and Richardson (2012) stated that more research is needed to help document the effects of various disturbances on riparian zones, and such data would help provide a scientific basis for riparian-sensitive management plans.

- On a related vein, Reeves et al. (2006) stated that studies were needed to determine if salvage logging could help restore riparian forests and make them more resilient to uncharacteristic wildfires in dry forest types. The authors concluded that, without such data, protecting post-fire riparian zones may be the most advisable policy and that "*Without a commitment to monitor management experiments, the effects of post-fire riparian logging will remain unknown and highly contentious*." (Reeves et al. 2006: 994).

- The SAGE team recently posed the following question about post-salvage reforestation: *Are there biogeographic areas that require or do not require replanting after salvage harvest?* The literature provided only general guidance on this issue. For example, low-elevation ponderosa pine stands on xeric sites may often require planting, whereas natural regeneration might be relatively abundant on mid-to-upper elevation mesic sites. Note, however, that scant research exists for other forest types.

- Similarly, Keyser et al. (2009) stated that more research is needed to address the difficult challenge of regenerating xeric ponderosa pine stands after severe fires and/or after salvage logging. The authors also stated that, "the effects of salvage logging may be dependent on when and how salvage logging is conducted as well as forest type rather than an invariant set of effects inherent to salvage logging." (Keyser et al. 2009: 457).

- The literature could not provide specific information to help answer the following SAGE reforestation question: *To what extent does excessive dead standing and/or down wood post-fire affect the reforestation of the upland forest stand and the riparian area?*

- The literature also could not provide much insight into the following SAGE question (in part because such questions are too broad in scope): *To what extent do standing dead or down trees help promote the establishment of new seedlings post-fire whether planted or naturally re-seeded)?*

- The literature was unable to provide enough specifics to help answer the following SAGE question about salvage methods: "*Are there significant differences between harvest methods in burned areas that potentially pose a greater risk to aquatic resources?*" In addition to the fact that salvage logging has not occurred in most riparian areas, uplands research typically did not conduct experiments to compare impacts from various logging methods.

- On a related vein, regarding soil impacts from specific types of logging equipment, most research to date has examined impacts from tire- or track mounted equipment; no studies in the database examined other harvesting methods, such as those using hydraulic shovel yarding.

- No literature exists to help answer the following SAGE question: *Are there any differences in bank stability benefits provided by standing trees vs. stumps*?

- Some researchers have raised questions about the potential effectiveness of retaining forested buffer zones as a means of protecting riparian resources. For example, Moore et al. (2005) stated that, because substantial warming of stream temperatures has been observed within both unthinned and thinned buffers, more research was needed to document the range of factors that can influence stream temperatures. Moore and Richardson's (2012) general overview of North American riparian forests likewise states that maintaining undisturbed forested buffers does not necessarily provide effective protection. However, other authors (Reeves et al. 2006; Peterson et al. 2009a) have recommended including buffer zones as a standard element of silvicultural prescriptions, at least until research can more thoroughly evaluate the practice.

- Regarding buffer zone design, most publications lack specifics for eastside forests. The sole exception to date has been Mellon et al.'s (2008) study evaluating salvage effects on stream macro-invertebrates in northeastern Washington. Their results were generally supportive of the project's 45-meter-wide buffers (i.e., standard INFISH guidelines). Otherwise we did not find any information about recommended buffer widths, lengths, or other design elements.

- Several authors (Macdonald et al. 2003; Reeves et al. 2006; Wagner et al. 2014) called for more research on potential effects of salvage logging on stream temperatures and aquatic biota. Similarly, Moore et al. (2005) stated that more research was needed on such topics as: 1) riparian microclimate and responses to harvesting, 2) influences of surface/subsurface water exchange on stream temperature regimes, and 3) methods for quantifying shade and its influence on radiation inputs to streams and riparian zones.

- Regarding soils, Wondzell and King's (2003) review of research on post-fire erosion processes in western U.S. forests stated that substantial knowledge gaps existed, in part, because studies tended to focus on the most-severe disturbance events. Consequently, the effects of lower severity wildfires and careful salvage logging remained poorly understood.

- Also in relation to soils, Jennings et al.'s (2012) study concluded that salvage effects may be more pronounced for soil nutrient processes than for soil microbial communities (at least on sandy volcanic soils). The authors stated that effects could be long-lasting because such ecosystems are already nutrient limited. That paper concluded that more soils research was needed, and that impacts from post-fire salvage logging need to be weighed against other values such as fire hazard reduction and commercial harvesting of trees.

- Regarding post-salvage seeding for erosion mitigation, Peppin et al. (2014) concluded that, 1) more research, 2) more long-term monitoring, and 3) better communication and collaboration between managers and scientists would likely help managers make better-informed decisions about such practices.

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Appendix A: List of Database Fields

The database produced during this literature review project was designed with user-friendliness in mind. For example, most of the data field names and associated data entries consist of descriptive text that is largely self-explanatory, and only rarely employ codes and abbreviations. Below is the complete list of database fields and their associated descriptions.

Data Field	Description
Identification Number (ID #)	Unique identifier assigned to each piece of literature
Author/Date	Lists primary author first, along with year of report
Author Name(s)	Lists all report authors
Full Citation	Formal bibliographic citation
Year of Publication	Year report was published or otherwise formally filed
Type of Item	Report type: - Peer reviewed document - Conference proceedings - White Paper
Primary Research Theme	Main focus or subject matter topic within the report: **Riparian/ Aquatic** – Research examining the structure and function of riparian systems relation to salvage logging. **Erosion/Soils** – Research examining the effects of fire and salvage logging on geomorp processes including erosion. **Fuels/ Fire** – Research examining interactions between fuels and salvage logging and e behavior, severity, and ecological effects of fire. **Silviculture/ Forest Practices** – Research examining specific harvesting practices and riparian areas. **Biodiversity/ Ecosystems** – Research examining the effects of fire and salvage logging biodiversity, including wildlife habitat.
Secondary Research Theme	- Secondary focus or subject matter topic within the report, if applicable (same codes as above)
Tertiary Research Theme	- Tertiary focus or subject matter topic within the report, if applicable (same codes as above)
Primary SAGE Question	Primary SAGE question addressed by report contents:

	1. Are there significant differences between harvest methods in burned areas that potentially pose a greater risk to aquatic resources? **2.** Does soil disturbance from logging in burned areas increase erosion and delivery of sediment to streams? **3.** To what extent does leaving standing and dead trees with the riparian management zone (RMZ) contribute to riparian function?
Secondary SAGE Question	Secondary SAGE question addressed by report contents (same codes as above)
Tertiary SAGE Question	Tertiary SAGE question addressed by report contents (same codes as above)
Forest Type	Applicable SAF cover type (Eyre 1980).
State / Province	Applicable state or province: **Washington, Oregon, California, Utah, Idaho, Nevada, Montana, Colorado, British Columbia, Alberta**, (or various combinations).
Region	Applicable region, such as: - **Blue Mountains** - **Southern Cascades** - **Eastern Cascades** - **Northern Sierra Nevada California** - **Eastern Sierra Nevada** - **Klamath Mountains** - **Western Canada** - **Western North America**
Summary	Narrative overview of study (who, what, when, where, why, etc.)
Findings	Narrative overview of key research results
Methods	Narrative overview of key methods
Limitations	Narrative overview of key study limitations if described by authors

Appendix B: Literature Review Bibliography
(Comprehensive list of publications in the database)

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Appendix C: Summary Reports Compendium

Introduction

The purpose of this overview is to familiarize readers with the Summary Reports Compendium, which is a collection of summary reports for the literature that was reviewed during Washington State Department of Natural Resources [DNR] contract number PSC 93-095317 (titled *Literature Review and Synthesis Related to Salvage of Fire Damaged Timber*). Individual summary reports were requested by the Scientific Advisory Group Eastside (SAGE) to help support the work of the Cooperative Monitoring, Evaluation, and Research (CMER) committee of the DNR Forest Practices Board.

Overview

Whereas the **Synthesis Report** for the literature review project provides an overview of the contract goals, objectives, methods, and overall results, the **Summary Reports Compendium** consists of brief reports that distill key information from all 73 pieces of literature in the project database.

Each 1-page report contains the following elements extracted from the database. First, we present an overview, using abstracts and other information from within the body of each article. The overview describes the research objectives, study locations, research methods, major findings, and any conclusions and recommendations that may have been provided by the article author(s). Next, the bottom of each summary report contains a bulleted list of additional SAGE-requested information for quick reference purposes. Therefore, the summary reports compendium can serve as a supplemental or alternative reference source for users who prefer to read narrative summaries instead of *Excel* spreadsheets. (Note, however, that the Excel database contains additional information that is not contained in the summary reports, such as a keywords matrix and other data.)

Literature Navigation

During the literature review, we classified publications according to major research themes to help organize and keep track of the extensive database. The classification also might help guide future users, and is presented below:

- **Riparian/ Aquatic –** Research examining the structure and function of riparian systems, especially in relation to salvage logging.
- **Erosion/Soils –** Research examining the effects of fire and salvage logging on geomorphic and soil processes including erosion.
- **Fuels/ Fire –** Research examining interactions between fuels and salvage logging and effects on the behavior, severity, and ecological effects of fire.
- **Silviculture/ Forest Practices –** Research examining specific harvesting practices and their effects on riparian areas.

- **Biodiversity/Ecosystems –** Research examining the effects of fire and salvage logging on biodiversity, including wildlife habitat.

Tables 1 through 5 below list all publications according to the 5 major research themes. In addition, the associated bibliographic citations appear after Table 5. Both sources of information can serve as your initial guide before accessing the 1-page summary reports.

Table 1. Database literature according to the *Riparian/Aquatic* primary research theme (n=20 articles) (ID No. = database reference number; locations that are regions indicate review-type articles).

ID No.	Author (Date)	Location
1	Reeves et al. (2006)	Western U.S.
8	Karr et al. (2004)	Western U.S.
21	Dwire and Kauffman (2003)	Western U.S.
33	Peterson et al. (2009)	Western U.S.
62	Bladon et al. (2014)	Western U.S.
56	Everett et al. (2003)	Washington
27	Moore and Wondzell (2005)	Pacific Northwest
66	Moore et al. (2005)	Pacific Northwest
3	Olson and Agee (2005)	Oregon
54	Halofsky and Hibbs (2008)	Oregon
55	Halofsky and Hibbs (2009)	Oregon
20	Moore and Richardson (2012)	N. America
19	Bixby et al. (2015)	Global
5	Berg et al. (2002)	California
6	Skinner (2003)	California
64	MacDonald et al. (2003)	Brit. Columbia
72	Leach and Moore (2010)	Brit. Columbia
74	Story et al. (2003)	Brit. Columbia
18	Silins et al. (2014)	Alberta
24	Wagner et al. (2014)	Alberta

Table 2. Database literature according to the *Erosion/Soils* primary research theme (n=18 articles) (ID No.: database reference number; locations that are regions indicate review-type articles).

ID No.	Author (Date)	Location
14	Ice et al. (2004)	Western U.S.

15	Moody and Martin (2009)	Western U.S.
59	Robichaud and Ashmun (2013)	Western U.S.
69	Wagenbrenner and Robichaud (2014)	Western U.S.
70	Wagenbrenner et al. (2016)	Western U.S.
9	Wagenbrenner et al. (2015)	Washington
13	Robichaud et al. (2013)	Washington
17	Wondzell (2001)	Washington
16	Wondzell and King (2003)	Pacific Northwest
71	Gomi et al. (2005)	Pacific Northwest
10	McIver and McNeil (2006)	Oregon
11	Slesak et al. (2015)	Oregon
12	Larsen et al. (2009)	Colorado
73	Eaton et al. (2010)	Brit. Columbia
7	Silins et al. (2009)	Alberta
60	Emelko et al. (2015)	Alberta
61	Bladon et al. (2008)	Alberta
63	Emelko et al. (2011)	Alberta

Table 3. Database literature according to the *Silviculture/Forest Practices* primary research theme (n=10 articles) (ID No.: database reference number; locations that are regions indicate review-type articles).

ID No.	Author (Date)	Location
43	Peppin et al. (2014)	Western U.S.
57	Beyers (2004)	Western U.S.
58	Peppin et al. (2011)	Western U.S.
67	Morgan et al. (2015)	Washington
68	Robichaud et al. (2006)	Washington
40	Keyser et al. (2009)	S.Dakota
39	Thompson et al. (2007)	Oregon
45	Sessions et al. (2004)	Oregon
42	Ritchie and Knapp (2014)	California
65	Moore and Scott (2005)	Brit. Columbia

Table 4. Database literature according to the *Fuels/Fire* primary research theme (n=12 articles) (ID No.: database reference number; locations that are regions indicate review-type articles).

ID No.	Author (Date)	Location
35	Monsanto and Agee (2008)	Washington

53	Everett et al. (1999)	Washington
31	Peterson et al. (2015)	Wash./Oregon
28	Dunn and Bailey (2015a)	Oregon
29	Donato et al. (2013)	Oregon
30	Campbell et al. (2016)	Oregon
32	McIver and Ottmar (2007)	Oregon
34	Donato et al. (2006)	Oregon
37	Dunn and Bailey (2015b)	Oregon
36	Russell et al. (2006)	Idaho
4	Kobziar and McBride (2006)	California
38	Ritchie et al. (2013)	California

Table 5. Database literature according to the *Biodiversity/Ecosystems* primary research theme (n=13 articles) (ID No.: database reference number; locations that are regions indicate review-type articles).

ID No.	Author (Date)	Location
26	Bisson et al. (2003)	Western U.S.
25	Mellon et al. (2008)	Washington
48	Lehmkuhl et al. (2003)	Washington
49	Haggard and Gaines (2001)	Washington
46	Peterson and Dodson (2016)	Oregon
47	Jennings et al. (2012)	Oregon
50	Dodson and Root (2013)	Oregon
51	Cahall and Hayes (2009)	Oregon
52	Clark et al. (2013)	Oregon
41	Johnson et al. (2005)	Nevada
22	Isaak et al. (2010)	Idaho
23	Dunham et al. (2007)	Idaho
44	Knapp and Ritchie (2016)	California

Summary Report: Berg et al. (2002)

Berg, N.H.; Azuma, D.; Carlson, A. 2002. Effects of wildfire on in-channel woody debris in the eastern Sierra Nevada, California. USDA Forest Service General Technical Report PSW-GTR-181. 63 p.

This general technical report examines changes in stream debris frequency, mobility, volume, aggregation, and carbon loading after the 1994 Cottonwood Fire, Tahoe National Forest, eastern Sierra Nevada Mountains. The authors state that post-fire increases in stream discharges can cause more frequent downstream flooding. The resulting heightened transport and accumulation of debris can wash out bridges and cause other damage. In-channel debris is sometimes removed or cut into smaller pieces to expedite flushing through the system and to avoid debris jam formation. Biotic values of debris for fish cover, pool formation, sediment storage, and food sources for invertebrates and microorganisms are lost or reduced, however, when debris is removed or cut up. Changes in debris frequency, mobility, volume, aggregation, and carbon loading after a 1994 wildfire in the eastern Sierra Nevada were quantified by before-and-after comparative measurements and by comparing selected attributes to a nearby [unburned] reference stream. Fifty-seven percent of wood volume, and 25 percent of the pieces, were consumed by the fire. The fire reduced aquatic carbon loading from about 2½ to 1½ times terrestrial loading after the fire. Although more pieces moved one year after the fire at [the burned site] than in the control stream, the size and number of debris jams both immediately and one year after the fire were appreciably reduced from pre-fire levels. The authors conclude that decisions on the disposition of post-fire debris must consider the interaction between fire intensity, channel width, and the size of the remaining wood. The authors also state that, although relatively little is known about post-fire dynamics in many forested riparian zones, indiscriminate removal or cutting of in-stream debris may be inadvisable without understanding the critical interaction between channel width, debris size, and fire intensity on downstream effects.

Additional information requested by SAGE:

- **Type of item**: White paper
- **Author(s)**: Berg, Neil H.; Azuma, David; Carlson, Ann
- **Publication date**: 2002
- **Topics addressed**: post-fire debris characteristics and dynamics, riparian habitat restoration, riparian management, wildfire.
- **Location**: California (Tahoe National Forest)
- **Forest Types**: Mixed Conifer/Jeffrey Pine
- **Forest practices examined**: Woody debris treatments
- **Analysis methods**: Comparative measurements of various debris characteristics and dynamics between burned and unburned streams.

Summary Report: Beyers (2004)

Beyers, J.L. 2004. Postfire seeding for erosion control: effectiveness and impacts on native plant communities. Conservation Biology 18: 947-956.

This article reviewed studies in the Western U.S. that examined the potential effectiveness of using post-fire seeding for controlling soil erosion. As of the 2004 publication date, few data existed on the effectiveness of erosion control. Of the existing literature reviewed in this article, less than half provided evidence of reduced sediment movement with post-fire seeding. When establishment and growth of seeded grasses was enough to reduce erosion, native or naturalized species (including shrub and tree seedlings) were generally displaced. Due to the competitiveness of seeded grasses, seeding can be used to attempt the suppression of noxious weeds in some post-fire operations. In recent years, native species and sterile cereal grains have increasingly been used for seeding. Use of aerially applied straw mulch has also increased, but such treatments have increased the risk of weed introduction from contaminated bales. The author concludes that more research is needed to document both the potential effectiveness and the potential ecosystem impacts from such erosion mitigation measures.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Beyers, Jan
- **Publication date**: 2004
- **Topics addressed**: post-fire seeding, erosion control, annual ryegrass, burned area rehabilitation, cereal grains, grasses, mulch
- **Location**: Western U.S.
- **Forest Types**: (unspecified; general review only)
- **Forest practices examined**: Article reviewed some common post-fire erosion control measures (i.e., seeding, mulching), but did not mention riparian areas *per se*.
- **Analysis methods**: Literature review

Summary Report: Bisson et al. (2003)

Bisson, P.A.; Rieman, B.E.; Luce, C.; Hessburg, P.F.; Lee, D.C.; Kershner, J.L.; Reeves, G.H.; Gresswell, R.E. 2003. Fire and aquatic systems of the western USA: Current knowledge and key questions. Forest Ecology and Management 178: 213-229.

This study reviews the literature on fire and aquatic ecosystems in the western United States and discusses limitations of current knowledge and identifies important research questions. Integrating fire and fuels management with aquatic ecosystem conservation begins with recognizing that terrestrial and aquatic ecosystems are linked and dynamic, and that fire can play a critical role in maintaining aquatic ecological diversity. To protect aquatic ecosystems, the authors argue that it will be important to: 1) accommodate fire-related and other ecological processes that maintain aquatic habitats and biodiversity, and not simply control fires or fuels; 2) prioritize projects according to risks and opportunities for fire control and the protection of aquatic ecosystems; and 3) develop new consistency in the management and regulatory process. Ultimately, all natural resource management is uncertain; the role of science is to apply experimental design and hypothesis testing to management applications that affect fire and aquatic ecosystems. Policy-makers and the public will benefit from an expanded appreciation of fire ecology that enables them to implement watershed management projects as experiments with hypothesized outcomes, adequate controls, and replication.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Bisson, Peter A.; Rieman, Bruce E.; Luce, Charlie; Hessburg, Paul F.; Lee, Danny C.; Kershner, Jeffrey L.; Reeves, Gordon H.; Gresswell, Robert E.
- **Publication date**: 2003
- **Topics addressed**: Wildfire; fire and fuels management; conservation; restoration; aquatic and riparian ecosystems
- **Location**: Western U.S.
- **Forest Types**: (multiple, unspecified)
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about fire and fuels management in riparian ecosystems
- **Analysis methods**: Literature review.

Summary Report: Bixby et al. (2015)

Bixby, R.J.; S.D. Cooper; R.E. Gresswell; L.E. Brown; C.N. Dahm; K.A. Dwire. 2015. Fire effects on aquatic ecosystems: an assessment of the current state of the science. Freshwater Science 34: 1340-1350.

This study provides a synthesis of papers in a special series that examines the effects of wildfire on freshwater ecosystems. The results presented in this paper expand knowledge of fire effects in different biomes, water bodies, and geographic regions, encompassing aquatic population, community, and ecosystem responses. In this overview, the authors summarize each paper and emphasize its contributions to knowledge about fire ecology and freshwater ecosystems. This overview concludes with a list of 7 research foci that are needed to further our knowledge of fire effects on aquatic ecosystems, including research on: 1) additional biomes and geographic regions, 2) additional habitats, including wetlands and lacustrine ecosystems, 3) different fire severities, sizes, and spatial configurations, and 4) additional response variables (e.g. ecosystem processes) 5) over long (>5 y) time scales 6) with more rigorous study designs and data analyses, and 7) consideration of the effects of fire management practices and policies on aquatic ecosystems. In addition, the authors identified several fire management practices that merit special concern when managing riparian ecosystems, such as use of fire retardant, construction of debris dams in streams, and pre- and post-fire vegetation removal (e.g., prescribed fire; tree thinning; salvaging). That authors also state that, although many streams might recover quickly after prescribed burning, more research is needed to help inform managers about such issues as ecologically appropriate fire severities and spatial extents of prescribed burning.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Bixby, Rebecca J.; Cooper, Scott D.; Gresswell, Robert.E.; Brown, LeeE.; Dahm, Clifford.N.; Dwire, Kathleen A.
- **Publication date**: 2015
- **Topics addressed**: wildfire, aquatic ecosystems, streams, rivers, wetlands, ecosystem, biota, prescribed burns
- **Location**: (global)
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study did not examine forest practices *per se* but provided potentially useful overview of state of science and research needs regarding fire's effects on in aquatic ecosystems; the authors also highlighted some management issues that should be addressed by future research, such as evaluating the effects of fire management policies and practices on aquatic ecosystems (e.g., prescribed burning).
- **Analysis methods**: Literature review (current state of science).

Summary Report: Bladon et al. (2008)

Bladon, K.D.; Silins, U.; Wagner, M.J.; Stone, M.; Emelko, M.B.; Mendoza, C.A.; Devito, K.J.; Boon, S. 2008. Wildfire impacts on nitrogen export and production from headwater streams in southern Alberta's Rocky Mountains. Canadian Journal of Forest Research. 38: 2359–2371.

This study examined the initial effects and recovery of concentrations and production (yield and total export) of several nitrogen (N) forms following wildfire in the Crowsnest and Castle River drainages, southwestern Alberta. During the first post-fire year, nitrate (NO3-), dissolved organic nitrogen (DON), and total nitrogen (TN) concentrations in severely burned watershed streams were 6.5, 4.1, and 5.3 times greater, respectively, than in reference streams. Weaker effects were evident for concentrations of ammonium (NH4+; 1.5 times) and total particulate nitrogen (TPN: 3 times). A rapid decline in mean watershed concentrations and production of NO3-, DON, total dissolved nitrogen (TDN), and TN was observed from the burned watersheds over three seasons after fire. However, elevated NO3-, TDN, and TN concentrations and production were still evident during the snowmelt freshet and following precipitation events after 3 years. Effects of the burn were strongly influenced by the regional flow regime, with most elevated N concentration and production occurring during higher discharge periods (snowmelt freshet and storm flows).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Bladon, Kevin; Silins, Uldis; Wagner, Michael; Stone, Micheal; Emelko, Monica; Mendoza, Carl; Devito, Kevin; Boon, Sarah.
- **Publication date**: 2008
- **Topics addressed**: Wildfire, cumulative watershed effects, eutrophication, land disturbance, nitrogen, sediment
- **Location**: Southwestern Alberta, Canada (Crowsnest and Castle River basins)
- **Forest Types**: lodgepole pine, Engelmann spruce, subalpine fir
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about the influence of sedimentation processes on riparian ecosystems.
- **Analysis methods**: Water-quality monitoring was conducted approximately every 10 days during snowmelt freshet, every 14 days after the freshet, and every 1 to 2 months throughout winter, and during periods storm events in five watersheds (2 unburned and 3 burned) for three years following a wildfire.

Summary Report: Bladon et al. (2014)

Bladon, K.D.; Emelko, M.B.; Silins, U.; Stone, M. 2014. Wildfire and the future of water supply. Environmental Science & Technology. 48: 8936-8943.

This article reviews the potential effects of wildfire on aquatic systems and community drinking water through impacts on water quantity and quality. In many parts of the world, forests provide high quality water for domestic, agricultural, industrial, and ecological needs, with water supplies in those regions inextricably linked to forest health. Wildfires have the potential to have devastating effects on aquatic ecosystems and community drinking water supply through impacts on water quantity and quality. In recent decades, a combination of fuel accumulations, climate change, extensive droughts, and increased human presence in forests have resulted in increases in area burned and wildfire severity—a trend that is predicted to continue. Implications for many downstream water uses are increasingly concerning, particularly the provision of safe drinking water, which may require additional treatment infrastructure and increased operations and maintenance costs in communities downstream of impacted landscapes. The authors state that a better understanding of the effects of wildfire on water is needed to develop effective adaptation and mitigation strategies to protect globally critical water supplies originating in forested environments.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Bladon, Kevin D.; Emelko, Monica B.; Silins, Uldis; Stone, Micheal.
- **Publication date**: 2014
- **Topics addressed**: wildfire, water quality, water supply, riparian management, riparian restoration
- **Location**: Western U.S.
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information (i.e., predictions about future wildfire effects on riparian ecosystems).
- **Analysis methods**: Overview article.

Summary Report: Cahall and Hayes (2009)

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.

This study analyzed temporal changes in forest bird communities after fire in unsalvaged stands versus stands subjected to one of two intensities of salvage logging in mixed-conifer forests in central Oregon. Two salvage treatments were used after the 2003 high-severity Davis Mountain fire burned 8511 ha. of dry ponderosa pine/Douglas-fir forest on the Deschutes National Forest. The moderate salvage prescription retained an average of 30 snags per ha, whereas the heavy prescription retained 5–6 snags per ha. No significant differences were found among treatments in densities or relative abundances for eight species and one genus of birds. Conversely, the sampling resulted in significant differences for seven species, though the patterns differed among species. Relative abundances or densities of the black-backed woodpecker (*Picoides arcticus*), hairy woodpecker (*P. villosus*), brown creeper (*Certhia americana*), western wood pewee (*Contopus sordidulus*) and yellow rumped warbler (*Dendroica coronata*) were lower in the heavy and moderate salvage treatment compared to the unsalvaged treatment, while densities of the dark eyed junco (*Junco hyemalis*) and fox sparrow (*Passerella iliaca*) were greater in the moderately and heavily salvaged stands than in the unsalvaged treatment. The findings suggest that both cavity-nesting and cup-nesting species respond to salvage logging, and that some species respond uniquely to habitat features influenced by salvage logging. For species that responded negatively to salvage logging, the moderate salvage intensity did not appear to mitigate the negative influence of salvage logging. Areas of unlogged burned forest appear to provide important habitat for some species of birds following forest fires. The study's findings parallel those of other recent studies of these species, suggesting robust patterns that transcend particular locations.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Cahall, Rebecca E.; Hayes, John P.
- **Publication date**: 2009
- **Topics addressed**: Birds, wildfire, salvage logging, ponderosa pine, Douglas-fir
- **Location**: Oregon (Deschutes National Forest)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir
- **Forest practices examined**: Salvage logging: 1) moderate prescription (30 snags retained per ha), 2) heavy prescription (5–6 snags retained per ha).
- **Analysis methods**: Study compares density and relative abundance of forest birds in 4 unlogged stands to 4 stands subjected to varying intensities of salvage logging (described above).

Summary Report: Campbell et al. (2016)

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.

This study examined fuel dynamics 10 years after post-fire salvage logging in southwestern Oregon (Biscuit Fire)—as a re-sampling of Donato et al.'s (2013) original plots (see also Donato et al. 2013 summary report). For surface woody fuels, which started from large treatment differences immediately following logging, the researchers found converging trends among treatments at 10 years, with convergence nearly complete for fine fuels but not for coarse fuels. Fire-killed snags for the dominant species (*Pseudotsuga menziesii*) decayed while standing at a statistically significant rate similar to or only slightly slower than down wood, suggesting that not all snag biomass will reach the forest floor. At year 10, live vegetation (largely resprouting sclerophyllous vegetation) began to dominate surface fuel mass and continuity (>100% cover) and moderated differences associated with woody fuels. Post-fire logging had little effect on live fuels or their changes over time, suggesting that the sampled early-seral communities had high potential for stand replacing fire regardless of post-fire harvest treatments. That is, once regenerating shrubs and trees approach 100% surface cover, burning under moderate to extreme weather conditions will likely result in near complete aboveground mortality of any vegetation in this canopy stratum, which for at least decades includes all regenerating conifers. The authors conclude by stating that landscape-scale studies would help supplement the information derived from plot-scale studies, so that managers can become better informed about the potential efficacy of post-fire fuel treatments in promoting desired fire behavior and forest resilience.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Campbell, John L; Donato, Daniel C.; Fontaine, Joseph B.
- **Publication date**: 2016
- **Topics addressed**: Biomass, Biscuit Fire, coarse woody debris, dead wood, decay, decomposition, fuel succession, Klamath–Siskiyou, salvage logging, snag, wildfire.
- **Location**: Oregon (Rogue River–Siskiyou National Forest; Biscuit Fire)
- **Forest Types**: Pacific Douglas-fir/mixed conifer
- **Forest practices examined**: Study analyzed fuel dynamics during post-fire year 10 in plots that had been salvaged logged with moderate- to high intensity prescriptions (as originally described in Donato et al. 2013).
- **Analysis methods**: During post-fire year 10, the researchers re-sampled a network of plots with varying logging intensities and compared results to untreated controls and to post-fire year 2 data (see Donato et al. 2013 summary report).

Summary Report: Clark et al. (2013)

Clark, D.A.; Anthony, R.G.; Andrews, L.S. 2013. Relationship between wildfire, salvage logging, and occupancy of territories by northern spotted owl. Journal of Wildlife Management 4: 672-688.

This study investigated the short-term impacts of wildfire and salvage logging on spotted owl occupancy of three large-scale burned areas in southwest Oregon (i.e., Biscuit, Quartz, and Timbered Rock fires). The researchers found that the unburned South Cascades control site had greater colonization probabilities than the paired Timbered Rock site before and after wildfire, and colonization probabilities declined over time at both areas. Extinction probabilities were greater at South Cascades than at Timbered Rock prior to the burn, but Timbered Rock had greater extinction probabilities following wildfire. The Timbered Rock and South Cascades study areas had similar patterns in site occupancy prior to the Timbered Rock burn (1992–2006). Timbered Rock also had a 64 percent reduction in site occupancy following wildfire (2002–2006) in contrast to a 25 percent reduction in site occupancy at South Cascades during the same period. This suggested that the combined effects of habitat disturbances due to wildfire and subsequent salvage logging on private lands negatively affected site occupancy by spotted owls. In a second analysis, the researchers investigated the relationship between wildfire, salvage logging, and occupancy of spotted owl territories at the Biscuit, Quartz, and Timbered Rock burns from 2003 to 2006. Extinction probabilities increased as the combined area of early seral forests, high severity burn, and salvage logging increased within the core nesting areas. The study was unable to identify any relationships between initial occupancy and colonization probabilities and associated habitat covariates. The authors concluded that site occupancy of spotted owl nesting territories declined in the short-term following wildfire, and habitat modification and loss due to past timber harvest, high severity fire, and salvage logging jointly contributed to declines in site occupancy.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Clark, Darren A.; Anthony, Robert G.; Andrews, Lawrence S.
- **Publication date**: 2013
- **Topics addressed**: Colonization, extinction, northern spotted owl, occupancy, salvage logging, site occupancy, southwest Oregon, wildfire.
- **Location**: Southwestern Oregon (Biscuit, Quartz, Timbered Rock burns)
- **Forest Types**: Interior ponderosa pine, Douglas-fir, white fir
- **Forest practices examined**: Study described post-fire salvage logging in general terms only (i.e., residual seral stages instead of detailed sylvicultural prescriptions).
- **Analysis methods**: Modeling of spotted owl territories (site occupancy) in relation to wildfire and salvage logging in the Biscuit, Quartz, and Timbered Rock burns from 2003 to 2006, compared to an undisturbed reference area in the south Cascade Mountains.

Summary Report: Dodson and Root (2013)

Dodson, E.K.; Root, H.T. 2013. Conifer regeneration following stand-replacing wildfire varies along an elevation gradient in a ponderosa pine forest, Oregon, USA. Forest Ecology and Management 302:163-170.

This study sampled conifer regeneration 10 years after the severe 2002 Eyerly fire in dry conifer types across a 700 m elevation gradient in the Metolius River watershed (Deschutes National Forest, Oregon). Conifer regeneration varied widely across the elevation gradient, with little tree regeneration at warm and dry low elevation sites. Logistic regression models predicted rapid increases in regeneration across the elevation gradient for seedlings of all conifer species and for ponderosa pine seedlings individually. This pattern was especially pronounced for well-established seedlings (>38 cm in height). Graminoids dominated lower elevation sites following wildfire, which may have added to moisture stress for seedlings due to competition for water. These results suggest moisture stress can be a critical factor limiting conifer regeneration following stand replacing wildfire in dry conifer forests, with predicted increases in temperature and drought in the coming century likely to increase the importance of moisture stress. The results also showed that relatively mesic upper-elevation sites had significantly more seedlings (especially well-established ones) than lower elevation sites. They found that upper elevation mesic sites had considerably more seedlings than low- to mid-elevation sites and that mesic sites may regenerate adequately without management intervention. Conversely, strongly moisture-limited forested sites may fail to regenerate for extended periods after stand-replacing disturbance, suggesting that such sites are high priorities for management intervention where maintaining forests is a priority.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Dodson, Erich K.; Root, Heather T.
- **Publication date**: 2013
- **Topics addressed**: Wildfire, ponderosa pine, eastern Cascade Mountains, Oregon, resilience, environmental gradient, climate change-type drought, seedling establishment, natural regeneration
- **Location**: Oregon (Deschutes National Forest)
- **Forest Types**: Interior ponderosa pine, grand fir, Interior Douglas-fir
- **Forest practices examined**: Study did not examine forest practices *per se* but provided potentially useful background information about tree regeneration recovery potential in severely burned dry forest types.
- **Analysis methods**: Sampling of tree regeneration in 18 plots across an elevational gradient in a 10-year old stand replacement fire location; logistic regression models were used to predict future trends for natural regeneration with changing climatic conditions.

Summary Report: Donato et al. (2006)

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

This somewhat controversial study examined conifer regeneration and fuel loads with and without salvage logging 2 to 3 years after the 2002 Biscuit Fire in southwestern Oregon. Natural conifer regeneration on sites that experienced high severity fire was variable but generally abundant, with a median stocking density of 767 seedlings per hectare, primarily of Douglas fir (*Pseudotsuga menziesii var. menziesii*). The authors stated that such density exceeded the regional standards for fully stocked sites, suggesting that active reforestation efforts may be unnecessary. Post-fire logging subsequently reduced regeneration by 71% to 224 seedlings per hectare due to soil disturbance and physical burial by woody material during logging operations. The researchers stated that, if post-fire logging is conducted in part to facilitate reforestation, replanting could result in no net gain in early conifer establishment. The results also suggested that post-fire logging significantly increased both fine- and coarse downed woody fuels, which were composed of unmerchantable material (e.g., slash), and far exceeded expectations for fuel loads generated by post-fire logging. In terms of short-term fire risk, a re-burn in logged stands would likely exhibit elevated rates of fire spread, fireline intensity, and soil heating impacts. The authors therefore concluded that post-fire salvage logging can be detrimental in terms of both forest regeneration and fuel reduction. (*Note*: See Synthesis Report for details about the controversy that stemmed from this study).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Donato, D.C.; Fontaine, J.B.; Campbell, J.L.; Robinson, W.D.; Kauffman, J.B.; Law, B.E.
- **Publication date**: 2006
- **Topics addressed**: Wildfire, post-fire salvage logging, conifer regeneration, wildfire risk, Douglas fir (*Pseudotsuga menziesii var. menziesii*).
- **Location**: Oregon (Rogue River–Siskiyou National Forest; Biscuit Fire)
- **Forest Types**: Pacific Douglas-fir
- **Forest practices examined**: Study examined fuel loads in the aftermath of salvage logging, and its effects on natural forest regeneration.
- **Analysis methods**: Study used a spatially nested design of logged and unlogged plots replicated across the fire area and sampled before (2004) and after (2005) logging.

Summary Report: Donato et al. (2013)

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 Wildland Fire 22:652–666.

This study examined fuel mass and forest structure 3-4 years following post-fire salvage logging in southwestern Oregon (Biscuit Fire), and compared results among different logging intensities and climatic settings. Stand-replacement fire consumed nearly 20% of above-ground biomass. Post-fire logging significantly reduced the standing dead biomass, with high-intensity treatment leaving a greater proportion (28%) of felled biomass on site compared to moderate-intensity treatment (14%) because of less selective tree felling. A significant relationship between logging intensity and resulting surface fuels indicated a broadly applicable predictive tool for management (as discussed below). Down wood cover increased by 3–5 times and became more spatially homogeneous after logging. Post-fire logging altered the fuel profile of early-seral stands (standing material removed or transferred, short-term increase in surface fuels, likely reduction in future large fuel accumulation). Moderate-intensity and unlogged treatments yielded surface fuel loads consistent with commonly prescribed levels, whereas high-intensity treatments resulted in greater potential need for follow-up fuel treatments. The authors state that the different harvest treatments produced wide ranging effects on both fuel profiles and stand structures, and the findings can be useful for development of fire management- and sylvicultural prescriptions. For example, the documented relationships between basal area cut and surface fuel accumulation by forest type can serve as a predictive tool for anticipating the ranges of surface fuel loads among different harvest intensities. In addition, the authors state that moderate-intensity treatments result in surface fuel loads that are the most consistent with prescribed levels when compared to high-intensity treatments, thus potentially reducing the need for follow-up fuel treatments such as slash piling and broadcast burning. Moderate-intensity treatments also tend to leave a greater proportion of snags, which can be highly compatible with wildlife habitat objectives.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Donato, Daniel C.; Fontaine, Joseph B.; Kauffman, J. Boone; Robinson, W. Douglas; Law, Beverly E.
- **Publication date**: 2013
- **Topics addressed**: Biomass, Biscuit Fire, coarse woody debris, dead wood, fuel succession, Klamath–Siskiyou,legacy, logging intensity, post-fire management, salvage logging, snag
- **Location**: Oregon (Rogue River–Siskiyou National Forest; Biscuit Fire)
- **Forest Types**: Pacific Douglas-fir/mixed conifer
- **Forest practices examined**: Study analyzed fuel dynamics following moderate- to high intensity post-fire salvage logging (as described below).
- **Analysis methods**: Study sampled multiple 1-ha plots that were burned and salvage logged 2 years post-fire; salvage logging treatments included unlogged (controls), moderate intensity (25-75% basal area cut), and high intensity (>75% basal area cut); fuels were measured 3-4 years post-fire.

Summary Report: Dunham et al. (2007)

Dunham, J.B.; Rosenberger, A.E.; Luce, C.H.; Rieman, B.E. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. Ecosystems 10:335–346.

This study examines spatial and temporal changes in stream temperature in headwater streams in relation to wildfire and channel disturbance history in central Idaho, then relates these to changes in habitat for two sensitive species, rainbow trout and tailed frog larvae. Results from these three studies indicated that summer maximum water temperatures can remain significantly elevated for at least a decade following wildfire, particularly in streams with severe channel reorganization. In the retrospective comparative study, the authors investigated occurrence of native rainbow trout (*Oncorhynchus mykiss*) and tailed frog larvae (*Ascaphus montanus*) in relation to maximum summer stream temperatures. Both species occurred in nearly every site sampled, but tailed frog larvae was found in much warmer water than previously reported in the field (26.6 C maximum summer temperature). Results show that physical stream habitats can remain altered (for example, increased temperature) for many years following wildfire, but that native aquatic vertebrates can be resilient. In a management context, this suggests wildfire may be less of a threat to native species than human influences that alter the capacity of stream-living vertebrates to persist in the face of natural disturbance.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Dunham, Jason B.; Rosenberger, Amanda E.; Luce, Charlie H.; Rieman, Bruce E.
- **Publication date**: 2007
- **Topics addressed**: stream temperature; stream heating; solar radiation; stream shading; wildfire; debris flows; disturbance; rainbow trout, tailed frog.
- **Location**: Idaho (Boise National Forest)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, lodgepole pine, subalpine fir-Englemann spruce
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about stream ecology and fish/amphibian habitat in an era of increasing wildfires.
- **Analysis methods**: Plot sampling based on short-term (3 yr.) and long-term (13 yr.) observations of pre–post fire temperatures on multiple sites.

Summary Report: Dunn and Bailey (2015a)

Dunn, C.J.; Bailey, J.D. 2015a. 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.

This study examined snag dynamics, decomposition rates, and fuel loadings within high-severity portions of 7 fires, spanning a 24-year chronosequence, in dry mixed conifer forests of Oregon's eastern Cascades. Total surface fine woody fuel loadings peaked 17–18 years post-fire (7–10 Mg/ha) in unmanipulated (control) stands; thereafter decay losses exceeded input rates and loadings decreased. Salvage logging immediately increased surface fine woody fuel loadings by 160–237% above maximum loadings observed in unmanipulated stands, and were higher during the initial 18–22 years post-fire. The 1000-h fuel loadings peaked 24–31 years post-fire in unmanipulated stands, but decomposition reduced total loadings by 35–50% of initial snag necromass by peak years. Available 1000-h fuel loadings in unmanipulated stands peaked 31, 34 and 82 years post-fire but were only 35% (41 Mg/ha), 31% (50 Mg/ha) and 27% (71 Mg/ha) of initial snag necromass. Salvage logging increased 1000-h fuel loadings for the initial 7 years post-fire, but 80–84% of initial snag necromass was removed or decayed when their maximum loadings were observed 17–22 years post-fire. Understory woody vegetation re-established quickly following high severity fire, creating another significant fuel layer and a source of post-fire fine woody fuels. Surface fuels accumulate quickly following high-severity fire, but modeling suggested that salvage logging has mixed effects on reducing hazardous fuel conditions since it increases fine woody fuel loadings and decreases coarse woody fuel loadings. Reducing hazardous fuel loadings and their contribution to re-burn hazard requires manipulation of residual and future fuel sources. However, treatment benefits should be evaluated against any negative effects to early seral forest structure and function if resilient forest ecosystems are the management goal.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Dunn, Christopher J.; Bailey, John D.
- **Publication date**: 2015
- **Topics addressed**: Fuel succession; re-burn; salvage logging; hazardous fuels; snag dynamics; decomposition
- **Location**: Oregon (Deschutes and Fremont-Winema National Forests; Crater Lake National Park)
- **Forest Types**: Interior ponderosa pine, grand fir, Interior Douglas-fir, lodgepole pine
- **Forest practices examined**: Salvaging details (actual and simulated): On average, 69-93% of snags >30 cm DBH were harvested in a commercial- and fuels reduction salvage prescription, respectively. Salvaged snags were only 40-60% of all snags present because small DBH snags were not merchantable. Those conditions were simulated by assuming that 80% of snags >23 cm DB were salvaged and 50% of snags <23 cm were immediately knocked over one year post-fire. Individual snags were randomly selected for harvest and 10–20% of harvested necromass was left on-site as cull wood.
- **Analysis methods**: This study uses a 24-year chronsequence of 7 fires as the foundation for a simulation model that describes fine- and coarse woody fuel dynamics.

Summary Report: Dunn and Bailey (2015b)

Dunn, C.J.; Bailey, J.D. 2015b. Temporal fuel dynamics following high-severity fire in dry mixed conifer forests of the eastern Cascades, Oregon USA. International Journal of Wildland Fire 24:470-483.

This study examined temporal changes in fuels following wildfire in the eastern Cascades of Oregon. Duff and litter accumulated as bark sloughed from snags and leaves senesced from recovering vegetation, averaging 14.6 Mg/ha and 22.1 Mg/ha at the 24-year post-fire site, respectively. In addition, 1-h fuels increased linearly, averaging 1.1 Mg/ha at our 24-year post-fire site, with additions occurring from recovering vegetation. The 10-h and 100-h fuels exhibited non-linear temporal trends, with maximum loadings occurring 14 years (3.9 Mg/ha) and 18 years (10.5 Mg/ha) post-fire, respectively. The 1000-h fuel accumulation slowed after 20 years post-fire (reaching 124.6 Mg/ha), concurrently with 90% snag fall and fragmentation. Maximum herbaceous fuel loading averaged 0.73 Mg/ha at the 5-year post-fire sites, but only averaged 0.02 Mg/ha at all sites thereafter. Live shrub biomass accumulation slowed after 21 years post-fire, averaging 14.3 Mg/ha at the 24-year post-fire site. Shrub layers can persist for decades but gradually collapse as trees outcompete shrubs. Eventually live vegetation will control fuel inputs as snag abundance decreases and the initial available necromass decays. The authors state that more research is needed on temporal fuel dynamics, and that managers can use such information to facilitate restoration of fire regimes while mitigating undesirable fire effects.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Dunn, Christopher J.; Bailey, John D.
- **Publication date**: 2015
- **Topics addressed**: Fuel dynamics; wildfire; hazardous fuels; decomposition
- **Location**: Oregon (Deschutes and Fremont-Winema National Forests; Crater Lake National Park)
- **Forest Types**: Interior ponderosa pine, grand fir, Interior Douglas-fir
- **Forest practices examined**: Study did not examine forest practices, but provides potentially useful information about post-fire fuel dynamics that can help inform management of dry-site riparian and upland forests.
- **Analysis methods**: This study uses plot sampling and a 24-year chronsequence of 7 fires to document post-fire fuel dynamics for fine- to coarse woody fuel profiles.

Summary Report: Dwire and Kauffman (2003)

Dwire, K.A.; Kauffman, J.B. 2003. Fire and riparian ecosystems in landscapes of the western USA. Forest Ecology and Management 178: 61-74.

The objectives of this paper are to synthesize the limited research conducted on fire regimes in riparian areas relative to uplands, summarize the distinctive features of riparian zones that influence the properties of fire, discuss the impacts of land use as they may affect fire behavior in riparian areas, and describe the adaptations of riparian plant species to fire. Riparian areas frequently differ from adjacent uplands in vegetative composition and structure, geomorphology, hydrology, microclimate, and fuel characteristics. These features contribute to different fire environments, fire regimes, and fire properties (frequency, severity, behavior, and extent) in riparian areas relative to uplands. In certain forested riparian areas, fire frequency has generally been lower, and fire severity has been more moderate than in adjacent uplands, but in other areas, fires burned riparian areas with comparable frequency. Impacts of land use and management may strongly influence fire properties and regimes in riparian areas. Fire suppression, livestock grazing, logging, damming and flow regulation, agricultural diversions, channel modifications, and introduction of invasive species have led to shifts in plant species composition, structure and distribution of fuel loads, and changes in microclimate and areal extent of riparian areas. Cumulative impacts of human alterations are likely to exert the most pronounced influence on fire behavior during periods of drought and under conditions of extreme fire weather. Riparian plant species possess adaptations to fluvial disturbances that facilitate survival and reestablishment following fires, thus contributing to the rapid recovery of many streamside habitats. Given the critical resource values of riparian zones, additional data are needed to understand interactions between fire and riparian ecosystems, and how riparian zones affect spatial and temporal patterns of fires at the landscape scale. An improved understanding of fire ecology and effects in riparian areas is needed to prescribe ecologically sound rehabilitation projects following fire.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Dwire, Kathleen A.; Kauffman, J. Boone
- **Publication date**: 2003
- **Topics addressed**: Riparian areas; Western USA; Fire behavior; Fire severity; Riparian fire regimes; Land use; Riparian-aquatic habitat; Post-fire recovery
- **Location**: Western U.S.
- **Forest Types**: (multiple, coniferous)
- **Forest practices examined**: Study did not examine forest practices *per se* but provided potentially useful background information about the effects of fire and human-caused disturbances on riparian ecosystems.
- **Analysis methods**: Literature review.

Summary Report: Eaton et al. (2010)

Eaton, B.C.; Moore, R.D.; Giles, T.R. 2010. Forest fire, bank strength and channel instability: the "unusual" response of Fishtrap Creek, British Columbia. Earth Surface Processes and Landforms 35: 1167-1183.

The main objective of this study in the southern interior of British Columbia was to explore the linkages between changes in streamflow, suspended sediment concentrations and changes in channel morphology after a recent wildfire. Although the short post-fire period (4 years) limited the researchers' ability to draw firm conclusions about streamflow changes, there has been no obvious increase in peak flows since the fire. However, the total runoff during the freshet period may have increased and the onset of snowmelt appeared to occur about 2 weeks earlier than it did prior to the fire. Suspended sediment records from Fishtrap Creek and from an unburnt reference stream nearby were similar, suggesting that the burnt areas had remained relatively stable and that the sediment supply to Fishtrap Creek had not been dramatically altered. In contrast, the stream channel morphology had changed, widening by over 100 percent of the original width in some places and transforming from a laterally stable plane-bed morphology to a laterally active riffle-pool morphology. The timing and magnitude of the observed morphologic changes were consistent with the predicted decline in bank strength due to root decay, implying that the observed changes were associated with an internal instability associated with changes to the stream boundaries—rather than with the more typically reported externally driven instabilities caused by changes in streamflow or sediment supply. This delayed response in the absence of large changes in streamflow or sediment supply, while unusual in that it had not been documented in previous literature, may be a common mode of response, particularly in watersheds with nival (i.e., heavily snow-driven) flow regimes.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Eaton, B.C.; Moore, R.D.; Giles, T.R.
- **Publication date**: 2010
- **Topics addressed**: Forest fire; bank erosion; gravel bed steam; suspended sediment
- **Location**: South-central interior British Columbia, Canada
- **Forest Types**: Interior Douglas-fir, interior ponderosa pine, lodgepole pine
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about post-fire erosion/sedimentation processes in riparian ecosystems.
- **Analysis methods**: This study compared stream flow, the magnitude and timing of channel change, and suspended sediment amounts between a recently burned stream basin and an unburned reference basin.

Summary Report: Emelko et al (2011)

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.

This study assessed the implications of wildfire and post-fire intervention (i.e., salvage-logging) on downstream drinking water treatment in the Crowsnest and Castle River drainages, southwestern Alberta. The 95th percentile turbidity measurements (Nephelometric Turbidity Units [NTU]) and dissolved organic carbon (DOC) measurements remained low in streams draining unburned watersheds (5.1 NTU, 3.8 mg/L), even during periods of potential treatment challenges such as stormflows and spring freshets. In contrast, levels were elevated in streams draining burned (15.3 NTU, 4.6 mg/L) and salvage-logged (18.8 NTU, 9.9 mg/L) watersheds. Persistent increases in these parameters and observed increases in other contaminants, such as nutrients, heavy metals, and chlorophyll-a, in discharge from burned and salvage-logged watersheds present important economic and operational challenges for water treatment—most notably, a potential increase in dependence on solids and DOC removal processes. Many traditional source water protection strategies would fail to adequately identify and evaluate many of the significant wildfire- and post-fire management-associated implications to drinking water "treatability." The authors proposed that source water supply and protection strategies should be developed to consider suppliers' ability to provide adequate quantities of potable water to meet demand by addressing all aspects of drinking water supply (i.e., quantity, timing of availability, and quality) and their relationship to treatability in response to land disturbance.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Emelko, Monica B.; Silins, Uldis; Bladon, Kevin D.; Stone, Micheal.
- **Publication date**: 2011
- **Topics addressed**: Wildfire, salvage logging, cumulative watershed effects, eutrophication, sediment, water quality, water treatability
- **Location**: Southwestern Alberta, Canada (Crowsnest and Castle River basins)
- **Forest Types**: lodgepole pine, Engelmann spruce, subalpine fir
- **Forest practices examined**: Study examined the effects of wildfire with and without salvage logging in headwater basins on downstream water quality, and resultant water treatment issues.
- **Analysis methods**: Four years' worth of comprehensive hydrology and water quality data were obtained by sampling both burned and salvage logged areas in seven watersheds.

Summary Report: Emelko et al. (2015)

Emelko, M.B.; Stone, M.; Silins, U.; Allin, D.; Collins, A.L.; Williams, C.H.S.; Martens, A.M.; Bladon, K.D. 2015. Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. Global Change Biology. 22: 1168-1184.

This study examined sediment and phosphorus behavior in two river basin 6 and 7 years following a severe wildfire (Crowsnest and Castle River drainages, southwestern Alberta). Concentrations of total particulate phosphorus (TPP) and the equilibrium phosphorus concentration (EPC0) were significantly higher downstream of wildfire-impacted areas compared to reference (unburned) upstream river reaches. Sediments from the burned tributary inputs contained higher levels of bioavailable particulate P (NAIP) – these effects were also observed downstream at larger river basin scales. The release of bioavailable P from postfire, P-enriched fine sediment is a key mechanism causing these effects in gravel-bed rivers at larger basin scales. Wildfire-associated increases in NAIP and the EPC0 persisted 6 and 7 years after wildfire. The authors state that the study demonstrated that fine sediment in gravel-bed rivers is a significant, long-term source of in-stream bioavailable P that contributes to a legacy of wildfire impacts on downstream water quality, aquatic ecology, and drinking water treatability.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Emelko, Monica; Stone, Micheal; Silins, Uldis; Allin, Don; Collins, Adrian; Williams, Chris; Martens, Amanda; Bladon, Kevin
- **Publication date**: 2015
- **Topics addressed**: Wildfire, cumulative watershed effects, eutrophication, land disturbance, phosphorus, sediment, treatability
- **Location**: Southwestern Alberta, Canada (Crowsnest and Castle River basins)
- **Forest Types**: lodgepole pine, Engelmann spruce, subalpine fir
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about the influence of sedimentation processes on riparian ecosystems.
- **Analysis methods**: Suspended sediment samples were collected from upstream reference (unburned) river reaches, multiple tributaries within the burned areas, and from reaches downstream of the burned areas; Total particulate phosphorus (TPP) and particulate phosphorus forms (nonapatite inorganic P, apatite P, organic P), and the equilibrium phosphorus concentration (EPC0) of suspended sediment were assessed.

Summary Report: Everett et al. (1999)

Everett, R.; Lehmkuhl, J.; Schellhaas, R.; Ohlson, P.; Keenum, D.; Riesterer, H.; Spurbeck, D. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA. International Journal of Wildland Fire. 9: 223-234.

This study documented variation in post-fire snag longevity among species, size, and microtopographic conditions following 26 high-severity wildfires in the eastern Cascades, Washington. Snag longevity and resultant snag densities varied spatially across burns in relation to micro-topographic position. Longevity of snags < 41 cm dbh was greater for thin-barked Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) than thick-barked Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). With larger diameter snags, however, Douglas-fir persisted longer than Engelmann spruce. The time period required for recruitment of soft snags > 23 cm dbh was estimated to exceed snag longevity for ponderosa pine, Engelmann spruce, lodgepole pine, and subalpine fir, causing an "on-site gap" in soft snags for these species. Snags of Douglas-fir ≥ 41 cm dbh stood for a sufficient time (40% standing after 80 years) to potentially overlap the recruitment of soft snags ≥ 23 cm dbh from the replacement stand. Providing continuity in soft snags following stand-replacement events would require a landscape-scale perspective, incorporating adjacent stands of different ages or disturbance histories. Results suggest that standards and guidelines for snags on public forest lands need to be sufficiently flexible to accommodate both disturbance and stand development phases and differences in snag longevity among species and topographic positions.

(**Note*: Also see Lehmkuhl et al. [2003] for a closely related study on cavity-excavated wildlife snags in the above study areas)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Everett, Richard; Lehmkuhl, John; Schellhaas, Richard; Ohlson, Pete; Keenum, David; Riesterer, Heidi; Spurbeck, Don.
- **Publication date**: 1999
- **Topics addressed**: Eastern Cascade Range, post-fire snags, snag longevity, wildlife habitat, Douglas-fir, lodgepole pine, ponderosa pine, Engelmann spruce, subalpine fir
- **Location**: Washington (Okanogan-Wenatchee National Forest; 26 wildfire sites)
- **Forest Types**: Douglas-fir, lodgepole pine, ponderosa pine, subalpine fir
- **Forest practices examined**: Study did not examine forest practices *per se* but provided useful information about post-burn snag longevity (i.e., potential wildlife habitat).
- **Analysis methods**: Snag numbers and decay class were measured on a chronosequence of 26 stand-replacing wildfires (ages 1-81 years) on the east slope of the Cascade Range in Washington.

Summary Report: Everett et al. (2003)

Everett, R.; Schellhaas, R.; Ohlson, P.; Spurbeck, D.; Keenum, D. 2003. Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests. Forest Ecology and Management 175: 31-47.

This study compares historical fire history between riparian areas and adjacent uplands. Upslope forests had more traceable disturbance events than riparian forests in each of the valley types with a mean difference of 8–62%. Approximately 55–73% of the total traceable fire disturbance for a stream segment occurred on the adjacent sideslopes and 24–27% occurred in the riparian forest. Plant association groups in the riparian forest had 25–42% fewer fire disturbance events than the same plant association group upslope. Fewer traceable disturbance events in riparian forests may indicate a reduced disturbance frequency or a more severe disturbance regime or both. The two sideslopes on either side of the riparian forest shared the same fire event in 65 and 54% of the recorded fire events on east/west and north/south sideslopes, respectively. Riparian forests shared fire events with adjacent sideslope forests 58–79% among valley types, and 64–76% among aspects. Shared fire events indicate significant continuity in fire disturbance between riparian and adjacent sideslope forests. Fire disturbance regimes of sideslope and riparian forests are quantitatively different, but interconnected through shared fire disturbance events. Disturbance events play a role in maintaining ecosystem integrity and the authors suggest that disturbance may need to be planned for in administratively defined riparian buffer strips to protect long-term ecological integrity of riparian and adjacent upslope forests.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Everett, Richard; Schellhaas, Richard; Ohlson, Pete; Spurbeck, Don; Keenum, David.
- **Publication date**: 2003
- **Topics addressed**: Historical fire regimes, wildfire, riparian forest, upland forest, ponderosa pine, Douglas-fir
- **Location**: Washington (Okanogan-Wenatchee National Forest)
- **Forest Types**: Interior ponderosa pine; Interior Douglas-fir
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about fire regimes in riparian versus upland ecosystems
- **Analysis methods**: Fire scars and cohort establishment dates were gathered from riparian stands and adjacent sideslopes in 49 stream segments on 24 separate streams on the east slope of the Washington Cascade Range.

Summary Report: Gomi et al. (2005)

Gomi, T.; Moore, D.; Hassan, M.A. 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest. Journal of the American Water Resources Association 41:877–898.

This study reviewed literature related to sources of suspended sediment and sediment transport in the Pacific Northwest in relation to riparian management. Mass movements, roading and yarding practices, and burning can increase the supply of suspended sediment to streams. Sediment yields recovered within one to six years in several paired catchment studies. However, delayed mass movements related to roads and harvesting may produce elevated suspended sediment yield one or more decades after logging. There is mixed evidence for the role of streamside tree-throw in riparian buffers in supplying sediment to streams. Harvesting within the riparian zone may not increase suspended sediment yield if near-stream soils are not disturbed. Key knowledge gaps relate to the relative role of increased transport capacity versus sediment supply, and the dynamics of fine sediment penetration into bed sediments, and the effects of forest harvesting on suspended sediment at different scales. Future research should involve nested catchments to examine suspended sediment response to forest practices at multiple spatial scales, in combination with process-based field experiments.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Gomi, T.; Moore, D.; Hassan, M.A.
- **Publication date**: 2005
- **Topics addressed**: sedimentation, timber harvest, riparian management, riparian buffer
- **Location**: Pacific Northwest
- **Forest Types**: (multiple coniferous)
- **Forest practices examined**: Article reviewed potential impacts on sedimentation caused by various logging practices, such as road construction, impacts from ground-based logging equipment, forest thinning, and riparian buffer management.
- **Analysis methods**: Literature review.

<u>Summary Report: Haggard and Gaines (2001)</u>

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.

This study monitored the response of cavity-nesting birds to three post-fire salvage treatments in dry Douglas-fir/ponderosa pine forests in the eastern Cascades, Washington. Sampling occurred in areas burned by the high severity 1994 Rat Creek fire (Leavenworth Ranger District) that were subsequently salvage logged with 3 snag-retention prescriptions. Stands with the medium snag density treatment (retention of 15-35 snags/ha) had the highest abundance, species richness, and nesting population of cavity nesters. Possible contributing factors include: 1) snags were unevenly distributed such that clumped and dispersed snag density habitats occurred in that treatment, and 2) a greater proportion of ponderosa pine snags in medium density treatments may have attracted species that prefer ponderosa pine for nesting and foraging. Ponderosa pine was preferred for nest sites, and large snags (>48 cm dbh) provided nesting habitat for more species than smaller snags. However, smaller snags were used for nesting and foraging by some species. For example, whereas Northern flickers preferred large trees (64 cm mean dbh), American kestrels nested in small trees (24 cm mean dbh). The study produced the following implications for snag management when conducting post-fire salvage logging in eastern Cascade dry forests: 1) snag densities of l5-35 snags ≥25 cm dbh per hectare provided the highest abundance, species richness, and nesting populations of cavity nesters; 2) snags >48 cm provided nesting habitat for more species; 3) an average of 21 snags >48 cm dbh per hectare yielded the highest nesting populations, supported multiple cavities, and were important for foraging; 4) smaller snags provided foraging and nesting habitat for some species; 5) the treatments with the highest bird abundances had 34 snags/ha in the 16-24 cm dbh size class, and 180 snags/ha in the <15 cm dbh size class; 6) treatments with snags distributed in clumps [as well as] individually dispersed snags had the highest abundance and species richness of cavity nesting species.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Haggard, Maryellen; Gaines, Willian L.
- **Publication date**: 2001
- **Topics addressed**: Post-fire snags, cavity nesting birds, wildfire, salvage logging, eastern Cascade Mountains
- **Location**: Washington (Wenatchee National Forest)
- **Forest Types**: Interior Douglas-fir, interior ponderosa pine
- **Forest practices examined**: Salvage logging treatments: 1) high snag retention (37-80 snags/ha); 2) medium retention (15-35 snags/ha); 3) low retention (0-12 snags/ha).
- **Analysis methods**: Snag surveys describing habitat and associated communities among three salvage treatments (described above); two plots in each treatment type during two breeding seasons 4-5 years after high-severity fire.

Summary Report: Halofsky and Hibbs (2008)

Halofsky, J.E.; Hibbs, D.E. 2008. Determinants of riparian fire severity in two Oregon fires, USA. Canadian Journal of Forest Research 38:1959-1973.

This study investigated the influence of vegetation and topography on understory and overstory wildfire severity for riparian areas and adjacent uplands. Riparian forest overstories were dominated by ponderosa pine, Engelmann spruce, grand fir and white fir hybrid, Douglas-fir, and several species of deciduous hardwoods (e.g., *Acer*, *Quercus* spp.). Understory fire severity (percent exposed mineral soil and bole char height) was significantly lower in riparian areas compared to adjacent uplands in both the Biscuit and B & B Complex fires, suggesting a decoupling in understory fire effects in riparian areas versus uplands. However, overstory fire severity (percent crown scorch and percent basal area mortality) was similar in riparian areas and adjacent uplands in both fires. Fire severity in riparian areas was most strongly associated with upland fire severity. In addition, vegetation indicators, particularly those describing riparian fine fuel component and species composition, were strong predictors of riparian fire severity. Consistency in factors controlling fire severity in the two fires suggests that controls on riparian fire severity may be similar in other regions. Although the results might be useful predictors of future fire severity in riparian zones within ponderosa pine/Douglas-fir/mixed conifer types elsewhere in the Northwest, more research would be needed to derive specific management implications for these types of riparian zones.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Halofsky, Jessica; Hibbs, David
- **Publication date**: 2008
- **Topics addressed**: fire behavior, riparian zones, mixed conifer forest, ponderosa pine, Douglas-fir, riparian management, wildfire, Biscuit Fire; B & B Complex fire
- **Location**: Oregon (Rogue River-Siskiyou National Forest; Deschutes National Forest)
- **Forest Types**: Interior ponderosa pine, Engelmann spruce, grand fir/white fir hybrid, Douglas-fir, deciduous hardwoods.
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about fire and fuels in riparian ecosystems.
- **Analysis methods**: Plot sampling in riparian areas and adjacent uplands to characterize wildfire severity covariates.

Summary Report: Halofsky and Hibbs (2009)

Halofsky, J.E.; Hibbs, D.E. 2009. Controls on early post-fire woody plant colonization in riparian areas. Forest Ecology and Management 258:1350-1358.

This study in severely burned portions of the Biscuit Fire and B & B Complex Fires had several objectives, which were to: 1) examine how fire severity interacts with riparian topographic setting, micro-environmental conditions, and pre-fire community composition to control post-fire regeneration, 2) document patterns and controls of post-fire riparian tree regeneration, and (3) document the recovery of critical riparian functions following fire. Riparian forest overstories were dominated by ponderosa pine, Engelmann spruce, grand fir and white fir hybrid, Douglas-fir, and several species of deciduous hardwoods (e.g., *Acer*, *Quercus* spp.). At a relatively coarse spatial scale, patterns in post-fire colonization were influenced by elevation. At finer spatial scales, both conifer and hardwood-dominated riparian plant communities were self-replacing, suggesting that each community type tends to occur in specific ecological settings. Abundant post-fire regeneration in riparian areas and the self-replacement of hardwood- and conifer-dominated communities indicate high resilience of these disturbance-adapted plant communities.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Halofsky, Jessica; Hibbs, David
- **Publication date**: 2009
- **Topics addressed**: post-fire reproduction, riparian zones, mixed conifer forest, ponderosa pine, Douglas-fir, riparian management, wildfire, Biscuit Fire; B & B Complex fire
- **Location**: Oregon (Rogue River-Siskiyou National Forest; Deschutes National Forest)
- **Forest Types**: Interior ponderosa pine, Engelmann spruce, grand fir/white fir hybrid, Douglas-fir, deciduous hardwoods.
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about post-fire vegetation recovery in riparian ecosystems.
- **Analysis methods**: Plot sampling characterized tree regeneration and vegetation cover 2 and 4 years post-fire for multiple vegetation associations, fire severity classes, stream classes, and tree classes.

Summary Report: Ice et al. (2004)

Ice, G.G.; Neary, D.G.; Adams, P.W. 2004. Effects of wildfire on soils and watershed processes. Journal of Forestry 102: 16 20.

This paper provides an overview of wildfire's potential effects on soils and watershed processes including runoff, erosion, and nutrient transport. Severe fires can cause water repellency and consume plant canopy, surface plants and litter, and structure-enhancing organics within soil. Changes in soil moisture, structure, and infiltration can accelerate surface runoff, erosion, sediment transport, and deposition. Intense rainfall and some soil and terrain conditions can contribute to overland runoff and in-channel debris torrents. Mineralization of organic matter, interruption of root uptake, and loss of shade can further impact water quality and aquatic habitat by increasing stream temperatures and nutrient concentrations. Where wildfires are unnaturally large and severe, watershed effects are likely to be negatively skewed. In addition, Ice et al. (2004) cited a study (Helvey 1980) that found that a control watershed in the Entiat Burn had yielded more post-fire sediment than sites that had been salvage logged. Regarding salvage logging, the article cited a study (Neary and Hornbeck 1994) that concluded that carefully planned and executed salvage logging is not necessarily a negative disturbance. For example, Ice et al. (2004) state that best management practices, such as hand felling, logging over snow, and minimizing the construction of new roads, can help reduce soil disturbance and resultant sedimentation.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Ice, George G.; Neary, Daniel G.; Adams, Paul W.
- **Publication date**: 2004
- **Topics addressed**: post-fire effects on soil processes such as runoff and erosion and nutrient budgets; post-fire riparian processes such as flooding, sedimentation, forest shading, fish habitat; post-fire restoration; post-fire salvage logging.
- **Location**: Western U.S
- **Forest Types**: Non-specific coniferous/deciduous
- **Forest practices examined**: Overview provides only general information and principles about post-fire salvage logging in western ecosystems.
- **Analysis methods**: Literature review

Summary Report: Isaac et al. (2010)

Isaak, D.J.; Luce, C.H.; Rieman, B.E.; Nagel, D.E.; Peterson, E.E.; Horan, D.L.; Parkes, S.; Chandler, G.L. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications 20: 1350-1371.

This study investigates temporal changes in stream temperature related to climate change and wildfire in a 6,900 km^2 watershed in central Idaho, and compares trends in summer temperatures and thermal habitat for bull- and rainbow trout. Between 1993 and 2006, basin average mean stream temperatures increased by 0.38°C (0.27°C/decade), and maximas increased by 0.49°C (0.35°C/decade), primarily due to long-term (30–50 year) trends in air temperatures and stream flows. Radiation increases from wildfires accounted for 9% of basin-scale temperature increases, despite burning 14% of the basin. Within wildfire perimeters, stream temperature increases were 2–3 times greater than basin averages, and radiation gains accounted for 50% of warming. Thermal habitat for rainbow trout (*Oncorhynchus mykiss*) was minimally affected by temperature increases, except for small shifts towards higher elevations. Bull trout (*Salvelinus confluentus*) were estimated to have lost 11–20% (8–16%/decade) of the headwater stream lengths that were cold enough for spawning and early juvenile rearing, with the largest losses occurring in the coldest habitats. Overall results suggest that a warming climate has begun to affect thermal conditions in streams and that impacts to biota will be specific to both species and context. Where species are at risk, conservation actions should be guided based on considerations of restoration opportunity and future climatic effects.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Isaak, Daniel J.; Luce, Charles H.; Rieman, Bruce E.; Nagel, David E.; Peterson, Erin E.; Horan, Dona L.; Parkes, Sharon; Chandler, Gwynne L.
- **Publication date**: 2010
- **Topics addressed**: bull trout; climate change; global warming; rainbow trout; spatial statistical model; stream temperature; thermal habitat; wildfire.
- **Location**: Idaho (Boise National Forest)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, lodgepole pine, subalpine fir-Englemann spruce
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about stream ecology and fish habitat in an era of global warming and increasing wildfires.
- **Analysis methods**: Plot sampling and modeling based on a stream temperature database from 780 sites across central Idaho.

Summary Report: Jennings et al. (2012)

Jennings, T.N.; Smith, J.E.; Cromack, K. Jr.; Sulzman, E.W.; McKay, D.; Caldwell, B.A.; Beldin. S.I. 2012. Impact of postfire logging on soil bacteria and fungal communities and soil biogeochemistry in a mixed-conifer forest in central Oregon. Plant Soil 350: 393-41.

This study compared bacterial and fungal communities in soils compacted and decompacted (subsoiled) by mechanical equipment during post-fire salvage logging to soils with no mechanical disturbance in mixed conifer stands in central Oregon (Deschutes National Forest; 2003 B&B fire complex). Soil compaction decreased plant-available nitrogen (N) by an average of 27 percent compared to no mechanical disturbance, while subsoiling decreased plant-available phosphorus (P) by an average of 26 percent compared to the compacted and non-mechanically disturbed treatments. Neither bacterial nor fungal richness differed significantly among the treatments. However, distinct separation by year in both bacterial and fungal community composition corresponded with significant increases in available N and available P between the first and second post-harvest year. Results suggest that nutrients critical to soil productivity were reduced by mechanical disturbances during timber harvesting, yet soil bacteria and fungi, essential to mediating decomposition and nutrient cycling, appeared resilient to mechanical disturbance. The authors summarize the study by saying, “Postfire logging in a dry, mixed conifer forest with sandy loam volcanic soils appeared to have minimal effects on soil microbial richness. However, this short-term study revealed decreased plant-available N and P in the soil after postfire logging disturbances that could have long-lasting effects in a system that already is nutrient limited. A shift in bacterial communities corresponding with an increase in plant available N and P suggests that soil microbes in these postfire landscapes are resilient to mechanical disturbance. Clearly, effects of postfire timber harvesting on soil microbes, nutrients, and processes warrant longer term investigation.” (Jennings et al. 2012: 406). The researchers also opine that soil impacts from post-fire salvaging need to be weighed against other values, such as fire hazard reduction and commercial harvesting of trees.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Jennings, T.N.; Smith, J.E.; Cromack, K. Jr.; Sulzman, E.W.; McKay, D.; Caldwell, B.A.; Beldin. S.I.
- **Publication date**: 2012
- **Topics addressed**: Wildfire, post-fire logging, soil effects, soil microbes, soil chemistry, soil compaction, soil decompaction.
- **Location**: Oregon (Deschutes National Forest; 2003 B&B fire complex)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, grand fir, white fir
- **Forest practices examined**: Study analyzed soil microbial communities after soil compaction or decompaction during mechanized salvage logging.
- **Analysis methods**: Comparison of soil bacterial and fungal communities and biogeochemical responses in replicate stands subject to the three treatments including compacted (compaction from heavy ground-based equipment), subsoiled (compaction followed by subsoiling), and no mechanical disturbance.

Summary Report: Johnson et al. (2005)

Johnson, D.W.; Murphy, J.F.; Susfalk. R.B.; Caldwell, T.G.; Miller, W.W.; Walker, R.F.; Powers, R.F. The effects of wildfire, salvage logging, and post-fire N-fixation on the nutrient budgets of a Sierran forest. Forest Ecology and Management 220: 155: 165.

This study examined the effects of fire, post-fire salvage logging and revegetation on long-term nutrient budgets (C, N, P, K, S, Ca, Mg). Approximately two decades after the fire, the salvaged ecosystem contained less C and more N than the adjacent forest ecosystem. Reconstruction of pre-fire nutrient budgets suggested that most C was exported in biomass during salvage logging and will not be recovered until forest vegetation occupies the site again. Salvage logging may have resulted in longer-term C sequestration in wood products than would have occurred had the logs been left in the field to decay, however. Reconstructed budgets suggested that most N was lost via volatilization during the fire rather than in post-fire salvage logging (assuming that foliage and O horizons were combusted). Comparisons of the pre-fire and present day N budgets also suggested that the lost N was rapidly replenished in O horizons and mineral soils, probably due to N-fixation by snowbush (*Ceanothus velutinus* Dougl.), the dominant shrub on the salvaged site. There were no significant differences in ecosystem P, K, or S contents and no consistent, significant differences in soil extractable P or S between the shrub and forested plots. Exchangeable K+, Ca2+, and Mg2+ were consistently and significantly greater in shrub than in adjacent forested soils, however, and the differences were much larger than could be accounted for by estimated ash inputs. In the case of Ca, even the combustion of all aboveground organic matter could not account for more than a fraction of the difference in exchangeable pools. The authors speculate that the apparent large increase in soil and ecosystem Ca content resulted from either the release of Ca from non-exchangeable forms in the soil or the rapid uptake and recycling of Ca by post-fire vegetation.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Johnson, D.W.; Murphy, J.F.; Susfalk. R.B.; Caldwell, T.G.; Miller, W.W.; Walker, R.F.; Powers, R.F.
- **Publication date**: 2005
- **Topics addressed**: Wildfire; carbon; nitrogen; salvage logging; volatilization; N-fixation; nutrients
- **Location**: Nevada (Humboldt-Toiyabe National Forest)
- **Forest Types**: Jeffrey Pine
- **Forest practices examined**: Study documented the effects of post-fire salvage logging (all merchantable snags) on soil nutrient budgets.
- **Analysis methods**: Plot sampling at 3 paired sites; shrub- versus tree dominated (salvaged vs. unsalvaged) sites with similar soils, slopes, and aspects.

Summary Report: Karr et al. (2004)

Karr, J.R.; Rhodes, J.J.; Minshall, G.W.; Hauer, F.R.; Beschta, R.L.; Frisell, C.A.; Perry, D.A. 2004. The effects of postfire salvage logging on aquatic ecosystems in the American West. Bioscience 54: 1029-1033.

This study presents an overview of the potential effects of post-fire salvage logging on aquatic ecosystems in the Western U.S. The article contains 10 recommendations that might help mitigate potential impacts from salvage logging, and that could help improve watershed- and aquatic ecosystem conditions: 1) allow natural recovery to occur on its own, or intervene only in ways that promote natural recovery, 2) retain large old trees (live or dead), 3) protect soils, especially those that are shallow, severely burned, erosion prone and otherwise fragile, 4) protect ecologically sensitive areas including riparian and roadless areas, steep slopes, and watersheds with sensitive or imperiled aquatic species, 5) avoid creating new road and landings in burned landscapes, 6) limit reseeding and replanting, 7) do not place structures such as sediment traps, riprap, and check dams, or artificially-installed large wood in streams, 8) protect and restore watersheds before fire occurs, 9) continue research, monitoring, and assessment, 10) educate the public about riparian functioning and intrinsic value.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Karr, James R.; Rhodes, Jonathan, J.; Minshall, G. Wayne; Hauer, F. Richard; Beschta, Robert L.; Frissell, Christopher, A.; Perry, David A.
- **Publication date**: 2004
- **Topics addressed**: Aquatic ecosystems, postfire salvage logging, public land management, salmonids, western forests
- **Location**: Western U.S.
- **Forest Types**: Multiple western forest types (generally coniferous)
- **Forest practices examined**: This article discusses general principles that can help guide RMZ management planning, and did not provide detailed information about specific forest practices.
- **Analysis methods**: Review of existing published literature and white papers

Summary Report: Keyser et al. (2009)

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

This study examined the effects of post-fire salvage logging on regeneration, fuel accumulation, and understory vegetation in ponderosa pine stands burned by moderate to high severity fire during the 2000 Jasper Fire (Black Hills). On unsalvaged sites, fire-related tree mortality created a large standing pool of available fuel, resulting in a rapid increase in surface fuel loads. After 5 years, fine woody debris (FWD) and coarse woody debris (CWD) increased ~1380 percent and 980 percent in unsalvaged sites, resulting in FWD and CWD loads of 13 and 25 Mg/ha, respectively. In contrast, salvage logging limited the rate of accumulation of FWD to ~110 percent over the same time period and total accumulation of CWD to 16 Mg/ha. In moderate-severity sites, regeneration was 75 percent lower in salvaged sites owing to low seed-tree retention, suggesting a re-evaluation of salvage guidelines during future operations in the Black Hills. The likelihood of timely regeneration in high-severity sites, regardless of salvage treatment, is low. The researchers found no discernible effect of salvage logging on understory development 5 years after fire. Logging caused neither a reduction in total plant cover nor an increase in the abundance of exotic species. Further research comparing the effects of salvage logging on fuel accumulation, regeneration potential, and understory vegetation across forest types and harvesting systems is needed to assess whether these results are applicable elsewhere. The authors conclude that “the effects of salvage logging may be dependent on when and how salvage logging is conducted as well as forest type rather than an invariant set of effects inherent to salvage logging.” (Keyser et al. 2009: 457).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Keyser, Tara L.; Smith, Frederick W.; Shepperd, Wayne D.
- **Publication date**: 2009
- **Topics addressed**: wildfire, salvage logging, regeneration, fuel load, ponderosa pine
- **Location**: South Dakota (Black Hills National Forest)
- **Forest Types**: Interior ponderosa pine
- **Forest practices examined**: Fire-killed timber and any live merchantable tree (e.g.>23 cm DBH) with ≥50% crown scorch and ≥50% bole circumference at root collar charred was designated for removal.
- **Analysis methods**: Study sampled fine woody debris, coarse woody debris, and ponderosa pine regeneration 2 and 5 years post-fire, on 18 salvaged sites versus 18 unsalvaged sites.

Summary Report: Knapp and Ritchie (2016)

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

This 10-year study monitored the response of understory vegetation after high-severity wildfire and salvage logging in a ponderosa pine forest in northeastern California (Blacks Mountain Experimental Forest). Richness of both native and non-native species did not differ among salvage treatments, but both showed strong changes over time. While cover of forbs and graminoids did not differ with salvage treatment, cover of shrubs was significantly reduced at the higher salvage intensities. Major shrub species such as prostrate ceanothus (*Ceanothus prostratus*) and snow brush (*Ceanothus velutinus*) are stimulated to germinate by fire, potentially leaving seedlings vulnerable to any mechanical disturbance occurring immediately post-germination. Many other native perennial species emerged from rhizomes or other deeply buried underground structures and appear to be less affected by salvage harvest. Over time, the plant community in all salvage treatments shifted from dominance by shrubs and forbs to shrubs and grasses. Most of the grasses were native, except for cheatgrass (*Bromus tectorum*), which was found in 4 percent of measurement quadrats in 2006 and 52 percent in 2012. Overall results indicated that understory vegetation changes during the 4–10 year-period after high-severity wildfire appeared to be influenced more strongly by factors other than salvage logging. Other studies have reported more substantial effects of salvage harvest, such as reduced species diversity and total cover (Leverkus et al. 2014), or a sparser and simplified (less species rich) understory (Purdon et al. 2004). Variation in the effect of salvage harvest on understory vegetation among published studies is likely due to differences in the postfire plant community including modes of reproduction, intensity of the salvage harvest disturbance, timing of salvage harvest after the high-severity event, and duration of vegetation monitoring.

(*Note*: Also see Ritchie et al. [2013] and Ritchie and Knapp [2014] related studies for this location.)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Knapp, Eric E.; Ritchie, Martin W.
- **Publication date**: 2016
- **Topics addressed**: high-severity wildfire; non-native species; ponderosa pine; postfire management; salvage logging; species diversity; species richness; variable retention salvage.
- **Location**: California (Lassen National Forest [Blacks Mtn. Experimental Forest])
- **Forest Types**: Interior ponderosa pine
- **Forest practices examined**: Salvage logging treatments: 1) 25% removal of snags; 2) 50% removal of trees; 3) 75% removal of trees; 4) 100% removal of trees).
- **Analysis methods**: Fifteen plots with three replicates in each treatment; snags and regeneration were measured every two years for eight years.

Summary Report: Kobziar and McBride (2006)

Kobziar, L.; McBride, J.R. 2006. Wildfire burn patterns and riparian vegetation response along two northern Sierra Nevada streams. Forest Ecology and Management 222: 254-265.

This case study documented the relationships between wildfire burn patterns, stream channel topography, and short-term response of riparian vegetation to a 1999 wildland fire at two study sites in a northern Sierra Nevada mixed-conifer forest (Plumas National Forest). This study contributed to the limited amount knowledge to date on the effects of natural fire on riparian zones, and helped inform strategies designed to restore and maintain riparian vegetation in the fire-prone forests of the Sierra Nevada. The study produced the following implications for management. First, riparian vegetation regenerates relatively quickly and seedling recruitment begins almost immediately following fire, perpetuating the role riparian vegetation plays in stabilizing soils after fires and maintaining stream water quality. The authors state that allowing fires to burn in riparian zones can help mitigate fire severities at the landscape scale, whereas long-term fire exclusion in the absence of other disturbances can promote fuel buildups and increased fire severity potential. In addition, fire suppression practices such as emergency road building, heavy manipulation of fuels, and other mechanical disturbances can promote negative impacts to riparian zones, by promoting sediment erosion, reducing beneficial woody debris and downed snags, diminishing stream shading, and promoting increased evapo-transpiration and subsequent fuel drying. The authors conclude by stating that more research documenting fire's effects on riparian vegetation would help document fire's role as a disturbance factor in forested watersheds, and could help guide management of fire-prone riparian ecosystems.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Kobziar, Leda N..; McBride, Joe R.
- **Publication date**: 2006
- **Topics addressed**: Fire behavior and riparian vegetation response; habitat restoration, riparian management, wildfire, fire suppression, mechanical manipulation of fuels.
- **Location**: California (Plumas National Forest)
- **Forest Types**: Mixed conifer riparian forest and upland ponderosa pine forest.
- **Forest practices examined**: Study did not address forest practices *per se* but provided potentially useful background information about riparian ecosystems; authors also discussed general implications of wildfire suppression/fuel treatment practices.
- **Analysis methods**: Post-fire sampling along sixty 3-meter wide transects across riparian zones was used to document the topography, species distribution, sprouting response, and seedling recruitment one year after the 1999 Lookout Fire.

Summary Report: Larsen et al. (2009)

Larsen, I.J.; MacDonald, L.H.; Brown, E.; Rough, D.; Welsh, M.J.; Pietraszek, J.H.; Libohova, Z.; Benavides Solorio, J.D.; Schaffrath. K. 2009. Causes of post-fire runoff and erosion: water cover, or soil sealing? Soil Science Society of America Journal 73: 1393–1407.

This study evaluated post-fire effects on soil water repellency, surface cover, and sediment yields on severely burned sites within the 2002 Hayman and Schoonover fire perimeters. The researchers also experimentally removed surface cover by raking and conducting rainfall simulations to compare runoff, erosion, and surface sealing from two soils with varying ash cover. Soil water repellency was stronger on burned hillslopes than on unburned hillslopes only during the first summer after burning. For the first 5 years after burning, the mean sediment yield from burned hillslopes was 32 Mg/ha, whereas unburned hillslopes generated almost no sediment. Sediment yields from raked and burned hillslopes were indistinguishable when they had comparable surface cover, rainfall erosivity, and soil water repellency values. Rainfall simulations on ash-covered plots generated only 21 to 49% as much runoff and 42 to 67% as much sediment as the plots with no ash cover. Bare plots rapidly developed a structural soil seal, whereas successive simulations on ash-covered plots quickly eroded ash cover and increased runoff and sediment yields to the levels observed from the bare plots. The results indicate that: 1) post-fire sediment yields were primarily due to the loss of surface cover rather than fire-enhanced soil water repellency, 2) surface cover is important because it inhibits soil sealing, and 3) ash temporarily prevents soil sealing and reduces post-fire runoff. The authors conclude that the most effective post-fire rehabilitation treatments will be those that immediately increase the amount of soil surface cover.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Larsen, Isaac J.; MacDonald, Lee H.; Brown, Ethan.; Rough, Daniella; Welsh, Matthew J.; Pietraszek, Joseph H.; Libohova, Zamir; Benavides Solorio, Juan D.; Schaffrath. Keelin.
- **Publication date**: 2009
- **Topics addressed**: Hillslope runoff and erosion potential after severe wildfires
- **Location**: Colorado (Pike and San Isabel National Forests)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful information about runoff and erosion potential on severely burned sites.
- **Analysis methods**: Paired plots were used to compare water repellency, surface cover, and sediment yield between 4 treatments (burned, unburned, raked, and unraked sites).

Summary Report: Leach and Moore (2010)

Leach, J.A.; Moore, R.D. 2010. Above-stream microclimate and stream surface energy exchanges in a wildfire-disturbed riparian zone. Hydrological Processes 24: 2369-2381.

This study in central interior British Columbia characterized the effects of radiation and shade on stream temperature and microclimate in a montane forest riparian zone after wildfire and simulated salvage harvesting. Modelled net radiation varied considerably along the reach, and measurements at a single location did not provide a reliable estimate of the modelled reach average. During summer, net radiation dominated the surface heat exchanges, particularly because the sensible and latent heat fluxes were normally of opposite sign and thus tended to cancel each other. All surface heat fluxes shifted to negative values in autumn and were of similar magnitude through winter. In March, net radiation became positive, but heat gains were cancelled by sensible and latent heat fluxes, which remained negative. A modelling exercise using 3 canopy cover scenarios (current, simulated pre-fire, and simulated complete vegetation removal) showed that net radiation under the standing dead trees was double that modelled for the pre-fire canopy cover. However, post-disturbance standing dead trees reduced daytime net radiation reaching the stream surface by one-third compared with complete vegetation removal. The results of this study have highlighted the need to account for reach-scale spatial variability of energy exchange processes, especially net radiation, when modelling stream energy budgets.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Leach, J.A.; Moore, R.D.
- **Publication date**: 2010
- **Topics addressed**: Wildfire, riparian microclimate, riparian management, simulated timber harvest.
- **Location**: British Columbia, Canada (Kamloops area)
- **Forest Types**: Interior Douglas-fir, interior ponderosa pine, lodgepole pine
- **Forest practices examined**: Study modeled the potential effects of various simulated logging scenarios on riparian microclimate.
- **Analysis methods**: This study develops a model of net radiation using hemispherical canopy photos coupled with microclimate measurements along a 1.5. km stream reach burned by a wildfire.

Summary Report: Lehmkuhl et al. (2003)

Lehmkuhl, J.F.; Everett, R.L.; Schellhaas, R.; Ohlson, P.; Keenum, D.; Riesterer, H.; Spurbeck, D. 2003. Cavities in snags along a wildfire chronosequence in Eastern Washington. Journal of Wildlife Management 67: 219-228.

This study analyzed the occurrence of bird-excavated cavities in snags following 26 high-severity wildfires on the east slope of the Washington Cascade Range. Cavities occurred in about 6 percent of the 1,867 recorded snags; most (~70%) were in burns <20 years old. Cavities occurred at higher rates in ponderosa pine (28%) and Douglas-fir (~9%) snags than in snags of other tree species (<5%). Few or no cavities were found in large samples (n > 250) of subalpine fir (<1%) and lodgepole (0%) snags. Cavities occurred in about 4 percent of the small samples (n < 100) of Engelmann spruce (n = 48) and western larch (n = 74) snags. Important predictors of cavities in ponderosa pine and Douglas-fir snags were 1) large diameter, 2) burn age >20 years, 3) soft-decay condition (Class 3+), 4) broken-top condition, and 5) moderate (10-21 m) height. Cavity-bearing ponderosa pine snags were best characterized as large- diameter (>34 cm dbh) snags >2 m tall and located in middle-age to older burns (>19 years old). Cavity-bearing Douglas-fir snags were best characterized as large-diameter snags (>33 cm dbh), or smaller soft snags (Class 4, 5) at elevations <1,200 m. In burns <20 years old, Douglas-fir snags with broken tops higher cavity excavation rates (6%) than snags with whole tops (<1%). To promote effective snag habitat, the authors suggest that management of pre-fire stands should include retention of particular species (e.g., ponderosa pine, Douglas-fir), large tree sizes, and tree defects (e.g., broken tops). The authors also state that, when conducting post-fire salvaging, managers should attempt to retain snags with defects that were incurred before the fire (especially broken tops) and large-diameter snags of species known to be most suitable for cavity excavation.

(**Note*: Also see Everett et al. [1999] for a closely related study on snag longevity characteristics in the above study areas)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Lehmkuhl, John F.; Everett, Richard L.; Schellhaas, Richard; Ohlson, Peter; Keenum, David; Riesterer, Heidi; Spurbeck, Donald.
- **Publication date**: 2003
- **Topics addressed**: Eastern Cascade Range, post-fire snags, cavity occurrence, bird habitat, Douglas-fir, lodgepole pine, ponderosa pine, subalpine fir
- **Location**: Washington (Okanogan-Wenatchee National Forest; 26 wildfire sites)
- **Forest Types**: Douglas-fir, lodgepole pine, ponderosa pine, subalpine fir
- **Forest practices examined**: Study did not examine forest practices *per se* but provided information about post-fire snags and their potential as wildlife microhabitats.
- **Analysis methods**: Snag cavity sampling along a chronosequence of 26 wildfires (1-81 years post-fire).

Summary Report: MacDonald et al. (2003)

Macdonald, J.S.; MacIsaac, E.A.; Herunter, H.E. 2003. The effect of variable-retention riparian buffer zones on water temperatures in a small headwater streams in sub-boreal forest ecosystems of British Columbia. Canadian Journal of Forest Research 33: 1371-1382.

This study investigated the influence of three variable-retention riparian harvesting prescriptions on temperatures in first-order streams located in the Fraser River basin of northwestern British Columbia, Canada. The treatment types were: 1) low retention - removal of all merchantable timber (>15 or >20 cm dbh) within 20-30 m of the stream; 2) high retention - removal of merchantable timber >30 cm dbh within 20-30 m of the stream; 3) patch cut - a high retention along the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed. Five years after the completion of harvesting treatments, temperatures remained 4 to 6 degrees warmer, and diurnal temperature variation remained higher, than in control streams regardless of the type of logging treatment. Initially, the high-retention treatment acted to mitigate the temperature effects of the harvesting, but 3 successive years of windthrow was antecedent to reduced canopy density and equivalent temperature impacts. The authors speculated that late autumn reversals in the impacts of forest harvesting also occur. Although temperature impacts in this study remained within the tolerance limits of local biota, even modest temperature changes could alter insect production, egg incubation, fish rearing, migration timing, and susceptibility to disease. In addition, the authors stated that the effects of large changes to daily temperature range were not well understood as of the 2003 publication year.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Macdonald, J.S.; MacIsaac, E.A.; Herunter, H.E.
- **Publication date**: 2003
- **Topics addressed**: riparian zones, water temperature, buffer zone retention, Engelmann spruce, subalpine fir
- **Location**: Northwestern British Columbia, Canada (Fraser River basin)
- **Forest Types**: Engelmann spruce, subalpine fir
- **Forest practices examined**: Study examined the potential stream-temperature buffering effects of 3 variable-retention harvests (described in detail below).
- **Analysis methods**: Temperatures were compared between streams in five harvest blocks and three un-cut control streams at three harvest levels (described above).

Summary Report: McIver and McNeil (2006)

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

This study measured soil disturbance and hill-slope sediment transport after salvage logging following the severe 1996 Summit Fire, Malheur National Forest, northeastern Oregon. There was a significant difference among treatments in the percentage of mechanically disturbed soil area, with an average of 19.4% disturbed in fuel reduction units (i.e., removal of most dead trees) and 15.2% in commercial units (i.e., removal of merchantable dead trees only). Displacement (13.7% of soil area), apparent compaction (3.1%), and erosion (0.4%) were the most common types of machine-caused soil disturbance. Controls had significantly less change in mean displacement from pre- to post-treatment compared to fuel reduction units, and significantly less change in erosion compared to commercial units. At the experimental unit level, there was a significant correlation between the number of stems removed and the total amount of mechanical soil disturbance. Results indicated that logging activity accounted for more soil disturbance than relative fire severity. There was no correspondence between disturbance within units and hill-slope sediment collected in silt fences below units. Visual inspections and sediment collected in silt fences indicated that little sediment exited the experimental units in the short term, and that the existing road system caused most of the observed hill-slope sediment transport. Low observed levels of sediment transport were likely due to the following factors: a combination of low-to-moderately steep slopes, low-to-moderate-risk soils, logging over snow or dry ground, hand felling, lack of new roads, two years of recovery of ground cover between the fire and the logging activity, problems with measuring hill-slope sediment, and the absence of severe weather events in the two years after postfire logging. The authors state that, given these mitigating factors, hill slope sediment transport measured in this study should be considered as representative of the low end of the range that would be expected in a post-fire tractor logging operation on similar soils and under similar burn severity conditions.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: McIver, James, D.; McNeil, R.
- **Publication date**: 2006
- **Topics addressed**: post-fire salvage logging; mechanical soil disturbance, compaction, erosion, hill-slope sediment transport
- **Location**: Oregon (Malheur National Forest)
- **Forest Types**: Interior Ponderosa Pine
- **Forest practices examined**: Salvage-logging (removal of two-thirds of dead merchantable trees); fuel reduction treatments (removal of all dead merchantable trees).
- **Analysis methods**: Plot measurements were taken in salvage logging treatments, fuel reduction treatments, and unlogged control plots.

Summary Report: McIver and Ottmar (2007)

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.

This study modeled the effects of salvage logging on dry-forest stand structure and fuel mass two years after the 1996 Summit fire in eastern Oregon (Malheur National Forest). Specifically, the researchers used a forest vegetation simulation model to project changes in fuel beds for 100 years. Post-fire logging decreased mean basal area to 46% pre-treatment level in commercial units, and to 25% in fuel reduction units. Logging significantly reduced tree density, especially for the smallest (<22 cm) and intermediate (23-41 cm) diameter classes. Fuel reduction units also had significantly fewer snags (4 snags >30 cm diameter per ha), compared to both commercial (23 per ha) units and to unlogged controls (64 per ha) in the year following timber harvest. Total woody fuel mass increased significantly in fuel reduction units when compared to controls, with the greatest difference among treatments in the slash fuel component. Model projections of the fuel bed using the forest vegetation simulator (FVS-FFE) indicate that the disparity in slash fuel mass between fuel reduction and on-logged units would be sustained until about 15 years after logging. However, a re-burn of moderate intensity occurring would likely kill all young trees, even in unlogged units, because of the influence of grasses and shrubs. Model projections of 1000-h fuels indicate that standing structure in all stands would collapse quickly, with the result that unlogged stands would contain two- or three-fold greater masses at 25 and 50 years after logging, leading to much higher consumption rates of fuel in the event of a re-burn. Despite treatment differences in heavy fuel accumulations over time, FVS-FFE predicts no differences among treatments in mortality of young trees due to either moderate or high intensity fire occurring in the same place at 25, 50, or 100 years post-salvage. However, regarding the potential efficacy of such modeling, the authors conclude by saying, "Until we know more about the mechanisms of fire-induced tree mortality, and incorporate this knowledge into fire-effects models, we will remain uncertain on the extent to which post-fire logging reduces re-burn severity, at least with respect to experimental studies that involve the use of fire behavior models." (McIver and Ottmar 2007: 278).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: McIver, James D.; Ottmar, Roger.
- **Publication date**: 2007
- **Topics addressed**: Salvage logging, re-burn hypothesis, restoration
- **Location**: Oregon (Malheur National Forest; Summit Fire)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir
- **Forest practices examined**: Commercial salvage where most dead merchantable trees were removed; fuel reduction harvest where most dead trees >10 cm were removed.
- **Analysis methods**: Plot sampling measured the effects on stand structure and fuel mass among two treatments versus an unlogged control; results were then projected over a 100-year period using the forest vegetation simulator (FVS-FFE).

Summary Report: Mellon et al. (2008)

Mellon, C.D.; Wipfli, M.S.; Li, J.L. 2008. Effects of forest fire on headwater stream macro-invertebrate communities in eastern Washington, USA. Freshwater Biology 53: 2331-2343.

The objectives of this study were to determine how benthic macroinvertebrate communities, macroinvertebrate drift and emergence from headwater streams changed 1 and 2 years following the severe Togo Fire (2003) in a managed forest in northeastern Washington. Since 1995, management practices on the Colville National Forest have followed Inland Native Fish Strategy (INFISH) guidelines that require a minimum 45-m riparian buffer on perennial, fishless streams (Inland Native Fish Strategy Environmental Assessment, 1995). Salvage logging occurred following the fire in 2003 and 2004 through much of the burned area, and this minimum 45-m riparian buffer was maintained at salvage logging sites. All sample sites were located in either mature live or burned forest and were selected to have at least a minimum 45-m buffer. Macroinvertebrate biomass was greater at burned sites only from emergence samples while in benthic and drift samples there was no significant difference between burn and control sites. For all sample types, diversity was lower in the burned catchments, and the macroinvertebrate community was dominated by chironomid midges. Compared to the effects of fire in less disturbed ecosystems, this study illustrated that forest fire in a managed forest may have greater impacts on headwater macroinvertebrate communities, influencing prey flow to adjacent terrestrial and downstream aquatic habitats for at least the first 2 years post-fire. The authors conclude by stating, although previous land management actions had undoubtedly affected the study results, future post-fire management can help minimize negative impacts on macro-invertebrates by protecting riparian vegetation and by using practices that mitigate against soil erosional processes.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Mellon, Cassie D.; Wipfli, Mark S.; Li, Judith L.
- **Publication date**: 2008
- **Topics addressed**: Forest management, headwater stream, macroinvertebrate, wildfire
- **Location**: Washington (Colville National Forest)
- **Forest Types**: Western larch, Engelmann spruce, interior Douglas-fir, lodgepole pine, grand fir, western red cedar
- **Forest practices examined**: Study did not examine forest practices *per se* but provided potentially useful information about riparian ecosystems (macroinvertebrates) in a severely burned and salvage-logged managed forest.
- **Analysis methods**: Study used 50-meter plot sampling to compare macroinvertebrate density, biomass, community structure and composition between streams in catchments with and without recent fires, using five replicate burned (post-fire) and five replicate control (unburned) catchments of similar size and logging history.

Summary Report: Monsanto and Agee (2008)

Monsanto, P.G. and J.K. Agee. 2008. Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington. Forest Ecology and Management 255: 3952–3961.

This study in dry conifer forests of Washington's eastern Cascades (Okanogan-Wenatchee National Forest) examined patterns of coarse woody debris from 1 to 35 years after wildfires with and without salvage logging. The researchers also documented patterns of soil heating and fine root mortality caused by experimentally burning logs. Total biomass averaged roughly 60 Mg/ha across all sites, although the proportion of logs to snags increased over the chronosequence. Units that had been salvage logged had lower log biomass than unsalvaged units, except for the most recently burned site, where salvaged stands had higher log biomass. In a complementary experiment, soils heating and surrogate-root mortality caused by burning of logs were measured to assess the potential site damage if fire was reintroduced in these forests. Experimentally burned logs produced lethal surface temperatures (60 °C) extending up to 10 cm laterally beyond the logs. Logs burned in late season produced higher surface temperatures than those burned in early season. Thermocouples buried at depth showed that mean maximum temperatures exponentially declined with soil depth. Large logs, decayed logs, and those burned in late season caused higher soil temperatures than small logs, sound logs, and those burned in early season. Small diameter (1.25 cm), live Douglas-fir branch dowels, buried in soil and used as surrogates for small roots, indicated that cambial tissue was damaged to 10 cm depth and to 10 cm distance adjacent to burned logs. When lethal soil temperature zones were projected out to 10 cm from each log, lethal cover ranged up to 25% on unsalvaged portions of the oldest fire, almost twice the lethal cover on salvaged portions. Prescribed burning for fuel reduction and stocking control can cause significant root damage, especially in young stands that have substantial coarse woody debris. Where prescribed fire is introduced to post-wildfire stands aged 20–30 years, effects of root heating from smoldering coarse woody debris can be minimized by burning in spring, at least on mesic sites. Whether stands have been salvaged or not, soil heating from smoldering logs will likely be a concern. Spring burning can help mitigate that issue where high levels of coarse woody debris occur, because such burns generate less heating than fall burns, and because early season burns typically cover less area.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Monsanto, Philip G.; Agee, James K.
- **Publication date**: 2008
- **Topics addressed**: Salvage logging, soil heating; wildfire, Pinus ponderosa, coarse woody debris
- **Location**: Washington (Okanogan-Wenatchee National Forest)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, grand fir
- **Forest practices examined**: Post-fire salvage logging and prescribed burning (effects on coarse woody debris)
- **Analysis methods**: Plot sampling to document long-term effects of salvage logging on coarse woody debris following four stand-replacing wildfires (1-35 yrs. post-fire).

Summary Report: Moody and Martin (2009)

Moody, J.A.; Martin, D. 2009. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. International Journal of Wildlife Fire 18: 96–115.

The authors compiled data from multiple studies across the western U.S. and compared measurements of post-fire sediment erosion, transport, and deposition during various rainfall regimes within 2 years of burning. Mean sediment yield from channels (240 t/ha) was significantly greater than from hillslopes (82 t/ha). This indicated that on the time scale of wildfire (10–100 years) channels were the primary sources of available sediment. A lack of correlation of sediment yield with topographic slope and soil erodibility further suggested that sediment availability may be more important than slope or soil erodibility in predicting post-fire sediment yields. Based on 80 years of data from the literature, wildfires have been an important geomorphic agent of landscape change when linked with sufficient rainfall. These effects are limited in spatial scale to the immediate burned area and to downstream channel corridors. The authors conclude that such studies not only can help guide post-fire management policies, but also can be used to develop predictive models of post-fire sediment yield.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Moody, John A.; Martin, Deborah
- **Publication date**: 2009
- **Topics addressed**: post-fire soil erosion, soil transport, soil deposition, sedimentation, rainfall regimes, western U.S.
- **Location**: Western U.S.
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about post-fire soil erosion in both riparian and hillslope terrain.
- **Analysis methods**: Literature review

Summary Report: Moore and Richardson (2012)

Moore, R.D. and J.S. Richardson. 2012. Natural disturbance and forest management in riparian zones: comparisons of effects at reach, catchment, and landscape scales. Freshwater Science 31: 239-247.

This study compares the effects of natural disturbance and forest management on riparian systems with a focus on in stream habitat and ecology. The paper summarizes general effects of wildfires and forest management practices such as harvesting and related activities in and adjacent to riparian zones (e.g., on hydrologic and soil processes, and aquatic habitat). The authors also review the characteristics of riparian forest disturbance regimes in the context of catchment-scale and broader landscape level processes of forest disturbance. Forest disturbance agents, such as wildfire and windthrow, often differ in magnitude and frequency between upland and riparian zones. Riparian forests may be subject to additional disturbance agents that do not affect uplands, including debris flows, floods, bank erosion, and avulsions. The effects of riparian forest harvesting on stream habitat and ecology can be qualitatively similar to those of wildfire, with the important exception of recruitment of large in-stream wood. Regarding harvesting practices, the authors list the following as potential impacts: 1) shade reduction and increased stream temperatures, 2) reduced or accelerated recruitment of in-stream wood, 3) decreased root strength and bank stability, 4) decreased water quality and increased temperatures, 5) alteration of stream processes such as increased sedimentation. The researchers also state that maintaining undisturbed forested buffers does not necessarily provide sufficient protection for riparian zones: “Riparian buffers typically have little effect on harvesting-related changes in stream flow and may not protect against increases in sediment input. . . removal of upland forest can increase windthrow in riparian zones, and thus, influence patterns of recruitment of in-stream wood . . . upland forest harvesting also increases light penetration in riparian forest and releases understory growth from shade limitation.” (Moore and Richardson 2012: 240). For most other disturbance agents, current knowledge is insufficient to assess the degree to which natural disturbance can be emulated via riparian forest harvesting. In particular, the effects of the spatial patterns and frequencies of disturbance on the trajectories and rates of post-disturbance recovery are poorly understood for many landscapes. Broadly based, long-term research on riparian disturbance regimes is needed to provide the scientific basis required for designing strategies for sustainable streamside forest management.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Moore, R. Dan; Richardson, John S.
- **Publication date**: 2012
- **Topics addressed**: Riparian forests, natural disturbance, wildfire, logging impacts, landscape management.
- **Location**: North America
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study provided a general overview of the role of forest management practices as riparian disturbance agents, and provided potentially useful background information for riparian forest management and future research needs.
- **Analysis methods**: Literature review.

Summary Report: Moore and Scott (2005)

Moore, R.D.; Scott, D.F. 2005. Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment. Canadian Water Resources Journal 30:331–344.

This study investigated the effects of salvage harvesting on streamflow for a snowmelt-dominated stream in the southern interior of British Columbia. Salvaging in response to a pine beetle infestation resulted in a significant increase in April stream flows. Specifically, the stream response persisted with no evidence of recovery through the 18-year post-treatment period, and there was a significant advance in the timing of peak flows relative to those for the control stream. No significant nor apparent changes in 7-day low flows were detected. Peak flows appeared to increase for smaller events, but not for larger events, although this result was not statistically significant. Detection of significant harvesting effects on low flows, peak flows and annual water yield may have been hampered by inherent differences between the two catchments, particularly in relation to aspect and elevation distribution. Data interpretation also was hampered by the effects of a climate shift that coincided with the harvesting treatment, and which was associated with low snow accumulation throughout the post-treatment period. The authors concluded that problems with finding well-matched catchment pairs likely represent a fundamental limitation in applying the paired-catchment approach to estimate the effects of forest harvesting in medium-to-large catchments.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Moore, R.D.; Scott, D.F.
- **Publication date**: 2005
- **Topics addressed**: Stream flows; salvage harvest; insect infestation; lodgepole pine; Engelmann spruce; subalpine fir
- **Location**: Southern interior British Columbia
- **Forest Types**: Lodgepole pine, Engelmann spruce, subalpine fir
- **Forest practices examined**: Study examined the effects of timber salvaging (after an insect infestation) on catchment streamflows.
- **Analysis methods**: This study used a paired-catchment approach to compare streamflows between salvaged and unharvested control sites for an 18-year period after a pine beetle infestation and subsequent harvesting.

Summary Report: Moore and Wondzell (2005)

Moore, R.D.; Wondzell, S.M. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. Journal of the American Water Resources Association 41: 763-784.

This study reviews literature related to the effects of timber harvesting on hydrologic processes in Pacific Northwest ecosystems. Most studies in the Northwest and elsewhere have found that annual water yields generally increase following forest harvesting, although harvesting might increase only the more frequent, geomorphically benign peak flows. Specifically, forest harvesting generally increases the fraction of precipitation that is available to become streamflow, increases rates of snowmelt, and modifies the runoff pathways by which water flows to the stream channel. Harvesting may potentially decrease the magnitude of hyporheic exchange flow (i.e., mixing of groundwater in adjacent stream bank) through increases in fine sediment and clogging of bed materials and through changes in channel morphology, although the ecological effects of these changes are unclear. In small headwater catchments, forest harvesting generally increases annual runoff and peak flows and reduces the severity of low flows, but exceptions have been observed for each effect. Low flows appear to be more sensitive to transpiration from vegetation in the riparian zone than in the rest of the catchment. Recovery to pre-harvest conditions appeared to occur within about 10 to 20 years in some coastal catchments but may take many decades in mountainous, snow dominated catchments. In addition, the authors point out that separating the effects of harvesting versus road building on catchment peak flows is difficult because both activities generally occur simultaneously; otherwise, the effects of road construction did not appear to have a significant effect on peak flows in most of the cases that measured road-only treatments.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Moore, R.Dan; Wondzell, Steven M.
- **Publication date**: 2003
- **Topics addressed**: Streamflow; forest harvesting; headwater; peak flow; low flow; water yield; small catchment; Pacific Northwest
- **Location**: Pacific Northwest
- **Forest Types**: (multiple, unspecified)
- **Forest practices examined**: Article summarized numerous studies that examined management treatments such as timber harvesting (clearcut, shelterwood systems) and associated road construction.
- **Analysis methods**: Literature review.

Summary Report: Moore et al. (2005)

Moore, R.D.; Spittlehouse, D.; Story, A. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41:813–834.

This publication is a review of the effects of forest harvesting on riparian microclimate and stream temperature. Stream temperature increases after forest harvesting are primarily controlled by changes in insolation but also depend on stream hydrology and channel morphology. Stream temperatures recovered to pre-harvest levels within 10 years in many studies, but took longer in others. Retaining riparian buffers can decrease the magnitude of stream temperature increases and changes to riparian microclimate, but substantial warming has been observed for streams within both unthinned and partial retention buffers. A range of studies has demonstrated that streams may or may not cool after flowing from clearings into shaded environments, and further research is required in relation to the factors controlling downstream cooling. The authors state that more research is required on 1) riparian microclimate and its responses to harvesting, 2) the influences of surface/subsurface water exchange on stream and bed temperature regimes, 3) biological implications of temperature changes in headwater streams (both on site and downstream), and 4) methods for quantifying shade and its influence on radiation inputs to streams and riparian zones.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Moore, R.Dan; Spittlehouse, D.; Story, Anthony.
- **Publication date**: 2005
- **Topics addressed**: Riparian microclimate, stream temperatures, timber harvest, logging effects, riparian buffers.
- **Location**: Pacific Northwest
- **Forest Types**: (unspecified coniferous)
- **Forest practices examined**: This publication did not examine forest practices *per se*, but provided an overview of timber harvesting effects on riparian microclimates and stream temperatures.
- **Analysis methods**: Literature review.

Summary Report: Morgan et al. (2015)

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: 31-58.

This study in southeastern Washington (Blue Mountains) examined understory plant species richness, diversity, and canopy cover to document post-fire vegetation response to burn severity, and post-fire seeding with native grasses. Understory vegetation responded rapidly post-fire due, in part, to low intensity rainfall events in the first post-fire growing season. Plant species richness and diversity in low and moderate burn severity plots in 2006 (Shannon-Wiener index species richness 18; diversity 2.3) were higher than in high burn severity plots (species richness 10; diversity 1.8). Species richness on the high severity plots reached 19 in the sixth post-fire year, which was similar to the initial values on the low and moderate burn severity plots. Plants that commonly resprout from surviving belowground sources were abundant post fire, while those establishing from off-site seed sources, including non-native species, were present but not abundant. Plots seeded with native grass post fire and not salvage logged had the highest canopy cover of graminoid species. That is, cover was more than 30 % six years after the fire (in 2011), along with low forb (15 %) and shrub (1 %) canopy cover and species richness. High severity plots that were not seeded and not salvage logged had 3 % graminoid cover, 14 % forb cover, and 26 % shrub cover. Plots that had been salvage logged from 1 to 3 years after the fire produced less canopy cover of shrubs and forbs, but 3 times more canopy cover of graminoids on the high burn severity plots by 2011. High severity plots that were salvage logged and not seeded with native grasses had the lowest species richness, diversity, and cover. Very few non-native species were found, regardless of salvage logging and seeding. Rapid post-fire growth dominated by native plants of high diversity suggests that this forest's vegetation and soils are highly resilient to disturbance. Overall, burn severity and post-fire seeding with native grasses were more influential than salvage logging on understory plant abundance 1 to 6 years after fire.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Morgan, Penelope; Moy, Marshell; Droske, Christine A.; Lewis, Sarah A.; Lentile, Leigh B.; Robichaud, Peter R.; Hudak, Andrew T.; Williams, Christopher J.
- **Publication date**: 2015
- **Topics addressed**: Wildfire, fire behavior, fire severity, timber harvest, salvage logging, vegetation recovery, grass seeding, mitigation.
- **Location**: Washington (Umatilla National Forest)
- **Forest Types**: Interior Douglas-fir, interior ponderosa pine, grand fir, lodgepole pine
- **Forest practices examined**: Post-fire salvage logging; grass seeding.
- **Analysis methods**: Study documented understory plant species richness, diversity, and canopy cover 1 to 6 years post-fire on 72 permanent plots selected in a stratified random sample to define post-fire vegetation response to burn severity, post-fire seeding with native grasses, and salvage logging.

Summary Report: Olson and Agee (2005)

Olson, D.L.; Agee, J.K. 2005. Historical fires in Douglas-fir dominated riparian forests of the southern Cascades, Oregon. Fire Ecology 1: 50-74.

This article describes historical fire regimes for riparian zones in Douglas-fir dominated forests within the drier western hemlock forest series of the Upper Steamboat Creek watershed, Oregon (Umpqua National Forest). Fire was common historically in both the riparian zones and upslope forests of this study area. Fire return intervals were somewhat longer in riparian zones (ranging from 35-39 years, with fire return intervals ranging from 4-167 years) than in the upslope stands (ranging from 27-36 years, with fire return intervals ranging from 2-110 years), but these differences were not significant. Fires were probably mixed in severity and likely patchy, considering the high incidence of fires occurring only at a riparian plot or only at an upslope plot within a pair, but not at both. Finally, fire return intervals showed a non-significant trend of decreasing length from west to east to north aspects. An increased sampling effort may have shown this decrease to be significant. Based on the results from this study, it is evident that restoring fire will be necessary to protect riparian forest health in this study area. Historical recruitment of large woody debris was likely patchy and pulsed for these mixed-severity fire regime forests.

Additional information requested by SAGE:

- **Type of item**: Peer reviewed publication
- **Author(s)**: Olson, Diana L.; Agee, James K.
- **Publication date**: 2005
- **Topics addressed**: historical fire regimes in riparian forest
- **Location**: Oregon (Umpqua National Forest)
- **Forest Types**: Riparian and adjacent upland forests in Douglas-fir/western hemlock types
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about riparian fire regimes.
- **Analysis methods**: Fire dates were determined from a total of 194 fire scarred wedges from stumps sampled at 15 riparian and 13 upslope one-hectare plots.

Summary Report: Peppin et al. (2011)

Peppin, D.L.; Fulé, P.Z.; Sieg, C.H.; Beyers, J.L.; Hunter, M.E.; Robichaud, P.R. 2011. Recent trends in post-wildfire seeding: analysis of costs and use of native seed. International Journal of Wildland Fire 20: 702−708.

This study reviewed scientific articles, government publications, unpublished documents, and USDA Forest Service Burned Area Reports to determine trends in post-fire seeding in forested ecosystems over time. Of 1164 USDA Forest Service Burned Area Reports, 380 contained information on seeding treatments conducted in forested ecosystems. A review of 40 papers and 67 Burned Area Reports reporting species seeded between 1970 and 2007 revealed a trend of increasing use of native species, annual cereal grains and sterile-grass hybrids, with natives dominating seed mixes. According to 380 Burned Area Reports with data on costs and area seeded, total post-fire seeding expenditures have increased substantially, averaging about 3.3 million dollars per year spent on post-fire emergency seeding treatments in forested ecosystems that involved the Forest Service during the period 2000 to 2007. This equates to an increase of 192% compared to the average spent during the previous 30 years. The percentage of the total burned area seeded averaged 21% in the 1970s, compared to only 4% between 2000 and 2007.

(*Note*: Also see Peppin et al.'s [2014] follow-up study in this compendium)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Peppin, Donna; Fulé, Peter; Sieg, Carolyn; Beyers, Jan; Hunter, Molly; Robichaud, Peter.
- **Publication date**: 2011
- **Topics addressed**: post-fire seeding, erosion control, annual ryegrass, burned area rehabilitation, cereal grains, grasses, mulch
- **Location**: Western U.S.
- **Forest Types**: (unspecified; general review only)
- **Forest practices examined**: Article reviewed some common post-fire erosion control measures (i.e., seeding, mulching), but did not mention riparian areas *per se*.
- **Analysis methods**: Literature review

Summary Report: Peppin et al. (2014)

Peppin, D.L.; Mottek-Lucas, A.L.; Fule, P.Z. 2014. Post-fire seeding in western United States forests. Fire Ecology 10: 31- 42.

Peppin et al. (2014) interviewed regional- to national level land managers (e.g., fire management- and other specialists) in the Western U.S. to document perceptions and opinions about the effectiveness of post-fire seeding, and provided a review of pertinent literature. Since 2000, reviews have questioned the effectiveness and effects of post-fire seeding treatments (Robichaud et al. 2000, Beyers 2004, Peppin et al. 2010, Peppin et al. 2011). The reviews suggest that: 1) seeding has a low probability of success during the first and second critical erosion years after fire (Robichaud et al. 2000); 2) successful grass establishment displaces native plant regeneration (Robichaud et al. 2000, Beyers 2004, Peppin et al. 2010); 3) seeded plots rarely reduce erosion compared to unseeded plots (Peppin et al. 2010); and 4) seeding has limited effectiveness in curtailing non-native species invasions (Peppin et al. 2010). Peppin et al. (2014) therefore conclude that there is often a disconnect between the continued use of seeding as a post-fire rehabilitation measure and scientific evidence regarding its effectiveness. During interviews and telephone surveys, the researchers found that 71 percent of the 23 respondents believed that information on the long-term effects of seeding was insufficient. Respondents' perception about the effectiveness of seeding in curtailing the spread of non-native species was mixed, with 64 percent believing that seeding was very or somewhat effective and the remaining 36 percent believing that such seeding was ineffective. Most of the available information on seeding has been derived from short-term studies (≤2 years). Testimonies and recent reviews demonstrate the need for review and refinement of current policy that includes stronger mandates and adequate funding for task-assigned staff to conduct 5-10 year-long monitoring efforts. Land managers and scientists agree that there is a need for data on the long-term effectiveness of seeding treatments and a need for more inquiry regarding the effectiveness of seeding in mitigating invasions by non-native species. Stronger communication and collaboration between these two groups would allow researchers to develop well-replicated monitoring designs for areas that land managers consider to be high priority for intensive quantitative long-term research of post-fire treatments.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Peppin, Donna L.; Mottek-Lucas, Anne L.; Fule, Peter Z.
- **Publication date**: 2014
- **Topics addressed**: Silviculture, post-fire restoration, seeding, forest policy, wildfire effects.
- **Location**: Western U.S.
- **Forest Types**: (unspecified conifer forest)
- **Forest practices examined**: Post-fire seeding (policy and practices) for conifer forest restoration (western U.S).
- **Analysis methods**: Interviews and telephone surveys with six national- and seventeen regional-level natural resource managers who are knowledgeable about post-fire seeding activities on federal lands.

Summary Report: Peterson and Dodson (2016)

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

This study examined the long-term (15 years) response of understory vegetation (cover, species diversity, composition, or exotic species cover) to two post-fire logging treatments (commercial salvage logging with and without additional fuel reduction logging) on terrain that was severely burned by the 1996 Summit Fire in northeastern Oregon (Malheur National Forest). Post-fire logging treatments produced no significant effects on understory vegetation cover, diversity, or composition 15 years after treatment. Sampling found no significant treatment effects on graminoid, forb, woody plant, or exotic plant cover and species richness, and differences among treatment means were generally small. Differences in treatment means were larger at the individual species level, but were only statistically significant for one native grass, California brome (*Bromus carinatus*), which responded differently to the two logging treatments. Analysis of understory plant communities revealed two major gradients in understory plant community composition, one related to sapling density and one related to residual overstory tree density. These results suggested that initial fire severity and post-fire regeneration may have greater long-term impacts on post-fire understory vegetation than post-fire logging. This study demonstrates that understory vegetation can be resilient to post-fire logging, particularly when best management practices, like logging over snow, are used to limit damage to soils and understory vegetation. The authors state that if further research confirms these findings, post-fire logging debates will be able to focus more on how to mitigate short-term disturbance impacts and manage fire-killed trees to meet wildlife habitat, fuel reduction, and economic objectives, and less on concerns over long-term ecosystem degradation.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Peterson, David W.; Dodson, Erich K.
- **Publication date**: 2016
- **Topics addressed**: Post-fire logging, salvage logging, understory vegetation, species richness, biodiversity, post-fire forest management
- **Location**: Oregon (Malheur National Forest-Summit Fire)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, grand fir
- **Forest practices examined**: Salvage logging (commercial harvest; commercial plus fuel reduction treatments)
- **Analysis methods**: Sampling of understory plant cover and species diversity on 10 to 11 sampling plots within each of nine experimental treatment units; researchers compared understory plant cover, species diversity, community composition, or exotic species cover on logged versus unlogged plots.

Summary Report: Peterson et al. (2009)

Peterson, D.L.; Agee, J.K.; Aplet, G.H.; Dyskstra, 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. General Technical Report PNW-GTR-776. Portland, OR: USDA Department of Agriculture, Forest Service, Pacific Northwest Research Station. 51 p.

Peterson et al.'s (2009) reviewed potential effects of post-fire salvage logging on coniferous forest ecosystems in the western North America. The authors summarized effects on vegetation, fuels, soils and hydrology, riparian systems and aquatic ecology, and terrestrial wildlife. Of particular interest is the chapter titled *Effects of Postfire Timber Harvest on Riparian Systems and Aquatic Ecology*. Below are some key points: "Intact riparian buffers reduce sediment delivery to streams, maintain cooler stream temperatures through shading, and minimize changes in aquatic habitat for fish and macroinvertebrates, all of which are especially important following wildfire. Vegetation in riparian areas also mitigates the effects of denuded slopes on wildlife by providing habitat for small mammals, birds, and amphibians. . . Few data exist on the effects of postfire logging on aquatic ecosystems, although effects can be inferred from the literature on riparian fire, fire effects, and logging effects. . . potential changes (in riparian zones produced by severe fires and salvage logging) include loss of in-channel wood, loss of vegetation, reduced soil infiltration, increased erosion, changes in timing and amount of runoff, elevated stream temperature, and altered channel morphology. . . Effects on aquatic systems of removing trees are mostly negative, and logging and transportation systems that disturb the soil surface or accelerate road-related erosion can be particularly harmful unless disturbances are mitigated. . . . although relationships of specific effects to harvest area and to proximity of logging to streams are poorly quantified. . . road building and log skidding can increase surface soil erosion, resulting in increased sedimentation of stream substrates. . . Mass wasting and debris flows, often associated with structural failure of roads or removal of trees near drainage headwalls are the most damaging to stream habitat. . . Conversely, management activities that complement ecosystem recovery processes [such as stand restoration treatments] may help minimize long-term damage to aquatic systems. . ." (Peterson et al. 2009: 21-23).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Peterson, David L.; Agee, James K.; Aplet, Gregory H.; Dyskstra, Dennis P.; Graham, Russell T.; Lehmkuhl, John F.; Pilliod, David S.; Potts, Donald F.; Powers, Robert F.; Stuart, John D.
- **Publication date**: 2009
- **Topics addressed**: Fire effects, post-fire logging, post-fire management, salvage logging, soil disturbance.
- **Location**: Western U.S.
- **Forest Types**: (multiple coniferous forest types)
- **Forest practices examined**: General overview of potential effects of post-fire salvaging operations, including tree harvesting, fuel treatments, and associated activities.
- **Analysis methods**: Literature review.

Summary Report: Peterson et al. (2015)

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.

This study documented patterns of woody fuel succession after stand-replacing wildfires for logged and unlogged stands at 68 burned sites in Washington and Oregon. Specifically, they sampled the effects of post-fire logging on mean woody fuel loads up to 39 years after wildfire, and assessed the influence of pre-fire stand basal area on post-fire woody fuel loads. In unlogged stands, woody fuel loads were low initially, but then increased and peaked 10–20 years following wildfire. In logged stands, small and medium diameter woody fuel loads peaked immediately after logging, whereas large diameter woody fuel loads peaked 10–20 years after wildfire. In general, post-fire logging initially increased surface woody fuel loads, increasing small diameter fuel loads by up to 2.1 Mg/ha during the first 5 years after fire, and increasing medium diameter fuel loads by up to 5.8 Mg/ha during the first 7 years after fire. Surface woody fuel loads on logged sites subsequently declined, with large-diameter fuel loads declining by up to 53 Mg/ha between 6 and 39 years post-fire. Medium-diameter fuel loads declined by up to 2.4 Mg/ha between 12 and 23 years post-fire, and small-diameter fuel loads declined by up to 1.4 Mg/ha between 10 and 28 years post-fire. The logging also reduced rotten, large diameter fuel loads by up to 24 Mg/ha between 20 and 39 years after wildfire. The authors concluded that salvage logging can be used to significantly reduce surface woody fuels in regenerating forests, but results depend on such factors as: 1) volume and sizes of wood removed, 2) logging methods, 3) post-logging fuel treatments, and 4) the amount of coarse woody debris left on-site to support wildlife habitat, erosion control, and other competing management objectives.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Peterson, David W.; Dodson, Erich K.; Harrod, Richy J.
- **Publication date**: 2015
- **Topics addressed**: Ponderosa pine, Douglas-fir, post-fire salvage logging, fuel succession, forest restoration
- **Location**: eastern Washington, Oregon (68 wildfire sites/multiple national forests;)
- **Forest Types**: Ponderosa pine, Interior Douglas-fir, mixed conifer
- **Forest practices examined**: Effects of post-fire salvaging logging on downed woody fuels in predominantly dry montane forests up to 4 decades after severe wildfire.
- **Analysis methods**: Plot sampling of surface woody fuels within 255 coniferous forest stands burned during high severity wildfires between 1970 and 2007.

Summary Report: Reeves et al. (2006)

Reeves, G.H.; Bisson, P.A.; Rieman, B.E.; Benda, L.E. 2006. Postfire logging in riparian areas. Conservation Biology 20(4): 994–1004.

This article reviews the potential ecological consequences of post-fire logging in the western U.S. Fire behavior in riparian zones is complex, but many aquatic and riparian organisms exhibit a suite of adaptations that allow relatively rapid recovery after fire. Unless constrained by other factors, fish tend to rebound relatively quickly, usually within a decade after a wildfire. Additionally, fire and subsequent erosion events contribute wood and coarse sediment that can create and maintain productive aquatic habitats over time. Potential effects of post-fire logging in riparian areas depend on the landscape context and disturbance history of a site. However, available evidence suggests two key management implications: (1) fire in riparian areas creates conditions that may not require intervention to sustain the long-term productivity of the aquatic network and (2) protection of burned riparian areas gives priority to what is left rather than what is removed. Research is needed to determine how post-fire logging in riparian areas has affected the spread of invasive species and the vulnerability of upland forests to insect and disease outbreaks, and how post-fire logging will affect the frequency and behavior of future fires. The effectiveness of using post-fire logging to restore desired riparian structure and function is therefore unproven, but such projects are gaining interest with the departure of forest conditions from those that existed prior to timber harvest, fire suppression, and climate change. In the absence of reliable information about the potential consequence of post-fire timber harvest, providing post-fire riparian zones with the same environmental protections they received before they burned is justified ecologically. Without a commitment to monitor management experiments, the effects of post-fire riparian logging will remain unknown and highly contentious.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Reeves, Gordon H.., P.A. Bisson, B.E. Rieman, and L.E. Benda
- **Publication date**: 2006
- **Topics addressed**: fire behavior, riparian habitat restoration, riparian management, timber harvest, wildfire
- **Location**: Western U.S.
- **Forest Types**: General discussion only (unspecified western riparian forests)
- **Forest practices examined**: General information only on harvest practices
- **Analysis methods**: Literature review

Summary Report: Ritchie and Knapp (2014)

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: 1-6.

This study monitored surface fuels and regeneration for 10 years following high-severity wildfire and salvage in a ponderosa pine forest in northeastern California (Blacks Mountain Experimental Forest). Surface fuel accumulations were rapid, corresponding with a high rate of snag decay and subsequent breakage or windthrow. Retained pine snags exhibited the fastest rates of breakage and transition to surface fuels, while white fir and incense-cedar were much more stable for the duration of this study. Natural regeneration after salvage was scarce and did not appear to be related to treatment. Similarly, growth and survival of artificial regeneration, although highly variable between treatment units, was not related to the salvage treatment. Although the 2002 wildfire prepared a receptive seedbed, the uniformly high severity of the fire destroyed most future seed sources. As evidence, seedling densities below 10 trees acre were observed for plots that were more than 200 feet from a potential seed source. Therefore, the authors state that natural regeneration cannot be relied on to re-establish the conifer stands in the foreseeable future. In unsalvaged areas, the researchers also observed rapid accumulations of surface fuels in excess of characteristic amounts for interior ponderosa forests historically. The authors therefore concluded that one potential benefit of salvage logging would be to reduce the risk of severe fire recurring over time.

(*Note*: Also see Ritchie et al. [2013] and Knapp and Ritchie [2016] related studies for this location.)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Ritchie, Martin W.; Knapp, Eric E.
- **Publication date**: 2014
- **Topics addressed**: Timber harvest, salvage logging, ponderosa pine, biomass, snag dynamics, regeneration
- **Location**: California (Lassen National Forest [Blacks Mtn. Experimental Forest])
- **Forest Types**: Interior ponderosa pine
- **Forest practices examined**: Salvage logging treatments: 1) 25% removal of snags; 2) 50% removal of trees; 3) 75% removal of trees; 4) 100% removal of trees).
- **Analysis methods**: Fifteen plots with three replicates in each treatment; snags and regeneration were measured every two years for eight years.

Summary Report: Ritchie et al. (2013)

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.

This study quantifies the dynamics of fine fuels, standing snags, and large surface fuels over an 8-year period in relation to varying levels of post-fire salvage logging in a ponderosa pine-dominated forest in northeastern California (Blacks Mountain Experimental Forest). The researchers also documented cavity excavation by nesting birds among retained trees. The salvage area of 442 ha, including the study units, was combined with an unburned thin from below of 300 ha elsewhere on the forest for a combined removal of 33 Mg ha (green weight) in sawtimber and 27.13 Mg ha in non-sawtimber (chips). Fire-killed snags fell rapidly during the observed period, leading to elevated surface fuel levels in areas where no salvage logging was done. The 1000 h and larger surface fuels were strongly related with basal area retention level, with values ranging from 0–60 Mg/ha by year 8. However, when expressed as a percent of standing retained biomass, surface fuel accumulation was not related to treatment. In year 8, surface fuel was 81% of retained bole biomass. The retention of snags after this wildfire event provided snags for wildlife foraging and nesting habitat, but most snags fell within 8 years after the fire. White fir snags were more stable than pine and appeared to be used with greater frequency than pine for cavity excavation by nesting birds. The authors conclude by stating that post-fire management should give special consideration to the retention of large diameter snags in ponderosa pine forests, especially since large trees might already be lacking in previously harvested areas.

(*Note*: Also see Ritchie and Knapp [2014] and Knapp and Ritchie [2016] related studies for this location.)

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Ritchie, M.W.; Knapp, E.E.; Skinner, C.N.
- **Publication date**: 2013
- **Topics addressed**: Coarse woody debris, snag dynamics, salvage logging, wildfire
- **Location**: California (Lassen National Forest [Blacks Mountain Experimental Forest])
- **Forest Types**: ponderosa pine, white fir,
- **Forest practices examined**: Salvage logging thin from below prescription: combined removal of 33 Mg ha (green weight) in sawtimber and 27.13 Mg ha in non-sawtimber (chips); results may be partially applicable to dry-site riparian forests.
- **Analysis methods**: Study was a designed experiment with harvest prescriptions for snag retention levels ranging from 0% to 100%; observations of standing snags and surface fuels were made 2, 4, 6, and 8 years post-fire.

Summary Report: Robichaud and Ashmun (2013)

Robichaud, P.R.; Ashmun, L.E. 2013. Tools to aid post-wildfire assessment and erosion mitigation treatment decisions. International Journal of Wildland Fire 22: 95−105.

This study reviews how post-fire research over the past decade has improved understanding of wildfire's effects on soil, hydrology, erosion, and erosion-mitigation treatment effectiveness. Several tools to assist land managers with post-wildfire assessment and treatment decisions are available. These include predictive models, research syntheses, equipment and methods for field measurements, reference catalogues and databases of past-practice, and spreadsheets for calculating resource valuation and cost–benefit analysis. These tools provide relevant science to post-fire assessment teams and land managers in formats that often can be directly entered into assessment and treatment decision-making protocols. Providing public access to these tools through the Internet not only has increased their dissemination, but also has allowed them to be updated and improved as new knowledge and technology become available. The use of these science-based tools has facilitated a broader application of current knowledge to post-fire management in the United States and in other fire-prone areas around the world.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Robichaud, Peter; Ashmun, Louise
- **Publication date**: 2013
- **Topics addressed**: Burn severity, erosion modeling, remote sensing, resource valuation.
- **Location**: Western U.S.
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about available management tools to aid decision making about soil erosional processes and mitigation treatments.
- **Analysis methods**: Literature review.

Summary Report: Robichaud et al. (2006)

Robichaud, P.R.; Lillybridge, T.R.; Wagenbrenner, J.W. 2006. Effects of postfire seeding and fertilizing on hillslope erosion in north-central Washington, USA. Catena 67: 56-67.

This study examined the effectiveness of post-fire seeding and fertilization on vegetative cover on steep, severely burned hillslopes on several study sites that were severely burned by the 1998 North 25 Fire (Wenatchee National Forest). Total precipitation was below average during the four-year study period, and most erosion occurred during short duration, moderate intensity summer rainfall events. The overall first year mean erosion rate was 16 Mg ha^{-1} yr^{-1}, and this decreased significantly in the second year to 0.66 Mg ha^{-1} yr^{-1}. There were no significant differences in erosion rates between treatments. In the first year, the seeded winter wheat provided 4.5% canopy cover, about a fourth of the total canopy cover, on the seeded plots; however, the total canopy cover on the seeded plots did not differ from the unseeded plots. The below average precipitation in the spring after seeding may have affected the winter wheat survival rate. In the fourth year of the study, the mean canopy cover in the fertilization treatment plots was 74%, and this was greater than the 55% mean canopy cover in the unfertilized plots ($p = 0.04$); however, there was no accompanying reduction in erosion rate for either the seeding or fertilization treatments. Revegetation by naturally occurring species was apparently not impacted by seeding during the four years of this study. The pH of the sediment as well as the concentrations of NO3–N, NH4–N, and K was not affected by seeding or fertilizing. The nutrient loads in the eroded sediment were minimal, with most of the nutrient loss occurring in the first postfire year. These results confirm that seeding success is highly dependent on rainfall intensity, amounts, and timing, and that soil nutrients lost in eroded sediments are unlikely to impair the site productivity.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Robichaud, P.R.; Lillybridge, T.R.; Wagenbrenner, J.W.
- **Publication date**: 2006
- **Topics addressed**: Wildfire, hillslope erosion, mitigation practices, post-fire seeding, post-fire fertilizer application, silt fence.
- **Location**: Washington (Okanogan–Wenatchee National Forest)
- **Forest Types**: (unspecified mixed conifer)
- **Forest practices examined**: Study examine several erosion mitigation practices, such as grass seeding, silt fencing, and application of fertilizer to enhance and accelerate post-fire vegetative cover.
- **Analysis methods**: Study plots were located with four randomly applied treatments: seed (winter wheat, Triticum estivum), fertilizer, seed and fertilizer, and untreated control; sediment fences were installed at the base of each plot to measure erosion rates and sample the eroded sediments; precipitation amounts and intensities, surface cover, canopy cover, and nutrient concentrations in the eroded sediments were measured for four years after the fire.

Summary Report: Robichaud et al. (2013)

Robichaud, P.R.; Lewis, S.A.; Wagenbrenner, J.W.; Ashmun, L.E.; Brown, R.E. 2013. Post-fire mulching for runoff and erosion mitigation. Part I: Effectiveness at reducing hillslope erosion rates. Catena 105: 75–92.

This study examined the effects of mulching with wheat straw, wood strands, and hydromulch on hill-slope erosion within the perimeters of 4 severe wildfires in southeastern Washington, northern and central Idaho, and west-central Colorado (one of which was the 2005 School Fire in eastern Washington). Storms with similar rainfall intensities produced nearly an order of magnitude less sediment on the control plots in the second post fire year as compared to the first post-fire year. Large storms produced sediment on all fires in all years where they occurred; however, sediment yields produced by large storms that occurred in the first post-fire year were larger than sediment yields from equivalent storms that occurred in later years at the same fire. Sediment yields decreased as ground cover increased. All mulch treatments increased total ground cover to more than 60% immediately after application, but mulch longevity varied substantially. The wood strand mulch was the most long-lived treatment and was observed in ground cover assessments throughout the study period (4 and 7 years) at two fire sites. The wheat straw mulch decreased nearly twice as fast as the wood strand mulch, and no hydromulch was detected after the first post-fire year on either fire where it was tested. Mulch treatment effectiveness varied when data were analyzed separately for each fire. Wood strand mulch reduced sediment yields at both fires where it was tested, wheat straw mulch reduced sediment yields at 2 of the 4 fires where it was applied, and the hydromulch tested at 2 fires did not reduce sediment yields on either site. When the data were normalized and analyzed by treatment across all fires, wood strand mulch reduced sediment yields for the first 4 post-fire years, but wheat straw mulch and hydromulch did not significantly reduce sediment yields in any post-fire year. Wood strand mulch persisted the longest during the 7-year monitoring period, wheat straw mulch decomposed about twice as fast as the wood strands, and hydromulch decomposed within the first post-fire year. Tree needle cast and seeding treatments were generally ineffective for mitigating post-fire runoff and erosion.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Robichaud, Peter R.; Lewis, Sarah A.; Wagenbrenner, Joseph W.; Ashmun, Louise E.; Brown, Robert E.
- **Publication date**: 2013
- **Topics addressed**: Post-fire mulching (wheat straw, wood strands, hydromulch)
- **Location**: Washington (Umatilla National Forest); Idaho (Boise N.F, Idaho Panhandle N.F.); Colorado (Pike and San Isabel National Forests)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, grand fir, subalpine fir
- **Forest practices examined**: Post-fire mulching with wheat straw, wood strands, or hydromulch; effects of tree needle cast and seeding with native seed were also studied.
- **Analysis methods**: Rainfall, ground cover, and soil water repellency were measured in severely burned plots within the perimeters of 4 wildfires after the above treatments.

<u>Summary Report: Russell et al. (2006)</u>

Russell, R.E.; Saab, V.A.; Dudley, J.G.; Rotella, J.J. 2006. Snag longevity in relation to wildfire and postfire salvage logging. Forest Ecology and Management 232: 179-187.

This study monitored Douglas-fir and ponderosa pine snags beginning at post-fire year 10 and continuing for 8–9 years at 2 fire sites in southwestern Idaho (1992 Foothills Fire; 1994 Star Gulch Fire). The researchers examined the influence of salvage logging and stand-scale factors (e,g, species, size) and large-scale factors (e.g. pre-fire crown closure, burn severity) on annual snag persistence. Small-scale variables (e.g., age, height, dbh, species, decay, snag density) were the best predictors of snag persistence following wildfire. In contrast, the large-scale variables such as fire severity were less predictive. Persistence was shorter for ponderosa pine than Douglas-fir snags. Additionally, smaller snags in plots with fewer snags fell sooner than did larger snags in more dense stands. Snag age was also an important variable, that is, older snags were more likely to fall during the monitoring period. Snag longevity (the total amount of time the snag remained standing) also varied between the two sites. The predicted half-life of a ponderosa pine snag was 7–8 years in salvage-logged plots and 9–10 years in unlogged plots. The predicted half-life of Douglas-fir snags was longer than ponderosa pine, at 12–13 years in the salvage logged burn versus 15–16 years in the unlogged burn. On partially logged sites, half the snags >23 cm dbh were removed. The primary effects of salvage logging appeared to be the reduction of the average snag size (diameter and height) and density, which in turn reduced the subsequent longevity of individual snags. The main effects of the partial-salvage logging appeared to be a reduction in snag density and mean size, which therefore promoted a reduction in mean persistence time. The authors concluded that management practices that preserve dense stands of snags will promote longer-term persistence of suitable snags as nesting habitat for cavity-nesting birds.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Russell, Robin E.; Saab, Victoria A.; Dudley, Jonathan G.; Rotella, Jay J.
- **Publication date**: 2006
- **Topics addressed**: Postfire salvage logging; Ponderosa pine; Douglas-fir; Snag longevity; Idaho; Wildfire; Snag dynamics
- **Location**: Idaho (Boise National Forest)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir
- **Forest practices examined**: Study examined snag retention and longevity rates on partially salvage logged sites; prescription removed half of standing snags (>23 cm dbh).
- **Analysis methods**: Plot sampling and remote sensing data were used to describe biophysical settings and interpret fire severity; snags were monitored within for 8–9 years on partially salvage logged sites versus unlogged sites.

Summary Report: Sessions et al. (2004)

Sessions, J.; Bettinger, P.; Buckman, R.; Newton, M.; Hamann, J. 2004. Hastening the return of complex forests following fire: The consequences of delay. Journal of Forestry 102: 38-45.

This paper discusses possible management alternatives for hastening the regrowth of structurally complex conifer-dominated forests based results from pre- and post-fire landscapes. For example, the authors examine the likely consequences and tradeoffs of natural ecosystem recovery versus management interventions. The authors state that generally only a narrow window of opportunity exists to promote cost-effective restoration of conifer forests, while simultaneously reducing insect- and fire risks and salvaging economic value to help offset restoration costs. Delays in decision making and implementation will likely destine much of the most intensely burned areas to cycles of shrubs, hardwoods, and recurring fires for many decades. Regarding potential costs versus benefits of natural- versus management-promoted restoration, the authors state that, "Researchers have found enormous variability in both the effects of natural processes and the consequences of human intervention on watersheds. For example, McIver and Starr (2001) find that human intervention can reduce adverse watershed impacts or be largely neutral as well as aggravate impacts. Following monitoring on the 1987 Silver Fire within the Biscuit Fire area, Kormeier and Park (1995) concluded that "the lack of adverse impacts from salvage logging is attributed to protection of riparian areas, improved road construction practices, and minimizing disturbance through the use of helicopter logging." (Sessions et al. 2004: 44). The authors also opine that, "The Biscuit Fire is not unique. Society faces similar choices after virtually every large burn in dry, fire-prone forests with high accumulations of fuels. The recent 91,000-acre Booth and Bear Fire on the Deschutes National Forest proves that point again in Oregon. The consequences of delay in hastening forest regrowth are large, important, and real. (Sessions et al. 2004: 45).

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Sessions, John; Bettinger, Pete; Buckman, Robert; Newton, Mike; Hamann, Jeff.
- **Publication date**: 2004
- **Topics addressed**: Biodiversity; forest health; Northwest Forest Plan; old-growth; policy; restoration
- **Location**: Oregon (Rogue River – Siskiyou National Forest [Biscuit Fire])
- **Forest Types**: Pacific Douglas-fir, Pacific ponderosa pine, grand fir
- **Forest practices examined**: Cost/benefit estimates for forest regeneration practices (seeding, planting) as potential interventions in post-Biscuit Fire severely burned terrain; this study did not examine forest practices *per se* but provided potentially useful information about the range of options for post-fire restoration in that locale.
- **Analysis methods**: Study used inventory data, remotely sensed fire severity maps, and classified vegetation maps, and projected forest growth and yield with a simulation model (Organon) to examine regeneration costs associated with reseeding.

Summary Report: Silins et al. (2009)

Silins, U.; Stone, M.; Emelko, M.B.; Bladon, K.D. 2009. Sediment production following severe wildfire and post-fire salvage logging in the Rocky Mountain headwaters of the Oldman River Basin, Alberta. Catena 79(3): 189–197.

This study examines the effects of wildfire and post-fire salvage logging in seven watersheds of the Oldman River Basin, Alberta. Stream discharges reflected runoff regimes consistent with high regional precipitation and the high relief physiographic setting of the study area. Suspended sediment concentrations and yields were significantly higher in both burned and post-fire salvage logged watersheds than in unburned watersheds, and were strongly influenced by topographic and hydro-climatic controls. Sediment availability was much higher in both the burned and post-fire salvage logged watersheds but it varied strongly with flow condition, particularly during the snowmelt freshet and high flow events. Post-fire salvage logging increased mass wasting and created more effective terrestrial sediment transport networks to stream channels, and produced more sediment than burned watersheds without salvage logging. The authors conclude that salvage logging accelerate sedimentation processes because logging often occurs soon after wildfires, when forests are often highly vulnerable to soil impacts. However, the authors state that only limited research had occurred to date, and that more studies were needed to describe potential impacts of post-fire salvage logging.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Silins, Uldis; Stone, Michael; Emelko, Monica B.; Bladon, Kevin D.
- **Publication date**: 2009
- **Topics addressed**: post-fire soil erosion and sedimentation, salvage logging, riparian habitat restoration, riparian management
- **Location**: Alberta, Canada (Crowsnest Pass area)
- **Forest Types**: lodgepole pine, Englemann spruce-subalpine fir
- **Forest practices examined**: Study did not indicate which salvage logging methods had been used (but presumably clearcutting was the preferred salvage method in those lodgepole pine and spruce-fir forest types).
- **Analysis methods**: Seven watersheds with various levels of land disturbance (burned, post-fire salvage logged, unburned) were instrumented and monitored for four years to measure stream discharge, sediment concentration, and sediment yields for a range of characteristic flow periods (baseflow, spring melt, and stormflow).

Summary Report: Silins et al. (2014)

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.S.; and Tichkowsky, I. 2014. Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, macroinvertebrate, and fish productivity. Ecohydrology 7: 1508-1523.

This study characterizes the ecological linkages between phosphorus (P), stream algae, benthic invertebrates, and fish communities for four years after a severe wildfire in high elevation forests of the northern Rocky Mountains. Mean concentrations of all forms of P were 2 to 13 times greater in burned and post-fire salvage-logged streams than in unburned streams. Post-disturbance recovery of P was slow with differences in P discharge relationships still evident 5 years after the fire. Coupled P and sediment interactions were likely responsible for slow recovery of P regimes in fire-disturbed watersheds. P loading was associated with strong ecological responses in stream biota. Annual algal productivity was 5 to 71 times greater in streams in burned watersheds than in reference watersheds and persisted for 5 years after the fire. Elevated algal production was associated with strong differences in benthic invertebrate community structure, including greater invertebrate densities, biomass, species diversity, and shifts in species composition. Monotonic shifts in invertebrate stable carbon and nitrogen isotope ratios indicated increased consumption of autochthonous food sources and effects on energy pathways for invertebrates from fire-affected streams. Wildfire-related changes at lower trophic lead to increases in size (weight and length) and growth rate (weight : age ratios) of cutthroat trout (Oncorhynchus clarki). This cascading series of effects of wildfire on stream productivity (primary production, secondary invertebrate consumers, and fish) may result in long-lived legacies of wildfire because of the slow recovery of P regimes. The authors conclude that both wildfires and salvage logging produce numerous and complex ecohydrological effects on biotic and abiotic communities and processes that are still not well understood.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Silins, Uldis; Bladon, Kevin D.; Kelly, Erin N.; Esch, Evan; Spence, John R.; Stone, Michael; Emelko, Monica B.; Boon, Sarah; Wagner, Michael J.; Williams, Chris H.S., and Tichkowsky, Ian.
- **Publication date**: 2014
- **Topics addressed**: post-fire hydrology, water quality, nutrient runoff, salvage logging, stream biota, fish habitat, riparian habitat restoration, riparian management,
- **Location**: Alberta, Canada (Crowsnest Pass area)
- **Forest Types**: Lodgepole Pine, Engelmann spruce, Subalpine Fir
- **Forest practices examined**: Study did not examine forest practices *per se* but provided potentially useful background information about riparian ecosystems
- **Analysis methods**: Plot sampling of stream nutrients and various hydrological biota in burned, unburned, and salvage logged terrain.

Summary Report: Skinner (2003)

Skinner, C.N. 2003. A tree-ring based fire history of riparian reserves in the Klamath Mountains. *In*: California Riparian Systems: Processes and Floodplains Management, Ecology, and Restoration. Riparian habitat and floodplains conference Proceedings. March 12-15, 2001, Sacramento, CA. Phyllis M. Faber, Editor. Riparian Habitat Joint Venture, Sacramento, CA. p. 116-119.

This article describes a preliminary fire history investigation in riparian reserves along the Shasta-Trinity divide in the Klamath Mountains, northern California (*note*: Skinner apparently did not publish any subsequent reports after this preliminary study.) The author stated that, at that time, little fire history information was available for riparian environments despite their ecological importance, creating uncertainty about the ecological role and management of fire in riparian environments. Although ranges of fire return intervals (FRIs) were similar for riparian reserve- and nearby upland sites, the median FRIs were approximately double in the riparian reserve sites compared to the upland sites. These data suggest that FRIs in riparian reserves may be more variable and longer than in adjacent uplands. Riparian areas may have enhanced the spatial and temporal diversity of landscapes by acting as occasional barriers to many low- and moderate-severity fires. The author concludes by saying that more information on riparian fire regimes is needed to help forest managers develop comprehensive and ecologically appropriate management plans for riparian reserves in California.

Additional information requested by SAGE:

- **Type of item**: Article in conference proceedings
- **Author(s)**: Skinner, Carl N.
- **Publication date**: 2003
- **Topics addressed**: fire history in riparian forests
- **Location**: California (Shasta-Trinity National Forests)
- **Forest Types**: Mixed conifer riparian and upland forest in Douglas-fir and Douglas-fir/ponderosa pine types
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about riparian fire regimes.
- **Analysis methods**: Fire scarred stumps in a paired riparian/upland design from five sites; fire return intervals were determined from fire scars on stumps in several riparian reserve sites along perennial streams.

Summary Report: Slesak et al. (2015)

Slesak, R.A.; Schoenhotz, 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.

This study in southwestern Oregon compares hillslope erosion two and three years following wildfire between salvage logged sites on private land and unsalvaged (control) sites on nearby BLM land. The primary objective was to determine if post-fire salvage logging increases surface soil erosion by comparing areas with and without salvage logging for two years following the 2002 Timbered Rock Fire. A secondary objective was to determine if any relationship exists between slope or vegetation cover and erosion rates in this landscape. Mean erosion was 0.02 and 0.05 Mg/ha/yr for 2004–05, and 0.04 and 0.14 Mg/ha/yr for 2005–06, for non-salvage and salvage-logged areas, respectively. Vegetation cover was much lower in the salvage-logged areas (5–20%) than the non-salvage areas (70–80%), and was negatively correlated with erosion in the first year of measurement. Increased erosion at salvage-logged plots is most likely associated with competing vegetation control and slash removal, but may also have been caused by some other management factor or pre-existing condition that differed between measurement locations on private and public land. Increased erosion in the second year of measurement at all sites was associated with increased rainfall and storm frequency. Results suggested that erosion potential is often highest immediately following fire, on both salvaged and non-salvage lands. The authors state that a frequently negative correlation between vegetation cover and erosion potential often exists on sites subject to wildfire, steep slopes, and frequent storms. Although control of competing vegetation may be important for successful tree establishment after wildfire, site preparation techniques (such as herbicide application) that inhibit vegetation growth may contribute to increased hillslope erosion in high-risk areas. Allowing vegetation re-growth in areas with high erosion potential following salvage harvesting therefore may be advisable, and retention of slash and other erosion control techniques may help reduce erosion potential if vegetation control is needed following salvage operations.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Slesak, Robert A.; Schoenhotz, Stephen. H..; Evans, Daniel
- **Publication date**: 2015
- **Topics addressed**: Hillslope erosion on salvage-logged versus non-salvaged sites for several years following wildfire
- **Location**: Oregon (BLM Medford District Office and nearby private lands)
- **Forest Types**: Interior Douglas-fir
- **Forest practices examined**: Post-fire salvage logging; mechanical soil disturbance
- **Analysis methods**: Sediment was collected from silt fences placed in locations with relatively uniform hillslope surface conditions beginning 2 years post-fire and monitored for two years on salvage logged sites and non-salvaged sites.

Summary Report: Story et al. (2003)

Story, A.; Moore, R.D.; MacDonald, J.S. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Research 33: 1383-1396.

This study in the central interior of British Columbia examined water temperature patterns and their physical controls downstream from forest management activities for 2 small clearing-heated streams in shaded reaches with different buffer treatments. For both reaches in the study, downstream cooling of up to 4°C had been observed during daytime over distances of ~200 m. Radiative and convective exchanges of energy at heavily shaded sites on both reaches represented a net input of heat during most afternoons and therefore could not explain the observed cooling. In one stream, the greatest downstream cooling occurred when streamflow at the upstream site dropped below about 5 L/s. At those times, temperatures at the downstream site were controlled mainly by local inflow of groundwater, because the warmer water from upstream was lost by infiltration in the upper 150 m of the reach. Warming often occurred in the upper subreach, where cool groundwater did not interact with the channel. At the second stream, creek temperature patterns were comparatively stable. Energy balance estimates from one afternoon suggested that groundwater inflow caused about 40 percent of the ~3°C gross cooling effect in the daily maximum temperature, whereas bed heat conduction and hyporheic exchange caused about 60%.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Story, A.; Moore, R.D.; MacDonald, J.S.
- **Publication date**: 2003
- **Topics addressed**: Riparian zones, riparian buffer, stream temperature, timber harvest
- **Location**: Central interior British Columbia, Canada
- **Forest Types**: Hybrid white spruce, subalpine fir, lodgepole pine.
- **Forest practices examined**: Study examined the potential effects of variable retention harvesting (itemized below) on riparian buffers and stream temperatures.
- **Analysis methods**: This study measured stream temperature, streamflow, and microclimate and compared between a high-retention riparian buffer (harvest only >30 cm dbh trees) and a low-retention buffer (harvest all trees >15 cm).

Summary Report: Thompson et al. (2007)

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 104: 10743-10748.

Thompson et al. (2007) studied fuel dynamics in managed versus unmanaged Douglas-fir forests in the Biscuit burn area of southwestern Oregon. The sample area had been burned by an initial wildfire in 1987, and some portions were subsequently salvage logged and replanted before reburning during the 2002 Biscuit Fire. Areas that burned severely in 1987 tended to reburn at high severity in 2002, after controlling for the influence of several topographical and biophysical variables. Areas unaffected by the initial fire tended to burn at the lowest severities in 2002. Areas that were salvage-logged and planted after the initial fire burned more severely than comparable unmanaged areas, suggesting that fuel conditions in conifer plantations can increase fire severity despite the removal of large woody fuels. Specifically, the authors found that the Biscuit Fire tended to burn at relatively high severity in young naturally regenerated stands and even more severely in young conifer plantations of comparable age and fire history. That is, the tree planting treatments created dense and/or continuous fuels that are prone to high severity fire during favorable burning conditions. The researchers therefore concluded that young forests, whether naturally or artificially regenerated, are vulnerable to positive feedback cycles of high severity fire, creating more early-successional vegetation and delaying or precluding the return of historical mature-forest composition and structure.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Thompson, Jonathan R.; Spies, Thomas A.; Ganio, Lisa M.
- **Publication date**: 2007
- **Topics addressed**: public land management; salvage-logging; Biscuit Fire; Landsat; landscape ecology
- **Location**: Oregon (Rogue-Siskiyou National Forest; Biscuit Fire)
- **Forest Types**: Pacific Douglas-fir
- **Forest practices examined**: Study interpreted reburn potential on sites that burned with varying fire severities during wildfires in 1987 and 2002, and that were subsequently salvage logged then planted.
- **Analysis methods**: This study uses remotely-sensed estimates of fire severity that were validated with aerial photo interpretation.

Summary Report: Wagenbrenner and Robichaud (2014)

Wagenbrenner, J.W.; Robichaud, P.R. 2014. Post-fire bedload sediment delivery across spatial scales in the interior western United States. Earth Surface Processes and Landforms 39: 865-876.

This study documents relationships for post-fire bedload sediment delivery rates in the western United States. Sediment yields and sediment delivery ratios (SDRs; sediment delivered at the catchment scale divided by the sediment delivered from a plot nested within the catchment) were related to site factors including rainfall characteristics, area, length, and ground cover. Unit-area sediment yields significantly decreased with increasing area in 5 of the 6 sites. The annual SDRs ranged from 0.0089 to 1.15 and these were more closely related to the ratio of the plot lengths than the ratio of plot areas. The developed statistical relationships will help quantify post-fire sediment delivery rates across spatial scales in the interior western United States and develop process-based scaling relationships.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wagenbrenner, J.W.; Robichaud, P.R.
- **Publication date**: 2014
- **Topics addressed**: erosion; hillslope; catchment; sedimentation; rainfall intensity
- **Location**: Western U.S.
- **Forest Types**: Interior ponderosa pine, interior Douglas-fir, grand fir
- **Forest practices examined**: Study did not examine forest practices but provided potentially useful background information about riparian ecosystems.
- **Analysis methods**: This study is a meta-analysis that evaluates rainfall and sediment yield across spatial scales up to 117 ha in size at 8 study sites across the western U.S.

Summary Report: Wagenbrenner et al. (2016)

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.

Wagenbrenner et al. (2016) conducted rill experiments in severely burned montane forest terrain that was salvage logged in eastern Washington, northern Montana, and southern British Columbia. The study compared results from logged and unlogged forests to evaluate the effectiveness of best management practices on rill overland flow and sediment production rates after ground-based salvage logging. The authors found that ground-based logging using heavy equipment compacted soil, reduced soil water repellency, and reduced vegetation cover. Vegetation recovery rates were slower in most logged areas than the controls. Runoff rates were higher in the skidder and forwarder plots than their respective controls in the Montana and Washington sites in the year that logging occurred, and the difference in runoff between the skidder and control plots at the British Columbia site was nearly significant ($p = 0.089$). Most of the significant increases in runoff in the logged plots persisted for subsequent years. The type of skidder, the addition of slash, and the amount of forwarder traffic did not significantly affect the runoff rates. Across the three sites, rill sediment fluxes were 5–1900% greater in logged plots than the controls in the year of logging, and the increases were significant for all logging treatments except the low use forwarder trails. There was no difference in the first-year sediment fluxes between the feller buncher and tracked skidder plots, but the feller-buncher fluxes were lower than the values from the wheeled skidder plots. Manually adding slash after logging did not affect sediment flux rates. There were no significant changes in the control sediment fluxes over time, and none of the logging equipment impacted plots produced greater sediment fluxes than the controls in the second or third year after logging. The study results indicate that salvage logging increases the risk of sedimentation regardless of equipment type and amount of traffic, and that specific best management practices are needed to mitigate the hydrologic impacts of post-fire salvage logging.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wagenbrenner, J.W.; Robichaud, P.R.; Brown, R.E.
- **Publication date**: 2016
- **Topics addressed**: Salvage logging, wildfire, runoff, soil compaction, soil water repellency, sediment
- **Location**: Eastern Washington (2005 School Fire), northern Montana (2006 Red Eagle Fire), south-central B.C. (2009 Terrace Mountain Fire)
- **Forest Types**: Mixed-conifer montane (e.g., lodgepole pine, interior Douglas-fir).
- **Forest practices examined**: Study examined potential erosional impacts caused by ground-based salvage logging with heavy equipment (feller-bunchers, tracked and wheeled skidders, and wheeled forwarders).
- **Analysis methods**: Sampling after simulated rill experiments to measure soil compaction, water repellency, and vegetation cover in salvage logged- versus control sites.

Summary Report: Wagenbrenner et al. (2015)

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.

This article summarizes data from recently burned sites in Washington, Montana, and Colorado to evaluate potential effects of ground-based salvage logging (skidder, feller-buncher) on: 1) surface cover (live vegetation, litter, dead wood), soil water repellency, and vegetative regrowth, 2) sediment production at the plot and catchment scales, and 3) soils, vegetation recovery, and sediment production after logging slash has been applied to skid trails. The skidder and feller-buncher plots generally had greater compaction, less soil water repellency, and slower vegetative regrowth than the control plots. Sediment production from the skidder plots was 10–100 times larger than that from the controls. The slightly less compacted feller-buncher plots produced only 10–30% as much sediment as the skidder plots, but regrowth was similarly inhibited. Adding slash to skid trails increased total ground cover by 20–30 percent and reduced the sediment yields by 5–50 times when compared to the untreated skidder plots. Vegetative regrowth and sediment production rates varied widely among the four study areas, largely due to differences in rainfall and soil properties. The susceptibility to surface runoff and erosion after high severity fires suggests that areas disturbed by ground-based salvage logging need additional mitigation practices. Salvage logging did not have as large an effect on ground cover, soil water repellency, or runoff and sediment production at the swale scale because much of the area was not directly affected by the logging equipment. The greater sensitivity of burned landscapes to surface runoff and erosion indicates that site-specific best management practices—particularly for areas disturbed by logging equipment—are needed to minimize the adverse impacts of post-fire salvage logging.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wagenbrenner, Joseph W.; MacDonald, Lee H.; Coats, Robert N.; Robichaud, Peter R.; Brown, Robert E.
- **Publication date**: 2015
- **Topics addressed**: Post-fire salvage logging, soil erosion, hydrophobic soils, forest regeneration
- **Location**: Washington (Okanagan-Wenatchee National Forest); Montana (Blackfeet Indian Reservation); Colorado (Pike and San Isabel National Forests)
- **Forest Types**: Interior ponderosa pine, Interior Douglas-fir, lodgepole pine
- **Forest practices examined**: Ground-based salvage logging with skidders, feller-bunchers.
- **Analysis methods**: Post-fire soil erosion was evaluated by comparing data from plots in skid trails, feller-buncher trails, and slash-covered skid trails to nearby unlogged control plots; data were collected 0-2 years before logging and 2-8 years after logging.

Summary Report: Wagner et al. (2014)

Wagner, M.J.; Bladon, K.D.; Silins, U.; Williams, C.H.S.; Martens, A.M.; Boon, S.; MacDonald, R.J.; Stone, M.; Emelko, M.B.; Anderson, A. 2014. Catchment-scale stream temperature response to land disturbance by wildfire governed by surface subsurface energy exchange and atmospheric control. Journal of Hydrology 517: 28-338.

This study examined wildfire's effect on stream temperature dynamics in post-fire salvage logged versus unburned (control) drainages in the Crowsnest Pass area, Alberta, Canada. Mean annual stream temperature (Ts) was elevated 0.8–2.1 °C in the burned and post-fire salvage logged streams compared to the unburned streams from 2004 to 2010. Mean daily maximum Ts was 1.0–3.0 °C warmer and mean daily minimum Ts was 0.9–2.8 °C warmer in the burned and post-fire salvage logged streams compared to the unburned catchments. The effects of wildfire on the thermal regime of the burned catchments were persistent and trend analysis showed no apparent recovery during the study period. Temporal patterns of Ts were strongly associated with seasonal variability of surface and groundwater interactions and air temperature. Advective heat fluxes between groundwater and surface water were likely the dominant controls on Ts, though the strength of these advective controls varied among catchments. These results highlight the importance of simultaneous catchment-scale and process-focused research to better elucidate the physical drivers influencing Ts response to disturbance. The authors conclude by calling for more research, because the potential impacts of wildfire and salvage logging on stream temperatures are not well understood.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wagner, Michael J.; Bladon, Kevin D.; Silins, Uldis; Williams, Chris H.S.; Martens, Amanda M.; Boon, Sarah; MacDonald, Ryan J.; Stone, Michael; Emelko, Monica B.; Anderson, Axel.
- **Publication date**: 2014
- **Topics addressed**: Forest disturbance, headwaters, Rocky Mountains, salvage harvesting, stream temperature, wildfire
- **Location**: Alberta, Canada (Crowsnest Pass area)
- **Forest Types**: lodgepole pine, Engelmann spruce, subalpine fir
- **Forest practices examined**: Study examined potential effects on stream temperatures after post-fire salvage harvesting (unspecified harvest system, but presumably clearcutting).
- **Analysis methods**: Seven headwater catchments with varying levels of disturbance (burned, post-fire salvage, unburned) were instrumented to measure streamflow, stream temperature, and meteorological conditions over a 7-year period.

Summary Report: Wondzell (2001)

Wondzell, S.M. 2001. The influence of forest health and protection treatments on erosion and stream sedimentation in forested watersheds of eastern Oregon and Washington. Northwest Science 75: 128-140.

This article reviews potential effects of forest health and protection treatments on soil physical processes, such as sediment production and channel formation, and on riparian vegetation and processes. Wildfires can greatly increase erosion risks. Conversely, maintenance of dense riparian vegetation can help regulate and reduce the amount of sediment reaching streams, but this effect is strongly dependent on geomorphic setting. The largest risk of accelerated erosion is expected from ground-disturbing activities during fuels reduction treatments, such as construction of roads and firebreaks for thinning or salvage logging. Intense grazing has changed composition and cover of riparian vegetation, leading to bank erosion and/or widening or incision of stream channels. Maintenance of substantial streamside buffers and undisturbed riparian vegetation can serve as effective measures to mitigate erosional processes. Improved grazing prescriptions can promote positive changes in riparian vegetation, but response of channel morphology will likely be slow. Most studies as of 2001 had been conducted at the site or small watershed scale. Consequently, conclusions at these scales are generally well supported by available literature. The author states that well designed small-scale treatments often pose little risk to watersheds because the treatment effects usually diminish substantially with increasing distance from those sites. However, more research is needed to help managers better understand the cumulative effects on watersheds of various management treatments over time, and to document the effects of large-scale disturbances such as those produced by wildfires and prescribed burning.

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wondzell, Steven M.
- **Publication date**: 2001
- **Topics addressed**: Erosion; fire; sediment; overland flow; debris slides; debris flows; forest health/protection treatments, grazing
- **Location**: Eastern Washington, Eastern Oregon
- **Forest Types**: (multiple unspecified)
- **Forest practices examined**: Article provides a general overview of forest health and protection practices such as thinning, mechanical fuel reduction, salvage logging, and livestock grazing.
- **Analysis methods**: Literature review

Summary Report: Wondzell and King (2003)

Wondzell, S.M. and J.G. King. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain Regions. Forest Ecology and Management 178: 75-87.

This study provides and overview of the effects of fire on erosional processes in the western United States by examining the physical processes driving erosion, sediment transport, and deposition and comparing between the Pacific Northwest and Rocky Mountains. Wildfire can accelerate erosion by reducing/removing vegetative cover, which serves as a key factor in controlling erosion. Large local and regional differences exist in the relative importance of varying erosional processes, due to differences in prevailing climate, geology and topography, differences in the degree to which vegetation regulates erosional processes, and differences in the types of fire effects on vegetative cover. Surface erosion, caused by overland flow, is a dominant response to wildfire in the Interior Northwest and Northern Rocky Mountains. A comparison of measured postfire infiltration rates and long-term records of precipitation intensity suggest that surface runoff from infiltration-excess overland flow should also occur in the Coastal and Cascade Mountains after fires, but this has not been documented in the literature. Debris slides and debris flows occur more frequently after wildfire. Debris flows can be initiated from either surface runoff or from soil-saturation caused debris slides. In the Pacific Northwest, debris flows are typically initiated as debris slides, caused by soil saturation and loss of soil cohesion as roots decay following fire. In the Interior Northwest, overland-flow-caused and debris-slide-caused debris flows often occur after wildfire. Surface erosion, debris slides, and debris flows often occur during intense storms. Therefore, their probability of occurrence depends upon the probability of intense storms occurring during a 5 to 10-year window of increased susceptibility to surface erosion and mass wasting following intense wildfire. The authors also state that major knowledge gaps exist in part because: 'Most studies examine the effects of either (1) severe wildfire followed by large to extreme storms that generate episodic erosion, or (2) clearcut harvesting followed by prescribed burning of residual logging slash. Therefore, the potential effects of lower severity wildfires, and associated practices like salvage logging and site preparation, remain poorly understood.'

Additional information requested by SAGE:

- **Type of item**: Peer-reviewed publication
- **Author(s)**: Wondzell, Steven L.; King, John G.
- **Publication date**: 2003
- **Topics addressed**: Erosion; fire; sediment; overland flow; debris slides; debris flows
- **Location**: Pacific Northwest, Rocky Mountains
- **Forest Types**: (unspecified)
- **Forest practices examined**: Study did not examine specific forest practices but provided potentially useful background information about post-fire soil erosion processes and riparian ecosystems
- **Analysis methods**: Literature review