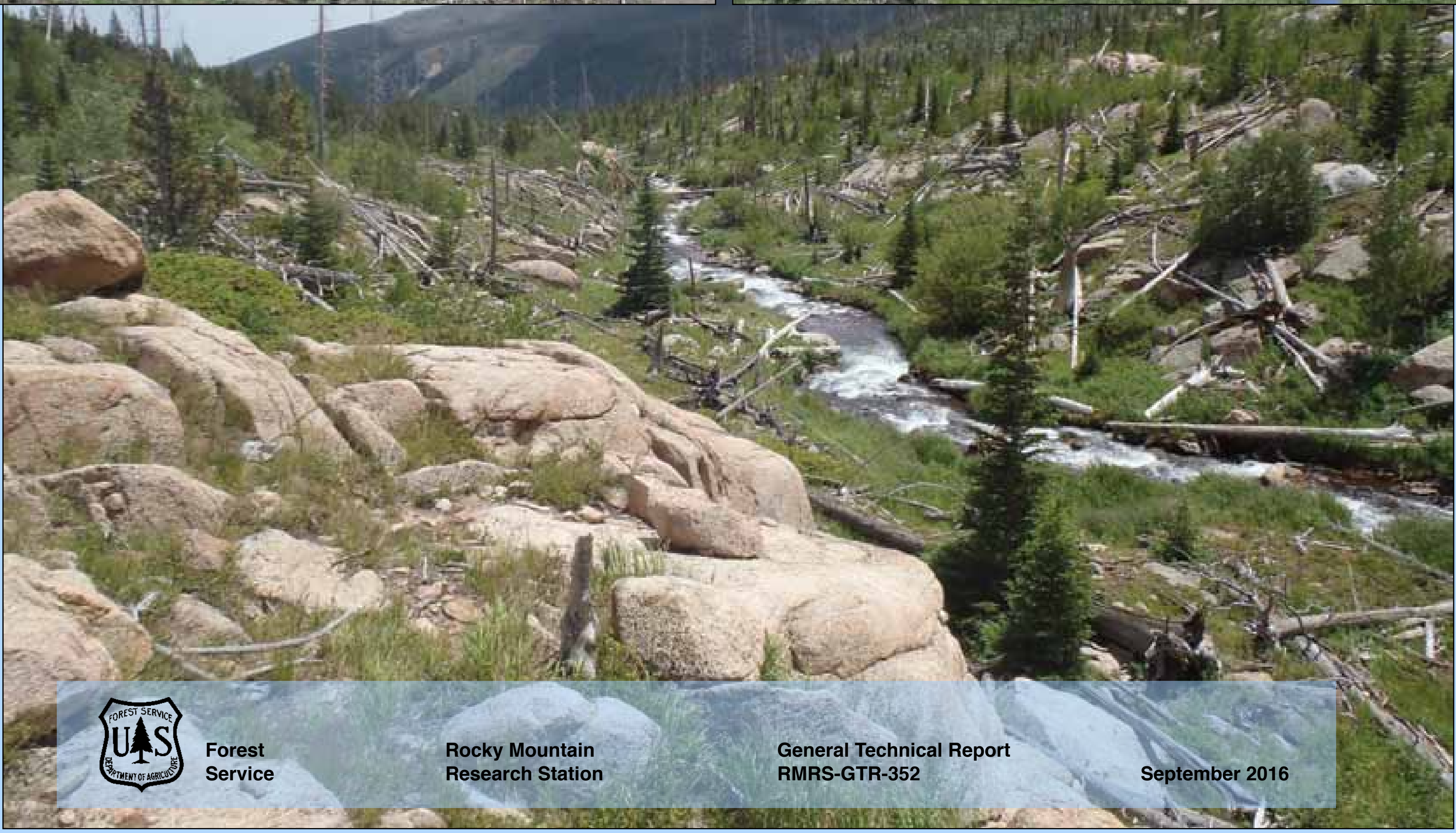
USDA
United States Department of Agriculture

Riparian Fuel Treatments in the Western USA: Challenges and Considerations

Kathleen A. Dwire, Kristen E. Meyer, Gregg Riegel, and Timothy Burton



Forest Service

Rocky Mountain Research Station

General Technical Report RMRS-GTR-352

September 2016

Dwire, Kathleen A.; Meyer, Kristen E.; Riegel, Gregg; Burton, Timothy. 2016. **Riparian fuel treatments in the western USA: Challenges and considerations.** Gen. Tech. Rep. RMRS-GTR-352. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 156 p.

Abstract

Fuel reduction treatments are being conducted throughout watersheds of the western United States to reduce hazardous fuels in efforts to decrease the risk of high-severity fire. The number of fuel reduction projects that include near-stream environments is increasing, bringing new challenges to riparian management. Riparian areas are protected by administrative regulations, some of which are largely custodial and restrict active management. However, riparian areas have also been affected by fire suppression, land use, and human disturbance, so manipulative treatments of vegetation and other fuels may be needed in some locations to maintain riparian biodiversity and restore valued functions. This report is a synthesis of current knowledge on the effects of wildfire and fuels treatments in riparian areas of the interior western United States, and includes the following: (1) a literature review of fire effects on riparian and aquatic characteristics and functions, provided as background for considering the need and potential impacts of fuel treatments; (2) a review of the potential effects of prescribed fire and mechanical treatments on riparian and aquatic resources and biota; (3) results of an online survey of resource managers, summarizing information about proposed and completed fuel reduction projects in riparian areas and wetlands in the interior west; (4) suggestions for pre- and post project-level monitoring for riparian fuels projects; and (5) a presentation of case studies, describing riparian fuel treatments with different objectives and methods. Research on the effects of fuel treatments on riparian and aquatic resources is limited, and monitoring of projects is highly encouraged, especially in watersheds supporting species of concern. Results of the online survey showed that habitat restoration is a common objective for many fuel treatments that include riparian areas; for each of the case studies, restoration of near-stream habitat for wildlife was a major goal. The integration of riparian fuel treatments with other aspects of fire and watershed management could potentially improve riparian condition in multiple stream and vegetation types.

Keywords: prescribed fire, mechanical fuel reduction treatments, valued riparian functions, monitoring, online survey, case studies

Cover photo credits: *Left:* Vegetation regrowth following a prescribed burn in willow stands along Fontenelle Creek, Kemmerer Ranger District, Bridger-Teton National Forest, Wyoming (Meyer et al. 2012). *Top left* photo was taken following the 2003 spring burn (photo: Dave Scott, Bridger-Teton National Forest, used with permission); the bottom left photo was taken in July 2010, 7 years post-treatment (photo: Kristen Meyer, Pike National Forest, Colorado, used with permission). *Top right:* Slow vegetative recovery along Ouzel Creek, Rocky Mountain National Park. Photo was taken in 2013, 36 years postfire (photo: Kate Dwire, Rocky Mountain Research Station).

Authors

Kathleen A. Dwire is a Riparian Research Ecologist with the Rocky Mountain Research Station in Fort Collins, Colorado. She holds a B.A. degree from the University of California, Santa Barbara, an M.S. degree from the University of California, Davis, with a Ph.D from Oregon State University. Currently, she studies riparian and wetland ecology in mountains of the western United States. Her research interests include impacts of disturbance (insects, fire, management activities) on riparian vegetation and function, and characterization of groundwater-dependent ecosystems (springs and fens) and other wetlands in headwater basins.

Kristen E. Meyer is a Fish and Wildlife Biologist with the Pike National Forest, South Park Ranger District in Fairplay, Colorado. She has been working on the South Park Ranger District of the Pike National Forest for the past 5 years. She holds B.A. and M.S. degrees from Colorado State University, Fort Collins, Colorado. Kristen performs a wide variety of work on habitat improvement projects for the Pike National Forest, including restoration and protection of riparian areas.

Gregg Riegel has been an Area Ecologist with the Pacific Northwest Region Ecology Program since 1991 in Bend, Oregon. Gregg holds a B.S. degree from the University of California, Davis, an M.S. degree from Humboldt State University, and a Ph.D. from Oregon State University. His work has focused on developing long-term monitoring programs for fire and fuel treatments in ponderosa pine and livestock grazing effects in riparian ecosystems. He serves as a graduate faculty member at Oregon State University, teaches Fire Effects and Ecology at Central Oregon Community College, and is a teaching cadre member for Introduction to Fire Effects (Rx310) and the interagency Implementing Indicators of Rangeland Health programs. He has served as an advisor for the U.S. Forest Service International Programs in Morocco and Ethiopia, monitoring livestock grazing and prescribed fire effects.

Timothy Burton is a retired Fisheries Program Leader, having worked in both the USDI Bureau of Land Management and the U.S. Forest Service, with 33 years combined experience. He received a B.S. degree in geology from the University of Utah, and an M.S. degree in watershed science from Utah State University. His background is mostly in stream and riparian ecology and hydrology, with a heavy emphasis on issues related to riparian management and the Endangered Species Act. Since 1983, his work has emphasized development and implementation of monitoring and assessment protocols for effects of land management on fisheries habitats. With the Endangered Species Act listings of salmon, steelhead, and bull trout in Idaho, Tim has been heavily involved in ESA Section 7 consultations, served as a member of the Regional ESA Consultation Technical Team for 8 years, and chaired the PACFISH/INFISH Implementation Monitoring Team. For the last 11 years, he has been engaged in development and implementation of the Multiple Indicator Monitoring (MIM) protocol for assessing and monitoring effects of land management activities on streams and riparian vegetation. He is currently co-owner of Riparian Management Services, LLC.

Acknowledgments

This project was funded by the Joint Fire Sciences Program. We greatly appreciate the input of over 500 resource professionals from the USDA Forest Service, and USDI Bureau of Land Management, National Park Service, and Fish and Wildlife Service who participated in the online survey on riparian and wetland fuels treatments. We extend many thanks to the following resource managers who graciously shared field time, information, and discussions on the case studies presented in Chapter 6: Jerry Altermatt (Wyoming Game and Fish Department); Steve Kilpatrick (Wyoming Game and Fish Department, retired); Cassity Bromley (Bighorn Canyon National Recreation Area, Wyoming); Diane Abendroth (Teton Interagency Fire, Wyoming); Ben Banister, Kirk Strom, Dave Scott, Phil Lockwood, Andy Norman, Dwayne Gibbons, and Tobin Kelley (Bridger-Teton National Forest, Wyoming); Edwin Brown, Faith Brown (Fremont-Winema National Forest, Oregon); Mack McFarland, and Chip Collins. We appreciate the assistance of Sandi Briscoe and Kathy Mason with analysis of the survey data, and to the Mountain Studies Institute (Silverton, Colorado) for administrative assistance. Thanks to Patty Champ (Rocky Mountain Research Station), who assisted with designing the online survey, including phrasing of the survey questions and planning the structure, flow, and presentation of the overall survey, and to Sandra Ryan (Rocky Mountain Research Station), who refined the survey questions related to stream physical characteristics and processes. We appreciate the constructive reviews by Matt Groce and John Korfmacher. Finally, many thanks to Martha Nichols for her careful editing and to Connie Lemos (Rocky Mountain Research Station Publications) for guidance and suggestions through all phases of preparation and revision of this report, and for creative layout and production of the final report.

Contents

Chapter 1: Managing Riparian Areas in Western Firescapes

1.1 Introduction

Public lands in the United States include thousands of miles of stream-riparian corridors and thousands of wetlands and lakes; on National Forest and Grasslands managed by the Forest Service, U.S. Department of Agriculture, there are more than 400,000 miles of streams and rivers (Cooper and Merritt 2012). Public lands are the largest single source of drinking water in the United States, and nearly 20 percent of the nation's water supply originates on National Forests. Streams and rivers in the western United States support many native aquatic and terrestrial species (Kauffman et al. 2001; Kelsey and West 1998), some of them federally listed as threatened or endangered under the Endangered Species Act (ESA; Suzuki and Olson 2007). Stream-riparian corridors also provide habitat for many valued invertebrate and vertebrate species and migration routes for numerous wildlife species (Kauffman et al. 2001; table 1).

Federal agencies are responsible for balancing multiple uses when managing land and water resources. Resource specialists are simultaneously charged with maintaining water quality and providing critical stream-riparian habitat to support both native and nonnative aquatic and terrestrial species while also supporting such uses as grazing, recreation, mining, timber harvest, energy development, and water extraction. Incorporating natural disturbance regimes, including the complex interactions of climate change, fire, and vegetation, further complicates managers' ability to safeguard these valuable natural resources (Luce et al. 2012).

The increase in fuel management treatments over the past decade has introduced another set of challenges to riparian management. Riparian areas are protected by administrative regulations, some of which are largely custodial and restrict active management. Forest Service regulations for riparian management can vary by region or forest, and generally reflect local issues of concern, including resource use, such as grazing and forest harvest, and protection of sensitive fish or amphibian species. However, riparian areas have also been affected by fire suppression, land use, and human disturbance, so manipulative treatments of vegetation and other fuels may be needed to maintain riparian biodiversity and restore valued functions. This report is a synthesis of the current knowledge regarding fuels treatments in riparian areas of the interior western United States and contains the following components:

1. literature review of the relation between wildfire and riparian areas (Chapter 2);
2. literature review of the potential effects of fuel reduction treatment on riparian resources (Chapter 3);
3. results of an online survey of resource managers, summarizing information about fuel reduction projects in riparian areas and wetlands in the Interior West (Chapter 4);

4. suggestions for pre- and postproject-level monitoring for riparian fuels projects (Chapter 5); and
5. description of case studies, highlighting riparian fuels and fuel treatments with different objectives, methods, and vegetation types (Chapter 6).

Table 1—Functions of riparian areas and key relationships to ecological service (from Dwire et al. 2010, modified from NRC 2002; Naiman et al. 2005).

Riparian functions	Indicators of riparian functions	On-site or off-site effects of functions	Valued goods and services provided
Distinctive terrestrial and aquatic habitat			
Contributes to overall biodiversity and biocomplexity	High species richness—plants and animals	Provides reservoirs for genetic diversity	Supports regional biodiversity
Maintenance of streamside microclimate	Presence of shade-producing canopy; healthy populations of native terrestrial and aquatic biota	Provides shade and thermal insulation to stream; provides migratory corridors for terrestrial and aquatic species	Maintains habitat for sensitive species (amphibians, cold-water fishes, avifauna, others)
Contribution to aquatic habitat; provision of large wood (coarse wood/ large wood inputs)	Aquatic habitat complexity (pool-riffle sequences, debris dams); healthy populations of aquatic biota	Maintains aquatic biota and natural geomorphic processes	Maintenance of fisheries and habitat for sensitive species; recreation
Provision of structural diversity	Availability of nesting/rearing habitat; presence of appropriate indicator wildlife species (e.g., neotropical migrants)	Maintains global biodiversity; provides migratory corridors for terrestrial and aquatic species	Recreation: bird watching, wildlife enjoyment, and game hunting
Biogeochemistry, organic matter and nutrient cycling			
Riparian vegetation provides source of organic carbon (allochthonous inputs to streams; organic matter inputs to soils)	Healthy mosaic of riparian vegetation	Maintains aquatic and terrestrial food webs	Supports terrestrial and aquatic biodiversity
Transformation and retention of nutrients and pollutants	Water quality and biotic indicators	Intercepts nutrients and toxicants from runoff; water quality	Improves and maintains water quality
Sequestration of carbon in riparian soils	Occurrence, extent, and distribution of organic-rich soils	Contributes to nutrient retention and carbon sequestration within and near channel	Potentially ameliorates global warming; provides source of dissolved carbon to streams via subsurface flow paths
Hydrology and sediment dynamics			
Short-term storage of surface water	Connectivity of floodplain and stream channel	Attenuates downstream flood peaks	Reduces damage from floodwaters
Maintenance of high water table	Presence of flood-tolerant, hydrophytic, and mesic plant species	Maintains distinct vegetation, particularly in arid climates	Contributes to regional biodiversity through provision of habitat
Retention and transport of sediments; riparian vegetation decreases stream bank erosion	Riffle-pool sequences, point bars, floodplain terraces, and bank stability	Contributes to fluvial processes	Creates predictable yet dynamic channel and floodplain features

1.1.1 Definition of Riparian Areas and Wetlands

Riparian areas have been ecologically defined as "three-dimensional zones of direct physical and biotic interactions between terrestrial and aquatic ecosystems, with boundaries extending outward to the limits of flooding and upward into the canopy of streamside vegetation" (Gregory et al. 1991). The first dimension of a riparian area encompasses the longitudinal continuum of a river or stream from its headwaters to the mouth, where it ultimately flows into the ocean or another body of water (Vannote et al. 1980); the second is the vertical dimension that extends upward into the vegetation canopy and downward into the subsurface, including hyporheic and belowground interactions along the length of the stream-riparian corridor (Stanford and Ward 1988, 1993). The third dimension is lateral, extending to the limits of flooding on either side of the stream or river (Stanford and Ward 1993). The lateral width of the riparian zone can be highly variable, depending on physical characteristics of the stream segment and location in the stream network, and can be delineated by soil and vegetation characteristics that differ from the surrounding uplands. The lateral dimension has also been described as "the portion of the stream channel occurring between the low and high water marks and adjacent terrestrial areas extending from the high-water mark toward the uplands where vegetation may be influenced by elevated water tables or flooding" (Naiman and Décamps 1997). In this ecological framework, riparian areas are viewed in terms of spatial and temporal patterns of hydrologic and geomorphic processes, terrestrial plant succession, and aquatic ecosystems (Gregory et al.1991; Naiman and Décamps 1997; Naiman et al. 2005).

Riparian areas have also been variously defined for different legal and regulatory purposes. To assist in managing riparian areas, numerous administrative definitions have been developed (see Text Box 1). Most administrative definitions describe a fixed distance on each side of a stream channel, with the distance depending on the stream size (Belt et al. 1992). Other definitions are based on ecological attributes that differentiate streamside areas from adjacent uplands (Belt et al. 1992; Knutson and Naef 1997), such as moist soils and occurrence of distinctive plant species and communities.

As suggested by both the ecological and management definitions, riparian areas have important influences on aquatic ecosystems that are not static in space or time. They are composed of a dynamic mosaic of landforms, plant communities, and environments that vary in width and shape within the larger landscape (Gregory et al. 1991; Naiman and Décamps 1997), and are not

Text Box 1—Aquatic Management Zone (AMZ)

The Aquatic Management Zone is an administratively designated zone adjacent to stream channels and other waterbodies. The AMZ is delineated for applying special management controls aimed at maintaining and improving water quality or other water- and riparian-dependent values, including groundwater-dependent ecosystems. The width of the AMZ is determined based on site-specific factors and local requirements. AMZ delineation may encompass the floodplain and riparian areas when present. AMZ designation can have synergistic benefits to other resources, such as maintaining and improving aquatic and riparian area-dependent resources, visual and aesthetic quality, wildlife habitat, and recreation opportunities.

A variety of names for the AMZ concept are used in different Forest Service regions:

- Riparian Conservation Areas (R5);
- Riparian Corridor, (Southern Region, R8);
- Riparian Habitat Conservation Areas, RHCA (R5 and R6 and portions of R4 via PACFISH and INFISH);
- Riparian Management Area (Alaska, R10);
- Riparian Management Corridor, RMC (Eastern Region, R9);
- Riparian Reserves (R5 and Pacific Northwest, R6);
- Stream Environment Zones (Pacific Southwest, R5);
- Streamside Management Unit, SMU (R6);
- Water Influence Zone, WIZ (Rocky Mountain Region 2, R2).

For purposes of the National Core BMPs, these areas are referred to as AMZs.

always easily delineated. In this report, we use the term 'riparian area' when referring to the three-dimensional streamside zone (Gregory et al. 1991). We focus on riparian areas bordering streams, rivers, and springs (*lotic*, or running, waters), although much of the information also pertains to vegetated areas surrounding *lentic* waters, such as lakes and wetlands.

Various definitions for wetlands have been developed for different administrative, academic, and regulatory delineation purposes (Cooper and Merritt 2012; National Research Council 1995). For Federal regulatory activities, wetlands are ecosystems "that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions" (Federal Interagency Committee for Wetland Delineation 1989). Wetlands are extremely diverse, exhibiting a wide range of vegetation, soil, and hydrologic characteristics (Cowardin et al. 1979; National Research Council 1995). All wetland definitions, however, emphasize hydrologic variables, particularly duration, seasonality, and depth of inundation and soil saturation that result in distinctive hydric soils and wetland vegetation.

Three broad categories of wetlands commonly occur on public lands in the western United States: palustrine, lacustrine, and riverine (Cowardin et al. 1979). Palustrine wetlands are freshwater wetlands that include marshes, wet meadows, and forested wetlands, and may be dominated by trees, shrubs, or emergent vegetation. Some palustrine wetlands may be associated with streams, particularly in headwaters, and many are isolated, occurring in basins, depressions, or wet meadows. Lacustrine wetlands are those that border lake shores. Palustrine and lacustrine wetlands are lentic ecosystems; that is, they are supported by "still waters" in contrast to riverine wetlands that are largely supported by flowing water and thus referred to as lotic ecosystems. Riverine wetlands are associated with streams and rivers, and occur along stream channels. Riparian areas are frequently classified as riverine wetlands (e.g., see Oregon Wetlands Geodatabase [http://oregonexplorer.info/wetlands/DataCollections/GeospatialData_Wetlands]), illustrating the overlap in definitions of riparian areas and wetlands. Wetland designation for many riparian areas likely results in an overestimate of wetland area, since some riparian areas may not qualify as jurisdictional wetlands (Federal Interagency Committee for Wetland Delineation 1989). However, such designation does provide a basis for management, since many wetland and riparian areas on national forests are managed as Aquatic Management Zones or Riparian Habitat Conservation Areas (USDA FS 2012).

1.1.2 Natural Variability of Riparian Areas

Riverine ecosystems are extremely variable on both spatial and temporal scales (Naiman et al. 2005; Stanford and Ward 1993). They vary from small, steep, numerous-headwater channels at high elevations (Gomi et al. 2002) to low-gradient alluvial rivers along broad floodplains at lower elevations (National Research Council 2002). Heterogeneity of drainage networks, process domains, and land management activities affect channel form and influence the variability of riparian vegetation (Naiman et al. 2005; National Council for Air and Stream Improvement 2005). Characteristics of riparian soils and plant communities are strongly correlated to valley form, the catchment hydrologic regime, hillslope and floodplain geomorphic processes, and distribution of geomorphic surfaces, such as floodplains, berms, banks, hummocks, side channels, beaver dams, and logjams (Naiman et al. 2005). Heterogeneity in riparian vegetation and soils is also closely linked to hydrologic connectivity, which is influenced by valley geometry and channel planform, and resulting gradients in soil moisture and redox potential in the riparian corridor (Dwire et al. 2006a; Polvi et al. 2011; Tabacchi et al. 1998). Riparian habitats are heterogeneous both within watersheds and across the landscape.

The diversity of riparian areas is also attributed to the temporal variability in physical events and natural disturbances, such as floods, debris flows, landslides, and wildland fire, and the subsequent successional changes in riparian plant communities over time (Gecy and Wilson 1990; Naiman et al. 2005). Fire is a critical disturbance that has shaped the structure of forests and rangelands throughout the western United States (Agee 1993, 1998; Stephens and Ruth 2005). Although limited research has investigated the role of fire in structuring streamside vegetation, riparian species and communities also evolved within the ecological context of regional fire regimes (Arno 2000).

The effects of wildfire and fuel reduction treatments on riparian areas will depend largely on the location within a watershed: proximity to the channel; in the headwaters, middle, or lower portions of the drainage; and position relative to the mainstem channel and tributaries in the stream network. The factors that vary in different portions of a watershed—including soil characteristics, slope, vegetation cover, moisture, and microclimate—also influence the behavior of wildland fire and the potential responses of riparian ecosystems to both wildfire and fuel treatments. Effects of wildfire on riparian resources will vary depending on the intensity and severity of wildfire, and the extent of burn. Effects of fuel treatments on riparian resources will vary depending on the type of treatment, sequence of application, and pretreatment ecological conditions.

1.2 Valued Riparian Functions

Riparian areas occupy a small percentage of the natural landscape and occur as linear features within the matrix of the surrounding upland vegetation. However, they have disproportionate ecological importance relative to the area they occupy (table 1; Gregory et al. 1991; Naiman and Decamps 1997; National Research Council 2002). As noted above, they include an unusually diverse mosaic of landforms, biotic communities, and physical environments and provide critical habitat and migration corridors for numerous species (Kauffman et al. 2001; Kelsey and West 1998; Naiman et al. 2005). Throughout the arid western United States, riparian ecosystems are the single most productive type of wildlife habitat, benefiting the greatest number of species (fig. 1; Arno 1996). Riparian vegetation also contributes to aquatic habitat in several ways: it provides localized microclimate, stream shading, bank stability, and inputs of large wood and organic matter to streams (fig. 1; Baxter et al. 2005; Dwire et al. 2010; Minshall et al. 1989; Naiman and Decamps 1997).

Riparian ecosystems are critical for maintenance of water quality and quantity and water storage, especially in basins with riparian wetlands. Riparian vegetation contributes to sediment retention and stream bank building and maintenance, and influences in-channel geomorphic processes through the provision of large wood to streams (table 1; Montgomery et al. 2003). Instream large wood, most of which originates in the riparian

Figure 1—Deciduous riparian vegetation provides shade and thermal insulation to small streams, as well as high quality allochthonous inputs to aquatic food webs (A); riparian vegetation contributes to aquatic habitat complexity through provision on instream large wood (B); stream-riparian corridors serve as migration routes for terrestrial wildlife species, and provide critical year-long habitat for moose, as well as spring, summer, and fall habitat for deer, elk, and other wildlife species (C).

area, provides instream cover and shade, contributes to nutrient and sediment retention, and increases channel complexity through the formation of pools, backwaters, and cascades (fig. 1; Gregory et al. 2003). Riparian areas also provide services of economic and social value, such as livestock grazing and recreation (table 1; Naiman et al. 2005; Prichard et al. 1998).

1.3 Management of Riparian Resources

Most guidelines for protection and management of riparian resources have been developed to comply with four Federal laws: the National Environmental Policy Act (NEPA) of 1969; the Clean Water Act (CWA) of 1972; the Endangered Species Act (ESA) of 1973; and the National Forest Management Act of 1976 (NFMA; Everest and Reeves 2006; Suzuki and Olson 2007). NEPA established procedural requirements for all Federal agencies to prepare environmental assessments (EAs) and environmental impact statements (EISs), which evaluate the ecological effects of proposed management actions. The objective of the CWA is to restore and maintain the chemical, physical, and biological integrity of the nation's waters by preventing point and nonpoint pollution sources, improving wastewater treatment, and maintaining the integrity of wetlands. The ESA was designed to protect critically imperiled species from extinction and is the overriding mandate to protect, maintain, and restore stream-riparian habitat conditions for rare species, especially those listed as threatened or endangered. The ESA has also been used as the legal basis to forestall perceived threats or disturbances that degrade habitat conditions that might result in a proposed species listing (Suzuki and Olsen 2007). Many federally listed plant and animal species (frequently selected as management indicator species) require riparian areas or wetlands as habitat. The National Forest Management Act (NFMA) is the primary statute governing the administration of the national forests, including protections for watershed and aquatic resources. The NFMA specified the need to maintain viable populations of native and desired nonnative vertebrate species on national forests. In conjunction, these Federal laws have provided the impetus for development of riparian protection guidelines.

On National Forest lands, protection of riparian areas is governed by special rules, stated as Standards and Guidelines in the Forest Plan for each National Forest, and best management practices (BMPs; Belt et al. 1992; Gregory 1997; USDA FS 2012). BMPs are officially approved practices and guidelines that are focused on reducing management impacts on streams, valued riparian functions or ecosystem services (Belt et al. 1992, 1997). The primary objective of most BMPs is to protect water quality and habitat along streams from timber harvest, road construction, grazing, recreation, and other land use or management activities (Belt et al. 1992; Mosley et al. 1997; USDA FS 2012).

Riparian buffers are administratively defined areas adjacent to either flowing or lentic surface water, and most are specified by a given distance from the stream. In the Pacific Northwest, riparian buffers are also called riparian reserves (Suzuki and Olsen 2007) and contribute to habitat and watershed protection by restricting management activities near streams and other water bodies (Norris 1993). Riparian influence decreases with distance from the stream channel (fig. 2; FEMAT 1993). Depending on stream width, location within a drainage basin, and management concerns, required riparian buffer width may vary from 5 feet to 300 feet on each side of the stream (Belt et al. 1992; Lee et al. 2004). Streams used for domestic water supplies are accorded wider riparian buffers to protect downstream reservoirs from nonpoint pollution resulting from forest management (Belt et al. 1992). Streams that are important for spawning, rearing, or migration of sensitive fish species often receive additional protection in the form of wider riparian buffers (USDA 1995). Existence of a riparian buffer, however, does not preclude

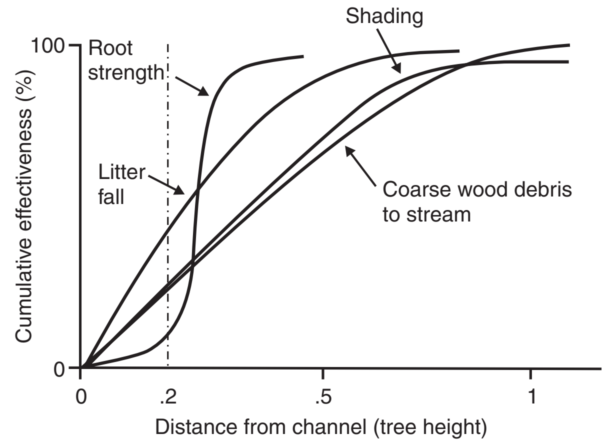


Figure 2—Generalized curves indicating cumulative percent effectiveness of riparian ecological functions occurring with varying distance from the stream channel (FEMAT 1993).

all types of management activities; Lee et al. (2004) reported that about 80 percent of State and provincial jurisdictions permitted riparian timber harvest. Federal rules are somewhat more restrictive but still allow active riparian management.

Implementation of BMPs and establishment of riparian buffers have generally decreased the negative effects of forest harvest activities on surface water quality (Belt et al. 1992; Norris 1993; Osborne and Kovacic 1993). However, less is known regarding BMP effectiveness in protecting other riparian functions (table 1). As more is learned about the effectiveness of individual BMPs, they are revised and updated. To establish more consistency and direction across different regions, the Forest Service published the first volume of National Core BMPs in 2012 to improve agency performance and accountability in managing water quality consistent with the CWA (USDA FS 2012). It includes a set of BMPs that address Wildland Fire Management Activities (table 2). These BMPs outline general guidance for common wildland fire management operations, including use of prescribed fire, managing wildfire using a range of strategies (from monitoring to control and suppression), and rehabilitating fire and fire-suppression damage to watersheds. The development of site-specific BMP prescriptions based on site conditions and local and regional requirements is still required to achieve compliance with established State, tribal, and national water quality objectives. However, the overall guidance has incorporated ecological knowledge regarding the role of fire in resource management and acknowledges the importance of addressing fire and fuel treatments in watershed and riparian management.

Table 2—Best Management Practices for Wildland Fire Management Activities (from USDA Forest Service 2012)

National Core Best Management Practice (BMP)	Objective
Wildland Fire Management Planning	Use the fire management planning process to develop measures to avoid, minimize, or mitigate adverse effects to soil, water quality, and riparian resources during wildland fire management activities.
Use of Prescribed Fire	Avoid, minimize, or mitigate adverse effects of prescribed fire and associated activities on soil, water quality, and riparian resources that may results from excessive soil disturbance as well as inputs of ash, sediment, nutrients, and debris.
Wildland Fire Control and Suppression	Avoid or minimize effects to soil, water quality, and riparian resources during fire control and suppression efforts.
Wildland Fire Suppression Damage Rehabilitation	Rehabilitate watershed features and functions damaged by wildland fire control and suppression-related activities to avoid, minimize, or mitigate long-term adverse effects to soil, water quality, and riparian resources.

1.4 Riparian Management in Western Firescapes

Wildland fire has played a vital role in shaping ecological heterogeneity across landscapes of the western United States (Agee 1998; Turner and Romme 1994). These landscapes are dissected by a complex network of drainages and stream-riparian ecosystems, which have also been influenced by fire as a recurring natural disturbance (Everett et al. 2003; Gresswell 1999; Pettit and Naiman 2007; Skinner 2003). Although knowledge is limited on the influence of wildfire on riparian biodiversity and functions (Chapter 2), there is general agreement that fire is part of the natural disturbance regime along stream-riparian corridors (Luce et al. 2012), and must be considered in planning and management actions (Chapter 3). While there is less agreement about conducting fuel treatments in riparian areas, managers are gradually including more riparian areas in fuels projects (Chapter 4). Effective riparian management preserves the dynamic connections to surrounding uplands, as well as to stream channels. Understanding the effects of wildfire and fuel reduction requires integration of information about the spatial extent of past management and other human disturbance and temporal aspects of natural disturbance regimes, including fire return intervals and frequency of landslides (Luce et al. 2012; McCormick et al. 2010). In the western United States, "we live in a fire environment and need to plan accordingly" (quote from Penny Morgan in Luce et al. 2012).

Chapter 2: Wildfire and Riparian Resources

Fire is a prevalent ecological disturbance that has shaped vegetation composition and structure and maintained a patchwork of different successional stages throughout watersheds of the western United States (Agee 1998; Bendix 1994; Turner and Romme 1994). The historic role of fire in many terrestrial ecosystems and forest types of the western United States is well-understood (Arno et al. 1996; Covington and Moore 1994; Fulé et al. 1997, 2003; Schoennagel et al. 2004). However, less is known about fire history and other fire properties in many riparian areas. Ecologically diverse riparian corridors are maintained by active natural disturbance regimes, including fire, that operate over a range of spatial and temporal scales (Gom and Rood 1999; Mahoney et al. 1991; Naiman and Decamps 1997; Pettit and Naiman 2007). However, the role of fire, the streamside factors that influence fire properties and the response of riparian and aquatic communities to fire can differ widely, depending on characteristics of both the fire and the riparian area. In this chapter, we update former reviews on the role of fire in riparian areas (Dwire and Kauffman 2003; Pettit and Naiman 2007) and discuss the following: (1) riparian fire regimes, including fire frequency and severity, (2) riparian physical and vegetative characteristics that influence fire behavior, and (3) postfire recovery of riparian and aquatic resources. We provide this discussion as background to inform fire management of streamside areas, including managing wildfire and planning and implementation of fuel treatments in riparian areas.

2.1 Properties of Wildland Fire in Riparian Areas

2.1.1 Fire Regimes

Fire plays a complex role in structuring vegetation across the landscape and has variable effects in space and time (Arno 2000). Natural fire regimes are characterized by fire intensity and severity, the frequency and seasonality of fire occurrence, and the fire size or spatial scale of fire (table 3; Agee 1993; Baker 1989; Barrett et al. 2010; Brown 2000). Fire frequency refers to the recurrence of fire in a given area over time, and is usually expressed as the mean fire return interval, estimated as the average number of years

Table 3—Fire regimes can be grouped by fire frequency and severity (from Barrett et al. 2010; http://www.fire.org/niftt/released/FRCC_Guidebook_2010_final.pdf).

Group	Fire frequency	Fire severity	Severity description
I	0–35 years	Low/mixed	Generally low-severity fires replacing less than 25% of the dominant overstory vegetation; can include mixed-severity fires that replace up to 75% of the overstory.
II	0–35 years	Replacement	High-severity fires replacing greater than 75% of the dominant overstory vegetation.
III	35–200 years	Mixed/low	Generally mixed severity; can also include low-severity fires.
IV	35–200 years	Replacement	High-severity fires.
V	200+ years	Replacement/ any severity	Generally replacement severity; can include any severity type in this frequency range.

between fire occurrences. Fire severity describes the degree of ecological change caused by a fire, that is, the effects of fire on the physical and biological components of the ecosystem resulting from the intensity of the propagating fire front and the heat released during fuel consumption (Keeley 2009; Lentile et al. 2006, 2007). In some ecosystems, fire frequency is inversely related to fire severity (Arno 2000). Fire intensity is a measure of heat (energy released per unit area during a fire) and is roughly characterized by flame length (Keeley 2009).

Fire regimes are classified as combinations of low-severity, mixed-severity, and replacement into five general groups (table 3). These groupings typically reflect the vegetation, live and dead fuels, local and regional weather patterns, climate, topography, and other environmental conditions that influence fire occurrence and behavior (Agee 1993, 1998). In fire regimes characterized by low-to-mixed-severity fires (groups I and III; table 3), frequent, low- to mixed-severity fires occur at intervals of approximately 5 to 35 years, and most of the dominant vegetation survives. In fire regimes characterized by high-severity fires (group IV; table 3), infrequent fires occur at intervals of 35 to 200 (or more) years, and are typically stand-replacing fires (Arno 2000). Mixed-severity fire regimes have variable or intermediate fire return intervals, and are typically more complex; fire severity can differ with each fire and within a single fire, resulting in a complex mosaic of unburned, low-severity, moderate-severity, and high-severity burned patches (Agee 1998; Arno 2000; Perry et al. 2011). Historical fire regimes have been described for dominant forest types in the western United States (fig. 3). Natural fire regimes have been significantly altered in many ecosystems (Shlisky et al. 2007), including many riparian areas (see Section 2.1.5 below), largely due to fire suppression and multiple land uses that have resulted in landscape fragmentation and alteration of fuel loads.

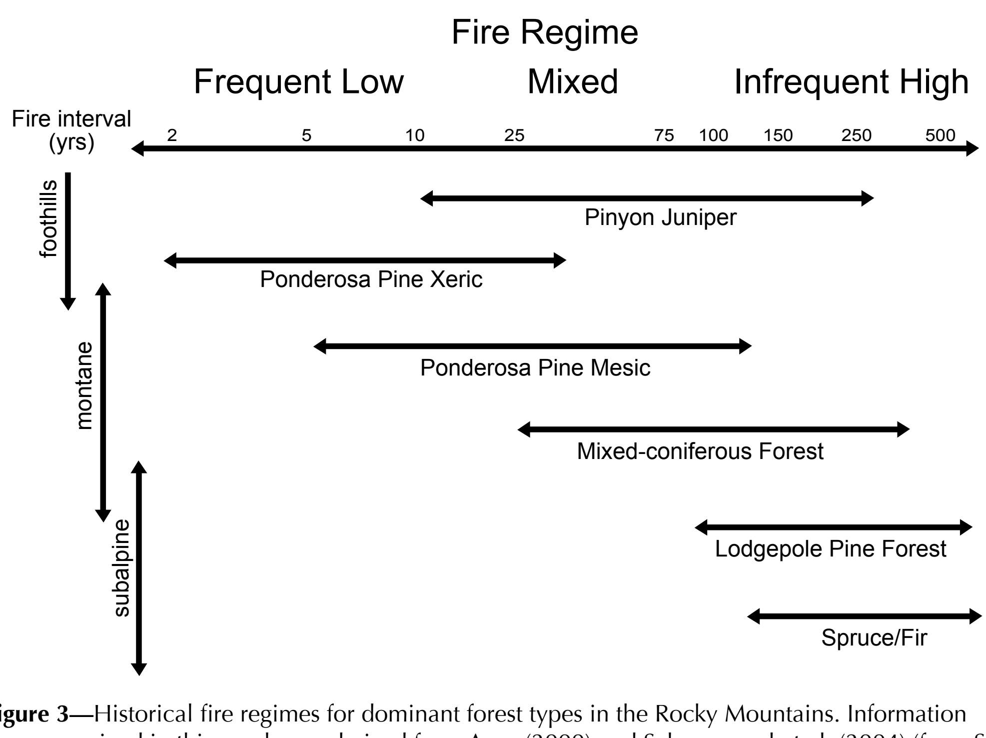


Figure 3—Historical fire regimes for dominant forest types in the Rocky Mountains. Information summarized in this graph was derived from Arno (2000) and Schoennagel et al. (2004) (from Saab et al. 2005).

2.1.2 Fire Frequency in Riparian Areas

Fire regimes in riparian areas relative to adjacent uplands vary depending on physical features of the watershed, location within a given watershed, vegetation type and fuel characteristics, and disturbance and land use history (Everett et al. 2003; Olson 2000; Olson and Agee 2005; Skinner 2003; Van de Water and North 2011). In many forested riparian areas, fires are generally thought to occur less frequently than in adjacent upslope forests. In subalpine forests of southeastern Wyoming, Romme and Knight (1981) found that fire was less frequent in sheltered valley bottoms, which contributed to differences in forest stand structure and composition between streamside and upland areas. For mesic riparian forests of the western Cascade Mountains in Oregon, Morrison and Swanson (1990) suggested that fire frequency was generally lower and fire severity was more moderate than in adjacent uplands. In the eastern Cascade Mountains of Washington, areas least likely to burn—late-successional forests or fire refugia—were frequently located in valley bottoms near confluences of perennial streams (Camp et al. 1997). In Mount Rainier National Park, Washington, high-intensity, stand-replacing fires contributed to a mosaic of different age classes in upland forests (Hemstrom and Franklin, 1982). However, old-growth conifers occurred mostly along river valleys, suggesting a more moderate fire regime in riparian areas.

Our understanding of fire frequency in different forest types is based on retrospective studies of tree rings, postfire stand ages, and analysis of fire scars, which provide information about the recent past (last several hundred years), but generally do not incorporate the longer-term influence of climate (Whitlock et al. 2003). Research on fire return intervals in riparian areas is limited to a few studies conducted in the Sierra Nevada Mountains (California) and Pacific Northwest region of the United States. In some locations, results show longer fire return intervals for riparian areas relative to uplands (table 4). For example, in the Klamath Mountains of northern California, Skinner (2003) found that the median fire return intervals were approximately twice as long in riparian

Table 4—Fire-return intervals for riparian versus upland forests (modified from table 1 in Stone et al. 2010; table T7-1 in Luce et al. 2012).

Location	Forest type	Riparian fire return interval (years)	Upland fire return interval (years)	Citation
Dry forest types				
Blue Mountains, OR	Douglas-fir and grand fir series	13–36	10–20	Olson 2000
Elkhorn Mountains, OR	Ponderosa pine, Douglas-fir series	13–14	9–32	Olson 2000
Salmon River Mountains, ID	Ponderosa pine and Douglas-fir series	11–19	9–29	Barrett 2000
Cascade Range, WA	Ponderosa pine and Douglas-fir series	15–26	11–19	Everett et al. 2003
Northern Sierra Nevada Mountains, CA	Dry, ponderosa-Jeffrey pine series	10–87	10–56	Van de Water and North 2011
Mesic forest types				
Cascade Range, OR	Douglas-fir series	35–39	27–36	Olson and Agee 2005
Klamath Mountains, CA	Douglas-fir series	16–42	7–13	Skinner 2003

reserves as in upland sites, indicating that fires occurred less frequently in riparian areas. In dry Douglas-fir (*Pseudotsuga menziesii*) forests of eastern Washington, longer fire-free intervals were found in riparian forests relative to adjacent side-slope forests regardless of aspect, valley type, or plant association group; the relative frequency of fire scars increased with distance from the stream (Everett et al. 2003). In the South Cascades of Oregon, Olson and Agee (2005) found that fire return intervals were only slightly greater in riparian areas of a mesic, Douglas-fir forest than the adjacent upslope forests (table 4).

In other locations, however, results indicate historical fire frequencies in uplands and riparian areas were often comparable. In dry ponderosa pine (*Pinus ponderosa*)/ Douglas-fir forests of central Idaho, the observed range of fire return intervals was similar for upland and riparian stands (table 4; Barrett 2000). In mixed conifer forests in the northern Sierra Nevada Mountains (California), Van de Water and North (2011) found that fires burned fairly continuously across the landscape and were historically common in both riparian and upslope forests (table 4). Similar results were found by Olson (2000) in dry forest types of the Blue Mountains of eastern Oregon, characterized by a low-severity fire regime. Olson (2000) studied the fire history of upland and riparian stands in forest types dominated by ponderosa pine, Douglas fir, and grand fir (*Abies grandis*). Although fires in riparian areas generally occurred less frequently than in uplands for a given forest type, overall differences between upland and riparian stands were not significant. At high elevations along low-order streams, where the vegetation composition of riparian areas is similar to that of adjacent uplands, streamside areas are also likely to burn as frequently as the surrounding uplands. Although most riparian areas in Mount Rainier National Park appeared to have less frequent or less severe fire occurrence, riparian areas located in higher elevation drainages with predominately south-facing aspects had fire frequencies that were similar to uplands (Hemstrom and Franklin 1982).

Fewer studies have investigated the relations between fire regimes in upland and riparian vegetation for semiarid shrublands and grasslands (Paysen et al. 2000), where the riparian plant communities are frequently dominated by deciduous hardwoods (Patten 1998). In prairie grasslands, fire return intervals range from 10 to 30 years (Paysen et al. 2000), and fires burn periodically into the deciduous riparian woodlands. In a tree-ring analysis of riparian cottonwoods on the Oldman River in Alberta, Canada, Mahoney et al. (1991) found up to four fire scars per century, suggesting the periodic occurrence of low-intensity surface fires rather than stand-replacing fires. Additional research is needed on how riparian areas and wetlands burn relative to adjacent uplands in nonforested ecoregions (Bixby et al. 2015).

2.1.3 Burn Severity in Riparian Areas

Patterns observed for fire behavior, intensity, and severity in riparian areas are similar to those reported for fire frequency. Fires in riparian areas can be less severe, as severe, or more severe than in adjacent uplands, depending on the local topography, vegetation characteristics (especially fuel moisture and loading), and fire weather. Burn severity is a feature of fire regimes used to express the degree of ecological change resulting from a fire and is a measure of cumulative fire effects, including vegetation mortality, soil heating, and fuel consumption (Keane et al. 2008; Keeley 2009; Lentile et al. 2006, 2007). Burn severity depends on fire intensity and the degree to which soils and vegetation are fire resistant. The condition and structure of live and dead fuels, topography, regional and local weather, and climate influence fire intensity and other components of fire behavior (Agee 1993; Keeley 2009). Fuels include the live and dead biomass available to burn that carry a fire across the landscape. Fuel characteristics include amounts of different size classes, extent of decay, horizontal and vertical continuity of the fuel bed, chemical content of the vegetation, and the fuel moisture of live and dead material (Ryan 2001). These fuel characteristics contribute to ignition probability, the ability of a fire to spread, and the intensity of the flaming fire front. Differences in fuel characteristics and distribution can influence how riparian areas burn relative to uplands.

A study conducted in conifer-dominated forests of Oregon specifically addressed fire severity in riparian areas, contributing to current understanding of riparian burn patterns. Halofsky and Hibbs (2008) compared fire severity in riparian vs. upland plots following the Biscuit Fire (Klamath-Siskiyou region) and the B&B Complex Fire (east Cascades). They found that the strongest predictors for riparian overstory fire severity were upland fire severity, riparian vegetation indicators, and local topography; that is, stream width, stream gradient, and adjacent hillslope steepness. Their study sites had diverse riparian understories, with varying levels of deciduous tree and shrub components. The researchers also found that riparian understories generally burned less severely than upland understories, and they attributed this burn pattern to higher fuel moisture in riparian vegetation, and cooler, moister streamside microclimates. In a related study, Halofsky and Hibbs (2009b) examined relations between ground-based and remotely sensed indices of fire severity in riparian areas of the Biscuit Fire and B&B Complex Fire in Oregon. Results indicated weak associations between both ground-based and remotely sensed fire severity assessments in riparian areas, highlighting the need for plot-and-reach-level research on fire impacts in different riparian vegetation types.

While keeping the limitations of remotely sensed fire severity evaluations in mind for riparian areas, the importance of upland burn severity as a predictor of riparian burn severity and fire intensity was supported by a geospatial analysis. Following four large fires, researchers utilized remotely sensed Burned Area Reflectance Classifications (BARC) to compare upland burn intensity to riparian burn intensity (Fisk et al. 2004). The fires occurred in dry forest types of the interior West: the Hayman and Missionary Ridge Fires in Colorado; Rodeo-Chediski Fire in Arizona; and the Stanford Fire in Utah. Researchers found that riparian areas burned 'less hot' than upslope areas. However, riparian burn values related positively to upslope burn values; that is, the hotter the watershed burned, the hotter (on average) the riparian areas burned. Results also indicated that smaller, lower-order streams burned more like uplands, while riparian areas along larger, higher-order streams burned less like surrounding uplands. Following the 1991 Warner Creek Burn in the Cascade Mountains of western Oregon, Kushla and Ripple (1997) examined landscape patterns of forest mortality, or live crown ratio (LCR), through interpretation of aerial photography. LCR was inversely related to perennial stream proximity in portions of the burned area, indicating that tree mortality was lower along some stream segments. However, significant explanatory variables differed among the four physiographic areas studied (Kushla and Ripple (1997). The researchers also observed that a large portion of unburned riparian forest remained along Kelsey Creek, one of the larger perennial streams in the study area. These results support previous observations of patterns of fire frequency, intensity, and burn severity in upland versus riparian areas, although more information is needed for a range of riparian plant associations, stream types, and precipitation regimes.

2.1.4 Fire Behavior in Riparian Areas

Conceptual models of fire behavior and different fire effects in riparian areas have been proposed based on observations and research results. Pettit and Naiman (2007) described four cases of fire effects, postdisturbance impacts, and riparian recovery based on their observations of wildfire in Kruger National Park, South Africa. The four cases were categorized by combinations of stream gradient (high or low) and amount of regional rainfall (high or low) and were related to fire behavior, which influenced fire severity and, hence, postfire recovery. Halofsky and Hibbs (2008) developed a sequence of hypotheses to test the influence of riparian vegetation, valley-bottom topography, and upland fire variables on riparian fire severity. The relative role of these driving factors varies locally and regionally, but can be used to predict how wildfire might burn along specific stream segments.

Based on published research and observations for the western United States, we present four generalized scenarios of fire behavior in riparian areas, speculate about when and where they might occur, and note potential ecological outcomes (table 5; Luce et al. 2012). The relative likelihood of occurrence for any scenario is largely driven by vegetation and fuel indicators, basic topographic variables, and characteristics of the fire and fire weather. Variations of each scenario are likely and different combinations could be observed in the same watershed or during the same wildfire.

1. Riparian Areas Burn Like Adjacent Uplands

This scenario is most likely to occur along stream reaches where the riparian vegetation, terrain, and general topography are similar to uplands. Stream reaches that drain shrub-dominated portions of drainage networks—such as shrub-steppe ecosystems throughout portions of the Great Basin or stream segments that drain the lower parts of stream networks in shallowly dissected terrain with low local relief—are likely to burn as frequently and severely as adjacent uplands. Other examples occur in the upper portions of drainages at high-to-moderate elevations in fairly steep terrain with steep stream valleys. This scenario could also occur under conditions of severe fire weather, that is, when a large fire carries across the entire landscape and overwhelms both the influence of local topography and vegetation differences between riparian and upland areas.

2. Riparian Areas Burn Less Frequently or Less Severely (or Both) Than Adjacent Uplands

This scenario is most likely to occur where riparian conditions are distinctly wetter or more mesic than upland vegetation. It is the most commonly documented scenario in the literature, especially for forests of the Pacific Northwest (table 4). In forested riparian reaches, particularly those located in deeply dissected terrain with north-facing aspects that foster cold-air drainage and cool riparian microclimates, fires tend to burn less severely and less frequently than nearby uplands. However, even within similar vegetation associations and in lower portions of drainage networks, the frequency of fire scars has been found to increase with distance from the stream, suggesting that fires burned less frequently or less severely or both in streamside areas (Everett et al. 2003; Russell and McBride 2001; Skinner 2003).

Table 5—Four generalized scenarios of fire behavior in riparian areas (from Luce et al. 2012). Variations on these four scenarios occur and different combinations may be observed in the same watershed or during the same wildfire. Ecological outcomes are given; please see text for additional explanation.

Fire behavior in riparian areas (generalized)	Where and when?	Ecological outcome
Riparian areas burn like adjacent uplands (i.e., wildfires burn with similar frequency and severity)	**Where** riparian vegetation, terrain, and topography are similar to uplands. **When** large fires burning under severe fire weather exceed the influence of local topography and riparian/upland vegetation differences.	Impact depends on fire severity, season, and extent, but generally moderate to high. Slow to moderate recovery via seedlings and resprouting. Fire adapted species will likely survive.
Riparian areas burn less frequently and/or less severely than adjacent uplands.	**Where** terrain fosters cold-air drainage, higher humidity, cooler microclimate relative to uplands. **Where** riparian vegetation is distinctly different from uplands (more hardwoods, higher herbaceous component, higher fuel moisture). **Where** saturated soil conditions, presence of riparian wetlands, or hydrologic inputs from hillslopes influence fire behavior. **When** fires burn with low intensity.	Low to moderate impact. Moderate to rapid recovery via seedlings and resprouting. Fire-adapted species (esp. conifers) will persist.
Riparian areas burn more frequently and/or more severely than adjacent uplands.	**Where** fuel abundance/accumulation is higher in riparian areas than uplands (due to riparian management or natural conditions). **When** riparian areas serve as chimneys or corridors for fire spread (e.g., **where** steep terrain and narrow stream valleys influence fire behavior).	Impact depends on fire severity, season, extent; can be high impact, with destruction of most of the riparian community. Slow to moderate recovery, via seedlings and resprouting. Postfire invasive species are a potential concern.
Riparian areas serve as fire breaks	**Where** large perennial stream and river valleys create significant breaks in fuel characteristics and continuity. **Where** saturated soil conditions, presence of riparian wetlands, or hydrologic inputs from hillslopes influence fire behavior. **When** fires burn with low intensity.	Low impact; rapid recovery.

3. Riparian Areas Burn More Frequently or More Severely (or Both) Than Adjacent Uplands

This scenario has been reported by the fire control/fire management community and warrants further study (Barrows 1951a,b; Countryman 1971). It could occur where steep, narrow stream valleys funnel hot updrafts, fostering convective heating of the fire, thus causing it to carry up the canyon rapidly and with high intensity (Skinner 2003). This fire behavior is most likely to occur in the middle or upper portions of drainage networks with south-facing aspects, along small perennial or intermittent stream channels. This scenario is locally dependent on fuel characteristics, physical context, and the characteristics of a given fire event. This fire behavior likely occurs where riparian vegetation is either (1) similar to upland vegetation in stand- and understory-species composition, or (2) contains higher levels or denser fuel loads (particularly ladder fuels) than adjacent uplands (Agee 1998). Although not well documented, riparian areas can also burn more severely in arid landscapes where frequent, low-intensity fires limit fuel buildup in uplands, while fuel accumulates in streamside areas. During periods of drought, differences in the riparian versus upland microclimate and fuel moisture might be high enough to promote plant growth, stand development, and fuel accumulation in riparian areas, but not high enough to protect riparian vegetation from fire. This scenario is of particular concern for resource managers and fuels specialists in locations in the Great Basin and southwestern United States where woody encroachment into riparian areas has increased streamside fuel loads.

4. Riparian Areas Serve as Fuel Breaks

Although most commonly observed where large stream and river valleys create breaks in fuel characteristics and continuity, this scenario has also been observed in wet meadows, stream segments with a high herbaceous component, and willow-dominated reaches or other riparian areas with notable hardwood tree or shrub components. In a burned mixed-conifer forest in the Sierra Nevada Mountains of California, Kobziar and McBride (2006) concluded that wider riparian areas tended to act as natural firebreaks, likely due to a combination of stream and floodplain physical features and moist riparian vegetation.

Critical considerations in predicting how a riparian area will burn relative to uplands include location within the watershed relative to precipitation regime (snow versus rain influence; Jarrett, 1987, 1990); topography (including aspect) and changes in stream gradient and slope relative to uplands; geomorphology, especially changing width of the channel and valley floor; and riparian versus upland vegetation and fuel characteristics. Researchers have documented high spatial variability in streamside burn patterns as indicated by local differences in fuels consumption, and distribution of low-to-high-severity burned patches, that is, exceptionally patchy fire behavior (Kobziar and McBride 2006; Jackson and Sullivan 2009). Although patchy burn patterns also occur in uplands, they are likely to be more common in riparian areas due to more heterogeneity in vegetation, geomorphic surfaces, and fuels characteristics. Large-scale assessments of burn severity for specific fires are conducted using remote sensing techniques and various imagery (http://www.fs.fed.us/eng/rsac/baer/) and are useful for planning postfire management in uplands. However, these assessments rarely represent the spatial variability of burn patterns in riparian areas. In burned watersheds that have been characterized as 'high burn severity,' there are frequently stream segments where riparian areas have not burned or experienced low- or mid-severity wildfire.

2.1.5 Shifting Fire Regimes

Humans have significantly altered historic fire regimes in many ecosystems (Shlisky et al. 2007). Fire history studies in low-to-mid-elevation forest types, such as those dominated by ponderosa pine (*Pinus ponderosa*), indicate that fires generally occurred more frequently before European-American settlement (Arno et al. 1996; Covington and Moore 1994). Fire suppression and landscape fragmentation due to multiple land uses have altered vegetation, accumulation of fuels, and natural fire frequencies in much of the western United States (Baker 1992; Jain et al. 2012; Peterson 1998). The departure from historical fire regimes has likely contributed to the severity, intensity, and unpredictability of recent wildland fires (Westerling et al. 2006). In the last decade, fires have covered much larger areas, and burned hotter and more intensely than previously (Westerling et al. 2006). The effects of fire suppression and exclusion have been documented for some forest and shrub vegetation types (Keane et al. 2002) and are most significant in types that previously sustained frequent, low- to moderate-severity surface fires (Westerling et al. 2006). Sagebrush ecosystems have been experiencing larger, more severe, and more frequent fire compared to historical conditions partly due to exotic cheatgrass (*Bromus tectorum* L.) invasion (Keane et al. 2008), and it is likely that associated riparian areas are also burning more frequently and severely.

Mixed-conifer forests that evolved with low-to-mixed-severity fire regimes contain higher densities of undergrowth and fuel loadings than in the past, making them more conducive to high-severity fires (Agee 1998; Fulè et al. 2003). The effects of fire suppression on riparian vegetation and fuel loads are largely unknown and depend on the many factors that differentiate riparian areas from surrounding uplands. An exception is a study conducted in the Rogue River basin of southwestern Oregon where researchers used dendrochronological methods to examine pre Euro-American settlement disturbance and tree recruitment patterns in riparian forests (Messier et al. 2012). Their results indicated major shifts in tree species composition, stem densities, and stand age classes, which they attributed to fire exclusion. In their discussion, they state the following:

> *"Fire exclusion in the 20th century triggered a shift in the stand dynamics of riparian forests in the Mixed Conifer vegetation zone from a model characterized by frequent fire disturbance and shade-intolerant tree recruitment in large canopy gaps to one characterized by the replacement of overstory trees by shade-tolerant species through individual tree-fall gaps. Fire-sensitive and shade-intolerant white fir is represented in far greater numbers that it was prior to 1900 and few Douglas-fir trees that established after 1900 are on a trajectory to canopy dominance."*

They conclude:

> *"Our findings support our hypothesis that riparian forests in southwestern Oregon experienced frequent fires and that fire exclusion has altered the structure, composition, and successional trajectory of these forests. We were surprised, however, to find many of the structural and compositional changes evident today date back to 20–70 years prior to effective fire suppression (approximately 1920) (Sensenig 2002). Historically, fires in riparian areas would likely have had similar effects on forest vegetation as those seen in upland forests, where low-and-mixed-severity fire regimes maintained patchy, multi-aged stands of fire-resistant conifer and hardwood species."*

In studies of fire frequency, dendrochronological analyses often detected the same fire events in upland forests and adjacent riparian areas, and declines in fire frequency in both areas corresponded with the onset of effective fire suppression (Everett et al. 2003). For example, Barrett (2000) examined fire frequencies in watersheds of the South Fork Salmon River drainage in central Idaho, where an active fire suppression program began in 1948. In study catchments with minimal management and other anthropogenic disturbance in the past 40–50 years, he found natural fire regimes to be considerably altered. From about 1471 to 1948, moderate to large, mixed-severity (high, low, and unburned patches) fires had occurred in both upland and riparian forests approximately every 19 years (table 4). However, since 1948, the fire-free interval in most catchments has been approximately eight times longer than during the time before active fire suppression (Barrett 2000; Barrett et al. 1997). The influence of fire suppression on changes in vegetation is likely to be similar in riparian and upland forests, resulting in shifts in species composition to more shade-tolerant or fire-sensitive species and increased fuel accumulation.

2.2 Riparian Characteristics That Influence Fire Behavior

2.2.1 Physical Influences on Fire Properties

Physical features of riparian areas can differ considerably from adjacent uplands and can influence fire behavior and severity (table 6; Dwire and Kauffman 2003; Halofsky and Hibbs 2008; Pettit and Naiman 2007). The location within drainage bottoms, combined with the presence of surface water, saturated soils, topographic features, and canopy shading contribute to distinct microclimates in many streamside areas. Relative to uplands, riparian microclimates are frequently cooler with higher relative humidity due to evaporation from the stream and transpiration and insulation from riparian vegetation (Brosofske et al. 1997; Naiman and Décamps 1997; Naiman et al. 1993; Williamson 1999). Local differences in microclimate likely exert control over fire behavior during low-to-moderate-severity fires but may be negligible under severe fire weather.

Table 6—Riparian characteristics that may influence fire behavior in forests and rangelands of the western United States (modified from table 1 in Dwire and Kauffman 2003).

Fire behavior factor	Riparian characteristic	Potential influence on fire behavior	Citation
Fuel loads	High fuel loads due to high net primary productivity. Accumulation of fuels due to low fire return intervals.	High fuel loads can increase vulnerability to a fire in drought conditions, and influence fire severity, intensity and return intervals.	Agee 1993; Williamson 1999; Van de Water and North 2011
Fuel moisture content	High fuel moisture content due to proximity to water, shallow water tables, and dense shade.	Fuel loads may remain too moist for sustained fire spread late into the fire season.	Agee et al. 2002; Williamson 1999
Fuel continuity	Active channels, gravel bars, and wet meadows may function as natural fuel breaks.	Breaks in fuel continuity can prevent or slow the spread of fire.	Agee 1993; Everett et al. 2003
Vegetation composition	Greater dominance of moisture-dependent shrubs and deciduous trees.	Tree and shrub species adapted to light-moderate fire; lower resistance to severe wildfire.	Halofsky and Hibbs 2008; Williamson 1999
Low topographic position	Canyon/drainage bottoms; lowest points on the landscape.	High fuel moisture, high relative humidity, and few lightning strikes may decrease fire frequency and severity; more human-caused ignitions may increase fire frequency.	Olson and Agee 2005
Steep topographic position	Narrow, steep stream channels that may serve as "chutes" or "chimneys."	If high fuel loads are present, could result in "wicking"—the rapid up-canyon spread of fire.	Agee 1998
Microclimate	Topography, presence of water, and dense shade can create cooler, moister conditions.	High relative humidity and cool temperatures may lessen fire intensity and rate of spread.	Williamson 1999; Brosofske et al. 1997

Topographic features—including aspect, slope, elevation, and terrain such as hills, terraces, ridgetops, and drainages—also influence fire behavior and spread. Weather can determine fire behavior on multiple scales and can change rapidly, sometimes in response to topographic features. Weather is the primary driver of large, high-severity fire events; during certain weather events, fuels become less important in regulating fire behavior (Bessie and Johnson 1995). During small, low-to-mixed-severity fires, factors such as fuel moisture, fuel type, relative humidity, temperature, and topography have significant influences on fire behavior (Turner and Romme 1994). An analysis following the B&B Complex Fire in central Oregon showed that riparian understory fire severity was strongly associated with the slope from riparian sample points to uplands—that is, steeper hillslopes burned more severely (Halofsky and Hibbs 2008). In the Biscuit Fire in southern Oregon, stream gradient was also found to be strongly associated with riparian understory fire severity (Halofsky and Hibbs 2008). Upper reaches of intermittent or low-order streams on steep slopes with small water sources can experience the same fire behavior and severity as nearby uplands (Fisk et al. 2006).

Topographic features can exert strong control on how fires move across landscapes, including movement and intensity from uplands to riparian areas or along stream-riparian corridors. Topographic conditions along drainages can influence wind and other weather elements during wildfires. Wind plays a significant role in the rate of fire spread and the intensity of the fire front. In extreme cases, riparian areas can burn more severely than surrounding uplands (table 5). In riparian areas bordering intermittent streams in the Klamath Mountains of California, Taylor and Skinner (1998) found that fires had been frequent and suggested that some headwater reaches act as chutes where fires spread readily and burn intensely. As noted above, this type of fire behavior has been observed where steep terrain and narrow stream valleys create more heat and serve as chimneys or chutes that promote updrafts and convective heating of the fire and cause it to carry upslope and up the drainage at a rapid rate of spread with high intensity (Skinner 2003). This fire behavior, referred to as 'wicking,' is most likely to occur in the middle or upper portions of drainage networks with south-facing aspects along small perennial or intermittent stream channels and also depends on riparian vegetation and fuel loads. There is a critical need for improved understanding of potential fire behavior for different stream reach types and riparian vegetation types, and for identifying the streamside conditions that most influence the intensity, severity, and spread of wildfire.

Along large perennial stream and river valleys, the stream channel can create a significant break in fuel characteristics and continuity (tables 5 and 6). Wide stream channels, alluvial terraces with extensive gravel bars, and large, sparsely vegetated areas with wet soils can function as fuel breaks. In the Cascade Mountains of western Oregon, Kushla and Ripple (1997) found that local topographic features, including proximity to perennial streams and ridgelines, had a significant influence on forest mortality following the Warner Creek Burn. Kobziar and McBride (2006) sampled riparian vegetation and physical features along two streams 1 year following the Lookout Fire that burned a northern Sierra mixed-conifer forest on the Plumas National Forest. They attributed patchy riparian burn patterns in part to the occurrence of gravel bars and streamside terraces that supported alders (*Alnus incana* spp. *tenuifolia*), which presumably acted as natural firebreaks. Other "firebreak" locations include wet meadows, stream segments with a high herbaceous component, and reaches dominated by willows (*Salix* spp.)

or other riparian hardwood shrubs. These reach types are frequently located in wider, lower-gradient portions of stream networks that can receive significant hydrologic inputs (surface and subsurface) from surrounding hillslopes, resulting in saturated soil conditions and the presence of riparian or slope wetlands. They include sites of past and current beaver (*Castor canadensis*) activity that has modified the channel and flooded portions of the valley bottom. Saturated soils combined with high fuel moisture can stop the advance of fire or cause a fire to "jump" from hillslope to hillslope and not burn in the riparian area. Fire characteristics and upland conditions can influence the extent to which riparian areas function as firebreaks. If a fire is burning with low-to-mid-intensity across the landscape, riparian areas along low gradient, perennial streams can serve as effective barriers and slow fire spread.

Lightning ignitions are less likely to occur in many riparian areas due to topographic position, cooler microclimate, and generally moister fuel conditions. However, during dry conditions, human-caused fire ignitions occur in streamside areas, especially in campgrounds, along roads, and in other recreational use areas (table 6).

2.2.2 Vegetation Influences on Fire Properties

Many riparian plant communities have complex canopy and subcanopy structure and well-developed shrub and herbaceous understories (Danehy and Kirpes 2000; Nierenberg and Hibbs 2000). They are frequently the most productive areas in a given region and contain structurally and floristically diverse vegetation (Pollock et al. 1998; Tabacchi et al. 1998). In many areas, riparian vegetation may differ from adjacent uplands in overstory species composition, have higher stem densities and basal area, have greater dominance of shrubs and deciduous hardwoods, and have higher herbaceous cover (Pabst and Spies 1998, 1999; Wimberly and Spies 2001). In Douglas-fir forests with mixed-severity fire regimes, Halofsky and Hibbs (2008) found that fire intensity in riparian areas was generally lower than that of uplands, although burn severity (overstory crown scorch and mortality) was similar to uplands. They attributed this to differences in the subcanopy, particularly the higher basal area of riparian deciduous hardwood species. Following a mixed-severity fire in a northern Sierra mixed-conifer forest, Kobziar and McBride (2006) noted that portions of riparian areas dominated by alder were less frequently burned, and suggested that the riparian vegetation and terrace topography may have slowed the progression of the predominantly 'backing fire' towards the stream. Fire behavior is also affected by characteristics of the vegetation, such as the foliar chemistry (volatile versus nonvolatile), bulk density (mass/volume), ratio of live to dead material (flammability), horizontal and vertical continuity, and moisture content, all of which can differ between upland and riparian areas (table 6; Agee 1993; Ryan 2001).

Despite these notable differences, many forested riparian areas in the western United States are occupied by the same overstory species as surrounding uplands. Even in these riparian stands, stem densities, standing biomass, and shrub and herbaceous understory diversity are usually greater than in upslope stands. In the Blue Mountains of eastern Oregon, stand basal area, stand density, and canopy foliage weight were greater in conifer-dominated riparian stands than in associated upland stands despite similarities in overstory species composition (Williamson 1999). In subalpine forests of northern Colorado and southern Wyoming, the overstory species composition and basal area were similar in riparian and upland plots, but understory stem densities and shrub diversity were generally higher in riparian plots (fig. 4; Dwire et al. 2015a,b). Where vegetation and fuel profiles are similar across upland and riparian stands, they are likely to burn with similar frequency and intensity.

The limited research on the influence of riparian vegetation and fuels on fire properties has mostly been conducted in conifer-dominated areas in the Pacific Northwest. Much less is known about riparian areas in the western United States where plant communities are dominated by deciduous trees and shrubs, including alders (*Alnus* spp.), willows (*Salix* spp.), quaking aspen (*Populus tremuloides*), and cottonwoods (*Populus* spp.; Patten 1998). These riparian plant community types differ considerably in fuel characteristics (chemistry, fuel composition, and moisture content) from conifer, shrub, or grassland-dominated uplands. Montane meadows border numerous stream segments in mountains of the western United States, including ranges throughout the Great Basin (Chambers and Miller 2004). These grass- and sedge-dominated meadows often produce high loads of fine fuels (3–11 mg/ha; Dwire et al. 2004; Otting 1999) that can burn late in the fire season.

Differences in riparian and upland vegetation result in differences in fuel profiles and total fuel loadings. Streamside areas frequently have more complex vertical layers within the canopy and subcanopy—that is, well-developed ladder fuels, more fine fuels, and greater fuel moisture than surrounding uplands—components that are strongly predictive of riparian fire severity (table 6; Halofsky and Hibbs 2008). Potential for crown

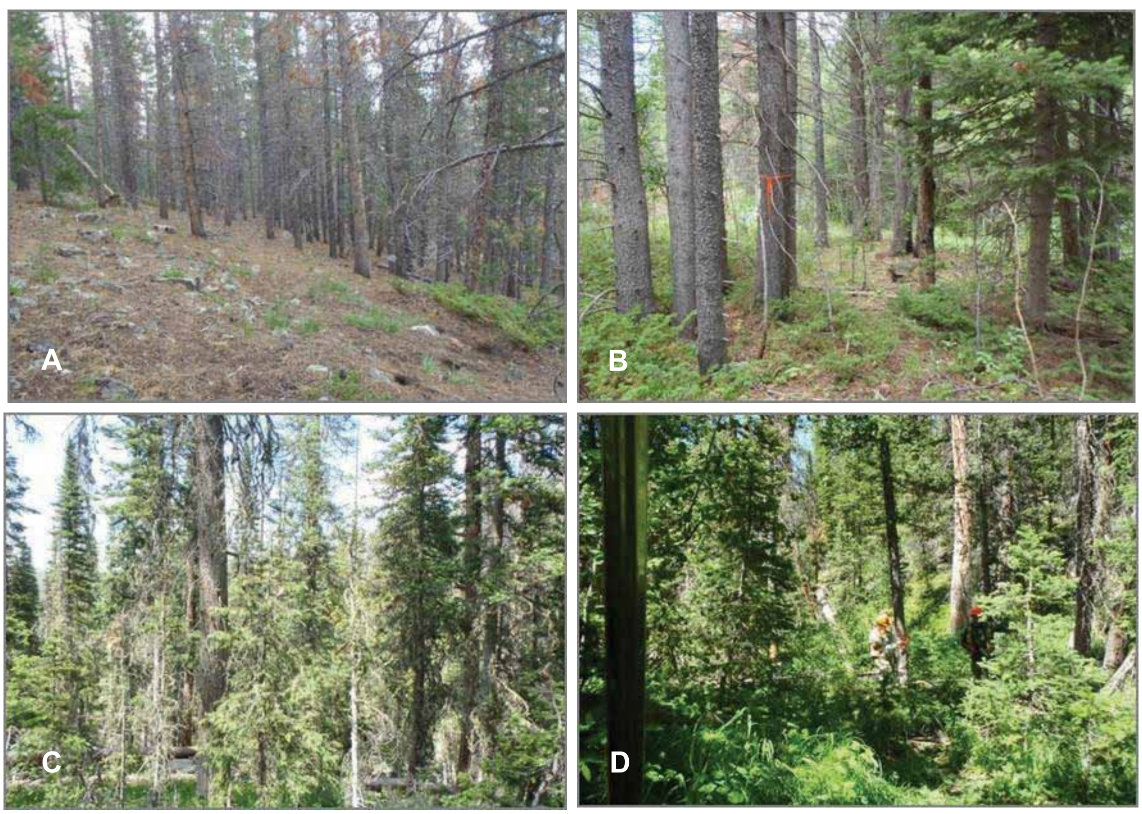


Figure 4—A range of stand conditions were sampled in both upland and riparian plots. However, similarities can be seen across stand types in these photos of paired upland and riparian plots. (A, upper left) Bennett Creek, Roosevelt National Forest, Colorado, upland; (B, upper right) Bennett Creek, riparian; (C, lower left) Cortez Creek, Medicine Bow National Forest, Wyoming, upland; (D, lower right) Cortez Creek, riparian (Dwire et al. 2015).

fire initiation (torching) and fuel characteristics were compared in upland versus riparian stands in Ponderosa pine/Douglas-fir, grand fir, and subalpine fir (*Picea engelmannii*) forest types in the Blue Mountains, northeastern Oregon (Williamson 1999). In both upland and riparian stands of all forest types, the potential for torching was high, suggesting that high-severity fire could behave similarly across uplands and streamside areas. In mixed conifer forests of the Sierra Nevada Mountains in California, Van de Water and North (2011) compared stand structure, fuel loads, and potential fire behavior between riparian and upland forests under current and reconstructed conditions. Relative to upland stands, current riparian forests had greater stem density, probability of torching, predicted mortality, canopy base height, and frequency of fire tolerant species—features that the authors attributed to fire suppression. However, reconstructed riparian and upland forests were similar for most of these characteristics, suggesting that historical (before fire suppression) forest structure and fuel loads were similar in uplands and streamside areas. In southern Rocky Mountain forests affected by recent bark beetle (mountain pine beetle, *Dendroctonus ponderosae*; spruce beetle, *Dendroctonus rufipennis*) infestations, fuel loads were largely similar in paired riparian-upland plots (fig. 4; Dwire et al. 2015a,b). The riparian stands sampled were dominated by the same overstory species as surrounding uplands and were among the driest riparian plant associations in the region (Carsey et al. 2003).

Fire severity can be greater in riparian areas if streamside fuel loads accumulate at greater rates relative to uplands (due to fire suppression, 'hands-off' riparian management, or natural processes) and if prefire moisture levels are low (due to drought or season; table 5). High riparian fuel loads can influence fire spread by serving as "wicks," especially where adjacent uplands have been harvested or actively managed for fuel reduction. This fire behavior was observed during the Angora Fire, Tahoe National Forest, California in late June 2007 (Murphy et al. 2007). Before ignition, the Angora Creek Stream Environment Zone (SEZ, or riparian area; Text Box 1) contained heavy dead woody fuel loadings. A retrospective evaluation of the Angora Fire behavior noted that "dense stands of trees in the Angora SEZ likely contributed to the rapid spread upslope to Angora Ridge and across the slope to the base of Tahoe Mountain" (Murphy et al. 2007; fig. 5). The well-documented fire behavior during the Angora Fire has focused attention on the role of riparian corridors and fuel conditions on fire severity and spread (Murphy et al. 2007; Safford et al. 2009).

Riparian fuel loads data are not available for most vegetation types, and the extent to which differences in forest structure and fuels between riparian areas and uplands affect fire behavior remains somewhat speculative. When estimates for fuels are required for project planning, resource specialists, particularly fuels specialists or fire management officers, frequently use fuels photo-series for the appropriate forest type and region (http://www.fs.fed.us/pnw/fera/research/fuels/photo_series/index.shtml). Photo series have been developed for many upland forest and vegetation types; for a range of fuel loading conditions that may occur on a specific national forest (e.g., Popp and Lundquist 2006); for given areas, such as the WUI in the Colorado Front Range (Battaglia et al. 2006); or for a specific purpose, e.g., comparing burned and unburned sites (Jain et al. 2007). Photos are accompanied by measured fuel loadings and usually grouped by forest or vegetation type and stand age, including regeneration stages following past forest harvest. Managers compare field conditions with the photos to assess approximate fuel loads. Photo series have not

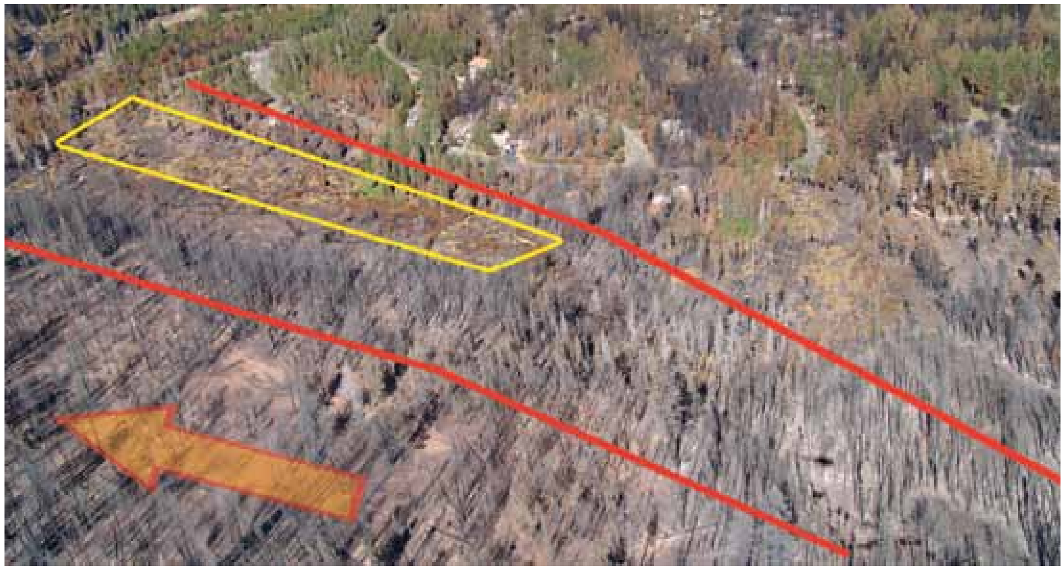


Figure 5—Stream Environment Zone (SEZ) along Angora Creek following the Angora Fire, Tahoe NF, California (2007). Dense, continuous stands of trees contributed to rapid spread rates (to the NNE) down this stream corridor. Arrow points in direction of wind and fastest fire spread (NNE). Note greater density of trees within the SEZ (roughly outlined in red). Moister portions of the SEZ (outlined in yellow) burned less severely than surrounding areas (photo originally published in Murphy et al. 2007).

been developed specifically for riparian vegetation types, but existing photo series can be used for conifer- and aspen-dominated riparian areas (http://depts.washington.edu/nwfire/dps/). Examples of estimated fuel loadings that might be useful for some conifer-dominated riparian areas in the Southern Rockies are shown in figure 6 (Popp and Lundquist 2006). Although this approach can be informative for certain applications, more quantitative assessments of riparian fuel characteristics are needed to inform fire management in streamside areas.

Moisture content of various fuel strata can be a critical feature in determining how some riparian stands burn relative to uplands. High relative humidity due to the cool, moist microclimates within riparian areas can increase fuel moisture content of both live and dead fuels (Williamson 1999). Agee et al. (2002) measured late-season foliar moisture in paired upland-riparian stands of Douglas-fir, grand fir, and subalpine fir in the Blue Mountains of northeastern Oregon. In the Douglas-fir and grand fir series, they observed no differences in conifer foliar moisture between the upland and riparian stands; however, understory shrub and herbaceous foliar moisture was considerably higher in the riparian stands. In addition, herbaceous foliar moisture was more variable in the riparian stands, which was attributed to the diversity of herbaceous species occurring in the understory. Understory fuel moisture has been shown to affect the rate of spread, fire line intensity, fuel consumption, and plant mortality in coniferous forests (Kauffman and Martin 1989, 1990), suggesting that higher moisture content of riparian fuels could reduce fire intensity and severity relative to uplands.

Seasonality also affects fuel moisture and thus plays a role in fire behavior and fire severity across the landscape (Knapp et al. 2005, 2009). In mixed-conifer forest types, Van de Water and North (2011) found that the majority of fire scars in both riparian and upland areas occurred in late summer and fall. As vegetation becomes dormant later in

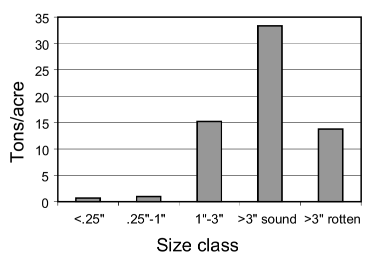
OLDER RENERATED SPRUCE-FIR STANDS (12C)

PLOT DATA				
Plot	utmx	utmy	Canopy Closure (%)	Average Tree Height (ft.)
59	384372	4557677	97	93

Basal Area (ft²/ac) by Species				
Total	aspen	spruce	subalpine fir	lodgepole pine
211	0	133	49	29

FUEL LOADING (tons/ac)			
0 - 0.25"	0.26 - 1"	1.1 - 3"	0 - 3"
0.70	0.98	15.21	16.88
> 3" sound	> 3" rotten	> 3" total	Grand Total
33.35	13.78	47.12	64.01

OTHER FUELS DATA	
% ground covered by fuels	11
Average fuels height (in.)	3.0
Average duff depth (in.)	2.3
Average litter depth (in.)	0.3



OLD GROWTH IN LODGEPOLE PINE (13D)

PLOT DATA				
Plot	utmx	utmy	Canopy Closure (%)	Average Tree Height (ft.)
12	397357	4562015	76	59

Basal Area (ft²/ac) by Species				
Total	aspen	spruce	subalpine fir	lodgepole pine
149	0	0	0	149

FUEL LOADING (tons/ac)			
0 - 0.25"	0.26 - 1"	1.1 - 3"	0 - 3"
0.14	0.19	3.03	3.37
> 3" sound	> 3" rotten	> 3" total	Grand Total
23.82	8.27	32.10	35.46

OTHER FUELS DATA	
% ground covered by fuels	9
Average fuels height (in.)	0.0
Average duff depth (in.)	0.0
Average litter depth (in.)	0.8

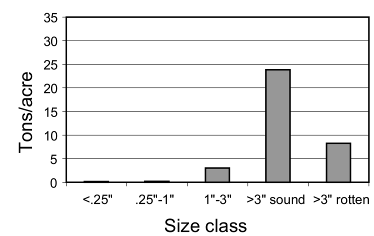


Figure 6—Examples of photos that could potentially be used to evaluate fuel loading in conifer dominated riparian areas in the southern Rockies. Panels present a visual representation of a range of fuel loading conditions found on the Medicine Bow National Forest, Wyoming (Popp and Lundquist 2006).

the growing season, foliar moisture decreases, increasing the probability of fire occurrence (Agee et al. 2002). The ratio between the current year's growth and older foliage also influences foliar moisture content as seasons change. Periods of drought contribute to lower foliar and fuel moistures and have been correlated with increased fire occurrence. Although this correlation is stronger in upland areas, riparian areas also experience a greater number of fires during times of drought (Van de Water and North 2011).

2.2.3 Legacies of Disturbance, Land Use and Management

Natural disturbances and processes—including flooding, fire, debris flows, and pest and pathogen outbreaks—have influenced the development and current condition of riparian and stream habitats (Luce et al. 2012). Along many stream and river segments, however, the effects of past and present human disturbance may be more pervasive than natural processes (Dwire et al. 1999; McAllister 2008; McIntosh et al. 1994a,b). Human effects on streams and rivers can be broadly considered with respect to five categories: flow regulation/alteration, water pollution, channel alteration, decreased biotic integrity, and land use (Wohl 2001, 2006). Direct human impacts result from activities conducted within the stream channel itself that alter channel geometry, the dynamics of water and sediment movement, or the species compositions of aquatic and riparian communities. Activities include channelization, removal of beavers, placer mining, and construction of dams or diversions (Wohl 2001, 2006).

Many riparian plant communities have experienced shifts in composition from dominance by native species to exotic, invasive species in response to flow alteration and other factors (Caskey et al. 2015; Merritt and Poff 2010; Stohlgren et al. 1998). Shifts in riparian species composition due to hydrologic modification of streams and the introduction of invasive nonnative species have resulted in changes in streamside fuel characteristics. In the southwestern United States, for example, river damming, flow regulation, and water diversions have contributed to the transformation of native riparian gallery forests, dominated by Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*), to riparian scrub thickets, dominated by exotic tamarisk species (*Tamarix* spp.; fig. 7; Busch 1995; Busch and Smith, 1993, 1995; Everitt 1998; Shafroth et al. 2002; Smith et al. 1998). Tamarisk produces large quantities of highly combustible fuels, and its dominance in riparian floodplains has altered the role and influence of fire in structuring riparian plant communities (Busch and Smith 1995; Shafroth et al. 2002). Increasing dominance of other invasive riparian species, including Russian olive (*Elaeagnus angustifolia*; Friedman et al. 2005; also see Chapter 6), Siberian elm (*Ulmus pumila* L.), and tree-of-heaven (*Ailanthus altissima*; Howard 2004), has likely altered fuel profiles along streams and rivers in arid and semiarid regions throughout the western United States.

Less direct human impacts result from activities within the watershed that alter the movement of water, sediment, and large wood and nutrients or introduce contaminants to the stream. Activities include urbanization, agriculture, road-building, forest harvest, and grazing. Urbanization and development of transportation networks result in the replacement of riparian vegetation and fragmentation of riparian-stream ecosystems (Blanton and Marcus 2009; Bledsoe and Watson 2001; Patten 1998). Mechanical operations associated with forest harvest, agriculture, road construction, postfire rehabilitation treatments, and mining can influence hillslope hydrology and erosion potential, resulting

Figure 7—Postfire tamarisk dominance along the Middle Rio Grande River, New Mexico. The overstory cottonwoods (*Populus fremontii*) were killed by the fire, and tamarisk (*Tamarix ramosissima*) in the understory has responded with increased growth. Gooding's willow (*Salix gooddingii*) also occurs in the overstory, is more resilient to fire than Fremont's cottonwood, and frequently resprouts following fire (photo by David M. Merritt, National Stream and Aquatic Ecology Center, USDA Forest Service, used with permission).

in increased erosion and delivery of sediment to stream channels and floodplains (Reid 2010; Robichaud et al. 2000, 2010). Timber harvest has altered upland and streamside forest habitat and changed riparian microclimates by increasing solar radiation and decreasing relative humidity and protection from wind, thereby increasing stream temperatures (Brosofske et al. 1997; Moore et al. 2005). Forest cutting has altered forest structure and fuel loading and profiles and has contributed to increased frequency and volume of debris slides to streams and riparian areas (Luce et al. 2012).

Livestock grazing, most notably overgrazing, alters the diversity and structure of riparian vegetation, reducing the quality of habitat within riparian and stream ecosystems (Beever et al. 2005; Hessburg and Agee 2003). Soil erosion and compaction typically increases due to livestock activity in riparian areas (Kauffman et al. 2004), while bank stability decreases due to the loss of riparian vegetation and trampling (Belsky et al. 1999). In shrub-steppe ecosystems, grazing and other land management practices have contributed to the increased dominance of cheatgrass, which has fueled more frequent fires than occurred in the past, altering regional fire regimes. Referred to as "the grass-fire cycle," it is an example of an ecological feedback loop (i.e., the higher the cover of annual grasses, the more frequently fire occurs and the more dominant grasses become; Brooks 2008; Brooks et al. 2004). Management of riparian resources in these arid ecosystems requires consideration of grazing and other past land uses, knowledge of different vegetation types, and active restoration (Wright and Chambers 2002).

Human impacts can result in changes in the timing, frequency, or magnitude of natural disturbances. As noted above, forest harvest and road building can accelerate the frequency and volume of debris slides and hillslope sediment loss that can result in delivery of sediment and other material to channels and floodplains. Several extensive reviews have described the impacts of human disturbance and land use on streams, rivers, and riparian areas (Naiman et al. 2005; Wohl 2001, 2006). Land use and management can affect fire properties in both uplands and riparian areas. Where streams and riparian areas have been degraded by land and water use, fire properties may begin to resemble drier uplands. As in uplands, fire suppression in forested riparian areas with low- to mid-severity fire regimes has resulted in increased fuel loads and changes in vegetation composition and structure (Arno and Allison-Bunnell 2002; Messier et al. 2012; Van de Water and North 2011). In landscapes typified by low- or moderate-severity fire regimes, the cumulative impacts of land use on fire behavior are likely to be most pronounced under conditions of extreme fire weather (Dwire and Kauffman 2003).

2.3 Post-fire Recovery of Riparian and Aquatic Resources

Recovery of stream and riparian ecosystems following wildfire depends largely on burn severity and extent, whether the fire burned both upland and riparian areas, precipitation patterns in the first few years following fire and, to a lesser extent, season of burn. More mesic conditions near streams can accelerate vegetative recovery relative to drier uplands, particularly following low- to mid-severity fires. Minshall et al. (2004) described four stages of postfire response: (1) immediate—the time of active burning to a few days after; (2) short-term—a few days to the beginning of spring runoff; (3) mid-term—usually from spring runoff of the first postfire year to sometime beyond the tenth year; and (4) long-term—occurring decades or even centuries later. Research of fire effects in stream-riparian ecosystems has largely focused on short-term or early mid-term (1–5 years following fire) period responses. Conceptual models of the impacts of fire and post-fire recovery in stream-riparian corridors and burned watersheds have been proposed for some regions (Bendix and Cowell 2010; Pettit and Naiman 2007). In these models, key factors driving postfire recovery are fire severity, rates of vegetative regrowth, physical features of the stream reach, and postfire precipitation and runoff patterns. In this section, we describe how adaptations of riparian vegetation to disturbance can influence postfire recovery, the postfire recovery of aquatic resources, interactions among geomorphic responses to fire and riparian recovery, and the impacts of herbivory and invasive species on postfire recovery.

2.3.1 Adaptations of Riparian Vegetation to Fire

Riparian species possess a range of ecological adaptations to disturbance that facilitates survival and regeneration following fire, and can thus contribute to the rapid postfire recovery of streamside habitats (table 7; Dwire and Kauffman 2003; Johansson and Nilsson 2002; Miller 2000). These include adaptations that facilitate the survival of individual plants and species on site, such as thick bark and basal sprouting, and those that contribute to recolonization of burned sites, including wind and water dispersal, vegetative reproductive responses, and the capacity to establish in burned areas (Kauffman 1990; Miller 2000; Stickney 1986).

Common riparian shrubs such as willow, alder, birch (*Betula* spp.), currant (*Ribes* spp.), snowberry (*Symphoricarpos* spp.), and rosaceous shrubs and trees (*Amelanchier,*

Table 7—Ecological adaptations that promote persistence and recovery of riparian plant species following fire (modified from table 2 in Dwire and Kauffman 2003).

Adaptation	Function	Example[a]
Adaptations that facilitate survival		
Epicormic sprouting (coppice sprouting)	Regrowth from dormant buds on branches and stems protected by bark	Cottonwoods, Oregon ash, oaks, hawthorn
Basal sprouting	Regrowth from subterranean buds on root, bulbs, lignotubers, and rhizomes	Willows, aspen, alder, birch, currant, snowberry, rosaceous trees and shrub, camas, sedges grasses
Thick bark	Protection of cambial tissues from heat damage	Ponderosa pine, redwood
Adaptations that facilitate recolonization		
Windborne seeds	Deposition and establishment on postfire soils	Willows, cottonwoods, willow herbs
Water-dispersed propagules	Dispersal of seeds or vegetative propagules to burned locations	Cottonwoods, willows, alders sedges, rushes
Fire-enhanced flowering and fruit production	Increased reproductive effort in the years following fire	Camas, blueberries, many shrubs, herbaceous dicots, and grasses
Refractory seed buried in soils	Resistant seed coat requires fire or scarification to germinate	Lupine, manzanita, *Ceanothus* spp.
On-plant seed storage	Seed storage in cones in canopy released postfire	Lodgepole pine

[a] Not all examples are riparian obligates, but all occur in riparian areas.

Crataegus, Physocarpus, Prunus, Rosa, Rubus, and *Spiraea* spp.) sprout from stumps, root crowns, lignotubers and belowground stems following fire (Adams et al. 1982; Dwire et al. 2006b; Halofsky and Hibbs 2009a; Jackson and Sullivan 2009; Kaczynski and Cooper 2015; Kobziar and McBride 2006; Miller 2000; Stickney 1986). Fire-caused tree and shrub mortality is highest when the litter layer and soil organic horizons are consumed by fire, and root crowns and other belowground tissue are killed (Kauffman and Martin 1990; Stickney 1986). In many riparian areas, higher levels of soil moisture can prevent the combustion of soil organic matter and protect belowground tissues, thus increasing the probability of shrub survival, particularly near the stream banks. Most riparian sedge and grass species recover rapidly following light surface fires through regeneration from roots and rhizomes (Racine et al. 1987). Under low-severity fire regimes, thick bark protects the cambium of tree species that can occur in riparian areas, such as ponderosa pine, western larch (*Larix occidentalis*), and coastal redwood (*Sequoia sempervirens*; table 7; Miller 2000). Riparian species that grow on stream banks or on vegetated gravel bars or islands can survive fire by persisting where fires generally do not carry.

Most cottonwood and willow species respond to fluvial disturbances and browsing through coppice sprouting from stems as well as production of root suckers (Rood et al. 1994), which are adaptations that also contribute to regeneration following fire. In floodplain forests along the Oldman River in southern Alberta, Canada, 75 percent of the cottonwood trees (*Populus angustifolia, P. balsamifera, P. deltoides*, and hybrids) sprouted vigorously from stumps within 5 months of an early spring fire (Gom and Rood 1999). Root suckers were also common, demonstrating that fire stimulated clonal regeneration of native riparian cottonwoods. In south-central New Mexico, more than 40 percent of

Rio Grande cottonwoods (*Populus deltoides* ssp. *wislizenii*) that burned within two study sites produced shoots that survived at least 2 years following fire (Ellis 2001). Nearly 73 percent of the native Goodding willow (*Salix gooddingii*) individuals produced shoot sprouts within the first 4 months of burning (Ellis 2001). Clonal regeneration of quaking aspen (*Populus tremuloides*) is promoted by light- to moderate-severity fire (Bartos and Campbell 1998; Jones and DeByle 1985; Romme et al. 1995). When aspen trees are top-killed by fire, the roots are stimulated to produce many suckers (Schier 1973; Shepperd and Smith 1993). Season of fire may be a critical factor in determining the capacity of cottonwoods and willows to survive fire. For example, severe summer fires in the southwestern United States can kill some cottonwoods (*Populus fremontii*), particularly trees that are stressed or senescent (Busch 1995; Busch and Smith 1993; fig. 7).

Most postfire recovery of riparian vegetation can be attributed to stump sprouting and other vegetative reproduction, although fire-enhanced flowering and fruit production can also foster establishment by seed (table 7; Dwire and Kauffman 2003). In the Boulder Creek watershed in western Wyoming, Dwire et al. (2006b) sampled 13 shrub species in severely burned riparian reaches. Only one species established from seed (snowbrush ceanothus, *Ceanothus velutinus*); the other 12 species either resprouted from root crowns that survived the fire or regenerated clonally. The study reaches were sampled three times (2 to 3 years postfire) and, for certain species, the number of resprouting riparian shrubs continued to increase during each sampling period, indicating that some plants required more time to regenerate than others but did survive the fire (table 8). Halofsky and Hibbs (2009a) sampled riparian plots in two different physiographic regions in Oregon 2 and 4 years postfire to examine patterns of vegetation regeneration. They found that both conifer and hardwood-dominated plant communities were self-replacing and that most hardwood species regenerated via sprouting. Although they observed considerable variability in sprouting stem densities, they also found that the number of sprouting stems increased in many plots between the two sampling periods, indicating that some plants survived the fire but required more than 2 years to regenerate. Kobziar and McBride (2006) found that numerous riparian hardwood species had resprouted just 1 year postfire along two streams in the northern Sierra Nevada.

In the Boise National Forest, repeat photos showed slow shrub recovery in the first 6 years following the North Fork Complex of fires (fig. 8). However, from years 6 to 11 postfire, resprouting and new establishment of shrubs was notable (fig. 8). In the Big Creek watershed in central Idaho, Jackson and Sullivan (2009) studied riparian plant

Table 8—Number of resprouting plants (by species) following the 2000 Boulder Creek Fire (western Wyoming, Bridger-Teton National Forest). Plants continued to regenerate over the three sampling periods (2–3 years postfire), highlighting the importance of monitoring fire effects beyond the first year following fire.

Species	Common name	Sept 2002 (no/100m^2)	June 2003 (no/100m^2)	Sept 2003 (no/100m^2)
Rosa woodsii	Wood's rose	1.9	5.0	6.7
Paxistima myrsinites	Mountain boxleaf	2.3	2.9	4.7
Ribes lacustre	Black gooseberry	5.3	6.4	7.0
Symphoricarpus albus	Snowberry	1.4	2.3	2.4
Salix boothii	Booths' willow	11.6	11.7	13.0
Amelanchier alnifolia	Serviceberry	5.0	5.2	5.9
All species		**47.4**	**54.4**	**62.7**

composition 5 to 6 years following the Diamond Point Fire (2000) in unburned, low-severity burned, and high-severity burned reaches. Upland forest stands were dominated by dry mixed-conifer forests. In riparian areas, data were reported for 24 woody species, 20 of which are generally considered to be riparian species, and all of which survived high-severity fire, primarily through stump sprouting and basal regrowth. Five years postfire, the researchers detected no differences in plant community composition between the unburned and low-severity burned reaches, indicating rapid recovery. However, comparisons in plant community composition between unburned and severely burned reaches revealed distinct differences. Although few long-term comparative data are available,

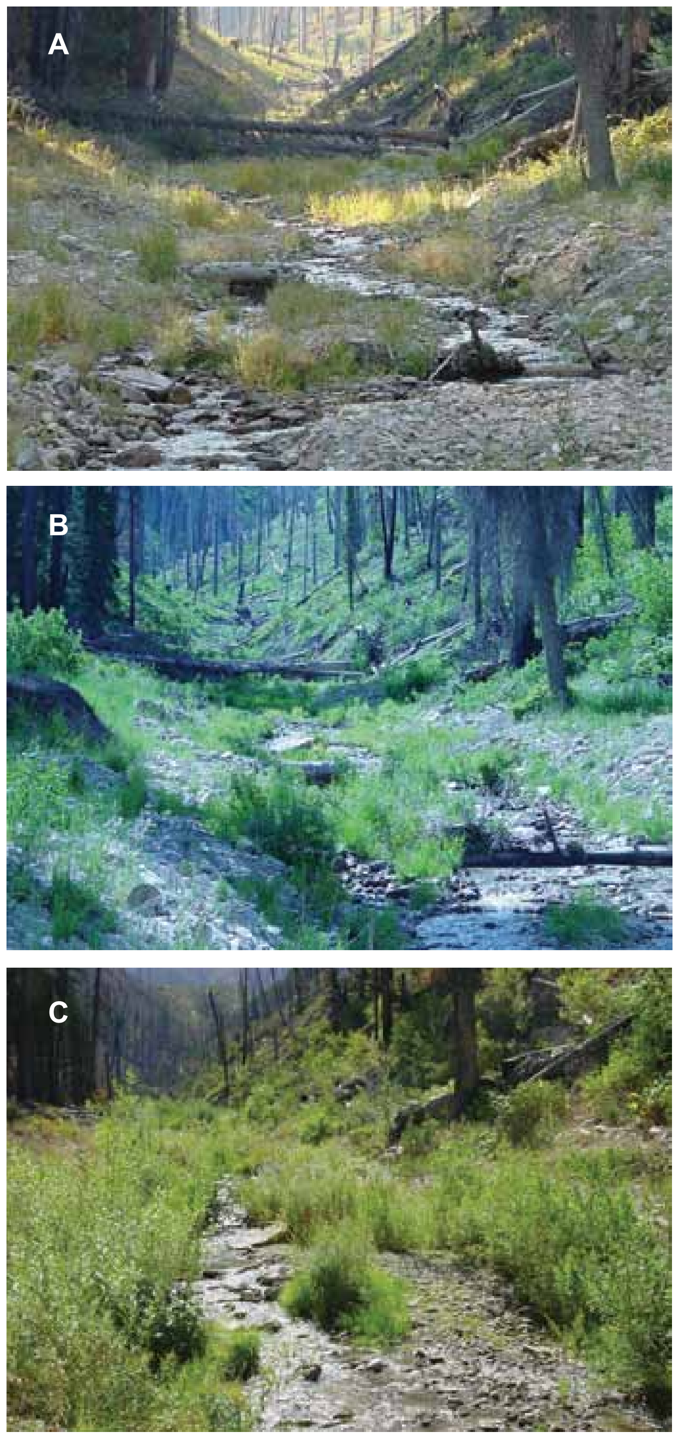


Figure 8—Recovery of riparian shrubs following the 1994 North Fork Complex of fires, Boise National Forest. Resprouting was slow during the first 6 postfire years (A: Trapper Creek 2000, 6 years postfire); however, from years 6 to 12, shrub resprouting was more notable (B: Trapper Creek 2003, 9 years postfire; C: Trapper Creek 2006, 12 years postfire) (photos by Tim Burton, used with permission).

Figure 9—Portions of the Ouzel Creek catchment, Rocky Mountain National Park, Colorado, burned in 1977. In the severely burned area, both upland and riparian vegetative recovery has been slow, marked by patches of lodgepole pine and aspen regeneration, as shown by the photos taken in 2013, 36 years postfire. Inputs of burned trees from the riparian area have resulted in large amounts of instream wood loading.

vegetative recovery in both upland and riparian areas can be much slower in severely burned portions of watersheds (fig. 9).

2.3.2 Post-fire Recovery of Aquatic Resources

Most studies examining fire effects on lotic systems have focused on changes in streamflow, sediment transport, water chemistry, aquatic biota, and fish habitat (see reviews by Bixby et al. 2015; Gresswell 1999; Rieman et al. 2003; and Verkaik et al.2013). Minshall et al. (1989) described the linkages between recovery processes in riparian and stream ecosystems following fire, noted the importance of riparian vegetation in providing increased shade and allochthonous inputs of organic matter over time, and suggested trajectories for consequent changes in benthic invertebrate communities. Following the 1988 fires in Yellowstone National Park, Minshall and others initiated extensive studies on the effects of wildfire to stream properties and biota, particularly macroinvertebrate communities (Mihuc and Minshall 1995; Minshall et al. 1995, 1997, 2001). Comparing burned and reference streams in the first several years following fire, they found differences in the relative abundance of certain invertebrate functional feeding groups, as well as differences in the transport and storage of organic matter, and movement of large wood. Postfire recovery rates of aquatic biota were faster than expected, and appeared to be related to the recovery of riparian vegetation (Minshall et al. 1997, 2001). Researchers working in other locations have also noted the importance of riparian regrowth to the response of aquatic biota, although recovery of different processes and biota varied seasonally and with the time since fire (Cooper et al. 2015; Verkaik et al. 2013; fig. 10).

Malison and Baxter (2010a,b) studied the impacts of wildfire on aquatic biota, riparian spiders, and streamside bats 5 years postfire, the period described as 'midterm' stage of response and recovery by Minshall et al. (2004). They investigated the effects of different fire severities on periphyton, benthic invertebrates, and emerging aquatic insects, spiders, and bats by comparing unburned sites with those burned by low- and high-severity wildfire on tributaries of Big Creek in the Middle Fork Salmon River drainage of central Idaho. They observed greater biomass of benthic macroinvertebrates, higher emergence of adult aquatic insects, more spiders, and more bat echo-location calls in severely burned reaches than in reaches burned with low severity. They concluded that fires of different severity have different effects on stream-riparian food webs, and that high-severity wildfire appeared to stimulate biotic responses. This suggests a high degree of ecological resilience in riparian and stream ecosystems and highlights both linkages

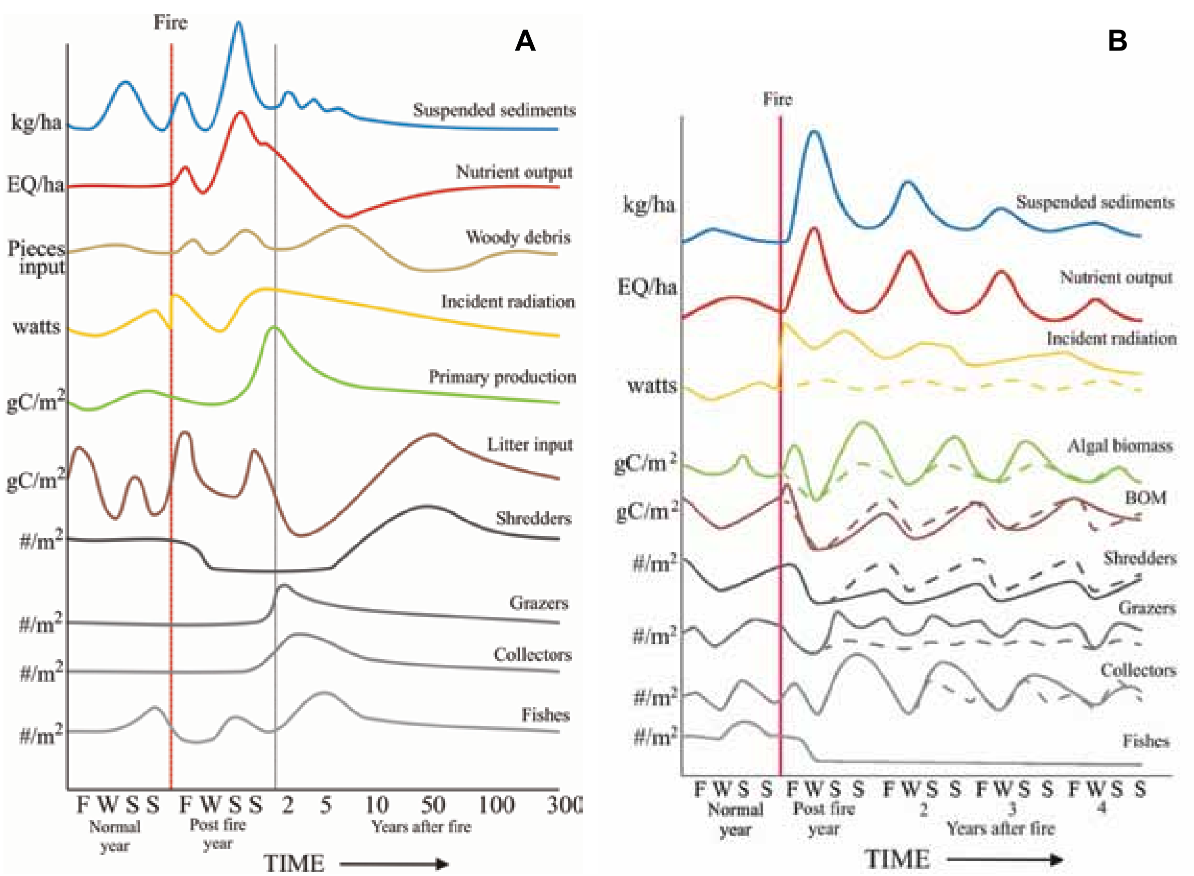


Figure 10—Hypothetical changes in physical, chemical, and biological characteristics of (A) a temperate stream before and after wildfire and (B) before and up to 4 years after wildfire in streams in Mediterranean climates (from Verkaik et al. 2013; adapted from Minshall et al. 1989 and Gresswell 1999). The letters *F, W, S,* and *S* indicate fall, winter, spring, and summer, respectively. In panel B, the solid lines represent streams in burned basins where riparian vegetation burned, and the dashed lines represent streams in burned basins where riparian vegetation remained intact. If only a solid line is shown, the response variable is hypothesized to be similar for streams in basins with burned and unburned riparian vegetation.

between aquatic and riparian recovery and the importance of monitoring postfire response over different periods.

Many of the published studies on postfire recovery of aquatic ecosystems, including the studies described above, have been conducted in dry mixed-conifer forest types of the Interior West (Jain et al. 2012). Yet similar results were found in streams of southern California, where uplands are dominated by chaparral shrublands and riparian vegetation is largely comprised of deciduous and evergreen trees and shrubs. Cooper et al. (2015) compared fire effects on macroinvertebrate community structure, food webs, and physicochemical variables in streams draining burned basins with burned riparian vegetation, burned basins with unburned riparian vegetation, and unburned basins of coastal southern California. Stable isotope analysis revealed that invertebrate diets in streams with burned riparian vegetation included a higher proportion of algal material than allochthonous detritus relative to invertebrate diets in streams with intact riparian vegetation. In the first postfire year, particulate organic matter, detritivore, and predator levels were lower in burned basins than in unburned basins, regardless of riparian condition. Shredder densities recovered quickly in burned basins with intact riparian vegetation, but remained low for 4 years in streams with burned riparian vegetation (Cooper et al. 2015).

In a retrospective study, Burton (2005) compared stream habitat characteristics of burned and unburned reaches of the Central Idaho Wilderness with reaches located on the Boise National Forest. He also examined trout abundance in a subset of streams in burned watersheds that had been sampled over time, including prefire and before- and after-fire-related debris flows. From 1986 to 2003, the Boise National Forest experienced a sequence of large, severe, uncharacteristic wildfires, which appeared to have more pronounced negative effects on trout populations in the first few postfire years compared with more characteristic, less severe wildfires that occurred in the Central Idaho Wilderness. However, within 5–10 years following fire, stream habitat conditions and trout populations improved dramatically. Aquatic habitats that were disrupted by fire and fire-related flooding and debris flows recovered within the "mid-term stage of postfire response" described by Minshall et al. (2004). The local extirpation of fishes following severe wildfire was generally patchy and short term. In several locations, fish rapidly recolonized burned reaches, where habitat conditions were improved by fire-related disturbances. Burton concluded that fish populations most at risk were those with small or isolated distributions, particularly in small watersheds with barriers to migration. Similar results have been observed in other streams in Idaho (Dunham et al. 2007) and elsewhere in the western United States (Dunham et al. 2003). The vulnerability of fish to fire depends on the quality of the impacted habitats, the extent of habitat fragmentation, and the degree of habitat specificity of individual fish species (Dunham et al. 2003; Luce et al. 2012; Rieman et al. 2003; Sestrich et al. 2011). To assist in evaluating the short- and long-term effects of fire on fish populations, management considerations are summarized in table 9.

The abundance of algae, detrital inputs, and aquatic and riparian invertebrates can show a wide range of responses to fires and subsequent floods and debris flow events, from negative to undetectable to positive. Responses vary depending on fire severity; timing of sampling relative to fires; postfire precipitation patterns and run-off intensity; fire-related disturbances such as flooding, erosion, and other physical disturbances; and

Table 9—Considerations and specific management-related questions regarding the effects of fire on fish populations and habitats (modified from table 2 in Dunham et al. 2003).

Considerations	Specific questions
Is fire an issue?	What is the probability that a fire will occur in a given area? If a fire occurs, how severe or widespread will the fire likely be? How different are current fire regimes from characteristic fire regimes?
Physical response to fire	What kinds of physical responses to fire are most likely for watersheds of concern? What are the likely spatial and temporal patterns (location, distribution, and scale) of physical processes?
Fish population and habitat responses	How important are likely physical responses to fish populations and habitats? What other constraints (e.g. land use, nonnative species) are acting to compromise fish populations and habitats? What are the immediate and longer-term risks and benefits of fire and related disturbances to fish populations and habitats?
Conflicting and complementary interests	Will fire management for aquatic resources conflict with protection of other forest values? Where are the opportunities to benefit multiple resources?

the conditions of the riparian canopy (Arkle et al. 2010; Cooper et al. 2015; Verkaik et al. 2013). Postfire riparian canopy cover was investigated for multiple years following wildfires in central Idaho (Arkle et al. 2010) and Oregon (Halofsky and Hibbs 2009b). In each study, canopy cover was assessed along transects placed perpendicular to channel, across the stream, within the study reaches. In the Idaho study, researchers included canopy cover estimates in multivariate analyses and found that percentage riparian canopy cover was an important habitat variable influencing stream macroinvertebrate communities in each of the three postfire years. In the Oregon study, Halofsky and Hibbs (2009b) found that both deciduous and conifer riparian canopy cover increased over time; in the B&B Complex fire, deciduous cover increased from 42 percent to 56 percent between the sampling periods (2 and 4 years postfire), and conifer cover increased from 11 percent to 15 percent.

Several studies have investigated the importance of fire severity on riparian conditions in regulating stream habitat variables and biotic responses, especially macroinvertebrate communities (Arkle et al. 2010; Cooper et al. 2015; Malison and Baxter 2010a,b). In general, research results suggest that fire effects on runoff, sediment, and nutrients are related to basin-wide fire impacts on vegetation and soils, but stream temperature, light, and particulate organic matter levels depend on fire impacts on riparian vegetation (Verkaik et al. 2013). Probable cause-effect relationships among fire and stream habitat and biota include interactions among driving and response variables that can change depending on fire severity and stream and watershed conditions (fig. 11). The recovery of stream communities to prefire conditions depends on the recovery of riparian and basin vegetation, postfire watershed physical processes and channel geomorphic processes, reestablishment of biogeochemical cycles, and the balance between detrital inputs and instream primary production (Pettit and Naiman 2007; Verkaik et al. 2013).

Fire is a natural disturbance process that directly influences the recruitment of large wood to streams (Benda et al. 2003a,b). Recruitment rates, timing, and

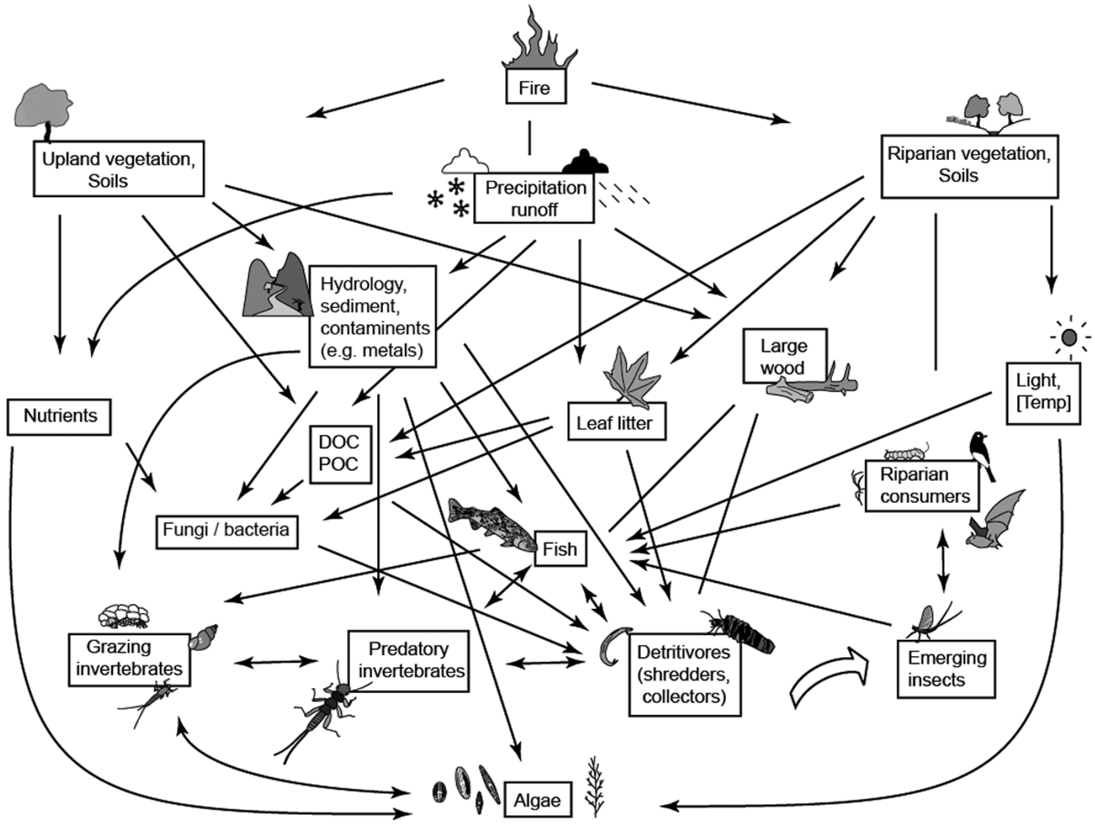


Figure 11—Possible cause-effect relationships between fire, physical and habitat variables, and stream biotic communities. Lines without arrows indicate variables that are associated with each other and unidirectional arrows point from driving variables to response variables. Double-headed arrows indicate consumer-resource interactions where consumers both depress and benefit from the consumption of their resources (from Bixby et al. 2015).

reach-level wood loads depend on the prefire forest conditions (upland and riparian forests), fire severity, location within the stream network, and watershed characteristics associated with wood transport and channel storage (May and Gresswell 2003a; Wohl and Jaeger 2009). Postfire instream wood loads may not increase for one or more decades following fire, depending on when standing dead trees fall. Also, more transport of instream large wood can occur after fire due to decreased channel stability and increases in discharge (Bendix and Cowell 2010; Young 1994). Zelt and Wohl (2004) compared instream large wood loads and channel features in adjacent burned and unburned basins in the Absaroka Range, Wyoming, 11–12 years after the 1988 Yellowstone fires. They found that instream wood loads were significantly lower in the burned drainage, which they attributed to increased transport due to higher stream discharge following fire. Timing of postfire recruitment of large wood to channels depends on reach-level conditions, extent of burn severity, local wind patterns, and other factors influencing tree fall (Minshall and Brock 1991; Young 1994). Postfire inputs can occur over several decades following fire, so extend into the ‘long-term’ stage of response and recovery described by Minshall et al. (2004; fig. 10).

Once large burned trees begin to fall, instream large wood volume can be considerably higher than prefire conditions (Minshall and Brock 1991). Increased large wood loading following fire contributes to stream habitat complexity and is generally beneficial to fish populations (Burton 2005), although the functionality of individual pieces changes over time (Scheidt 2006; Vaz et al. 2013).

Over the long term (decades and longer), after burned trees have fallen into the channel or onto the floodplain, large wood recruitment from the regenerating riparian and upland forest will depend on forest type, growth rates of the dominant tree species, and site potential of floodplains and hillslopes (Bragg 2000; Bragg et al. 2000). In a burned watershed on the Bridger-Teton National Forest, Wyoming, inputs of large wood from adjacent hillslopes and riparian areas to the channel are being tracked over time. Thirteen years postfire, nearly 90 percent of the burned trees had either entered the channel or fallen on the floodplain (unpublished data; fig. 12). Scheidt (2006) compared instream large wood characteristics in stream channels with three different times-since-fire: recent (15–20 years), mid (80–110 years), and old (>150 years) in central Idaho. He found few significant differences among the three periods, suggesting that wildfire disturbance did not have a lasting long-term effect on most large wood characteristics in the moderate-gradient, unconfined channels he studied.

Figure 12—Postfire inputs of large wood to Boulder Creek, Bridger–Teton National Forest. Thirteen years postfire, approximately 52 percent of the recruitable wood load has entered the channel, 38 percent has fallen directly on the floodplain, and 10 percent is still standing, with potential to either enter the channel (wholly or partially) or fall to the floodplain.

2.3.3 Interactions Among Physical Processes and Recovery of Riparian and Aquatic Resources

Fires interact with physical processes at both local and landscape scales to influence the form and dynamics of stream networks, hydrology, geomorphology, and riparian plant communities (Arno and Allison-Bunnell 2002). Channel erosion and mass-wasting processes can be initiated following wildfire due to the removal of vegetation, consumption of litter and duff, increased susceptibility of bare soils to erosion, and response to precipitation (table 10; Gartner et al. 2008). Physical processes, including overland flow, debris flows, earthflows, mudslides, and bank sloughing can deliver sediment to the channel and floodplain (Meyer et al. 2001; Pierson et al. 2001; Ryan et al. 2011; Wondzell and King 2003). The occurrence of these processes depends on topography, underlying geology, and soil and vegetation characteristics and is frequently associated with fire, past

Table 10—Characteristics and potential influences of major channel erosion and mass-wasting processes (modified from Reid 2010).

Erosion process	Grain size	Timing of sediment input	Location	Potential Influences
Bank erosion	fine to medium	High flows Runoff after high flows	Highest concern in moderate to large channels	Altered large wood loading Altered riparian vegetation Altered channel form Increased channel migration
Gully erosion	fine to medium	Periods of runoff Early season flows	Hillslopes Small to medium channels Below diversions	Altered site productivity Lowered water tables Accelerated runoff More hillslope sediment delivery Increased bank erosion Altered channel form Reduced floodplain connectivity
Soil creep	fine to medium	chronic	Steeper hillslopes; Pervasive in certain sedimentary lithologies	Increased bank erosion
Shallow slides	fine to coarse	High intensity rain on wet ground Rain-on-snow events	Inner gorges Hillslope swales Undercut banks Certain sedimentary lithologies	Altered site productivity Flow defection Altered large wood loading
Debris flows	fine to coarse	High intensity rain on wet ground Rain-on-snow events	Steep swales Certain sedimentary lithologies	Altered channel roughness Flow deflection Altered large wood loading Channel blocking and/or migration
Deep-seated slides	fine to very coarse	Very wet seasons, following high snow pack winters Rain-on-snow events	Certain sedimentary lithologies	Altered site productivity Flow deflection Altered large wood loading Channel blocking and/or migration
Earthflows	fine to very coarse	Very wet seasons, following high snow pack winters Rain-on-snow events	Certain sedimentary lithologies	Altered site productivity Flow deflection Altered large wood loading Channel blocking and/or migration

management activities (especially roads and forest harvest), and storm events. Numerous studies have documented increased frequency of debris flows following large-scale, severe fires (Cannon et al. 2001; Gabet and Bookter 2008; Gartner et al. 2008; Meyer et al. 1992; Santi et al. 2008). In the Oregon Coast range, May and Gresswell (2003b) found that a pulse of debris flow activity occurred following the last stand-replacement fire on mid- and upper-slope positions. In their study basins, the most recent fire in the upper slopes did not directly impact the lower elevation channels or valley bottoms, but the influence of the fire was propagated through the stream network by debris flows in the tributaries. The impacts of debris flows on postfire riparian recovery are not well documented (but see Johnson et al. 2000; May and Gresswell 2003a,b; Wohl 2006) but have likely exerted localized influence on forested riparian areas in mountainous regions.

Postfire soil erodibility is affected by geological substrate, fire severity, local and watershed impacts of the fire to vegetation and soil, and precipitation patterns, especially in the first few postfire years (Moody and Martin 2001; Wondzell and King 2003). Hillslope and steep channel processes, including postfire surface erosion and mass wasting, have been well studied and can be significant in some environments (Benda et al. 2003a; Pierce et al. 2004, Robichaud et al. 2009; Wondzell and King 2003), yet less dramatic processes may also be important ecologically as channels and watersheds undergo adjustments following fire (Ryan et al. 2011). In the Little Granite Creek watershed in western Wyoming, Ryan et al. (2011) compared stream sediment loads from a burned subwatershed (Boulder Creek) to prefire levels and to loads from an adjacent, unburned control subwatershed. Elevated suspended sediment concentrations and sediment yields were observed during spring runoff and in response to storms, and were highest during the first postfire year. However, the magnitude of increase was low relative to other studies, due partly to dry conditions in the first 3 years following fire. Also, regrowth of riparian and other vegetation likely contributed to interception of hillslope erosion. More extreme fire-related flood and sedimentation events can result in localized removal or burial of riparian vegetation, alteration of floodplain surfaces, and deposition of various substrates, thus resetting successional dynamics within streamside plant communities. Existing riparian vegetation contributes to retention of fine sediment, which will eventually be incorporated into the floodplain soils.

Physical processes can increase instream large wood loading by delivering wood to channels via debris flows, shallow and deep-seated slides, earthflows, and bank erosion (Benda et al. 2003a,b; May 2002; May and Gresswell 2003a,b; Reid 2010; table 10). In third- to fifth-order streams in the Oregon Coast Range, the contribution of large wood from debris flows ranged from 11 to 57 percent of the total volume of instream wood (May 2002). However, the influence of postfire physical disturbances on recruitment of large wood to stream channels has only been investigated for a few stream types (Bendix and Cowell 2010; Scheidt 2006). Additional research is needed to address the role of postfire physical processes in large wood recruitment to streams in different forest types and over a range of time periods, that is, in the first few years following fire, as well as over decadal scales (Scheidt 2006).

Flooding is a natural disturbance in stream-riparian corridors and can interact with postfire recovery of riparian and aquatic biota. In a central Idaho wilderness area, Arkle et al. (2010) compared the interaction between wildfire and annual variations in peak streamflow on stream habitat variables and macroinvertebrate communities in seven unburned and six burned catchments for 4 postfire years. They found that riparian burn severity and extent were correlated with greater annual variation in sediment loads, organic debris, instream large wood, and undercut bank structure. Changes in these variables over time were correlated with annual peak flow in the burned basins but not in the unburned basins, indicating that the interaction between the fire and flow disturbances resulted in decreased habitat stability in the burned basins. Macroinvertebrate communities showed high annual variability, especially in severely burned catchments, which the authors attributed to changing influence of sediment, instream large wood, and riparian canopy cover. The researchers concluded that interactions among fire, flow, and stream habitat influence year-to-year habitat variability and macroinvertebrate community composition, potentially for a period similar to the historic fire return interval.

Two of the conceptual models that have been developed to predict fire effects on stream ecosystems have emphasized the importance of fire-related physical disturbances over different periods (Bendix and Cowell 2010; Pettit and Naiman 2007). Verkaik et al. (2013) described hypothetical postfire changes in drainage basins dominated by coniferous forest, representing temperate streams and three different vegetation types that occur in Mediterranean climates, with particular focus on fire severity (severely burned versus moderately burned) and the occurrence of landslides. In their conceptual model, they recognized that postfire landslides occur in all four vegetation types, depending on the steepness of the catchment, and that the timing of landslides and debris flows is largely regulated by the timing and intensity of precipitation in the first few years following fire. Based on the rapidity of vegetative recovery, they speculated that burned basins in Mediterranean climates would recover more quickly than those in temperate regions. Bendix and Cowell (2010) summarized interactions among fire, riparian vegetation, fluvial processes and landforms, and instream large wood in a conceptual model. They emphasized the role of postfire flooding in delivery and redistribution of large wood to channels, particularly for streams in Mediterranean climates.

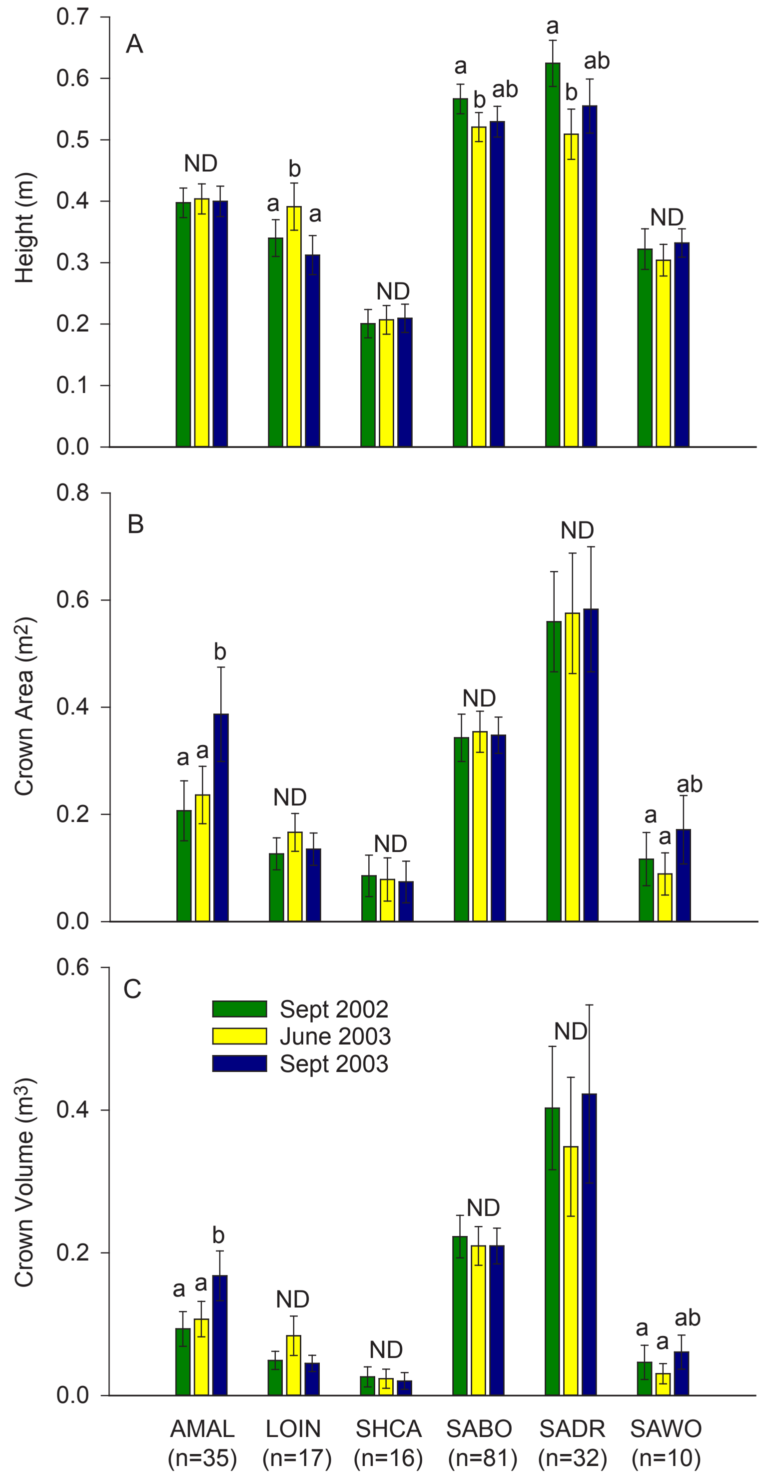
2.3.4 Challenges to Postfire Recovery of Riparian Vegetation

In all terrestrial ecosystems, a major management concern and challenge following fire is the potential increase in cover of nonnative invasive plant species (Harrod and Reichard 2001). Management activities have generally increased the vulnerability of riparian areas to invasion by nonnative species (DeFerrari and Naiman 1994; Fleischner 1994; Parks et al. 2005; Planty-Tabacchi et al. 1996), and the combined influence of fire and past land and water use has contributed to increased dominance of some riparian areas by invasive nonnatives (fig. 7). Even in a fairly remote wilderness area in Idaho, cheatgrass and reed canary grass (*Phalaris arundinacea*) were observed in severely burned riparian reaches 5 years postfire (Jackson and Sullivan 2009). The increase in dominance of cheatgrass has been related to altered fire regimes (Brooks et al. 2004) and has been studied extensively in the Great Basin and elsewhere throughout the West (Chambers et al. 2007; Mack and D'Antonio 1998) but is usually not reported in forested riparian areas. Reed canary grass is considered highly invasive in wetlands and riparian areas throughout most of its range in North America (Foster and Wetzel 2005; Kilbride and Paveglio 1999) and generally responds favorably to fire (Hutchinson 1992; Waggy 2010). The occurrence of these invasive grasses in a wilderness area is of definite concern and highlights the challenge of managing invasive species following fire.

The same basic principles of managing invasive species apply in riparian areas as in uplands: minimize the potential for their dispersal and establishment, focus on prevention of spread, maintain resistant native ecosystems, and conduct incremental treatments within an adaptive management framework. However, control of invasive species can be more difficult in riparian areas because use of mechanical and chemical treatments is restricted or not allowed along many streams (but see Chapter 6). Control of invasive species in many remote areas is limited by access and funding. Interaction and feedback between fire and response of invasive plant species are likely to increase in complexity, requiring expanded coordination for invasive species control at watershed and regional scales.

Postfire herbivory by livestock and native ungulates is frequently noted as a management concern (see Chapter 4, this report) and may contribute to increased cover by nonnative species. In a wide shrub-dominated floodplain in Rocky Mountain National Park, Colorado, Kaczynski and Cooper (2015) examined the effect of ungulate browsing on postfire basal sprouting of shrubs by comparing biomass of caged plants, enclosed to exclude ungulates, with uncaged plants. They found that browsing resulted in a 64 percent reduction in biomass for the uncaged plants. In a severely burned portion of Boulder Creek, western Wyoming, Dwire et al. (2006b) studied the impacts of browsing (cattle, elk, and deer) on postfire growth for 13 shrub species, 2 to 3 years following wildfire. Shrub height, crown area, and crown volume were sampled three times to capture winter browsing by native ungulates as well as summer utilization by both cows and native ungulates (fig. 13). Results indicated that growth of riparian shrubs was severely limited by herbivory in the first few years following wildland fire. Native ungulates browsed resprouting riparian shrubs heavily, especially palatable forage species such as serviceberry (*Amalanchier alnifolia*) and willows (*Salix* spp. fig. 13). For most riparian species, the addition of cattle contributed to higher percentages of browsed stems and arrested growth in the third growing season following wildland fire. Most riparian areas are susceptible to heavy browsing by native ungulates following fire, and managers are encouraged to postpone livestock grazing for several postfire growing seasons to foster recovery of valued riparian shrubs.

Figure 13—Postfire growth in height (A), crown area (B), and crown volume (C) for three sampling periods (September 2002, June 2003, and September 2003) for six common riparian shrub species occurring along Boulder Creek, Wyoming. For each species, mean (±1 standard error) is shown; different letters denote significant differences in means; ND denotes no difference; sample size (number of shrubs measured) is shown in parentheses (Dwire et al. 2006).



Species codes are: AMAL = *Amalanchier alnifolia*; LOIN = *Lonicera involucrata*; SHCA = *Sheperdia canadensis*; SABO = *Salix boothii*; SADR = *Salix drummondiana*; SAWO = *Salix wolfii*.

Chapter 3: Effects of Fuel Management Activities on Riparian Resources

3.1 Fuel Management Treatments

Fuel reduction treatments are land management actions taken to reduce the threat of severe wildland fire and are being planned and implemented on public lands throughout the United States (Ager et al. 2014). Most treatments have the overall goal of decreasing the risk of high-severity fire by fragmenting the forest canopy, removing ladder fuels, and reducing the abundance of ground fuels (Agee and Skinner 2005; Peterson et al. 2007). Fuel management treatments have been underway for over a decade as the Forest Service and other natural resource agencies implement the National Fire Plan (USDA/DOI 2001), the Healthy Forests Restoration Act (GAO 2003), and the President's Healthy Forest Initiative (Dombeck et al. 2004; Graham et al. 2004; Stephens and Ruth 2005; USDA/DOI 2008). One of the four goals of the National Fire Plan Comprehensive Strategy is to reduce hazardous fuels, thus potentially decreasing the risk of severe wildfire and modifying fire behavior so that some wildland fires may be more readily and safely managed (Graham et al. 2004; USDA/DOI 2002).

Fuel reduction treatments typically target crown, ladder, and surface fuels (Hunter et al. 2007; Jain et al. 2012; Peterson et al. 2007) and include prescribed fire, thinning, and other silvicultural operations, as well as chemical and biological treatment (Graham et al. 2004, 2010; Rummer 2010). Various combinations of different treatments are frequently used to modify vegetation in the canopy, subcanopy, and near and on the ground surface (Harrod et al. 2009). Treatment combinations and sequence of implementation depend on project objectives, targeted fuels, current condition of the vegetation, past management, and logistics (Peterson et al. 2007; Rummer 2010). Each treatment type and treatment combination could have different effects, ranging from negative to positive to benign, on ecosystem processes and attributes.

The objective of this chapter is to summarize the current knowledge on the impacts of fuels management on riparian resources. Despite the focus of ongoing research on the effects of fuel treatments (Graham et al. 2009; Jain et al. 2012; USDA/USDI 2008), results from studies specifically conducted in riparian areas are limited. We have summarized numerous studies from the literature that investigated the effects of wildfire, prescribed fire, and mechanical thinning or forest harvest on riparian and stream ecosystems. Our geographic focus is the western United States, although we present relevant findings from studies conducted elsewhere.

3.2 Effects of Fuel Management Activities on Riparian Resources

3.2.1 Effects of Fuel Management Activities on Riparian Vegetation

There is increased recognition that fire was historically common in many riparian areas (see Chapter 2). As in surrounding uplands, fire suppression has contributed to the accumulation of fuels in riparian areas, particularly in forest types with low- to mid-severity fire regimes (Everett et al. 2003; Messier et al. 2012; Olson and Agee 2005; Van de Water and North 2011). Yet, for most riparian plant communities, few data are available on fuel loads, fuel characteristics, or fuel distribution (but see Van de Water and North 2011; Dwire et al. 2015a,b).

Most of the valued habitat and biogeochemical functions of riparian areas are provided either directly or indirectly by vegetation (table 1). The potential effects of prescribed fire and mechanical treatments on vegetation features important for wildlife include decreased stem densities, reduced canopy continuity, fewer snags, and changes in nesting/rearing requirements and forage availability (table 11; Pilliod et al. 2006). Results from studies of prescribed fire and more extensive forest harvest treatments in upland and riparian areas are helpful in evaluating potential effects of fuels treatments on riparian vegetation (table 12; Sarr et al. 2005). Bêche et al. (2005) sampled riparian vegetation before and after a fall prescribed burn along stream segments in the central Sierra Nevada Mountains of California. As expected, plant cover and structure were reduced in the first few years following treatment. But researchers also found that ground-cover taxa richness decreased more in the burned plots than unburned plots, Simpson's species diversity index decreased in both, and ordination results showed little difference in community composition between burned and unburned plots (Bêche et al. 2005; table 12). Similar results have been observed in other locations following prescribed fire (Elliot et al. 1999) and may be partly due to patchy burning. In dry riparian meadows in central Nevada, Wright and Chambers (2002) used prescribed fire to restore cover of native graminoids. They concluded that prescribed fire combined with proper grazing management could be used to restore grass and sedge dominance under certain conditions; they developed a conceptual state-and-transition model to illustrate interactions among prescribed fire, grazing, and environmental conditions.

In the South Fork Salmon River drainage in central Idaho, a spring prescribed burn was ignited in the mixed-conifer uplands and allowed to burn into the riparian area (Arkle and Pilliod 2010). Researchers sampled transects placed perpendicular to the stream channel (1-km reaches) in the treated stream and four unburned reference streams for 3 years before treatment and 3 years following treatment (table 12). The prescribed fire burned with low to moderate severity in the uplands but left much of the riparian area unburned and had no effect on riparian cover or instream large wood. The researchers also compared patterns of burn severity and extent among the Diamond Peak wildfire (2000, central Idaho) and three other prescribed burns in the South Fork Salmon River drainage. They found that the riparian area burned by wildfire within a given basin was proportional to the basin area burned. However, a much smaller proportion of the riparian area was burned by prescribed fire than expected for a wildfire of similar size. In addition, the prescribed fires did not burn any of the riparian forest at high severity (Arkle and Pilliod 2010). These results indicate that the ecological effects of prescribed fires are much different (weaker) than those of wildfire in this mixed-conifer forest type, because burn severity and extent of burn were notably lower in treated areas.

In naturally burned riparian plant communities in Central Idaho, Jackson and Sullivan (2009) found no difference in species composition between unburned reaches and reaches that burned with low severity, 5 to 6 years postfire (table 12). Following the Biscuit Fire in southwestern Oregon and the B&B Complex Fire in the Cascade Mountains of west-central Oregon, Halofsky and Hibbs (2009a) measured the regeneration of postfire woody species 2 and 4 years following the wildfires. They found that most woody species in both

Table 11—Features of vegetation and wildlife and invertebrate habitats altered by fuel reduction treatments (modified from Pilliod et al. 2006).

Habitat element	Treatment	
	Thinning	Prescribed fire
Trees	Decreased stem density; number and size class removed depends on method; Removal of small diameter trees, (ladder fuels); Reduction in regeneration and canopy continuity; Increased canopy base height; Reduced living trees with decay; Reduced number of trees with dwarf mistletoe brooms.	Mortality of small diameter trees; Decreased density, but highly variable due to variability in fuel profiles; Increased canopy base height; Reduced canopy bulk density; Reduction in hardwoods and aspen; Reduced living trees with decay; Reduced number of trees with dwarf mistletoe brooms.
Shrubs	Removal or reduction of large shrubs (ladder fuels); Trampling of small shrubs; Regrowth within 1–10 years.	Small mortality in patches, but potential loss of above-ground forage, cover, and structure; Regrowth within 1–10 years
Forbs and graminoids	Minimal disturbance, except where trampling, skidding or pile burning; Regrowth within 1–5 growing seasons; Potential for increase in cover of invasive plant species.	Minimal mortality, mostly loss of above ground forage and cover; Regrowth within 1–5 growing seasons; Potential for increase in cover of invasive plant species.
Litter and duff	Generally minimal disturbance; Possible increase with mastication.	Reduction or elimination in places, but highly variable; Burning may alter nutrient content and dynamics, water holding capacity, other properties.
Soil	Potential soil compaction	Variable heating to soils; Possible erosion on steeper slopes.
Snags	Number and sizes removed depends on treatment; Removal of larger snags could take decades to recover.	Variable, but larger snags are generally not consumed; Could result in many small-diameter snags, most too small for most wildlife to use; Burning/charring of snags could alter wildlife and invertebrate use; Loss of larger snags could take decades to recover.
Down wood	Amount and size classes removed depends on treatment; Number of small-diameter pieces could increase with lop-and-scatter; Removal of large diameter down wood could take decades to recover.	Reduced number of pieces and volume, but variable due to fire intensity, size, moisture content, and decay state of down wood; Burning/charring of down wood could alter wildlife and invertebrate use; Loss of large-diameter down wood could take decades to recover.

Table 12—Effects of wildfire, prescribed burning and forest harvest treatments on characteristics of forest and riparian vegetation (modified from Dwire et al. 2010).

Treatment and study type	Time scale[a] (years)	Location	Findings	Source
Wildfire; riparian sampling along unburned, low-severity burned, high-severity burned reaches	+5	Mixed conifer: Ponderosa, pine lodgepole pine, Douglas-fir; central Idaho (15 streams)	No difference in riparian species composition between unburned and low-severity burned reaches. Plant cover remained low in high-severity burned reaches	Jackson and Sullivan 2009
Wildfire; retrospective sampling in riparian plots; stratified random sampling design to include low, moderate, and high severity burn classes and stream size (1-3 order).	+2 and +4	Port-Orford cedar, Douglas-fir, western hemlock, western red cedar, SW Oregon; ponderosa pine, Engelmann spruce, grand fir, Douglas-fir, central Oregon	Vigorous regeneration of woody species in both conifer and hardwood dominated riparian plant communities.	Halofsky and Hibbs 2009[a]
Spring prescribed burn; experimental study; sampled 1 treated stream and compared to 4 unburned, reference streams (1-km reaches)	–3 to +3	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River drainage, central Idaho (5 streams)	No effects of prescribed fire on riparian habitat, including riparian cover and large wood. Prescribed fire burned less severely and less riparian area than wildfires of equivalent size.	Arkle and Pilliod 2010
Stand-replacing **wildfire**; retrospective sampling in riparian plots	+145	Western hemlock-Douglas fir-forest type; Oregon Coast Oregon (9 streams)	Understory shrubs and red alder dominate initially; eventually replaced by conifers	Nierenberg and Hibbs 2000
Logging, wildfire, logging + wildfire; retrospective sampling in riparian plots	+2 to +135	Western hemlock-Douglas fir forest type; Oregon Coast Range (28 streams)	Rapid regeneration of shrub and herbaceous species; initial increase in exotic species; overall increase in alder cover/dominance	Andrus and Froehlich 1988
Spring prescribed burn on hillslope gradient including riparian cove; experimental study	–1 to +2	Mixed-oak and pine/hardwood forest types; No. Carolina	No change in riparian species composition	Elliott et al. 1999
Fall prescribed burn in riparian plots; experimental study	–1 to +1 (with unburned controls)	Mixed-conifer forest type; Sierra Nevada, CA	No clear treatment effects in riparian community composition; diversity decreased in both burned and unburned plots	Bêche et al. 2005
Unharvested alder-dominated buffers across chronosequence of **upland logging** compared alder-dominated riparian forests undisturbed by upland logging; retrospective sampling in riparian plots	+1 to +32 (with controls)	Western hemlock-Douglas fir forest type; Oregon Coast Range	No difference in herbaceous species richness, evenness, or diversity between buffered and undisturbed plots	Hibbs and Giordano 1996
Unharvested riparian buffers across chronosequence since **upland logging**; retrospective sampling in riparian buffers; compared buffer results to those from unmanaged riparian areas	+1 to +33	Four overstory canopy types: pure conifer (western hemlock-Douglas fir); conifer dominated; pure hardwood (alder, maple), hardwood dominated; Oregon Coast Range	Understory shrub and herbaceous diversity strongly correlated with canopy cover type; no strong differences in shrub and herbaceous cover or composition between riparian buffers and undisturbed riparian forests.	Hibbs and Bower 2001; Pabst and Spies 1999
Clear-cut logging, slash burning, thinning; permanent-plot and chronosequence sampling in managed and unmanaged upland forests	Varied; for most plots, before (–1) and after (+2 to +20) logging	Douglas fir-dominated (young, mature, old-growth); West Cascades, Oregon and Washington	Temporal trends varied; for most plots, understory richness was reduced following logging, but recovered over time.	Halpern and Spies 1995

[a]Timescale relative to treatment (year of treatment = 0)

conifer- and hardwood-dominated riparian plant communities regenerated vigorously after fire, and were largely self-replacing, consistent with responses observed in prescribed fire treatments of several willow species (see Chapter 6).

Mechanical operations alter vegetation differently than prescribed fire and could yield different results. However, in the Oregon Coast Range, riparian herbaceous plant diversity did not differ significantly between riparian forests located in unharvested watersheds and unharvested riparian buffers surrounded by logged uplands (table 12; Hibbs and Bower 2001; Hibbs and Giordano 1996). In forested uplands of the Cascade Mountains (Oregon and Washington), clearcut logging and other types of forest harvest have tended to reduce plant diversity initially, although most shrub and understory species recover with time as succession proceeds (Halpern and Spies 1995; Halpern et al. 1992). Certain rare species, however, have been locally extirpated by forest harvest in uplands (Halpern and Spies 1995; Hansen et al. 1991).

The immediate goal of most fuel reduction treatments is to change vegetative structure and reduce fuel continuity to reduce crown fire behavior and potential wildfire size. The effects of prescribed burning on both upland and riparian species composition appear to be either negligible or similar to effects of low-severity wildfire and are generally neutral or beneficial. Results of the study by Arkle and Pilliod (2010) indicate that the effects of prescribed fires are much smaller and shorter-lived (i.e., not ecologically comparable) to the effects of wildfire. The effects of mechanical treatments on riparian species composition are more complex, and could result in longer-term changes, depending on magnitude of environmental impacts, such as soil compaction.

3.2.2 Effects of Fuel Management Activities on Riparian Habitat and Terrestrial Wildlife

Riparian areas provide essential habitat features, namely water, food, and cover, for numerous wildlife species (Kauffman et al. 2001; Kelsey and West 1998). The transitional nature between upland and aquatic habitats results in cooler, moister streamside microclimates. The generally linear shapes with high edge-to-area ratios serve as routes of seasonal migration for many vertebrate species (table 1; Kauffman et al. 2001; Kelsey and West 1998). Riparian vegetation can be structurally and spatially complex and provide wildlife habitat requirements, such as downed wood, snags, multiple and diverse vegetative strata and canopy layers (cover), and complex branching patterns (Canterbury et al. 2000; Merritt and Bateman 2012; Pilliod et al. 2006; Saab et al. 2007; Steel et al. 1999).

Wildlife species that use riparian areas are generally divided into riparian obligates, riparian generalists, and exotic species (Kelsey and West 1998). Riparian obligates require or depend highly on riparian and aquatic resources to the extent that they could be locally extirpated with loss of riparian habitat; species include amphibians, reptiles, small mammals, and bird species (Kelsey and West 1998). Riparian generalists utilize both riparian and upland habitats, and include some salamander species, reptiles, large and small mammals (particularly bats), and birds (Kauffman et al. 2001; McComb et al. 1993; Pilliod et al. 2006; Raedeke 1988). Riparian areas also support nonnative species, including introduced game birds, as well as undesirable exotic species, such as nutria (*Myocastor coypus*) and bullfrogs (*Rana caresbeiana*; Hayes and Jennings 1986). In some regions, breaks in riparian corridor continuity can impact animal movement (Smith 2000). The fragmentation of native riparian vegetation can influence the distribution of certain wildlife species, often favoring opportunistic species over those with more specific habitat requirements (Knopf et al. 1988; Raedeke 1988). Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators (Knopf 1986; Knopf et al. 1988).

The effects of wildfire, prescribed fire, and mechanical operations on wildlife species and habitat can vary considerably for different taxa and by region (Andrus and Froehlich 1988; Pilliod et al. 2003, 2006; Saab and Powell 2005; Saab et al. 2007; Smith 2000; table 13). Wildfire and management practices affect fauna in the ways that they affect habitat, including nesting, rearing, cover, and food availability (Lyon et al. 2000; Pilliod et al. 2006; Tiedemann et al. 2000). Results from an extensive review on the influence of wildfire on avian species (203 bird species, over 100 studies) highlighted the range of responses of different species and guilds to burned conditions (Saab and Powell 2005). Different bird species responded in distinctive ways to high-severity, mixed-severity, and stand-replacement fires; some species benefitted from certain postfire conditions, while others declined. The authors concluded that a mosaic of habitat patches of different sizes across a range of burn severities is required to maintain source habitats for native avifauna. Riparian areas—both burned and unburned—are a necessary part of that mosaic. Similar results have been observed for birds in response to prescribed fire (Saab et al. 2007). Depending on the species, treatment effects ranged from beneficial to adverse and included neutral and mixed responses. In general, more bird species showed a response during the year of treatment implementation than in following years, suggesting that impacts of prescribed fire can be relatively short term. Beneficial outcomes of both wildfire and prescribed fire for birds and other wildlife are the creation of snags of various sizes and an increase in large, downed wood. Snags provide nesting and roosting sites, and downed wood provides thermal cover and concealment for birds as well as for reptiles, amphibians, and mammals (Bull et al. 1997; Converse et al. 2006; Saab et al. 2007). However, the number of snags and cover of downed wood could also be decreased by some fuel treatments (table 11; Pilliod et al. 2006).

Different species of small mammals were also found to respond differently to thinning and prescribed fire in upland ponderosa pine forests (Converse et al. 2006), depending on changes in certain habitat variables. Thinning and prescribed burning may impact some wildlife species by altering shrub cover and understory plant species composition in treated stands (Tiedemann et al. 2000). However, fuel reduction treatments may also benefit some species. For example, riparian burning and thinning resulted in increased butterfly species richness and diversity along streams in the Sierra Nevada Mountains of California (table 13; Huntzinger 2003). Arkle and Pilliod (2010) found no immediate or delayed effects of prescribed fire on the density of Rocky Mountain tailed frog tadpoles in a treated basin of central Idaho (table 13). These amphibians are good indicators of riparian and stream habitat conditions, due to relatively long larval life stages (at least 3 years; Corn and Bury 1989; Pilliod et al. 2003).

Wildlife responses to mechanical operations are also mixed, depending on species and extent of ecological impacts. Some wildlife taxa (or certain life stages of some taxa) could benefit from a particular forest management practice while others could be harmed. Certain mammals and birds have been shown to increase in species numbers with forest harvest while reptiles and amphibians have decreased (Raedeke 1988; Salo and Cundy 1987; Thomas et al. 1979;). In headwater streams of western Oregon, Olson et al. (2014) found no

Table 13—Effects of wildfire, prescribed burning and mechanical treatments on riparian habitat and terrestrial wildlife (modified from Dwire et al. 2010).

Wildlife or habitat feature studied	Study type treatments	Time scale[a] (years)	Vegetation type location	Findings	Source
Amphibians (and fish)	**Upland forest thinning** with variable riparian buffer widths	–1 to +10	Western hemlock zone; West Cascades and Coast Range, OR	No negative effects to populations of salamanders (11 spp) or fish (2 spp).	Olson et al. 2014
Rocky Mountain tailed frog tadpoles	**Spring prescribed burn**	–3 to +3	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River; Central Idaho (5 streams)	No effects of prescribed fire on densities of tailed frog tadpoles	Arkle and Pilliod 2010
Amphibians, habitat attributes	**Upland forest thinning** with variable riparian buffer widths	+ 5-6	Western hemlock zone; Coast Range, OR	No treatment effects; variable width and streamside retention riparian buffers adequate to maintain suitable habitat	Kluber et al. 2008
Amphibians (and fish)	**Clearcut logging**	+2 to +25	Mixed conifer; Pacific Northwest forests	Initial increases in fish and salamander populations, followed by declines	Hawkins et al. 1983
Amphibians	Various **logging** practices	Literature review	Mixed conifer; Pacific Northwest forests	Declines in amphibian populations following logging; severity of decline depended on species	Bury and Corn 1988
Amphibians	**Wildfire, prescribed fire**	Literature review	Different vegetation types, largely conifer or hardwood forests; USA and Australia	Limited research; wildlife responses vary with species' habitat requirements; declines in several amphibian species following wildland and prescribed fire	Pilliod et al. 2003
Vertebrate wildlife; invertebrates	**Fuel reduction treatments**	Literature review	Dry coniferous forests of the western USA	Limited research; wildlife responses vary with species' habitat requirements; most notable differences occur for species dependent on either open or closed-canopy habitats.	Pilliod et al. 2006
Vertebrate wildlife	**Wildfire**, various **fuel treatments**	Literature review	Mixed conifer; Pacific Northwest forests	Limited effects on terrestrial amphibian species and riparian generalists; negative effects on riparian obligates	Bury 2004
Vertebrate wildlife	**Wildfire, prescribed fire**	Literature review	Range of vegetation types, largely conifer or hardwood forests; USA	Wildfire and prescribed burning affect habitat and food availability; impacts vary by species and with time since fire	Smith (ed.) 2000
Birds (5 spp)	**Fuel treatment**; thin, pile burning, and prescribed fire	–1 to +1	Mixed-conifer/hardwood forest, SW OR	No negative effect on bird density (4 spp) or reproductive success.	Stephens and Alexander 2011
Birds (203 spp)	**Wildfire**	Literature review	Range of forest types, across USA	Responses differed by species, forest type, fire severity	Saab et al. 2005
Birds	**Wildfire; prescribed fire**	Review & ongoing studies	Interior west, USA	Responses differed by species, forest type; greater response during the treatment year than following years	Saab et al. 2007
Butterflies	**Wildfire, prescribed fire**; experimental study	+1 to +10	Mixed-conifer forest types; Yosemite National Park, CA; southern OR	More butterfly species in burned areas (wildfire and prescribed fire) relative to controls	Huntzinger 2003

[a] Timescale relative to treatment (year of treatment = 0)

negative effects of upland thinning on populations of amphibians and fish (table 13). Using a before/after/control/impact methodology, they analyzed count data, which were collected pretreatment and 10 years posttreatment, and examined the effectiveness of four types (4 widths) of riparian buffers in protecting 11 species of amphibians and two fish species. No negative effects were found on population numbers, suggesting that the riparian buffers were effective in maintaining adequate terrestrial and aquatic habitat. Similar results were found in a related study that also considered habitat variables (Kluber et al. 2008).

The presence of sensitive wildlife species could preclude fuel reduction treatments in particular areas, including some riparian areas. As described in Chapter 4, however, habitat restoration is a common goal for many fuel projects that include treatment of streamside areas. The basic life history traits and riparian habitat elements required by rare wildlife species need to be considered at different spatial and temporal scales during the project planning stages, since some habitat conditions could change over time in response to different treatments. Northern goshawks (*Accipiter gentilis*) generally nest close to surface water (streams and wetlands; Squires and Reynolds 1997), sometimes use deciduous riparian trees for nesting (fig. 14), and can benefit from some aspects of wildland fire (Saab et al. 2005) and potentially to some fuel treatments. Boreal toads (*Bufo boreas*) use ponds for rearing and riparian wetlands for foraging, particularly those surrounded by mesic spruce-fir forest (Pilliod et al. 2006). Wildlife species will likely respond differently to

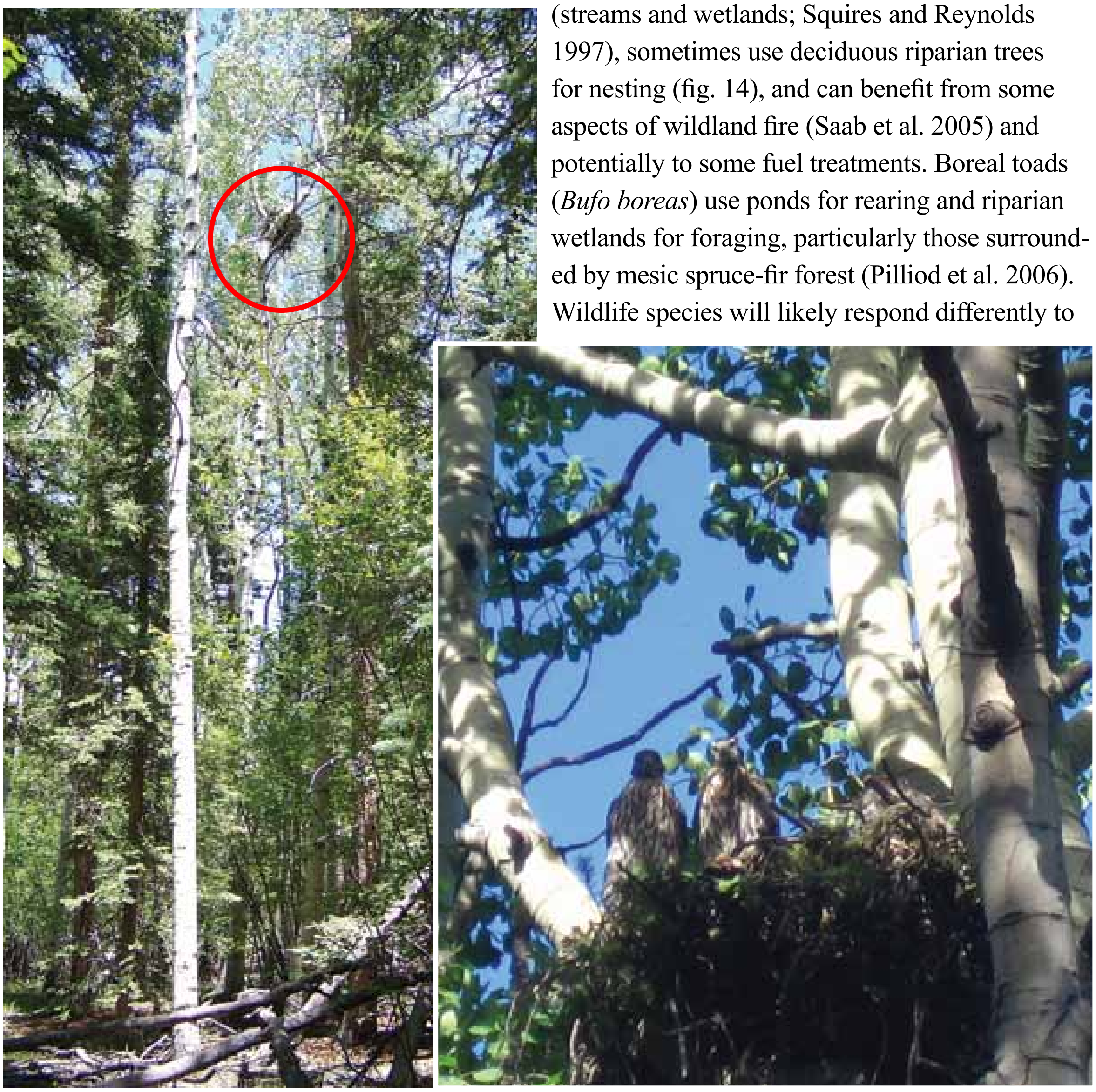


Figure 14—In some locations, northern goshawks frequently nest in aspen draws and riparian areas with accessible surface water (Pike-San Isabel National Forest, Colorado) (photos by Kristen Meyer, Pike-San Isabel National Forest, Colorado, used by permission).

various prescriptions and successional changes following fuel reduction treatments, as has been observed with other management practices (Bury 2004; Knopf et al. 1988; Pilliod et al. 2006; Raedeke 1988). Although there may be short-term risks to some riparian habitat, fuel reduction treatments (including reintroduction of fire to riparian areas) could result in a more spatially diverse range of habitat components with long-term benefits for more species. Saab et al. (2007) conclude: "Ultimately, managing for particular fire conditions—including wildland fire, prescribed fire, or fire exclusion—entails ecological tradeoffs among selected wildlife species and habitats."

3.2.3 Effects of Fuel Management Activities on Aquatic Habitat and Biota

The effects of wildfire and fire-related processes on aquatic ecosystems and fish have been summarized in earlier reviews (Dunham et al. 2003; Gresswell 1999; Rieman et al. 2003) and recently updated (Bixby et al. 2015; Luce et al. 2012; Verkaik et al. 2013; also see Chapter 2, this report). Riparian vegetation contributes to the maintenance of aquatic habitat for native fishes and other aquatic biota through (1) provision of shade for modification of stream temperature, (2) allochthonous organic matter inputs to aquatic food webs, (3) inputs of large wood for instream habitat complexity, and (4) provision of streamside habitat and stabilization of streambanks (table 1). Each of these functions could be altered at the reach scale with changes in riparian vegetation, including short- and long-term responses to fire and fuel treatments (Luce et al. 2012).

Provision of Shade

Stream temperature is critically important for aquatic biota and ecosystem processes such as productivity and nutrient cycling (Allan 1995; Beschta et al. 1987; Caissie 2006; Coutant 1999; Ruff et al. 2011). Water temperature influences growth, development, and behavioral patterns of aquatic biota both directly and through its influence on dissolved oxygen concentrations (Armstrong and Schindler 2013; Ebersole et al. 2001). Stream temperature is an important factor in determining the distribution of fish in freshwater streams, and most species of concern in the Pacific Northwest have limited temperature tolerances (Torgersen et al. 1999). Water temperature varies markedly within and among streams and watersheds (Caissie 2006; Poole and Berman 2001). Natural drivers of water temperature include topographic shade, upland and riparian vegetation, ambient air temperature and relative humidity, elevation, latitude, discharge, water source, and solar angle and radiation (Caissie 2006; Poole and Berman 2001).

Following fire, water temperatures are frequently elevated, although the extent and duration of increased temperatures vary depending on fire severity, extent of riparian and upland vegetation burned, and physical features of the burned watersheds (Cooper et al. 2015; Dunham et al. 2007; Gresswell 1999). Streams in different regions and stream segments in different parts of a drainage basin vary in response and sensitivity to wildfire (Poole and Berman 2001). In southern coastal California, Cooper et al. (2015) observed that water temperature was higher in streams draining watersheds where riparian vegetation burned than in streams in unburned watersheds or burned watersheds with intact riparian vegetation (table 14). Following two wildfires in Oregon, Halofsky and Hibbs (2009b) also found that reduction in riparian canopy cover resulted in higher stream temperatures. They observed increases in riparian cover (more shade) over streams between

Table 14—Effects of wildfire, prescribed burning and mechanical treatments on riparian and aquatic habitat features and biota (modified from Dwire et al. 2010). Please see table 13 for additional studies that included effects of forest thinning and logging on some fish species.

Wildlife or habitat feature studied	Study type treatments	Time scale[a] (years)	Vegetation type location	Findings	Source
Aquatic biota	**Fall prescribed burn** in riparian plots; experimental study	–1 to +1 (with unburned controls)	Mixed-conifer forest type; Sierra Nevada, CA	Periphyton biomass initially lower in burned stream, but exceeded biomass in unburned streams within 1 year; aquatic macroinvertebrate communities showed no detectable response	Bêche et al. 2005
Aquatic biota; riparian and aquatic habitat	**Spring prescribed burn**; treated basin vs. four reference, unburned basins; also comparisons with basins burned by wildfire	–3 to +3	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River; central Idaho (5 streams)	No differences between treated basin and reference basins in riparian canopy cover, stream temperature, stream chemistry (pH, N and P), % undercut banks, % organic debris; macroinvertebrate density, % EPT, or species richness	Arkle and Pilliod 2010
Fish	**Thinning** in riparian areas; various upland logging practices	Literature review	Mixed conifer; Pacific Northwest forests	Negative impacts on native salmonid species; degradation of habitat and reduction in number of fish	Hicks et al. 1991
Fish, aquatic habitat	**Multiple**—cumulative effects	Review of management impacts	Range of vegetation types, mostly mixed conifer, northeast OR	Cumulative effects of grazing, forest harvest, water diversions result in increased stream temperature, degraded fish habitat	Li et al. 1994
Fish, aquatic habitat	Retrospective synthesis of effects of **wildfires** (1987–2003)	+5 to +17	Mixed conifer Southwest and central ID	Short-term fire effects on fish and aquatic habitat more pronounced in managed forest relative to wilderness; dramatic improvements in habitat conditions and fish populations within 5-10 years postfire	Burton 2005
Riparian microclimate	Upland **clearcut logging**	–2 to +2	Douglas–fir dominated; West Cascades, WA	Harvesting affected riparian microclimate gradients; increased air temperature, decreased relative humidity; riparian environments became more similar to uplands	Brosofske et al. 1997
Aquatic habitat and biota	**Wildfire**	Extensive review	Forested watersheds, USA and Canada	Direct and indirect fire effects on biota varied, depending on species characteristics (especially mobility), and extent of physical and hydrologic modification of watershed	Gresswell 1999
Stream macro-invertebrate communities	**Wildfire**; comparison of five burned and five unburned headwater streams	+2	Mixed conifer, northeast Washington	Higher macroinvertebrate densities and biomass (emergence samples only) in burned streams; biomass in benthic and drift samples did not differ; lower diversity in burned streams (dominated by chironomid midges)	Mellon et al. 2008

Table 14—*Continued.*

Wildlife or habitat feature studied	Study type treatments	Time scale[a] (years)	Vegetation type location	Findings	Source
Stream benthic communities	**Wildfire**	Review	Western USA	Fairly fast recovery of benthic macroinvertebrate populations, depending on watershed management. Post-fire changes in channel restricted to 1st 5–10 years.	Minshall 2003
Riparian and aquatic habitat; Stream macro-invertebrate communities	**Wildfire**; retrospective study of six burned and seven unburned catchments. Also examined effects of postfire flooding.	+4	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River; central Idaho (13 streams)	Riparian burn severity and interaction with flooding associated with decreased habitat stability, i.e. greater annual variation in sediment loads, instream large wood, undercut banks. Severely burned basins had highly dynamic macroinvertebrate communities	Arkle et al. 2010
Aquatic foodwebs	Wildfire, unburned vs burned reaches	0 (immediate) to +5	Glacier National Park, NW MT	High N and P levels in stream water immediately after fire; stable isotopes of multiple organisms showed food web shifts	Spencer et al. 2003
Aquatic foodwebs	Wildfire; unburned, high and low severity burned reaches	+5	Mixed conifer, central Idaho	No difference in periphyton among reaches; greater macroinvertebrate biomass in high severity and unburned reaches; more insect emergence from high severity reaches	Malison and Baxter 2010 a,b
Aquatic foodwebs	Wildfire; unburned high and low severity burned reaches	+5 to +6	Mixed conifer, central Idaho	Riparian litter and insect inputs greatest in unburned reaches	Jackson et al. 2012
Aquatic foodwebs; macro-invertebrate communities; stream temperature	Wildfire; comparison of burned streams with burned riparian vegetation, streams in burned basins with unburned riparian vegetation, and unburned streams	+1 to +4	Chaparral, coastal southern CA	Canopy cover lower, stream temperature higher in burned streams with burned riparian vegetation. Fire impacts on food webs largely determined by riparian burn severity: algal-based food webs in streams with burned riparian canopies, detrital-based food webs in streams with intact riparian canopies	Cooper et al. 2015
Stream temperature	Wildfire; 3 related studies—retrospective comparisons	–0 to +13; –1 to +1;	Mixed conifer; Boise River Basin, ID	Summer maximum water temperatures remained elevated 10+ years post-fire; native vertebrates appeared resilient	Dunham et al. 2007
Stream temperature	Wildfire; analysis of spatial stream temperature patterns	Various	Mixed conifer; upper Boise River Basin, ID	Within wildfire perimeters, stream temperature increases were 2–3 times greater than basin averages	Isaak et al. 2010

[a] Timescale relative to treatment (year of treatment = 0)

the second and fourth postfire years. As the riparian canopy recovers, stream temperatures have been predicted to decrease, approaching prefire levels (Rieman and Clayton 1997). However, recent work in the Boise River basin, Idaho, suggests that elevated stream temperatures can persist for one or two decades in some locations (Dunham et al. 2007; Isaak et al. 2010). Although increased water temperature following fire is primarily related to loss of forest and riparian shading (table 14; Gresswell 1999; Isaak et al. 2010), other factors include alterations to the channel, hyporheic flow, and hydrologic changes that can either accentuate or modify losses in vegetative shading (Cooper et al. 2015; Dunham et al. 2007).

Fuel reduction treatments could potentially have impacts on vegetative shade similar to those of low-severity wildfire, although effects are likely to be patchy and short term. In a comparative study of reference basins and a basin treated with prescribed fire, Arkle and Pilliod (2010) found no difference in percent riparian canopy cover between basins. In this case, the fuel treatment was typical of many projects being conducted in conifer-dominated forests of the western United States (see Chapter 4), where a large prescribed fire was ignited in the uplands and allowed to move into the adjacent riparian areas. In some watersheds stream shading by riparian and upland vegetation is one of the few factors that can be actively managed to achieve targeted stream temperatures. In western Oregon and Washington, riparian buffer width has been designed to correlate with degree of shade (Beschta et al. 1987; Reeves et al. 1995), and riparian buffers of 100 feet or more have been reported to provide as much shade as undisturbed late-successional and old-growth forests (FEMAT 1993). Less is known about the effectiveness of buffer widths in providing adequate shade in other regions. In locations where particular stream temperature regimes are management goals, the impacts of fuel reduction treatments on shade, provided by both upland and riparian vegetation, and adequacy of riparian buffer width need to be explicitly addressed.

Allochthonous Organic Matter Inputs to Aquatic Food Webs

Riparian vegetation is an important source of allochthonous organic matter inputs for many streams and frequently provides the primary source of energy to aquatic food webs, particularly in headwaters (Finlay 2001; Vannote et al. 1980). Research has also shown that riparian areas are a valuable source of terrestrial invertebrates, an important component of many fish diets (Baxter et al. 2005). Before the 1988 Yellowstone fires, little was known about the effects of fire on aquatic communities and food webs. As discussed herein (Chapter 2), considerable research on burned streams was initiated following the Yellowstone fires (Minshall and Brock 1991; Minshall et al. 1989), and more has been learned about different aspects of postfire ecological succession in stream food webs and benthic communities over time (Minshall 2003; Minshall et al. 1995, 1997, 2001, 2004). Short-term ecological effects of fire can vary widely from little change to nearly complete loss of invertebrates and algae. Invertebrate and algal communities generally recolonize quickly, although abundance and composition vary with local fire severity and time since fire and are closely linked to recovery rates of riparian vegetation (Cooper et al. 2015; Minshall et al. 2004).

Following fire, the riparian canopy can be substantially reduced and patchy. Algal productivity can be high in response to increased sunlight, stream temperatures, and nutrient flux (Cooper et al. 2015). Food webs can shift from allochthonous to autochthonous sources of organic matter (Cooper et al. 2015), with a cascading response in macroinvertebrate trophic guilds and shifts in feeding strategies by generalist species (Mihuc and Minshall 1995; figure 11). In a comparison of stream reaches in central Idaho that had burned with different severity (unburned, low severity, and high severity; 5 years postfire), Malison and Baxter (2010a,b) found higher primary productivity and a shift to primary consumers in the severely burned reaches. They also reported that severely burned reaches had greater biomass of predatory insects and more insect emergence and concluded that burn severity appears to regulate differences in postfire aquatic insect assemblages (table 14). Working in the same streams, Jackson et al. (2012) measured inputs of leaf litter and terrestrial invertebrates falling into the streams. They found that deciduous leaf litter inputs were 1.5 times greater, and terrestrial invertebrates were twice as great in unburned reaches relative to severely burned reaches 5 years postfire. They also reported that inputs of large-bodied insects (Hymenonptera, Lepidoptera, Orthoptera, and Diptera) were greater in unburned and low-severity reaches, indicating how fire can alter terrestrial-aquatic connectivity (table 14).

In coastal southern California, Cooper et al. (2015) compared fire effects on community structure, food webs, and physicochemical variables in streams draining burned basins with burned riparian vegetation; burned basins with unburned, intact riparian vegetation; and unburned basins. Again, overall findings indicated that wildfire impacts were largely determined by the extent to which riparian vegetation burned. One year postfire, algal levels were highest in burned streams with burned riparian vegetation and lowest in streams located in burned basins with intact, unburned riparian vegetation. Algal densities remained high in streams with burned riparian vegetation for another year (2 postfire years), then declined to levels comparable to the unburned streams. Longer-term (>10 years) fire effects on aquatic food webs have not been empirically studied, and predictions are based partly on successional patterns of terrestrial and riparian vegetation. Trophic pathways are expected to shift from autochthonous to allochthonous sources as riparian vegetative cover increases (Minshall et al. 1989). However, other watershed processes, notably flooding, may also influence long-term postfire recovery of stream food webs (Arkle et al. 2010).

The effects of fuel treatments on aquatic food webs will depend on the types and sequence of methods used and the extent to which they alter the quality or quantity of allochthonous inputs. As noted above, Arkle and Pilliod (2010) found no difference in percent riparian canopy cover between reference, unburned basins, and a basin treated with a largely upland prescribed fire. As might be expected given the effect on riparian condition, they also found no differences in macroinvertebrate density, percent EPT, or species richness. If prescribed fire is actually conducted in the riparian area, it could have similar short-term effects on stream food webs as low-to-moderate-severity wildfires. Following a streamside prescribed fire in the Sierra Nevada, periphyton biomass was initially lower in the burned stream, but within 1 year of treatment, exceeded biomass in the unburned streams (table 14; Bêche et al. 2005). Aquatic macroinvertebrate communities showed no detectable response to prescribed burning (table 14; Bêche et al. 2005).

Mechanical fuels treatments will likely have different effects. In forested watersheds of the Pacific Northwest, logging practices that included the removal of riparian trees had negative consequences for some native salmonid species (Hicks et al. 1991). However, several studies have shown increases in summer biomass of fish species in headwater streams of the Pacific Northwest after logging (Bilby and Bisson 1992; Bisson and Sedell 1984). In these systems, the fish communities appear to be largely supported by autotrophic food pathways (i.e., by invertebrate groups that ingest algae and algal-conditioned organic matter; Bisson and Bilby 1998). Increased productivity in summer populations of salmonids has also been observed following losses of riparian vegetation caused by other land uses, such as livestock grazing (Chapman and Knudson 1980). This seasonal increase in fish productivity is attributed to more light reaching the stream, which stimulates autotrophic production and supports secondary production of algal-dependent invertebrates (Bisson and Bilby 1998). As described above (Section 3.2.2), Olson et al. (2014) found no negative effects of upland thinning on populations of amphibians and fish in western Oregon headwaters (table 13). In locations where fish-bearing streams are management priorities, however, potential impacts of mechanical fuel reduction prescriptions on riparian vegetation—and thus on aquatic food webs and stream-riparian nutrient and organic matter dynamics—need to be considered.

Inputs of Large Wood

The importance of large instream wood is widely recognized among stream and fish ecologists (Gregory et al. 2003). Instream large wood has been commonly referred to as large woody debris or coarse woody debris. However, some large wood ecologists have discouraged use of these terms, because instream large wood is valued and not debris, or trash (Gregory et al. 2003). Large instream wood influences channel form in small streams, creating pools, backwaters, and cascades and affecting channel width and depth (Montgomery et al. 2003). Many aquatic species use pools formed by large wood as habitat and instream wood for cover (Bilby and Bisson 1998; Wondzell and Bisson 2003). The occurrence and distribution of large wood in streams affects sediment transport and deposition, creation and growth of gravel bars, and channel and floodplain sedimentation (Montgomery et al. 2003). Dams formed by accumulations of large wood increase channel complexity and retention of organic matter, thus providing a food source for many invertebrate species and contributing to nutrient cycling (Bilby and Bisson 1998; Bisson and Bilby 1998; Wondzell and Bisson 2003).

Many natural and anthropogenic disturbances have been shown to affect large wood recruitment to streams. Chronic inputs of large wood to stream channels occur as a result of bank cutting, windthrow, and mortality of individual trees from adjacent riparian areas (Bragg and Kershner 2004; McDade et al. 1990). Large inputs of wood can occur from near-channel sources following fire, windthrow, or insect infestations, although periods of recruitment vary by disturbance and watershed conditions (Bilby and Bisson 1998; Bragg 2000; Bragg et al. 2000). In forested watersheds, riparian areas are the primary source of large wood for streams and floodplains following natural disturbance. Large wood can also be transported from distant, upland sites by debris torrents, avalanches, or landslides (Benda et al. 2003b; May and Gresswell 2003a,b; Scheidt 2006). Many streams in forested mountain regions are depauperate in large wood because trees were harvested from riparian areas and other source zones, and wood was removed from channels to protect infrastructure or facilitate recreation. In many western watersheds, tree harvest for railroad ties greatly reduced instream large wood loads (Nowakowski and Wohl 2008; Young et al. 1994) and left lasting impacts on riparian areas and stream channels, thereby decreasing roughness and the capacity to retain instream large wood (Ruffing et al. 2015). Interactions among natural disturbances and watershed processes regulating the supply, transport, and storage of large wood can result in considerable variability in reach-level large-wood loads within and among individual streams and over time (May and Gresswell 2003b; Wohl and Jaeger 2009). Large in-channel wood has also received attention from resource managers due to the notable channel responses to wood removal or additions (Chin et al. 2008; Piegay et al. 2005).

As described in Chapter 2, fire is a natural disturbance that directly influences the recruitment of instream large wood (Benda 2003a,b). Fire can influence the rates, timing, and amounts of large wood delivered to streams (table 15). Prescribed fire treatments could potentially influence the recruitment of instream large wood; however, effects are likely to be negligible or small unless projects specifically consider large wood in planning and implementation. Prescribed burns are typically conducted in spring or fall when predicted fire severity is low to moderate due to cool air temperatures and higher relative humidity and fuel moisture (Knapp et al. 2005, 2009). Under these conditions, live trees do not generally burn and large, downed wood does not readily ignite (especially pieces in and over the stream channel), although rotten pieces are consumed (Bêche et al. 2005; Brown et al. 2003; Stephens and Moghaddas 2005). In mixed-conifer forests in central Idaho, Arkle and Pilliod (2010) found no difference in percent coverage of instream large wood between reference, unburned streams, and a stream in a basin treated with a largely upland prescribed fire (table 15). Their final data collection occurred 3 years posttreatment, which may not have allowed sufficient time for burn effects to influence instream large wood loading. Additional research is needed to determine longer-term effects of prescribed fire on large wood recruitment to streams.

On floodplains, decomposing large wood could contribute to soil formation and provide wildlife habitat in riparian areas (Chen et al. 2005), although only sound pieces are likely to resist breakage and have significant influence on local erosion or sediment storage. In some forest types, prescribed burns could potentially emulate low- to moderate-severity wildfires that were part of the historical disturbance regime and contributed to the structural and functional diversity of streams and riparian areas (Reeves et al. 1995). However, the historical interaction among fire, forest type, and instream large wood loads varied regionally (Agee 2002; Skinner 2002), and it is expected that the effects of riparian prescribed burning also vary.

Mechanical fuel reduction treatments could potentially have greater effects on the recruitment of large wood to streams. Considerable research has focused on the consequences of streamside logging on instream wood loading (table 15). Studies conducted in forested portions of the western United States have shown marked long-term reduction in recruitment of large wood to streams in logged basins. Timber harvest adjacent to riparian buffers eliminates large wood recruitment to the riparian area while increasing the potential for windthrow (Grizzel and Wolff 1998). In western Oregon and Washington, the probability that a falling tree will enter the stream is low at distances greater than about one tree height away from the stream channel (McDade et al. 1990; Van Sickle and Gregory 1990). Similarly, the effectiveness of upland forests to deliver large wood to streams and riparian areas declines at distances greater than about one tree height from the upland forested edge, and depends on steepness of slope (fig. 2; FEMAT 1993). Forest harvest can affect instream large wood characteristics and loading. In Montana, researchers found differences in features of large wood in logged and reference streams that

Table 15—Effects of wildfire, prescribed fire, and forest harvest on large wood (LW) inputs to streams (modified from Dwire et al. 2010).

Treatment and study type	Time scale[a] (years)	Vegetation type location	Findings	Source
Spring prescribed burn; treated basin vs. four reference, unburned basins; also comparisons with basins burned by wildfire	–3 to +3	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River; central Idaho (5 streams)	No differences between treated basin and reference basins in percent coverage of instream large wood	Arkle and Pilliod 2010
Retrospective study of six burned and seven unburned catchments following **wildfire**; also examined effects of postfire flooding.	+4	Mixed conifer: Ponderosa pine, fir spp., Engelmann spruce; SF Salmon River; central Idaho (13 streams)	Riparian burn severity and interaction with flooding associated with decreased habitat stability, i.e. greater annual variation in sediment loads, instream large wood, undercut banks.	Arkle et al. 2010
Sampled reaches in burned and adjacent unburned watersheds (after Yellowstone **wildfires**)	+2 to +3	Engelmann spruce, subalpine fir, lodgepole pine; Absoroka Range, NW Wyoming	Wood loads lower in burned reaches; wood pieces more mobile in burned reaches	Young 1994
Sampled reaches in burned and adjacent unburned watersheds (after Yellowstone **wildfires**)	+11 to +12	Engelmann spruce, subalpine for, lodgepole pine; Absoroka Range, NW Wyoming	Wood loads lower in burned reaches	Zelt and Wohl 2004
Sampled reaches in burned watersheds with different times since **wildfire**: recent (15–20 years), mid (80–110 years, and old (>150 years)	+15 to +20 +80 to +110 > 150	Subalpine fir, grand fir, Engelmann spruce lodgepole pine; 3rd order, unconfined, moderate-gradient streams, Idaho	No differences in most LW characteristics, suggesting that fire does not have long-term effects on channels of this stream type	Scheidt 2006
Retrospective synthesis of effects of **wildfires** (1987–2003)	+5 to +17	Mixed conifer Southwest and central ID	Post-fire inputs of large wood and sediments improved aquatic habitat conditions (and fish populations) within 5–10 years postfire	Burton 2005
Sampled reaches in two burned watersheds following **wildfire**	+3	Chaparral, southern CA	Species (riparian hardwoods) varied in snagfall timing; recruitment of large wood increased with postfire flooding	Bendix and Cowell 2010
Comparative **simulation study** of large wood inputs to streams following **clearcutting** and slash removal, relative to **wildfire** and **insect-caused mortality**	+10 to +250	Lodgepole-pine dominated, mixed-conifer Wyoming	Overstory removal and slash burning reduced long-term large wood contributions by 50% relative to wildfire or beetle kill	Bragg 2000
Retrospective sampling of near-stream areas in **clearcuts**, second-growth and old growth	+5 to +100	Douglas fir dominated mixed conifer, southwest Washington	Near-stream clearcuts reduced channel large wood counts and size within 5 years of clearcut, relative to old growth	Bilby and Ward 1991
Retrospective sampling of large wood in streams (3–4th order) located in **unlogged wilderness**, and watersheds that were **logged with no buffers**, and **logged with buffers**.	Not specified	Mixed conifer, Flathead Basin, northwest Montana	Marked differences between logged and reference streams in ratios of large to small pieces of wood, numbers of unattached and unattached pieces, and large wood pieces with and without root wads.	Hauer et al. 1999
Retrospective sampling of streams draining watersheds with **unlogged** old-growth forests, and **intensively and moderately logged** forests	+3 to +40	Western hemlock- Douglas fir-western red cedar forest types; western Washington	Clear reduction in size of large wood in streams, and shift in location of large wood towards channel margins in harvested basins relative to reference (old-growth) streams	Ralph et al. 1994
Retrospective sampling of streamside areas with **logged riparian** forest, **burned riparian** forest, and **undisturbed old-growth riparian forest**	+10 to +40	Lodgepole pine dominated-mixed conifer; central Interior British Columbia	Higher volume (3X), biomass and carbon content of large wood in disturbed (wildfire or harvest) stands relative to old-growth stands	Chen et al. 2005

[a] Timescale relative to treatment or fire disturbance (year of treatment = 0)

provide important habitat for bull trout (*Salvelinus confluentus*), a federally threatened species (Hauer et al. 1999). These included difference in ratios of large to small pieces of large wood, the proportion of pieces associated with the stream channel or bank, and the proportion of large wood pieces with root wads.

The influence of fuel treatments on large wood is a sensitive issue because of the many management actions that have reduced wood abundance in stream channels. There is little ecological justification for the direct removal of large riparian trees or snags that could enter the channel and become instream large wood (Reeves et al. 2006). However, in regions where fire suppression has resulted in high riparian fuel loads, understory thinning might be required to reduce fire risk (Messier et al. 2012; Van de Water and North 2011). Because large wood dynamics in streams and riparian areas are complex, we suggest that managers proceed with caution in removal of trees near streams, particularly in watersheds that have been logged. The role of large wood is so valuable in structuring aquatic habitat that efforts are under way to restore streams by adding large wood (Bisson et al. 2003; Reich et al. 2003). In some cases, fuel reduction projects could be used as opportunities to add large wood to channels.

Streambank stability

Riparian vegetation is also important for maintenance of streambank stability (Pollen et al. 2004; Simon and Collison 2002). Root systems can armor stream banks (Abernathy and Rutherford 2001; Stokes and Mattheck 1996) and bind bank sediment, thus contributing to bank stabilization, reduction of sediment inputs to streams (Dunaway et al. 1994), and development and maintenance of undercut banks (Sedell and Beschta 1991). Removal of woody riparian vegetation with beneficial rooting characteristics can result in erosion of alluvial streambanks; removal of herbaceous vegetation can decrease retention and accumulation of sediment, possibly influencing floodplain soil development (Thorne 1990).

Prescribed fire may top-kill certain riparian trees and shrubs but is unlikely to negatively affect belowground structures. The contribution of woody roots to streambank stabilization was modeled for forested reaches and predicted to extend approximately one-half the average crown diameter (Wu 1986). Native trees growing along the banks are important for maintenance of streambank stability in most locations, and we suggest that they be retained and protected during mechanical fuel reduction treatments.

3.2.4 Effects of Fuel Management Activities on Riparian Soils and Nutrient Cycling

The biogeochemical function of riparian areas (table 1) is critical for maintenance of surface water in many agricultural areas but is also important in forest-, shrub-, or grassland-dominated watersheds. Riparian soils are frequently moist because of their low landscape position and proximity to streams and shallow water tables. Water movement from upslope areas, hyporheic zones, and surface stream water regulates the flux of nutrients and carbon through riparian areas as well as the soil moisture conditions that influence biogeochemical processes (McClain et al. 2003; Triska et al. 1989). The intersections of near-surface hydrologic flowpaths with carbon- and nutrient-rich soils in riparian areas can form "hotspots" of biogeochemical activity (McClain et al. 1998, 2003; Wagener et al. 1998), which can directly influence stream water quality. Chemical, physical, and biological processes occurring within riparian soil profiles have the potential to filter, immobilize, and detoxify organic and inorganic compounds before they enter stream water (McClain et al. 1998). In subalpine forest watersheds, greater than 95 percent of snowmelt passes along shallow groundwater flowpaths and through riparian areas before entering streams (Troendle and Reuss 1997). Increased soil moisture in riparian areas also enhances the productivity of streamside vegetation; root production, soil nutrient uptake, and biomass production (above- and belowground) and turnover tends to be higher in streamside plant communities relative to uplands.

The regulation of nitrogen transfer from terrestrial to aquatic ecosystems is an important biogeochemical process that occurs in riparian soils. Attenuation of nitrate in riparian soils is attributed to a combination of plant uptake and denitrification (the microbially mediated transformation of nitrate to N_2 or N_2O gas) and subsequent loss to the atmosphere (Groffman et al. 1992; Hedin et al. 1998; Hill 1996). Denitrification rates are low in most upland forest soils (Groffman et al. 1992), but frequent saturation of riparian soils provides a redox environment that favors denitrification (Lowrance et al. 1997; Peterjohn and Correll 1984; Vidon and Hill 2004).

After fire, stream nutrient levels are frequently elevated. The extent and severity of wildfire influences the capacity of soils and vegetation to retain nutrients and sediment (DeBano et al. 1998; Fisher and Binkley 2000; Neary et al. 1999). Immediately following a large wildfire in northwestern Montana, stream phosphorus and nitrogen levels increased 5- to 60-fold (above background) largely due to inputs from smoke and ash (Spencer et al. 2003). Within several weeks following the fire, stream water nutrient concentrations returned to background levels. In subsequent years, nutrient levels increased periodically in fire-impacted streams relative to reference (unburned) streams in response to storm events and spring runoff. Following the 2002 Hayman Fire in Colorado, nitrate levels in basins that burned with high severity were twice as high as levels in basins that burned with low to mid severity while turbidity levels were four times as high (Rhoades et al. 2011). During periods of spring runoff, levels of nitrate and turbidity remained elevated for 5 years postfire (duration of sampling). In southern coastal California, Cooper et al. (2015) found that phosphorus and nitrogen concentrations were higher in streams in burned basins relative to unburned basins during the rainy season. Similar results have been observed in surface waters in other locations (Baker 1990; Brass et al. 1996) and remain a concern, especially during seasons of large forest fires. Although postfire recovery of upland and riparian vegetation and other watershed features ameliorate nutrient and sediment inputs over time, increased levels in surface water are a natural consequence of fire, especially in areas that burn with high severity.

Effects of prescribed fire on stream water chemistry, nutrient cycling, and erosion are likely to be much weaker and shorter lived than those of high-severity wildfire (Wondzell 2001; Certini 2005). Effects of upland fuels management on nutrient cycling and other riparian soil processes will differ with the type of treatment, and depend on landscape, vegetation, soil, and hydrogeologic factors that determine the flux of water, nutrients, and sediment into riparian areas. In forested uplands, some effects of controlled slash burns (Feller 1988; Giardina and Rhoades 2001) and broadcast burns (table 16; Covington and Sackett 1992; Johnson et al. 1998; Knoepp and Swank 1993; Monleon et al. 1997) can be similar to wildfire impacts. Combustion of standing or surface fuels coupled with decreased plant uptake and fluctuating microbial activity often results

Table 16—Effects of prescribed burning, mechanical fuel treatments, and forest harvest treatments on soil resources and sediment movement (modified from Dwire et al. 2010).

Study type treatments	Time scale[a]	Location	Findings	Source
Postfire erosional processes	Review	Pacific Northwest, Interior Northwest, Northern Rocky Mountains	Wildfire can accelerate erosion rates; local and regional differences influence type of erosion	Wondzell and King 2003
Broadcast burn	–1 wk to +1 yr	Ponderosa pine, Ft. Valley Experimental Forest, near Flagstaff, Arizona	Increase in soil NH_4-N immediately after burning, followed by increase in soil NO_3	Covington and Sackett 1992
Low-intensity **broadcast burn**	+ 0.3, 5, 12 years	Ponderosa pine, Central Oregon	Burning increased release of N and P from litter and reduced litter decomposition rates	Monleon and Cromack 1996
Slash pile burn	+10 to +50	Retrospective study on vegetation and soil properties of different aged burn piles (1960s–2000s)	Limited regeneration of woody species (trees and shrubs); for smaller burn scars, soil N and native herbaceous cover return to pre-burn levels within 2 years of pile burning	Rhoades and Fornwalt 2015; Fornwalt and Rhoades 2011
Slash pile burn	1 to 25 years	Pinyon-Juniper, Coconino NF near Flagstaff, Arizona	Increase in soil NH_4-N immediately after burning, followed by increase in soil NO_3. Each returned to preburn conditions in ≈ 5 years.	Covington et al. 1991
Slash pile burn	0 to +2 years	Ponderosa pine, Coconino NF near Flagstaff, Arizona	Higher soil pH, NH_4 and NO_3 and lower total C and N inside burn scars	Korb et al. 2004
Mulching mastication	+2 to +6 years	Colorado conifer forests dominated by lodgepole pine, ponderosa pine, pinyon-juniper	Lowered maximum summer soil temperature; increased soil moisture; increased soil N availability	Battaglia et al. 2010; Rhoades et al. 2012
Mulching	+5 years	Lodgepole pine, Bridger Teton NF, western Wyoming	Surface runoff and soil erosion lower in mulched areas than in undisturbed forest	Bensen 1982
Clear cut	1 to 10 years +20 years	Lodgepole pine-dominated subalpine forest, Fraser Experimental Forest, central Colorado	Harvest increased soil nitrification and cation and nitrate export. Effect remains significant after 20 years	Ruess et al. 1997; Starr 2004
Clear cut + slash retention; Clear cut followed by **surface fire**	5 year after cutting 1 year after burning	Lodgepole pine, Medicine Bow NF, S. Wyoming	Clear cuts had higher NH_4, NO_3, net mineralization and soil moisture than uncut forest. Slash burning doubled soil N availability compared to unburned cut.	Giardina and Rhoades 2001
Clear cut	Reviews of research and monitoring results	Pacific Northwest North America	Increase in suspended sediment concentrations associated with forest roads	Swanson et al. 1987; Brown 1983; Binkley and Brown 1993

[a] Timescale relative to treatment (year of treatment = 0)

in a temporary increase in soil nitrogen availability that occurs shortly after broadcast (Covington and Sackett 1992; Giardina and Rhoades 2001; Kaye and Hart 1998) and slash pile combustion (Covington et al. 1991; Korb et al. 2004). Elevated soil nutrient pools can lead to greater nitrate and cation leaching (Knoepp and Swank 1993; Trammel et al. 2004) and in some cases higher streamwater export (Chorover et al. 1994). In uplands, fire can also alter soil structure, porosity, infiltration, and water repellency (Benavides-Solorio and MacDonald 2001; DeBano 2000; Robichaud 2000) and increase surface runoff and sediment movement. The effects of upland fires on the flux of nutrient and sediment into and through riparian areas can be ameliorated by residual upland or riparian vegetation and forest floor organic matter (Pannkuk and Robichaud 2003; Robichaud 2000). The processes determining the outcome of prescribed burning conducted in riparian ecosystems are likely to be similar, though we are not aware of comparable published results for streamside areas.

Effects of upland mechanical fuel reduction treatments on riparian soil resources, nutrient cycling, and sediment retention depend on the valley bottom and hillslope topography, geomorphic setting, soil properties, and condition of the upland and riparian vegetation. In uplands, disturbance of organic and mineral soil layers during harvest or thinning operations can alter soil structure, infiltration, bulk density, and site nutrient balance (Bormann and Likens 1979; Swank 1988) and sometimes lead to channelized runoff and erosion (table 16; Binkley and Brown 1993; Brown 1983). Forest harvest and thinning in uplands can also increase soil nitrogen availability (Giardina and Rhoades 2001), leaching (Fahey and Yavitt 1988; Parsons et al. 1994), and groundwater flux (table 16; Reuss et al. 1997; Stottlemyer and Troendle 1999). The impacts of mechanical tree removal on riparian soils are likely similar to those observed in uplands (table 16), but additional research is needed to determine short- and long-term effects. In western watersheds, mechanical operations and other ground-disturbing activities, such as road and fire break construction associated with fuel management activities, can also increase suspended sediment yield (Binkley and Brown 1993; Swanson et al. 1987; Wondzell 2001). Overland flow and sheet erosion are typically minimal in undisturbed forests, but steep slopes of many forested watersheds are susceptible to sediment transport via channelized flow even in the absence of disturbance (Megahan et al. 1992).

Slash pile burning is a common practice used to dispose of woody residues accumulated from logging and postharvest site preparation (Fornwalt and Rhoades 2011; Rhoades and Fornwalt 2015). Thousands of burn pile scars occur on national forests throughout the western United States; although small in size, burn piles can cumulatively influence nutrient cycling and native plant diversity. Negative effects from the practice, notably diminished native plant richness and cover and reduced woody tree regeneration, can persist for decades (Miller 2015; Rhoades and Fornwalt 2015; Rhoades et al. 2015). In the past, burn piles were located in uplands, away from streams, to eliminate the risk of nutrient release to surface water. However, the increase in standing fuels due to the recent mountain pine beetle (*Dendroctonus ponderosae*) and spruce beetle (*Dendroctonus rufipennis*) epidemics has resulted in widespread fuel reduction treatments, including projects along transportation corridors. Because many roads are located along stream corridors—that is, in former riparian areas—roadside hazard treatments have resulted in burn piles near streams where cutting was formerly avoided (Miller 2015). The impacts of pile burning on riparian areas are expected to be similar to those observed in uplands (table 16), but additional research is needed to determine short- and long-term effects on wildlife and aquatic habitat. Research on the best methods for burn scar rehabilitation is ongoing; currently, researchers recommend that larger burn pile scars (>5 m in diameter) be revegetated with seeding (Miller 2015; Rhoades et al. 2015).

Mechanical fuel reduction prescriptions usually target nonmerchantable material, so mechanical chipping and mastication operations are frequently used after thinning to treat and distribute woody fuels on site. These combined treatments rearrange the amount, size, and orientation of surface woody fuels (Battaglia et al. 2010). A recent study evaluated the effects of mulch addition on soil nitrogen availability for 15 fuel reduction projects in upland forests of the southern Rocky Mountains and Colorado Plateau regions of Colorado (Rhoades et al. 2012). Researchers found that mulching lowered maximum summer soil temperatures and increased soil moisture, and that added mulch had a lower N concentration and wider C:N ratio than natural material of similar size in untreated areas. They also found that 3 to 5 years after mulch addition, available N was 32 percent higher in mulched fuel reduction treatments compared to untreated sites. Although heavy mulch addition can temporarily reduce availability of soil N in some areas, fuel reduction mulch treatments increased available soil N in this study.

Chipping and mastication treatments, and the amount of woody debris added, can vary considerably among sites depending on equipment and operational differences (Jain et al. 2012), as can the influence of treatments on soil properties. However, soil carbon and moisture generally increase following the addition of mastication material, and maximum summer soil temperature and understory vegetation generally decrease. Woody debris additions can have variable effects on soil nutrients; in some cases, soil nitrogen availability decreased as carbon-rich woody material stimulated microbial nitrogen immobilization (Binkley et al. 2003; Blumfield and Xu 2003; Lalande et al. 1998); in other cases, availability of soil N increased (Rhoades et al. 2012). The potential for upland chipping or mastication to significantly alter nutrient and sediment movement into riparian areas partly depends on the horizontal continuity and depth of woody material additions. Beyond designation of riparian buffers, land managers are urged to consider how upland fuel reduction operations can influence surface water quality and nutrient and sediment retention in riparian areas. The impacts of masticated mulch additions on riparian soils and nutrient cycling are likely similar to those observed in uplands. Research is needed to address this management practice in riparian areas, because it is being applied in many watersheds impacted by bark beetle infestations (Miller 2015; also see Chapter 6).

3.3 Fuel Management Activities in Riparian Areas: Challenges and Considerations

3.3.1 Challenges

1. **Current knowledge on the effects of prescribed fire on streams, riparian areas, and aquatic and near-stream habitat and biota is limited.** Two studies, both conducted in mixed-conifer forest types, have been published on the effects of prescribed fire on aquatic habitat in the western United States (Bêche et al. 2005; Arkle and Pilliod 2010). The treatments were conducted differently: in the Bêche et al. (2005) study, the

prescribed fire was ignited in the riparian area; in the Arkle and Pilliod (2010) study, the prescribed fire was ignited in the uplands and allowed to burn into the riparian area, which is more typical of treatments that include riparian burning (see Chapter 4). Despite these differences, results from both studies indicated that treatment effects were largely minimal and short term for the stream and riparian variables measured. While these results have confirmed observations on impacts of prescribed fires on stream and near-stream environments, recognition of uncertainty is encouraged during planning and implementation, especially in understudied riparian vegetation types (shrub- and herbaceous-dominated; cottonwood- or willow-dominated) and where effects on riparian habitat for terrestrial species are a concern (Pillod et al. 2006).

2. **Current knowledge on the effects of mechanical fuel treatments on streams, riparian areas, and aquatic and near-stream habitat and biota is limited.** Mechanical fuel reduction treatments are highly variable and each treatment, sequence, or combination of treatments could have different environmental effects (see Chapters 4 and 6 for range of treatments). Little is known about the impacts of multiple-stage projects on riparian soils, riparian-dependent species of concern, or riparian habitat variables (tables 12–16). Effects of fuel reduction treatments on wildlife species can vary for different species, as well as for different types of treatments. We have summarized potential effects of mechanical fuel reduction treatments on riparian vegetation, terrestrial and aquatic habitat, and recruitment of instream large wood, and riparian soil resources (tables 12–16), but more information is needed for a range of upland and riparian vegetation types, and for different aquatic and terrestrial species of interest.

3. **Determination of desired riparian conditions remains challenging.** Many riparian areas have been compromised by past land and water use. Restoration of natural conditions can be difficult, especially with limited understanding of historic or natural conditions. Lack of agreement among resource specialists on optimal canopy and understory species composition, stem densities, and other habitat components are not uncommon (see Chapter 4 on constraints to planning fuel treatments), especially in riparian areas that have been impacted by grazing, logging, flow alteration, and other management activities and land uses. Information on riparian fuel loads is also very limited, and estimates or targets for near-stream fuel profiles need to consider the inherent productivity of streamside areas, as well as departure from the natural fire and disturbance regime.

4. **Control of invasive species remains a challenge during and following fuel reduction treatments.** The occurrence of nonnative invasive plant species is common in many treatments areas. For some projects, control of invasive species can be an explicit project objective (Text Box 2; also see Chapters 4 and 6).

5. **Uncertainty regarding future changes in climate, streamflow, and fire frequency and severity increases the complexity of treatment design.** Stream-riparian corridors are dynamic, and planning for project outcomes needs to allow for changes, ranging from natural successional processes to multiscale responses to episodic disturbances like flooding or high-severity wildfire. Impacts of fuel treatment activities will vary depending on where they are implemented in a watershed, and the fire and management history of the treated basins. Incorporating adaptations to climate change

Text Box 2—Considering the effects of fuel management treatments on valued riparian functions.

Riparian Vegetation Considerations:

- What is the *spatial and temporal extent of the disturbance* to riparian vegetation (size of fuel reduction treatment in riparian areas)? How long will impacts last? Will treatments result in "improved" condition over the long term?
- What are the potential effects of fuels treatments on *riparian plant species composition, diversity, structure and condition*? Will target fuel loads (and projected sequence of plant succession) provide the composition and structure necessary to maintain valued riparian functions over short- and long-term time frames?
- Do any *rare plant species* occur in the treated area? Is there potential for increase in the cover or occurrence of invasive species as a result of the fuel treatment? In adjacent uplands, are there existing populations of exotic species that could move into the riparian area with disturbance?
- Will potential shifts in riparian vegetation composition affect *streambank stability*?
- How will potential shifts in riparian vegetation influence the quality, quantity, and timing of *organic matter inputs and terrestrial invertebrates to aquatic food webs*?

Terrestrial and Aquatic Habitat Considerations:

- Will *resident or migratory wildlife species of concern* be impacted (positively or negatively) by changes in riparian plant species composition, structure, or complexity?
- Which wildlife species will potentially benefit from fuel reductions? Which species could be detrimentally impacted? Over what time frames would those species be detrimentally impacted?
- Will fuel reduction treatments in riparian areas significantly *increase fragmentation* and reduce stream corridor connectivity for wildlife species?
- How will fuel reduction treatments influence *riparian microclimate?*
- How will fuel reduction treatments impact the primary drivers of *stream temperature,* namely riparian vegetation?
- Will fuel reduction treatments reduce the inputs and recruitment of *large wood* to streams and riparian areas?
- Will fuel reduction treatments provide an opportunity to improve riparian habitat for certain wildlife species?

Riparian and Upland Soils Considerations:

- Will fuel reduction treatments in riparian areas cause soil compaction or disturbance that may alter subsurface hydrology or nutrient transport along near-surface flowpaths?
- How will fuel reduction treatments in riparian areas and uplands influence short- and long-term nitrogen dynamics? Cycling of other critical soil nutrients?
- Will fuel reduction treatments in uplands or riparian areas channelize flow, increase soil erosion, or stream sedimentation?

Cumulative Effects Considerations:

- What other current management activities are being planned or implemented in the watershed? Where are the management activities located relative to the stream-riparian corridor?
- What is the historical (recent and longer-term) spatial distribution of management activities in the watershed?
- What is spatial and temporal distribution of natural disturbances in the watershed?
- What are potential additive and/or interactive impacts of past and current management activities, natural disturbance, and fuel reduction treatments (both temporal and spatial additive/interactive impacts)?
- What effects will the fuel reduction treatments have on other land uses and ecosystems components?

Table 17—Alternatives for managing fire and fuel-treatment related disturbances, with examples of management activities (modified from Dale et al. 2001 and table 1 in Dunham et al. 2003).

Alternative	Potential management activities
Pre-disturbance management	Alter habitat / stand structure through prescribed fire and other fuel treatments for riparian and upland forests; restore altered stream channels and riparian areas; mitigate road effects. Modify landscape structure by improving connectivity among habitats; preserve or restore large, high quality habitats.
Managing the disturbance (fire or fuel treatments)	Restoration of natural processes to mimic natural variability (e.g. natural fire regimes). Rapid response to reduce the impacts of disturbance, e.g. active management of wildfire near high quality habitats. Conduct fuel treatments to minimize soil disturbance and erosion potential.
Managing recovery (postfire management)	Manage to speed recovery following a disturbance event, such as postfire rehabilitation; possibly seed or plant with desirable natives following fuel treatments.
Monitoring for adaptive management	Understand how fire interacts with other sources of disturbance. Measure conditions before and after disturbance (fire or fuel treatments) to improve understanding of impacts (short- and long-term). Implement studies to understand impacts of disturbance or management actions.

can be particularly difficult in near-stream environments, where predicted changes in timing and magnitude of streamflow will likely complicate management strategies.

6. **Promote landscape resilience through improved integration of fuels projects with other restoration activities, fire management and postfire stabilization, and climate change adaptation.** The need for more holistic, ecosystem-level approaches has been advocated for decades (Luce et al. 2012). These approaches are increasingly facilitated with new tools and advances in landscape ecology. Although different locations within a watershed may be managed along lines of resource specialties or disciplines—wildlife, forestry, fisheries, range, fuels—the interconnectedness of all components is an important feature of building resilient landscapes. Watershed-scale fuels projects could present opportunities for ecosystem restoration that cannot be achieved with site or reach scale projects (table 17).

3.3.2 Considerations

1. **Riparian areas are spatially diverse; the spatial arrangement of different riparian plant communities and attributes within a watershed can influence both the response to fuels treatments and the effectiveness of fuels reduction.** In the design and implementation of fuels treatments, attention to ecological context within a drainage basin and the larger landscape is critical, as well as the connectivity between upslope and upstream management and condition of the stream and riparian area. Consideration of potential impacts on key riparian functions will assist in minimizing local and immediate effects as well as cumulative, longer-term effects (table 1, Text Box 2). Local and regional issues will dictate which riparian functions are priorities for management goals and critical for protection.

2. **Riparian areas are part of the landscape.** Be cautious about leaving riparian areas untreated when fuel loads in surrounding uplands are planned for treatment. Riparian fuel loads have been influenced by fire suppression and administrative protection policies (Section 2.2.2) and could be considered hazardous in some wildland environments, as well as the wildland-urban interface.

3. **Fuel reduction treatments can potentially assist in riparian and stream restoration.** Objectives for fuel reduction treatments could explicitly include the return to fuel loads and vegetation that support ecosystem processes and natural disturbance regimes (Text Box 2; Dwire et al. 2010; Luce et al. 2012; Rieman et al. 2003). Short- and long-term targets for the vegetation condition of uplands and riparian areas need to be stated as clearly as possible in planning documents. Given data limitations on historical composition and structure of riparian vegetation, the natural fire regime and fire history of the treated watersheds needs to be considered when target fuel loads are defined for riparian areas. Using concepts such as natural or historical range of variability (Gage and Cooper 2013; Landres et al. 1999), reference areas, and desired future condition, the planning and implementation of fuel reduction treatments can be regarded as opportunities to restore certain riparian and stream (e.g., instream large wood) ecological conditions (table 17; Arno 1996). Fuel reduction treatments (including reintroduction of fire to riparian areas) could result in a more spatially diverse range of habitat components with long-term benefits for multiple wildlife species. Fire managers are frequently able to implement fairly exact prescriptions, such as reducing certain fuelbeds while retaining others. Restoration objectives, in addition to emphasis on fuels management, are encouraged. The consideration of management activities that allow the retention of critical habitat elements is warranted, particularly those that are slow to recover such as large-diameter down wood and snags. As noted above, there is little ecological justification for the direct removal of large riparian trees or snags that could enter the channel and become instream large wood. Where possible, fuel reduction projects could be used as opportunities to add large wood to channels.

4. **Certain fuel treatments are NOT recommended in some riparian vegetation types.** In the southwestern United States, prescribed burning is not recommended in native riparian woodlands (Bock and Block 2005). Wildfires have destroyed native woody vegetation and fostered the spread of saltcedar (*Tamarix* spp.) along many southwestern streams and rivers, with negative short- and long-term impacts to habitat for native bird species (Busch 1995). Along certain segments of fish-bearing streams, the role of streamside trees as potential sources of instream large wood needs to be considered. Mechanical treatments that remove streamside conifers are not recommended, particularly in watersheds with histories of clear-cut logging or streamside tree removal.

5. **Fuel treatments are not intended to (and do not) replicate wildfire.** The overall goal for most treatments is to decrease the risk of high-severity fire by reducing or removing certain fuel components. However, wildfire is a critical natural disturbance for many ecosystems of the western United States, where wildlife, aquatic biota, and riparian plant populations have evolved with fire as a natural disturbance. Most research on fire impacts has shown beneficial effects over different time scales and

highlighted the resilience of native plant and animal communities in response to fire. Designing fuels treatments to recreate natural disturbance patterns while reducing fire risk could contribute to restoration of ecosystems and may assist managers in advancing from single-species management toward ecosystem management and broader-scale benefits. Where possible, allowing watersheds or portions of watersheds to burn naturally could be part of both fire management and restoration strategies.

6. **Pre- and postmonitoring of riparian fuel reduction projects is critically needed.** Each individual fuel reduction project is essentially an ongoing experiment, and we emphasize the need for monitoring to track the impacts of prescribed burning, tree removal, chipping and mastication, and salvage logging on riparian and aquatic resources. Needed research has been described throughout this report; however, research cannot keep up with assessing the impacts of the wide range of fuel treatments that are being conducted in near-stream environments. Given limitations of current knowledge on the effects of fuel reduction treatments on wildlife and aquatic biota, monitoring the response of species of concern before and after fuel treatments may be essential to avoid litigation in some locations (Pilliod et al. 2006). For treatments that are conducted over several years and require multiple entries into project areas, longer-term monitoring of populations and riparian and aquatic habitat variables could assist in determining if certain treatment combinations or sequences are having beneficial, neutral or adverse effects on species or habitat variables of interest. Follow-up monitoring for achievement of project objectives (short- and long-term) is critical to understanding the impacts and influence of fuel management, particularly in riparian areas.

Chapter 4: Survey of Fuels Treatments in Riparian Areas and Wetlands of the Interior West

4.1 Introduction

Following decades of severe fire behavior and a landmark fire season in 2000, the National Fire Plan (NFP) was established to develop a collaborative approach among government agencies to actively respond to wildland fires and ensure sufficient firefighting capacity for the future. In addition, the Healthy Forest Restoration Act (HFRA) of 2003 was passed to expedite and encourage the development and implementation of hazardous fuels reduction projects on Federal lands. This sequence of events has led to an increase in restoration efforts aimed at creating vegetation communities that are more resistant to wildfire (Agee and Skinner 2005; Stephens and Ruth 2005). However, some management activities endorsed by the NFP have not been tested in many vegetation types and their ecological consequences are unknown, raising concerns regarding their effectiveness (Bisson et al. 2003; Schoennagel et al. 2009). The primary goals of fuel treatments are to restore fire-adapted ecosystems, reduce hazardous fuels, mitigate risks to communities, and improve fire prevention and suppression strategies. However, the importance of information sharing and monitoring of project effectiveness and resulting forest conditions has also been emphasized (Jain et al. 2012).

Many fuels treatments and forest restoration projects have been implemented in upland settings of drier forest types, such as ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests, where the response of fire behavior to thinning and prescribed fire treatments has been advantageous (Jain et al. 2012). However, fuels treatments are being conducted in many other forest and vegetation types where risks to sensitive ecosystems or the wildland-urban interface are high in the event of a severe wildfire. Riparian areas are among those ecosystems receiving increased attention as components within the landscape that could be negatively affected by high-intensity wildfires. There is also concern that some riparian areas contain fuel loads that could carry a fire across an otherwise fire-resistant landscape (Murphy et al. 2007; Pettit and Naiman 2007; Van de Water and North 2011).

An increasing number of fire managers are conducting fuels treatments in riparian areas throughout the western United States. In 2007 a phone survey of U.S. Forest Service fire management officers in 11 western States indicated that 43 percent were conducting fuel reduction treatments in riparian areas, primarily for fuel reduction and ecological restoration goals (Stone et al. 2010). In light of the information gathered from this phone survey (Stone et al. 2010), we conducted a second, more extensive survey in an effort to gather additional information about the practices currently being carried out and the concerns and constraints associated with conducting fuels treatments in riparian areas of the interior western United States. Our expanded online survey included wetlands and incorporated the experience of many resource professionals from four agencies. We were interested in the following information: (1) identifying project objectives and short-term effectiveness at meeting these objectives; (2) types of treatments applied; (3) types of riparian vegetation treated; (4) pre- and posttreatment monitoring; and (5) concerns or constraints affecting the planning and implementation of projects.

4.2 Study Area

We targeted fire program managers and other resource professionals from the U.S. Department of Agriculture (USDA), Forest Service (USFS) and the U.S. Department of the Interior (USDI)—Bureau of Land Management (BLM), National Park Service (NPS), and Fish and Wildlife Service (USFWS)—within 10 States of the interior western United States. Our intent was to focus on wetlands and riparian areas in the Interior West and northern Great Plains, where less is known about implementation and effectiveness of fuels management treatments. The entire States of Colorado, Idaho, Montana, Nevada, Utah, and Wyoming were included, as well as the portions east of the Cascade Mountains in Oregon and Washington. The Black Hills region of South Dakota and a small area in northeastern California, containing the Modoc and Klamath National Forests and all other FWS, BLM, and NPS land near those forests, were included. Some land management units extended beyond State boundaries, which resulted in small portions of Arizona, Kansas, Nebraska, and North Dakota also being included.

4.3 Methods

4.3.1 Online Survey Development

An online survey form was selected as the most feasible method to deliver and administer the survey to a large number of potential respondents. Survey questions and format went through many informal, internal peer reviews and several revisions before a trial run. The survey questions and format were initially developed in a Microsoft Word document and then recreated online using a provider for web-based surveys (SurveyMonkey) in fall 2010. Following a test run with selected colleagues from different agencies and organizations, the survey was restructured and some questions were revised and clarified (Appendix). The general organization and flow of the final survey is illustrated in a streamlined flowchart (fig. 15).

4.3.2 Development of Contact List of Potential Survey Respondents

During the initial stages of developing the survey, we compiled a contact list of potential survey respondents. The target population of survey respondents initially included resource specialists and fire managers working at the field level who were involved in fuels planning for the USFS, BLM, NPS, and USFWS within the study area. Resource specialists included hydrologists, fisheries biologists, wildlife biologists, soil scientists, archaeologists, recreation planners, botanists, rangeland management specialists, ecologists, and environmental planners. Fire managers included fuels planners, fuels specialists, fire ecologists, and fire management officers. At the recommendation of several fire managers, line officers—including NPS Park Superintendents, USFWS Refuge Managers, and USFS District Rangers—were added to the contact list.

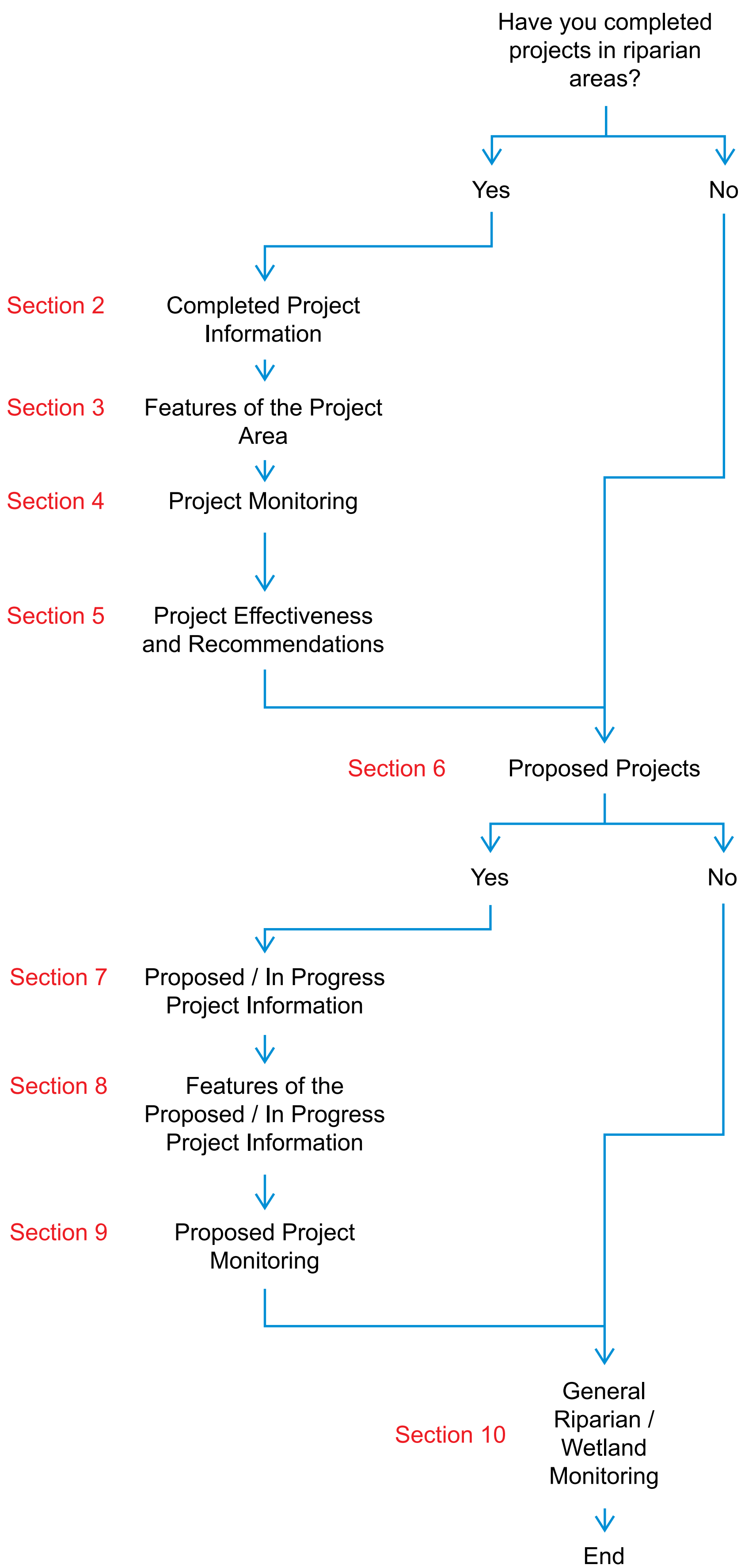


Figure 15—Organization of the different sections in the online survey developed to document features of completed and proposed fuel treatments in riparian areas and wetlands.

To obtain contact information for the potential survey respondents, agency contact lists were obtained from the USFS intranet, BLM website, by mail from USFWS regional offices, and the online directory for the National Park Service. Directories were obtained for 196 USFS ranger districts in 45 national forests, 6 national grasslands, and 3 USFS national recreation areas; 30 BLM district offices and 71 BLM field offices; 39 national parks, monuments, historic sites, and recreational areas; and approximately 49 national wildlife refuges and complexes (fig. 16). Using the contact lists, the names and contact information of targeted resource specialists were selected and compiled into a database. Forest Service employees were cross-checked with the Lotus Notes Forest Service Directory to verify their location, title, and contact information. The survey was sent to all potential respondents on the list with the anticipation that at least one fire planner and one other resource specialist would respond per administrative unit (e.g., ranger district, park, field office, wildlife refuge, etc.).

As a courtesy, and in an attempt to improve the response rate, letters notifying regional executives, forest supervisors, and national level contacts were sent to all agencies before launching the survey. The letters requested endorsement for the survey within their regions and permission for staff to use work time to participate in the survey. Responses to the letters were received, and none denied permission to administer the survey. The survey was launched to all potential survey respondents within the study area in late April 2010.

4.3.3 Launching and Administering the Survey

An invitation to participate in the survey and a survey link were sent by email to a total of 2,273 potential survey respondents. The survey link was sent to the entire contact list with the realization that some of the targeted resource specialists may have moved or changed positions or were not involved in fuels planning and implementation. Within a week, 54 potential respondents were removed from the survey contact list due to invalid email addresses, “out of office” replies indicating that individuals would be out of the office past the deadline for the survey, or explicit requests to be removed, resulting in a total of 2,219 potential respondents. Throughout the duration of the survey, responses were tracked, and email and phone correspondence were documented in the database. Over the course of the survey, new respondents were added as recommendations for additional participants were received, and other respondents were removed for reasons noted above.

Considerable effort was devoted to reaching as many potential target respondents as possible. In mid-May, it seemed that the USFWS list was deficient, and the responses from the agency were limited, so each refuge was called to acquire more contacts. Additional contacts were added to the survey list, and the survey request and link were emailed to additional USFWS contacts in mid-May. During the course of the survey, three reminder messages were sent out in an effort to improve the response rate. In total, 2,413 respondents actually received an invitation to participate in the online survey.

4.4 Survey Response

There were 532 respondents to the survey (22 percent response rate), representing a variety of resource specialists. Fire managers, hydrologists, fisheries biologists, wildlife biologists, ecologists, cultural resource specialists, and some line officers (21 percent response rate) either completed or partially completed the online survey (table 18). Responses were received from all four agencies (BLM, NPS, USFS, and USFWS) and from the 10 States (fig. 16). Nearly 90 percent of the responses were BLM and USFS employees, reflecting the large portion of public lands collectively administered by these two agencies. Although these two agencies represented similar percentages of the survey population (~45 percent), the USFS had a higher response rate (26 percent) than BLM (19 percent).

Of the 532 respondents who participated in the survey, 446 respondents completed the survey and 86 respondents replied partially to the survey. A total of 272 respondents opted out of the survey, mostly because they were not involved in planning or conducting

Table 18—Percent response by agency, professional resource specialty, and State. The values in the fourth column show the percent of those within a category (agency, specialty, or State) who participated in the survey. Respondents were given a chance to "opt out" if they were not involved in fuel treatment planning, did not have sufficient information to answer the survey questions, or otherwise decided not to participate; the percent of these individuals within a category is shown in the last column.

	Category	Percent of survey population	Percent response within category	Percent of respondents who completed survey (of those who started)	Percent of respondents who opted out of participating in the survey
Agency	BLM	45	19	86	11
	NPS	7	18	87	15
	USFS	44	26	82	11
	USFWS	4	21	74	14
Specialty	Line Officers (e.g. Park Superintendent, Refuge Manager, District Ranger)	3	21	98	11
	Cultural/Archaeology	8	15	96	13
	Fire (FMOs, Fuels Specialists)	20	30	80	6
	Fisheries/Aquatic	5	35	77	7
	Forestry	6	35	92	16
	Hydrology	4	36	67	9
	NEPA Specialist	3	24	88	13
	Range	15	21	91	13
	Recreation	7	11	94	14
	Resources/Botany/Ecology	15	16	84	14
	Riparian/Wetlands	<1	20	100	0
	Soils	1	15	100	12
	Wildlife	13	16	80	12
State	California	3	18	83	15
	Colorado	13	20	92	12
	Idaho	15	25	76	9
	Montana	12	23	90	12
	Nevada	9	21	92	12
	Oregon	15	25	74	9
	South Dakota	2	32	82	6
	Utah	12	17	82	10
	Washington	4	22	77	18
	Wyoming	14	22	92	14

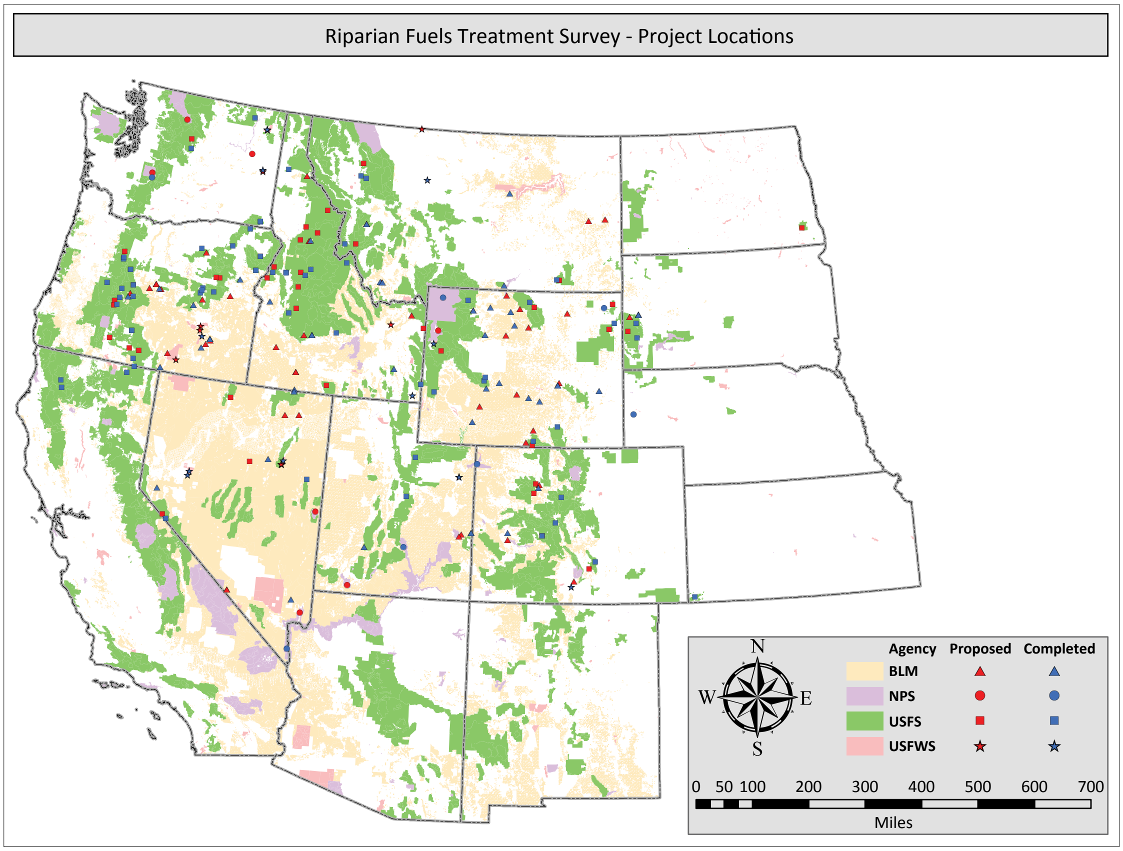


Figure 16—Locations of completed and proposed riparian fuels treatment projects by agency (from Meyer et al. 2012). The online survey targeted Federal resource managers in the Interior West and northern Great Plains. Arizona, New Mexico, western Oregon and Washington, and most of California were not included.

fuels treatments. The total number of responses, including complete and partial responses and those opting out, was 845. Partial responses were completed by providing a null response for the survey questions that were left unanswered. The entire population of respondents (2,413 potential respondents) was the number used as the basis for determining the response rate for this survey (table 18); this included those who received the survey and had an opportunity to respond, whether they were available to respond or not, and/or whether or not they are involved in fuels planning. Since participation in the survey was voluntary, it should be noted that respondents might not be representative of the entire sampled population.

The percent response by State ranged from 17 percent (Utah) to 32 percent (South Dakota) and averaged approximately 22 percent. The percent response by resource specialty ranged from 11 percent (recreation) to 36 percent (hydrology) and averaged approximately 22 percent. Of the resource specialists who started the survey, the percentage of those who completed it ranged from 67 percent (hydrologists) to 100 percent (riparian-wetlands specialists) and averaged 88 percent (table 18). Although some States and resource specialties may be better represented in the responses than others, survey results do include input from a wide range of Federal land managers who are involved in planning and implementing fuel treatment projects in wetlands and riparian areas.

4.5 Survey Findings

Of the 532 respondents, 249 described vegetation treatment projects that were either completed or initiated in riparian or wetland areas within the previous 10 years (2000–2010). Of those, 105 had completed projects, 87 reported on projects planned or in progress, and 57 reported on both completed and planned projects (fig. 16). Nearly 27 percent of the completed and proposed projects were planned specifically in riparian or wetland areas while the others included these areas as part of larger projects. Interagency participation was reported to be an important component for 23 percent of completed and 63 percent of proposed projects.

Responses to three yes-or-no questions regarding local administrative policies demonstrated the shifting approaches to riparian management relative to fuels treatments (table 19). Nearly 30 percent of the respondents indicated that prescribed fires are allowed to burn into riparian-wetland areas during fuel treatment implementation. When asked if prescribed fire ignitions were allowed in riparian areas, 28 percent of the respondents were not certain, but 44 percent answered 'no,' indicating the caution against actively treating riparian-wetland fuels with prescribed fire in some locations.

4.5.1 Fuel Treatment Objectives and Effectiveness

Respondents were asked to rank five specific objectives that applied to their project as primary, secondary, or tertiary (fig. 17). The number of projects per agency reflects the relative proportion of respondents from each agency (table 18). More than half of the respondents described completed projects with more than one objective; of these, nearly all had secondary and tertiary objectives (fig. 17). Priority objectives were very similar for completed (fig. 17a) and proposed (fig. 17b) projects. The most common primary objectives for both the completed and proposed projects were hazardous fuels reduction and habitat restoration. Virtually all of the USFWS's completed and proposed projects included habitat restoration as the primary objective. Restoring the historic fire regime was the most common secondary objective and was reported as an objective for approximately 20 percent of both completed and proposed projects. Protecting values at risk was an objective that included protection of campgrounds, roads, and other infrastructure located in the wildland-urban interface or wildland-urban intermix, cultural resources, and sensitive ecosystems. Protecting values was reported as an objective for approximately

Table 19—Responses to yes/no questions regarding administrative policies. Percentage of respondents is shown for each question; note that the number of respondents (in parentheses) varied with the question.

Administrative policies	Yes	No	Not sure/not specified
Under your forest/fire management plan, are prescribed fires permitted to burn into riparian or wetland areas outside of the prescribed fire boundary?	29% (155)	37% (194)	34% (183)
Under your forest/fire management plan, are fires designated as "Wildland Fire Managed for resource benefit" permitted to burn into riparian or wetland areas?	44% (234)	18% (98)	38% (200)
During a prescribed burn, are ignitions allowed in riparian areas?	28% (149)	44% (234)	28% (149)

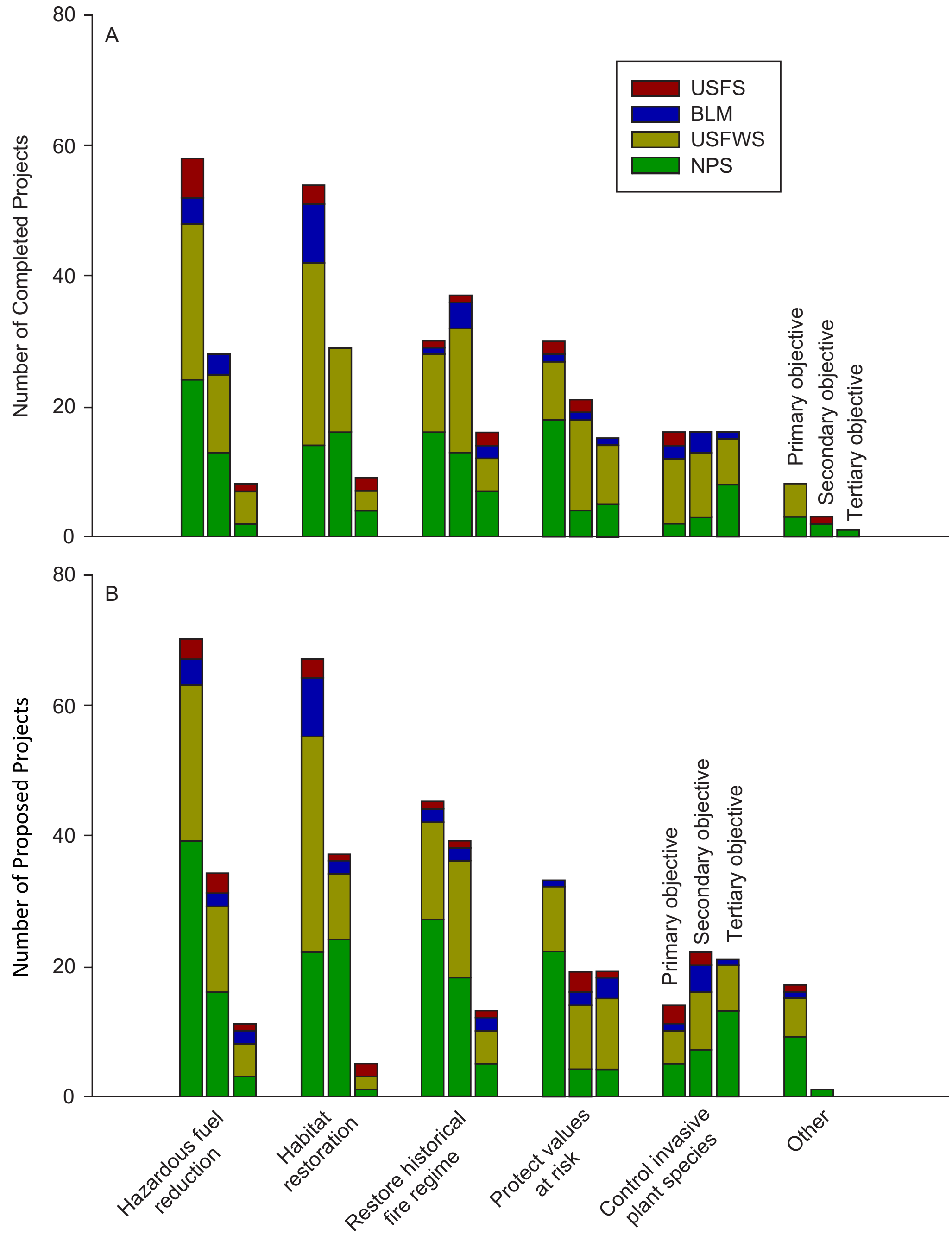


Figure 17—Objectives for completed (A) and proposed (B) projects by agency. For each project, six objectives could be ranked as primary, secondary, or tertiary. Respondents were encouraged to list all project objectives that applied.

17 percent of both completed and proposed projects. Treatment of invasive species was a primary objective in only a few projects, and the least common objective overall. In the 'other' category, survey respondents noted the following additional project objectives: rangeland improvement, greater recreational access and opportunities for hunting and fishing, reduction of the influence of mountain pine beetle, salvage logging, and enhancement of aspen regeneration.

For completed projects, survey participants were asked to rank project effectiveness at meeting objectives by using a 5-point scale from 'very effective' to 'not at all effective.'

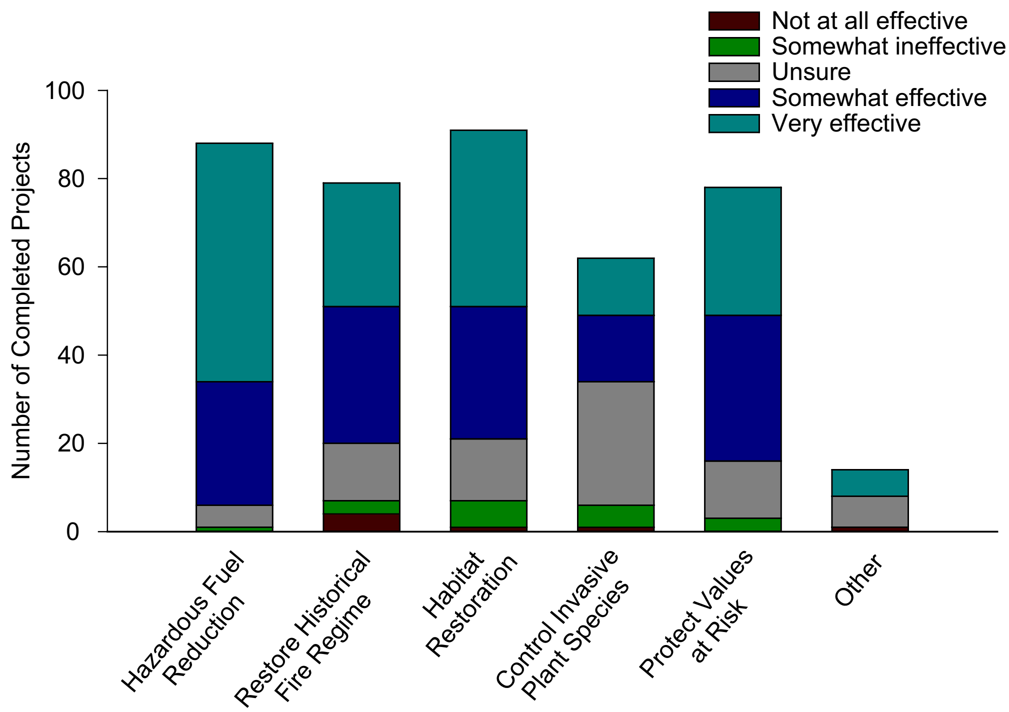


Figure 18—Effectiveness at meeting project objectives (from Meyer et al. 2012). Survey participants were asked to rank project effectiveness at meeting objectives, using a 5-point scale from 'not at all effective' (designated as '1') to 'very effective' (designated as '5').

Project effectiveness was variable, depending on the objective and treatment (fig. 18). All agencies considered projects successful at reducing hazardous fuels. Reduction in fuel loadings is a fairly immediate treatment outcome, and relatively straightforward to assess, although there was still some uncertainty in project effectiveness (6 percent "unsure"). The objectives "habitat restoration" and "protection of values at risk" were also effectively met by most projects. The objective "restore historical fire regime" was effectively met by approximately 75 percent of the projects but also had the greatest number of ineffective projects. For "control of invasive plant species," it may be too early to determine effectiveness, as reflected in the high number of "not sure" rankings. In general, most projects were perceived to be "somewhat effective" to "very effective" at achieving most objectives (fig. 18).

4.5.2 Fuel Treatment Methods

Prescribed fire was the primary tool for fuels treatments used by all agencies in riparian and wetland areas (fig. 19). The USFWS used prescribed fire on all of the projects they reported. Mechanical thinning (using chain saws) and pile burning were the second and third most commonly used treatments. Mechanical thinning (using heavy equipment) and scattering were also included in many projects, especially those implemented by the USFS and the BLM. Mastication was used by all four agencies in a number of projects. Additional treatments reported by the survey respondents in the "other" category were follow-up herbicide application or tamarisk beetle release, mowing, flooding to reduce cattail (*Typha* spp.) re-establishment (USFWS projects), and seeding of desirable species.

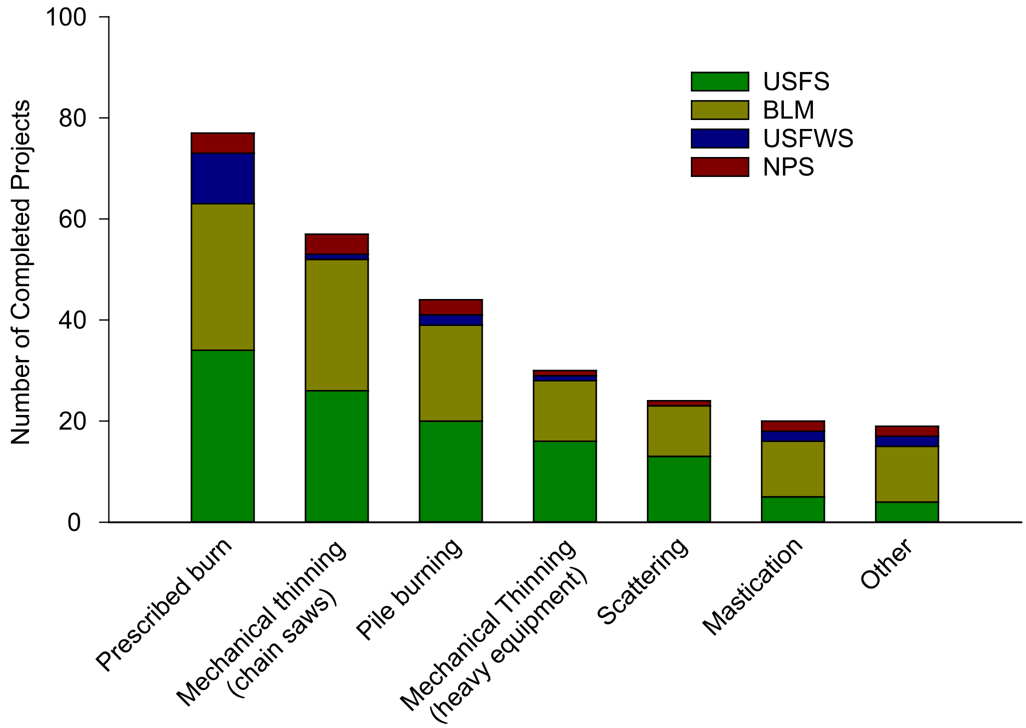


Figure 19—Number of completed projects that used different types of treatments by agency (from Meyer et al. 2012). Most projects used multiple treatments, all of which are tallied here.

For projects using a single treatment method, prescribed fire was the predominant method used in more than 90 percent of the completed projects (fig. 20a). It was clear, though, that most projects combined treatment methods; more than two-thirds of the completed projects combined different methods (fig. 20b). A tally of the number of times a method was used in a treatment combination shows that prescribed fire and mechanical thinning were most frequently combined with other treatments (fig. 20b). Methods that retain biomass on site, such as scattering and mastication, were frequently combined with thinning treatments. However, nearly 50 percent of the projects using heavy equipment to thin were combined with pile burning. Treatment combinations reported by survey respondents are fairly common in western conifer forests and frequently used to alter fuel profiles in upland portions of the project areas (Jain et al. 2012).

Most projects were completed in 3 years or less, although some were of longer duration (fig. 21). In some cases, the same treatment (e.g., mechanical thinning) was applied in different portions of the project area in successive years; in other projects, different treatments were applied in different years in the same area. Most projects required re-entry to the treated area to achieve the desired outcome.

4.5.3 Riparian and Upland Vegetation Types

The survey also requested information about riparian and upland vegetation types in the fuels treatment project areas. For riparian vegetation, most completed and proposed projects were located in conifer-dominated vegetation types, followed by willow-dominated vegetation types (fig. 22). Projects in conifer- and willow-dominated riparian areas were most common on USFS lands; projects in riparian areas dominated by upland shrubs were most common on BLM lands. Conifers were rarely present on

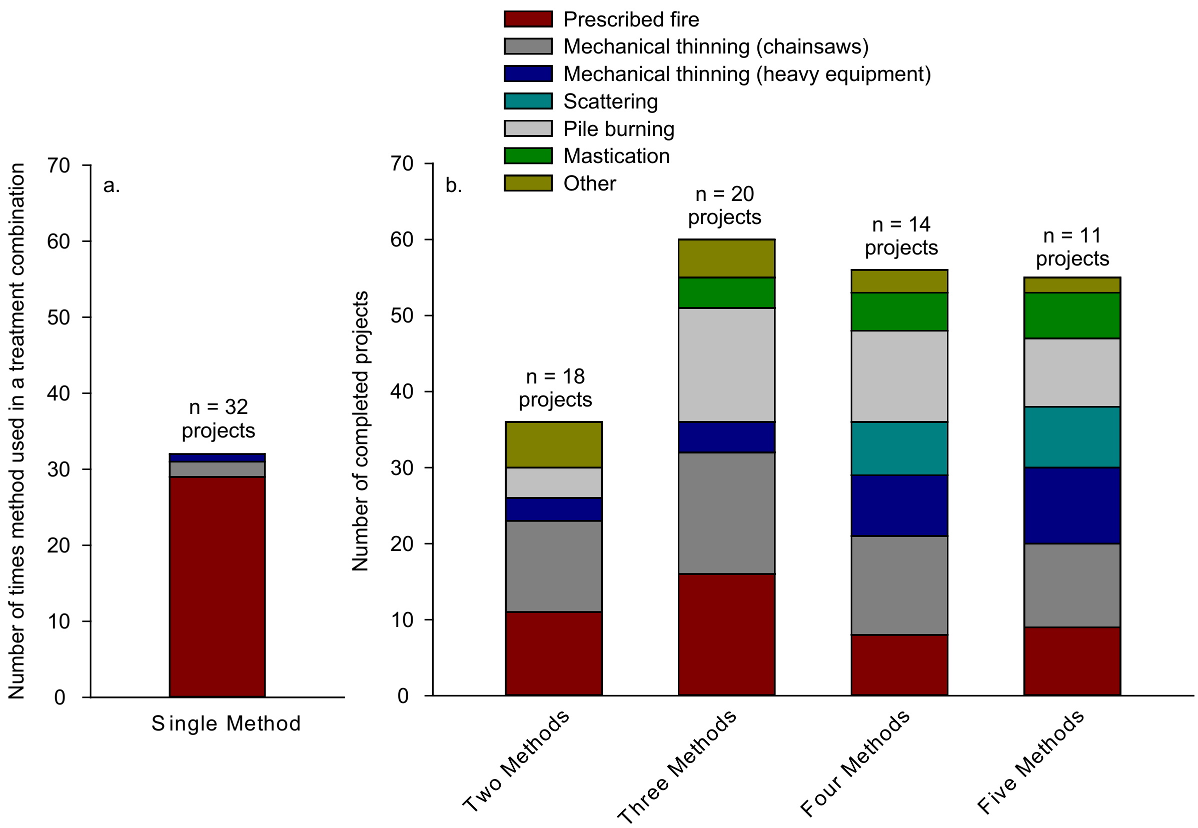


Figure 20—(A) Number of completed projects that used a single method of treating fuels, and (B) number of times a method was used in a specific project. More than half of the completed projects combined three or more methods.

the USFWS projects, which were largely conducted in wetlands and riparian meadows. Approximately 27 percent of the completed projects included some palustrine habitats (wetlands, marshes), and while they were located on public lands administered by all agencies, most were on USFWS lands. Nearly 70 percent of all projects were conducted in riverine habitats, and the remaining 30 percent were located on the margins of lakes or ponds. Cottonwoods occurred at numerous project sites and a few projects focused on cottonwood restoration; however, cottonwoods were not present at many of the project areas (fig. 22). Specific vegetation that was noted in treated riparian areas included aspen (*Populus tremuloides*) and birch (*Betula* spp.); boxelder (*Acer negundo*); greasewood (*Sacrobatus* spp.); upland shrubs, such as rabbitbrush (*Chrysothamnus* spp.) and juniper (*Juniperus* spp.; primarily on BLM lands); and invasive species such as tamarisk (*Tamarix* spp.), Russian olive (*Elaeagnus angustifolia*), and whitetop (*Cardaria draba*).

For completed projects, upland treated areas were dominated by a range of vegetation types, but nearly 67 percent occurred in conifer-dominated vegetation, including pinyon-juniper woodlands (fig. 22b). For both completed and proposed projects, ponderosa pine and mixed-conifer dry forests were the most common forest types, but a range of other vegetation types were also dominant in treated areas. For proposed projects, there was a notable increase in the number of projects planned for shrub steppe and grasslands. Specific vegetation that was noted as "other" in treated upland areas included Douglas fir (*Pseudotsuga menziesii*), hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*); western larch (*Larix occidentalis*); aspen and aspen-birch; and mixed mountain shrub.

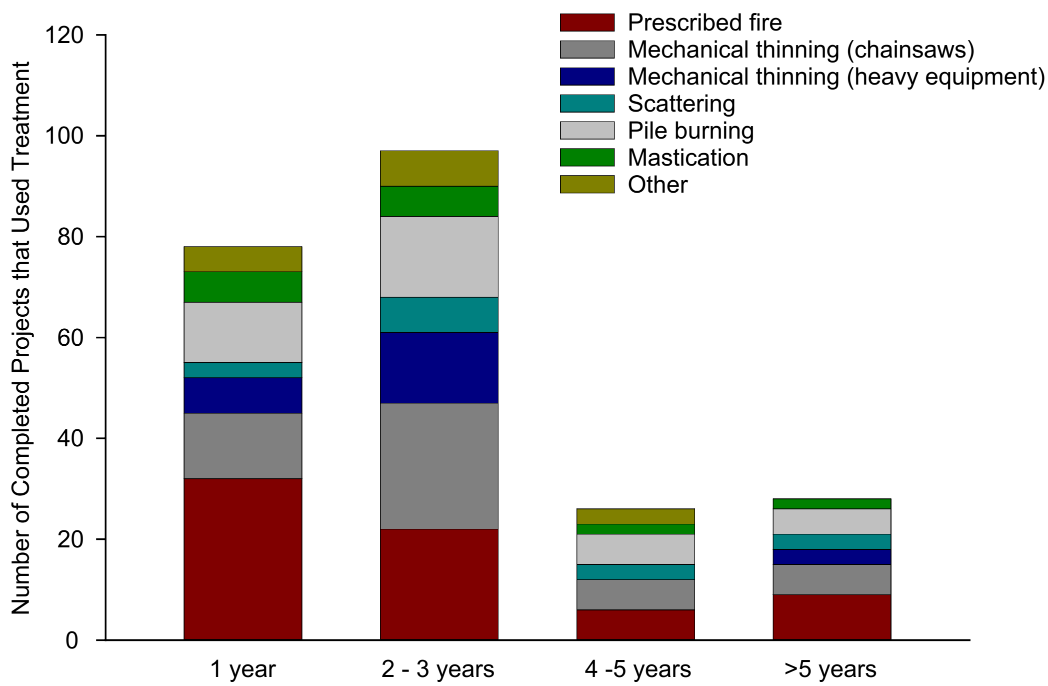


Figure 21—Number of completed projects that have applied a sequence of treatments over time. In some cases, the same treatment (e.g., mechanical thinning) is applied in different portions of the treated area in successive years; in another case, different treatments are applied in the same area to achieve the desired outcome. Most projects require re-entry to the treated area over several years.

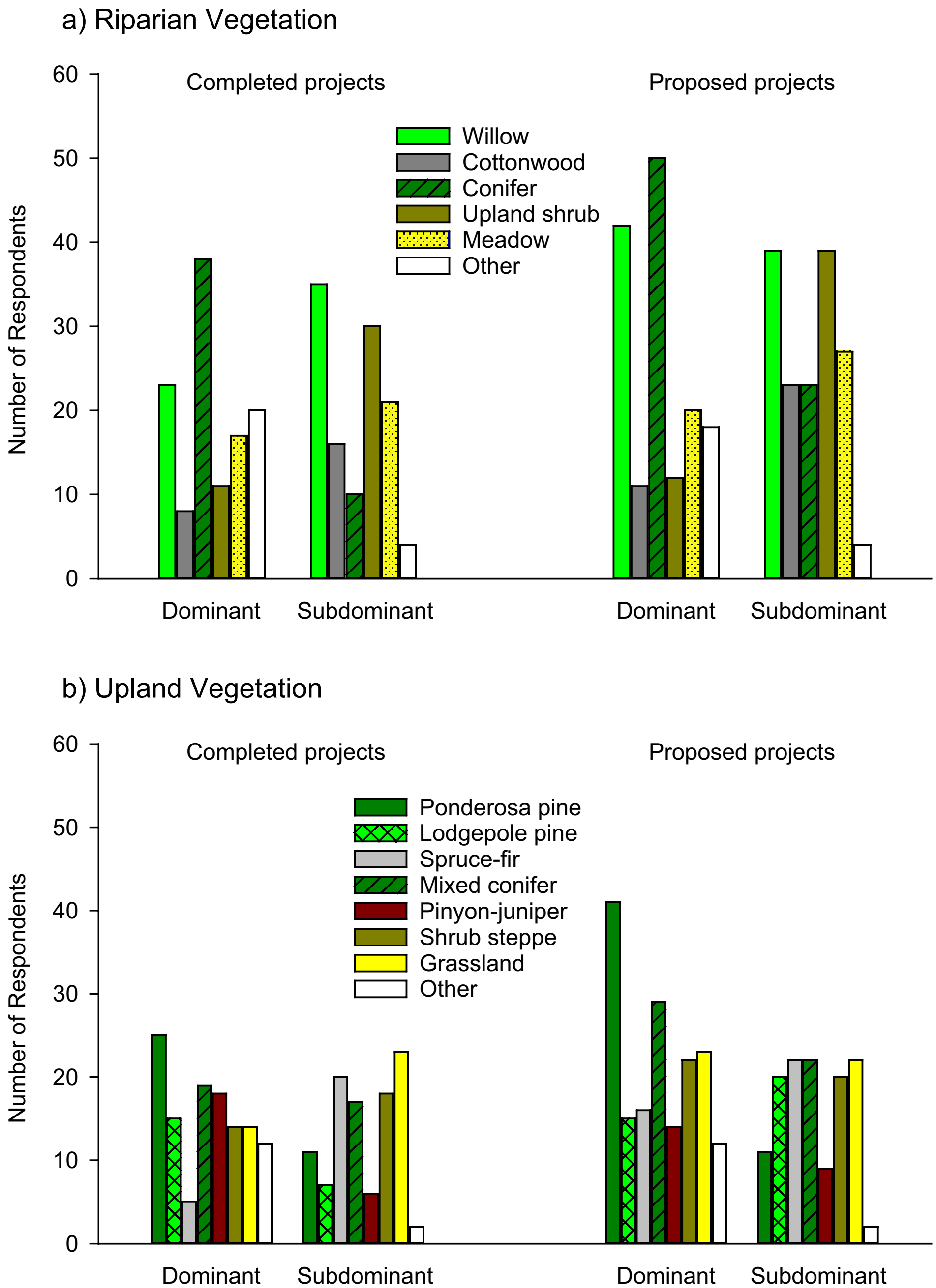


Figure 22—Dominant and subdominant vegetation occurring in (A) riparian and (B) upland portions of completed (n = 98 respondents) and proposed (n = 125 respondents) project areas. Categories for estimating abundance of six riparian vegetation types and eight upland vegetation types were (1) dominant—>50 percent cover; (2) subdominant—≤50 percent cover; (3) present—occurred within the project area (data not shown); (4) not present—did not occur within the project area (data not shown).

4.5.4 Features of the Project Areas

Survey participants were asked to provide additional information about project area conditions (table 20). For completed projects, 41 to 43 percent of the survey participants reported that invasive or noxious plant species were prevalent in either the riparian or upland portions of the project area. The percentage of respondents was slightly lower for proposed projects (35 to 41 percent; table 20). Six to 20 percent of the respondents were unsure regarding the prevalence of invasives (table 20). We were curious about how recent bark beetle infestations were influencing fuel treatments, and we asked if insects or disease were prevalent in project areas. In upland habitats, 32 percent of the respondents reported that completed projects were conducted in infested areas, while 40 percent noted that proposed projects would be conducted in infested areas (table 20). Percentages were considerably lower for riparian habitats for both completed (15 percent) and proposed projects (24 percent; table 20), suggesting that insects may be having less impact in streamside areas. However, 10 to 22 percent of survey respondents were unsure about the prevalence of insects and disease in the project areas. As noted previously, approximately 56 percent of the respondents noted that both completed and proposed projects were either wholly or partially located in the WUI. When asked about the applicability of Fire Regime Condition Class (FRCC) to riparian-wetland portions of the project areas, 49 percent of the survey respondents indicated that FRCC applied to completed projects, and 44 percent indicated that FRCC applied to proposed projects. However, a large proportion of respondents (35 to 44 percent) were not sure about applicability of the FRCC classification system to riparian or wetland habitats. It should be noted that the number of respondents varied widely for the questions about project areas. Depending on the question, approximately half of the survey participants did not answer these questions.

Table 20—Responses to yes/no questions regarding features of the project area in the online survey. Percentage of respondents is shown for each question; note that the number of respondents (in parentheses) varied with the question.

Survey question	Yes		No		Not sure/not specified	
Features of the project area	**Completed projects**	**Proposed projects**	**Completed projects**	**Proposed projects**	**Completed projects**	**Proposed projects**
Are invasive/ noxious plant species prevalent in riparian/ wetland habitats within the project area?	41% (40)	35% (45)	48% (47)	45% (57)	11% (11)	20% (25)
Are invasive/ noxious plant species prevalent in uplands within the project area?	43% (42)	41% (52)	51% (50)	42% (53)	6% (6)	17% (22)
Are insects and / or disease prevalent in riparian/ wetland habitats within the project area?	15% (15)	24% (31)	65% (64)	54% (68)	19% (19)	22% (28)
Are insects and / or disease prevalent in upland habitats within the project area?	32% (31)	40% (51)	58% (57)	43% 54)	10% (10)	17% (22)
Was any part of the project area in the Wildland Urban Interface (WUI)?	56% (58)	56% (74)	39% (40)	35% (46)	5% (5)	9% (12)
Are Fire Regime Condition Classes (FRCCs) applicable to the riparian or wetland areas within the project area?	49% (48)	44% (56)	16% (16)	12% (15)	35% (34)	44% (56)

4.5.5 Project Monitoring

Most of the respondents reported that project-related monitoring was planned or conducted for both their completed (71 percent) and proposed (82 percent) projects to determine effectiveness at meeting project objectives. In the survey, we asked questions about project monitoring, including duration, frequency, and methods used. Depending on the question about details of monitoring, response rate ranged from 10 to 60 percent. The varied response rate to specific questions partly reflected the discipline of the respondent; some survey participants (e.g., fire managers and fuels specialists) were not directly involved with all aspects of monitoring.

The most common ecological variables monitored in the completed projects were vegetation attributes and fuels, both before and after treatment implementation (table 21). Overall, monitoring appeared to be focused on project effectiveness at meeting objectives rather than on ecological impacts of the treatments. For example, monitoring of vegetation and fuels was expected, given the three most common project objectives: hazardous fuel reduction, habitat restoration, and restoration of the historical fire regime (fig. 17). However, it was surprising that 21 percent of the respondents did not monitor fuels (table 21). Additional vegetation variables explicitly noted in the "other" category were stand density, seedling counts, and percentage of cover of bare ground, grasses, and forbs. In riparian areas, sampling of the "greenline" (Burton et al. 2008; Winward 2000) and assessment of "proper functioning condition" (Prichard et al. 1998) were also noted in the "other" category. The impacts of treatments on terrestrial wildlife were monitored by 40 percent of the respondents, while impacts of treatments on aquatic biota were monitored by only 19 percent of the respondents. More than half of the respondents did no monitoring of water quality of erosion or hillslope runoff (table 21). Monitoring of recreational impacts was noted in the "other" category.

For those respondents who conducted monitoring, information on the type of monitoring is also shown in table 21. The most common monitoring methods were qualitative rapid assessment techniques and comparison of pre- and posttreatment photos. Approximately one-third of the respondents collected samples to monitor impacts on

Table 21—Summary of responses (from on-line survey) to questions regarding project-related monitoring (from Meyer et al. 2012). Values are expressed as percentages of completed projects. (Note: Percentages do not add to 100 percent because some survey participants responded "not sure" or did not respond to all monitoring questions.)

	Monitoring? (% of respondents)		Type of Monitoring (% of respondents who conducted monitoring)			
Ecological variable	**Yes**	**No**	**Pre- and post-treatment monitoring**	**Visual rapid assessment**	**Sample collection**	**Quantitative data collection**
Water quality and/ or quantity	27	54	51	25	10	5
Erosion / runoff	29	56	59	61	0	6
Stream biota	19	62	29	20	33	0
Vegetation attributes (e.g. rare plants, invasives, utilization)	87	8	76	34	4	36
Fuel types and Loads	71	21	76	40	5	21
Terrestrial wildlife	40	38	61	39	13	26
Other	26	60	27	50	0	17

aquatic biota; 13 percent of the respondents collected samples to monitor impacts on terrestrial wildlife; and 10 percent collected samples to monitor water quality (table 21). Quantitative data were collected to assess treatment effects on fuels, vegetation attributes, and terrestrial wildlife by 21 to 36 percent of the respondents (table 21). For most projects, duration of monitoring was limited to the first few years following treatment. Lack of resources (funding and staff) to support more extensive monitoring was explicitly noted by several respondents in the "comments" section.

4.5.6 Constraints to Conducting Fuels Treatments in Riparian Areas

Managers face multiple challenges when planning and conducting fuels treatments in all vegetation types, but wetlands and riparian areas pose additional concerns (fig. 23). Responses from the survey indicated that the most significant constraint for all agencies was the potential presence of threatened, endangered, or sensitive species in the project area. While this is also a major concern for upland fuels projects, inclusion of aquatic and riparian obligate species increases the number of species of concern. Cultural resources were also an issue in planning fuels projects in riparian areas, particularly in the Great Basin region where archeological sites are concentrated along stream-riparian corridors. BLM and USFS respondents from Nevada and Utah most frequently noted this constraint. Administrative policies, resource management plans, and lack of agreement among resource specialists were commonly encountered constraints among USFS, BLM,

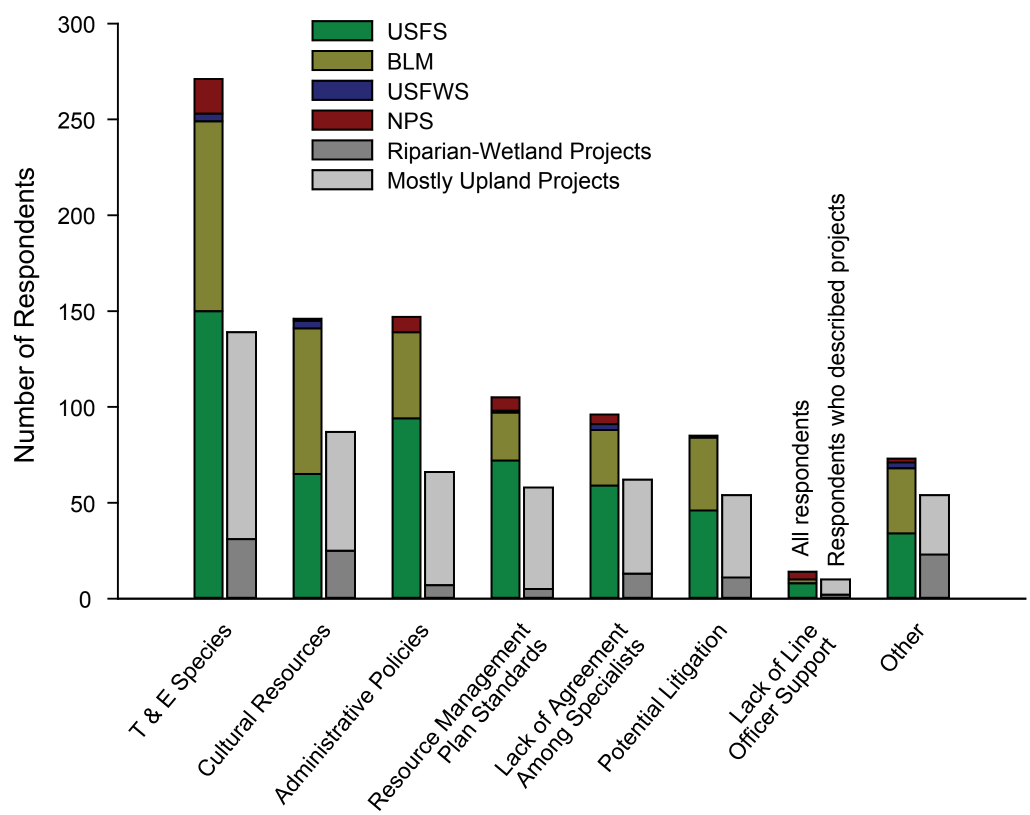


Figure 23—Constraints to planning and conducting fuels treatments. Survey participants were asked to select all constraints that applied to their projects. For each constraint, the first column displays responses from all survey participants who answered the questions (n = 464); and the second column displays responses from survey participants who described completed (n = 103) and proposed (n = 132) projects.

and NPS respondents (fig. 23). Approximately 19 percent of the respondents, almost evenly divided between BLM and USFS, recorded potential litigation as a constraint to riparian fuels projects. Limited support from line officers was the least common constraint noted (3 percent of survey respondents).

Several additional constraints were recorded by survey respondents, most notably funding. Budgets generally do not target vegetation treatments in riparian areas as a priority; therefore, managers interested in treating riparian fuels include streamside areas as part of larger projects. As noted above, approximately 70 percent of the projects (completed and planned) were part of predominantly upland projects. Much of the funding available for fuels treatments is focused in the WUI. This was reflected in the survey results: 56 percent of the completed and planned projects reported by respondents are located in the WUI (table 20). Other constraints noted by respondents included the following: challenges in attaining the appropriate window of season and/or weather conditions conducive for prescribed burning; availability of adequate fire staff and equipment support; land ownership patterns around riparian areas; visual and recreation conflicts; local environmental issues, politics and public perception; and limited scientific information on effects of fuel treatments on riparian and aquatic ecosystems.

4.6 Summary: More Riparian Fuels Treatments to Come…

The survey results clearly demonstrate that fuels projects are being implemented in wetlands and riparian areas throughout the survey area and that there is increasing interest in continuing certain projects and planning new ones. Riparian areas are highly diverse in this region, and fuel reduction treatments are being planned and conducted with multiple objectives (fig. 17) and across a range of riparian types (fig. 22). Results of our 2010 online survey were largely consistent with the 2007 phone survey of Forest Service FMOs (Stone et al. 2009). However, more USFS riparian projects are being planned and conducted than previously, suggesting a shift from "hands-off" riparian protection to more active manipulation of riparian areas on Forest Service lands. Although resource managers are experiencing similar constraints as in 2007 (Stone et al. 2010), the level of line officer support for treating riparian fuels seems to be growing (fig. 23; Meyer et al. 2012).

Results from both surveys also showed that most riparian treatments are part of predominantly upland projects, focused on larger-scale fuel reduction across portions of managed landscapes. This active management of riparian vegetation and fuels implies a trend towards incorporation of riparian corridors into broader-scale (watershed-scale or larger) treatments. This has likely resulted from recent information on landscape-scale fire behavior, fire return intervals, and greater appreciation of linkages between streams, riparian areas, and uplands (USDA Forest Service 2011; Luce et al. 2012). Managers are concerned about riparian fuel loads and perceive them to be high along many streams in the Interior West. They are reluctant to leave high streamside fuel loads while uplands are treated, so they are including these areas in an effort to exert some influence on fire behavior. In many cases, managers are also using fuel treatments as restoration projects in both uplands and riparian areas. This may be a consequence of funding—that is, funds are available for fuel reduction, so managers use this funding to simultaneously reduce fuels, restore habitat and historical fire regimes and, in some locations, to control invasive plant species. In these cases, prioritization of objectives is necessary, as some may be achieved more effectively than others (fig. 18).

Despite increased level of interest in treating riparian areas, numerous constraints were identified in the online survey (fig. 23). Noteworthy concerns include the unknown or unpredictable effects of treatments to riparian and aquatic habitat, during both treatment and recovery phases, and the limited scientific research that has been conducted on the topic (Bixby et al. 2015). Research results on the impacts of fire and fuel treatments on riparian functions and characteristics are restricted to a few localized studies in the Pacific Northwest in a limited range of vegetation types (Arkle and Pilliod 2010; Bêche et al. 2005; Bisson et al. 2003; Dwire and Kauffman 2003; see reviews in Chapters 2 and 3). Limited scientific knowledge restricts the ability of managers and resource specialists to justify the need for riparian treatments and to make informed decisions when planning projects (but see Chapter 3). Our survey results indicate that the state of the practice has preceded the state of the science regarding riparian fuel treatments, and that more sharing of experiences, "lessons learned" about what worked and what failed, would be beneficial for practitioners.

Chapter 5: Monitoring Fuel Treatments

5.1 Role of Monitoring

Monitoring is an important component of all adaptive management, including the treatment of fuels. Although resource specialists recognize the need for monitoring, limited resources—staff, time, expertise, and funding—frequently preclude the implementation of monitoring, especially quantitative data collection (Jain et al. 2012; Chapter 4, this report). As previously noted (Chapter 4), the most common monitoring methods for fuel treatment projects were qualitative rapid assessment techniques and comparison of pre- and posttreatment photos. In addition, most monitoring appeared to be focused on project effectiveness at meeting objectives rather than on ecological impacts of the treatments.

We encourage some level of monitoring for all fuels treatments projects, particularly those conducted in riparian areas and wetlands. Information on all aspects of project planning, implementation, short- and long-term treatment effects, and effectiveness are needed to advance our understanding of the utility of fuel treatments in different locations and vegetation types (please see case studies in Chapter 6). For projects conducted in highly sensitive areas or in habitats that support sensitive species, quantitative data are especially useful in guiding adaptive management. We strongly encourage the assessment of fuels in riparian areas and wetlands before and after treatments. More information is needed on the diverse range of riparian fuel profiles and their responses to different treatments, and resource managers are urged to collect quantitative data on riparian fuels whenever possible and—at a minimum—to photograph before- and after-treatment conditions. From our survey, we also learned that the duration of monitoring was limited to the first few years following treatment (Chapter 4). Again, we recognize the many constraints limiting monitoring efforts but emphasize the need for longer-term and, in some cases, retrospective monitoring.

It is beyond the scope of this report to provide extensive direction in the development of project monitoring. Instead, we briefly discuss elements of a monitoring approach and direct readers to other resources that are focused on monitoring (Text Boxes 3 and 4). Many protocols have been developed for different ecological attributes of interest (table 22).

5.2 Developing a Monitoring Approach

Relative to surrounding uplands, riparian areas often have more diverse vegetation and greater physical heterogeneity and may have higher rates of plant species turnover through time, especially in herbaceous and shrub layers. The dynamic nature of stream channels adds to the challenges of sampling and monitoring riparian and stream conditions. Developing an effective monitoring approach requires an understanding of dynamic natural disturbances, including climatic fluctuations (drought, high snow-pack winters) and their influence on flooding frequency and stream-floodplain interactions and inundation; local and regional fire return intervals; and past and current influence of beaver. In addition, an appreciation of the legacies of past land use and management is also

Table 22—Monitoring effects or effectiveness of fuel reduction treatments in riparian areas may require information on some or all of the following ecological attributes.

Ecological variables of interest	Ecological attributes to measure	Monitoring protocols and references
Riparian and wetland vegetation attributes (e.g. rare plants, invasives, utilization, cover)	Vegetation structure, composition, snags, downed wood	Archer, E.K.; Van Wagenen, A.R.; Coles-Ritchie, M.; Ebertowski, P.; Leary, R. 2014. Effectiveness monitoring for streams and riparian areas: sampling protocol for vegetation parameters. Unpublished paper on file at: http://www.fs.fed.us/biology/fishecology/emp.
		Burton, T.A.; Smith, S.J.; Cowley, E.R. 2011. Multiple indicator monitoring of stream channels and streamside vegetation. TR 1737-23. U.S. Department of the Interior, Bureau of Land management. 170 p.
		Elzinga, C.L.; Salzer, D.W.; Wiloughby, J.W.; Gibbs, J.P. 2001. Monitoring plant and animal populations. Malden, MA: Blackwell Publishing, Inc. 360 p.
		Kershner, J.L.; Archer, E.K.; Coles-Ritchie, M.; Cowley, E.R.; Henderson, R.C.; Kratz, K.; Quimby, C.M.; Turner, D.L.; Ulmer, L.C.; Vinson, M.R. 2004. Guide to effective monitoring of aquatic and riparian resources. Gen. Tech. Rep. RMRS-GTR-121. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 57 p.
		Platts, W.S.; Armour, C.; Booth, G.D.; Bryant, M.; Bufford, J.L.; [et al.] 1987. Methods for evaluating riparian habitats with applications to management. Gen. Tech. Rep. INT-221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.
		Prichard, D.; Barrett, H.; Cagney, J.; Clark, R.; Fogg, J.; Gebhardt, K.; Hansen, P.; Mitchell, B.; Tippy, D. 1993; revised 1995, 1998. Riparian area management: Process for assessing proper functioning condition. Tech. Ref. 1737-9. Denver, CO: U.S. Department of the Interior, Bureau of Land Management. BLM/SC/ST93/ 003+1737+REV95+REV98. 60 p.
		Scott, M.L.; Reynolds. E.W. 2007. Field-based evaluation of sampling techniques to support long-term monitoring of riparian ecosystems along wadeable streams on the Colorado Plateau. Open-File report 2007-1266. Washington, DC: U.S. Geological Survey. 57 p.
		USDA Forest Service [USDA FS]. 2012a. Groundwater-dependent ecosystems: Level I inventory field guide: Inventory methods for assessment and planning. Gen. Tech. Rep. WO-86a. Washington, DC: U.S. Department of Agriculture, Forest Service.
		USDA Forest Service [USDA FS]. 2012b. Groundwater-dependent ecosystems: Level II inventory field guide: Inventory methods for assessment and planning. Gen. Tech. Rep. WO-86b. Washington, DC: U.S. Department of Agriculture, Forest Service.
		USDI Fish and Wildlife Service. [n.d.] [Draft] Fuel and fire effects monitoring guide. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service. http://www.fws.gov/fire/downloads/monitor.pdf.
		Winward, A.H. 2000. Monitoring the vegetation resources in riparian areas. Gen. Tech. Rep. RMRS-GTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Fuel types and loads	Distribution of fuels; characterization of fuelbeds	Keane, R.E. 2015. Wildland fuel fundamentals and applications. Springer. 191 p.
		Lutes, D.C.; Keane, R.E.; Caratti, J.F.; Key, C.H.; Benson, N.C.; Sutherland, S.; Gangi, L.J. 2006. FIREMON: Fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. http://www.fs.fed.us/rm/pubs/rmrs_gtr164.pdf;
		Peterson, D.L.; Evers, L.; Gravenmier, R.; Eberhardt, E. 2007. A consumer guide: Tools to manage vegetation and fuels. Gen. Tech. Rep. PNW-GTR-690. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 151 p. www.treesearch.fs.fed.pubs/25953.
		Brown, J.K.; Oberheu, R.D.; Johnston, C.M. 1982. Handbook for inventorying surface fuels and biomass in the Interior West. Gen.Tech. Rep. INT-129. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 48 p.
		USDI Fish and Wildlife Service. [n.d.] [Draft]. Fuel and fire effects monitoring guide. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service. http://www.fws.gov/fire/downloads/monitor.pdf.
		USDI National Park Service. 2001. Fire monitoring handbook. Boise, ID: National Interagency Fire Center. 283 p.
Soil resources	Erosion, landslides; stream crossing density; road density	Soil Quality Monitoring for Long Term Ecosystem Sustainability on Northern Region National Forests (SOLO). Volume 1 and Volume 2; Soil–disturbance field guide and associated forms. Available at: http://forest.moscowfsl.wsu.edu/smp/solo/index.php

Table 22—*Continued*.

Ecological variables of interest	Ecological attributes to measure	Monitoring protocols and references
Water quality	Sediment, nutrients, temperature	Environmental Protection Agency (EPA). 1987. Nonpoint source controls and water quality standards. In: Water quality standards handbook, chapter 2 general program. Washington, DC: U.S. Environmental Protection Agency.
		Environmental Protection Agency 1996. Biological criteria, technical guidance for streams and small rivers. EPA822-B-96-001. Washington, DC: U.S. Environmental Protection Agency, Office of Water.
		Environmental Protection Agency. 2007. Water quality standards handbook. 2nd ed. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/wqs-tech/water-quality-standards-handbook.
Aquatic habitat	Instream wood; substrate; pools, undercut banks	Burton et al. 2011. (full citation above).
		Harrelson, C.C.; Rawlins, C.L.; Potyondy, J.P. 1994. Stream channel reference sites: An illustrated guide to field technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. http://www.stream.fs.fed.us/publications/documentsStream.html
		Hauer, F.R.; Lamberti, G.A. 2006. Methods in stream ecology. 2nd ed. Elsevier. 877 p.
		Herger, L.G.; Hayslip, G.A.; Leinenbach, P.T. 2007. Ecological condition of wadeable streams of the Interior Columbia River Basin. EPA-910-R-07-005. Seattle, WA: U.S. Environmental Protection Agency, Region 10.
		Kershner et al. 2004. (full citation above).
		Wohl, E.; Cenderelli, D.; Dwire, K.A.; Ryan, S.E.; Young, M.K.; Fausch, K. 2010. Large instream wood studies: A call for common metrics. Earth Surface Processes and Landforms. 35: 618–625.
Stream Biota; aquatic resources	Species occurrence or abundance; benthic macroinvertebrates; primary production	Vesely, D; McComb, B.C.; Vojta, C.D.; Suring, L.H.; Halaj, J.; Holthauen, R.S.; Zuckerberg, B.; Manley, P.M. 2006. Development of protocols to inventory or monitor wildlife, fish, or rare plants. Gen. Tech. Rep. WO-72. Washington, DC: U.S. Department of Agriculture, Forest Service. 100 p.
		Kershner et al. 2004. (full citation above)
		USDA Forest Service [USDA FS]. 2012a,b. (full citations above)
Terrestrial habitat	Vegetation metrics (see above) important for cover and food	Bate, L.J.; Garton, E.O.; Wisdom, M.J. 1999. Estimating snag and large trees densities and distributions on a landscape for wildlife management. Gen. Tech. Rep. PNW-GTR-425. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 76 p.
Terrestrial wildlife	Population / reproduction estimates of resident & migratory species	Manley, P.N.; et al. 2006. Multiple species inventory and monitoring technical guide. Gen. Tech. Rep. WO-73. Washington, DC: U.S. Department of Agriculture, Forest Service. 204 p.
		Elzinga et al. 2001. (full citation above).
Photo documentation	Visual change over vegetative cover, fuel loads	Hall, Frederick C. 2001a. Photo point monitoring handbook: part A- field procedures. Gen. Tech. Rep. PNW-GTR-526. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 1-48.
		Hall, Frederick C. 2001b. Photo point monitoring handbook: part B- concepts and analysis. Gen. Tech. Rep. PNW-GTR-526. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 49-134.

necessary to understand current condition as well as potential responses to certain treatments. This requires consideration of cumulative effects that includes historical (recent or longer-term) management activities in the watershed, current management activities, and potential additive and interactive impacts (Text Box 3).

Several methods have been developed for assessing riparian and stream resources; frequently used methods, especially by Federal and State resource practitioners, are listed in table 22. Protocols developed for monitoring programs (Text Box 4) were designed for assessing general stream-riparian condition, either through a single site visit or over time. Some methods were largely designed to monitor management actions, such as grazing, mechanical disturbance, or forest harvest impacts, and for specific stream channel types. With the exception of methods specifically developed for measuring fuel types and fuel loads (table 22), these methods were not focused on monitoring either fire effects or impacts of fuel treatments. For specific fuel treatment projects in riparian areas, there is no "ideal" or "best" method for every setting or objective. Monitoring plans tailored to meet clearly defined objectives and a defined scale and scope are preferred.

Selection and modification of existing methods are required to meet project objectives as well as possible tailoring for specific sites, valley settings, or other conditions. In addition, monitoring must ensure that projects are satisfying the requirements defined in the NEPA documents for the specific project (Text Box 3).

5.2.1 Elements of a Monitoring Design

Explicit statement of the critical questions of interest will focus the monitoring effort (Text Box 3): Will the monitoring assess project implementation, treatment effectiveness, or both? Will the monitoring evaluate the impacts and effects of wildfire or fuel treatments. Additional questions to ask when designing a monitoring approach include: (1) Are fuel treatments (or wildfire) degrading or negatively influencing attainment of desired conditions for riparian areas, soil, water, or aquatic desired conditions? and (2) Are fuel treatments (or wildfire) meeting desired future conditions?

Effective monitoring projects are supported by a monitoring plan that includes management and/or sampling objectives, management response, and method

Text Box 3—Considerations for Developing a Monitoring Approach (Modified From Chapter 10 in Jain et al. 2012).

Project Objectives and Goals:

1. For Federal agency projects, use 'Purpose and Need' sections of project NEPA documents for clear statement of objectives and goals. Consider the information needs of multiple stakeholders when developing a monitoring approach.
2. For postfire monitoring, clarify objectives and ecological variables most important for evaluating fire impacts. In watersheds with concerns regarding rare aquatic or terrestrial species, an overriding question is whether critical habitat features are affected by either fire or fuel treatments over both short- and long-term time frames.
3. For monitoring impacts of fuel treatments, clarify objectives and ecological variables most important for evaluating treatments impacts.

Focus of a Monitoring Approach - Questions of Interest:

- ***Monitoring to evaluate impacts of fuel treatments or wildfire on sensitive species, other aquatic or riparian species of interest, habitat characteristics, water quality, or vegetation attributes***

  Monitoring of the impacts of fuel treatments is conducted using comparisons of pretreatment data (preferred) or comparisons of posttreatment conditions with a reference, ecologically analogous, untreated stream-riparian segment or watershed. Postfire monitoring is conducted using comparisons of prefire data (where available) or comparisons of postfire conditions with a reference, ecologically analogous, unburned watershed. Postfire monitoring is valuable over both short- and long-term time frames to evaluate both impacts and recovery.

- ***Monitoring to evaluate project implementation: was the project implemented as intended?***
  Evaluation monitoring is conducted using comparisons of pre versus posttreatment measurements or comparisons of posttreatment conditions with reference baseline conditions. Reference conditions can be the current condition or desired future conditions; measured attributes should reflect the elements identified as fundamental to the desired future condition.

- ***Monitoring to evaluate treatment effectiveness; did the project meet the objectives?***
  Short-term evaluation monitoring is conducted using comparisons of pre versus posttreatment measurements, especially fuel components. Longer-term monitoring may be conducted if the treated area later burns.

Elements of a Monitoring Design:

1. Clearly stated monitoring objectives.
2. Clear description of baseline and desired future conditions, recognizing the dynamic nature of riparian areas.
3. Identification of the ecological variables most important for evaluating desired conditions and deviations from desired conditions (see table 22).
4. Determination of the type of data required to evaluate riparian condition within a stated level of confidence (see table 22).
5. Statement of acceptable uncertainty in monitoring data.
6. Strong, statistically valid sampling design, including scale of sampling (reach level, watershed level, or landscape level); replication in both space and time; sampling layout within the consideration of scope-of-inference; systematic versus random sampling; timing and interval of sampling.
7. Clear plan for data management, analysis, and evaluation.

Logistical and Financial Considerations:

How will monitoring be accomplished?

Includes decisions about when data will be collected (season, frequency interval of data collection); where data will be collected (reach length, plot size, sampling density); number of required repeated measures to adequately assess implementation and effectiveness of treatments, or fire impacts. Sampling theory, statistical analysis and monitoring design are crucial considerations at this step.

Who will do the monitoring?

Crew structure and leadership have implications for quality assurance/quality control, data management, and training.

Cost of monitoring (especially over time)? Who will pay?

Availability of expertise, time, and financial resources are best considered up-front.

How and where will monitoring data be stored, archived, and documented?

Data should be accessible to managers and researchers; archived in stable formats on stable media; resistant to corruption and accidental destruction; accompanied by adequate metadata; preferably stored and archived as corporate data.

How, when, and by whom will monitoring data be analyzed?

Depending on the size, complexity, and visibility of the project, multiple analysts with different disciplinary expertise may be involved in data analyses. Priority analyses will address the impacts of treatment or fire on sensitive species and habitats, valued riparian/wetland functions; quantify reduction in different fuel components; evaluate project implementation and treatment effectiveness.

Cumulative Effects Considerations:

1. What other current management activities are being planned or implemented in the watershed? Where are the management activities located relative to the stream-riparian corridor?
2. What is the historical (recent and longer-term) spatial distribution of management activities in the watershed?
3. What is spatial and temporal distribution of natural disturbances in the watershed?
4. What are potential additive and/or interactive impacts of past and current management activities, natural disturbance, and fuel reduction treatments over space and time?
5. What effects will the fuel reduction treatments have on other land uses and ecosystems components?

documentation. Monitoring plans provide a description of the fuel treatment project and the monitoring objectives and proposed method(s) as a means to communicate with and solicit input from all interested parties. It also documents a management commitment to implement monitoring. The basic monitoring plan should cover the elements necessary to communicate who, what, when, where, and how the monitoring will be

Text Box 4—Existing Programs and Tools for Monitoring and Assessment of Riparian Condition, Including Fuel Loads (Modified From Chapter 10 in Jain et al. 2012).

Monitoring Programs:

- **PACFISH INFISH Biological Opinion Effectiveness Monitoring Program for Streams and Riparian Areas (PIBO Monitoring).** This program provides a consistent framework for implementing effectiveness monitoring of aquatic and riparian resources within the range of the Pacific Anadromous Fish Strategy (PACFISH) and the Inland Fish Strategy (INFISH). Monitoring approach was developed in response to needs addressed in the Biological Opinions for bull trout (U.S. Department of the Interior, Fish and Wildlife Service) and steelhead (U.S. Department of Commerce, National Marine Fisheries Service). Primary objectives are to assess the effects of land management activities on aquatic and riparian resources and to determine whether PACFISH/INFISH management practices are maintaining or improving riparian and aquatic conditions at landscape and watershed scales on Federal lands throughout the Columbia River Basin (Kershner et al. 2004). http://fsweb.r4.fs.fed.us/unit/nr/pibo/index.shtml.
- **Multiple Indicator Monitoring (MIM): Monitoring the Effects of Management on Stream Channels and Streamside Vegetation.** This program is focused on assessing the impacts of grazing on riparian and stream condition in the Intermountain Region. The MIM protocol was collaboratively developed by U.S. Department of the Interior, Bureau of Land Management (BLM, Idaho State Office) and U.S. Department of Agriculture, Forest Service (Burton et al. 2011). http://www.blm.gov/or/programs/nrst/monitoring.php.
- **Forest Health Monitoring Program, U.S. Department of Agriculture Forest Service.** This is a national program designed to determine the status, changes, and trends in indicators of forest condition on an annual basis. The program uses a variety of approaches to address forest health issues that affect the sustainability of forest ecosystems. Although the focus is on upland forests, the condition and health of riparian woody species are also examined in some locations. http://fhm.fs.fed.us/
- **Forest Inventory and Analysis National Program (FIA)**. This program reports on the status and trends in U.S. forests. Although the focus is on upland forests, some randomly located plots occur in riparian areas. http://www.fia.fs.fed.us.
- **Soil Quality Monitoring for Long-Term Ecosystem Sustainability on Northern Region National Forests (SOLO)**. This program is focused on monitoring soil quality and soil disturbance, including guidance on how to conduct a rapid assessment of soil disturbances. http://forest.moscowfsl.wsu.edu/smp/solo/index.php.

Tools:

- **USFS Remote Sensing Application Center (RSAC)**. This is the national technical services center of the U.S. Department of Agriculture, Forest Service. The center provides remote sensing tools and technical services for delineating riparian areas; mapping riparian vegetation; classifying valley bottoms; mapping cover of invasive plant species; postfire mapping of burned areas (areas of different fire severity). http://fsweb.rsac.fs.fed.us.
- **Fuel and Fire Tools (FFT)**. This is a software application that integrates Fuel Characteristics Classification System (FCCS), Consume, Fire Emission Production Simulator (FEPS), Pile Calculator, and Digital Photo Series (fuel load estimates) into a single user interface. All of the tools were developed by the Fire and Environmental Research Applications Team (FERA; U.S. Department of Agriculture, Forest Service). http://www.fs.fed.us/pnw/fera/fft.
- **FEAT/FIREMON (FFI)**. This is a monitoring software tool designed to assist managers with collection, storage, and analysis of ecological information. Lutes, Duncan C.; Benson, Nathan C.; Keifer, MaryBeth; Carrati, John F.; Streetman, S. Austin. 2009. FFI: A software tool for ecological monitoring. International Journal of Wildland Fire 18: 310–314.

conducted and used to make management decisions. A question-driven approach for formulating a customized, concise monitoring plan is provided by Derr et al. (2005). Elements of a monitoring plan or design are listed in Text Box 3.

The first step in developing a monitoring plan is to establish simply stated, purposeful objectives that clearly express specific, measurable, achievable, relevant, and tractable management objectives. It can be helpful to identify a primary objective, followed by secondary and other objectives that communicate the nature and depth of the monitoring effort. Why is the project being undertaken? Who will use the information and how? What kind of output is expected? A clear description of baseline and target or desired future conditions can assist in assessing the effectiveness of fuel treatment projects. As noted above, the natural disturbance regime and dynamic nature of riparian areas needs to be considered in statements of target conditions. Objectives should be quantifiable and achievable and should contain clearly stated targets or thresholds, thus facilitating evaluation of progress or effectiveness. All resource specialists involved in the project should agree to the objectives.

Another important early step is determining what attributes to monitor. The identification of ecological attributes or variables to monitor may be specific to a project, site, or region, but usually includes fuel profiles, some vegetation attributes, and certain habitat features (table 22; Text Box 3). Ecological variables need to be prioritized in order of importance for evaluating desired conditions or deviations from those conditions. Next, the types of data required to evaluate the selected attributes with confidence need to be determined. It is advised that the acceptable amount of uncertainty for each critical variable also be determined and explicitly stated.

To be defensible, data and other information should be collected using published methods (table 22) within an experimental design or sampling framework that employs unbiased sampling and adequate sample sizes to assess data statistically. In many cases, comparisons to untreated, ecologically analogous reference reaches are part of the sampling design. Reference reaches might be located in the same drainage (e.g., upstream) or in nearby streams. Comparisons to other sites can sometimes be problematic, but there are techniques to account for potential bias or pseudoreplication (Van Mantgem et al. 2001). Sampling considerations include the spatial extent of sampling, timing and intervals of sampling, systematic versus random sampling, and ability to make inferences. The sampling techniques, number and spacing of transects, number and spacing of point samples, and specific methodologies may need to be modified for specific projects. Readers are referred to the references cited in table 22 for discussion of these and additional considerations. Monitoring plans may include collection of samples, such as water and aquatic insects, that require in-lab processing or analysis. Description of methods used to collect and process samples is a critical component of some monitoring plans. As noted in Chapter 4, about one-third of the survey respondents collected samples to monitor impacts on aquatic biota; 13 percent of the respondents collected samples to monitor impacts on terrestrial wildlife; and 10 percent collected samples to monitor water quality.

A clear approach to data management, analysis, and evaluation also needs to be addressed in the monitoring plan. This includes data entry and the types of data analysis, synthesis, and interpretation that will be undertaken. In many cases, determination of the types of data analysis and syntheses to be conducted will influence decisions about the sampling design, particularly replication and spatial distribution of sampling sites. The frequency and type of reporting will also influence data management and evaluation.

The intensity and scale of monitoring should reflect the importance of the project treatment area and the resources (staff, funding, time) available to conduct the monitoring. The intensity of monitoring can range from detailed before-and-after assessment of fuels to a single photo point revisited every 5 years. The scale or spatial extent of monitoring can range from a set of nested plots placed along transects in selected treated and untreated areas to coverage of all treated areas. As noted above in Chapter 4, approximately 21 to 36 percent of the survey respondents' collected quantitative data to assess fuel treatment effects on fuels, vegetation attributes, and terrestrial wildlife. For most projects, duration of monitoring was limited to the first few years following treatment. Limited funding and staff time to support monitoring will remain an issue, but resource specialists are urged to conduct as much monitoring as is financially and logistically feasible and to augment monitoring with administrative studies in areas of special resource interest.

5.2.2 Logistical and Financial Considerations

The availability of expertise, time, and financial resources must be considered at the beginning and during all stages of planning. Basic questions addressing logistical and financial constraints are listed in Text Box 3. Many considerations will be taken into account during planning and drafting the monitoring plan (Derr et al. 2005). Budgets largely determine what kind of monitoring is possible and play a critical role in logistical choices. Logistical considerations include sampling details for how monitoring will be accomplished, including when, where, and how the data will be collected; sequence of data collection; implementation of the sampling design; and the required number and expertise of crew members. Costs and logistics of data management, including storage, archival, and documentation, are also critical and need to be explicitly addressed in the monitoring plan.

5.3 Existing Resources

In addition to the monitoring protocols and references listed in table 22, ongoing monitoring programs are also worth noting as potential sources to assist in evaluation of current condition during fuels treatment project planning and development of a monitoring approach. For the Columbia River Basin, the PACFISH INFISH Biological Opinion Monitoring Program assesses the effects of land management activities on stream and riparian resources on Federal lands administered by the Forest Service and BLM (Archer et al. 2012a,b; Kershner 2002; Kershner et al. 2001; http://fsweb.r4.fs.fed.us/unit/nr/pibo/index.shtml; Text Box 4). Other existing monitoring programs focus primarily on uplands, but may be helpful in some applications or locations or both (Text Box 3).

Many tools are available that focus on fuels, fire effects, soils, wildlife, and other elements; a few are noted in Text Box 4. Information on the range of existing tools for managing vegetation and fuels is summarized well in Peterson et al. (2007) and Stratton (2006). In Peterson et al. (2007), the assumptions, trade-offs, and benefits of various tools are presented, and examples of site-specific and watershed-scale projects are provided. Decision support tools on fire emissions, fire effects, fuels description and planning, and other fire-related topics are also described in Appendix B in Jain et al. (2012). New information and decisions support tools are continually being developed, and many existing tools and models are updated regularly. Although fuels and fire behavior models are generally lacking for most riparian vegetation types, readers are encouraged to visit FRAMES, a web-based portal for information exchange and technology transfer that includes recent developments and updates (http://www.frames.gov).

Chapter 6: Case Studies of Riparian Fuels Treatments: Challenges and Opportunities for Restoration and Management

6.1 Prescribed Burning in Willow and Aspen Stands, Bridger-Teton National Forest and Grand Teton National Park, Wyoming

For more than 20 years, resource managers have included prescribed fire as a management strategy in willow-dominated riparian areas on public lands of northwest Wyoming. The primary objective for most prescribed fire treatments is to improve habitat for wildlife, primarily moose (*Alces alces*), elk (*Cervus canadensis*), and deer (*Odocoileus* spp.). Projects have been implemented on the Bridger-Teton National Forest and in Grand Teton National Park and have included close collaboration among wildlife biologists from the Wyoming Game and Fish Department and resource specialists and fire staff from the National Park Service, Teton Interagency Fire, and the Bridger-Teton National Forest (Meyer et al. 2012). Most willow species resprout vigorously following low- to moderate-severity wildfire (see Section 2.3.1 above; Dwire and Kauffman 2003; Kaczynski and Cooper 2015), as well as prescribed fire treatments (fig. 24; Boggs et al. 1990), likely due to extensive rooting structures in moist soils that are not impacted directly by surface fires. Treated willow stands in northwest Wyoming had been characterized by managers as "decadent" with high proportions of dead stems (fig. 25). This dead component is the target for treatment with prescribed fire because it presents a fuel hazard and limits access to live portions of the shrubs—that is, the valuable browse forage. In most cases, prescribed fire projects have achieved management goals of increasing willow regeneration and growth rates to improve the quality of wildlife browse and fuel reduction in select locations.

Figure 24—Resprouting willows following the 2003 spring prescribed burn treatment along Fontenelle Creek, Bridger-Teton National Forest, Wyoming. The photo was taken in late August, approximately 3 months following treatment.

Figure 25—Willow with a large number of dead stems (characterized as decadent) in an untreated area, Buffalo River Valley, Bridger-Teton National Forest, Wyoming.

6.1.1 Fontenelle Willows Prescribed Burn, Bridger-Teton National Forest, Wyoming

In spring 2003, the Fontenelle Willows Prescribed Burn project was implemented on the Fontenelle Allotment, Kemmerer Ranger District, Bridger-Teton National Forest (Banister and Lockwood 2010). Part of the area was prescribed burned in 1989. Outside of the treated area, the willow stands—dominated by Booths willow (*Salix boothi* Dorn) and Geyer's willow (*Salix geyeriana* Andersson)—were up to 5 meters tall, dense, and with many dead stems. In untreated stands, the percentage of cover of dead stems was nearly twice the cover of live stems. The primary objective of the multiyear project was "to remove decadent Booth and Geyer willow adjacent to Fontenelle Creek in order to promote new growth within the stands, thus improving grazing and forage conditions for wildlife and livestock to agency, State, and private lands while restoring fire-adaptive ecosystems" (Banister and Lockwood 2010). The entire project area provides both critical winter and yearlong habitat for moose (*Alces alces*), as well as spring, summer, and fall habitat for mule deer (*Odocoileus hemionus*), pronghorn antelope (*Antilocapra americana*), and elk (*Cervus canadensis*). Specific objectives of project implementation were to (1) burn willow communities in a mosaic pattern with at least 60 percent blackened, to return late seral stands to early seral; (2) identify and protect archeological resources; (3) maintain State water quality standards and Forest Service water quality goals; and (4) identify and protect visually sensitive areas (Banister and Lockwood 2010). Additional ecological objectives were to attain specified increases in the percent of live willow cover within 3 years posttreatment and to attain average willow heights greater than or equal to preburn heights within 10 years posttreatment.

Shrub height and percentage of cover were estimated in the project area using standard protocols with some modifications to evaluate the amount of dead standing willow; no fuel models existed for the fuel conditions or predicted the potential fire behavior for burning in willow communities (Banister and Lockwood 2010). In May 2003, approximately 184 acres were burned along the wide floodplain in the Fontenelle Creek drainage using both ground and aerial ignition. The prescribed fire was implemented as planned;

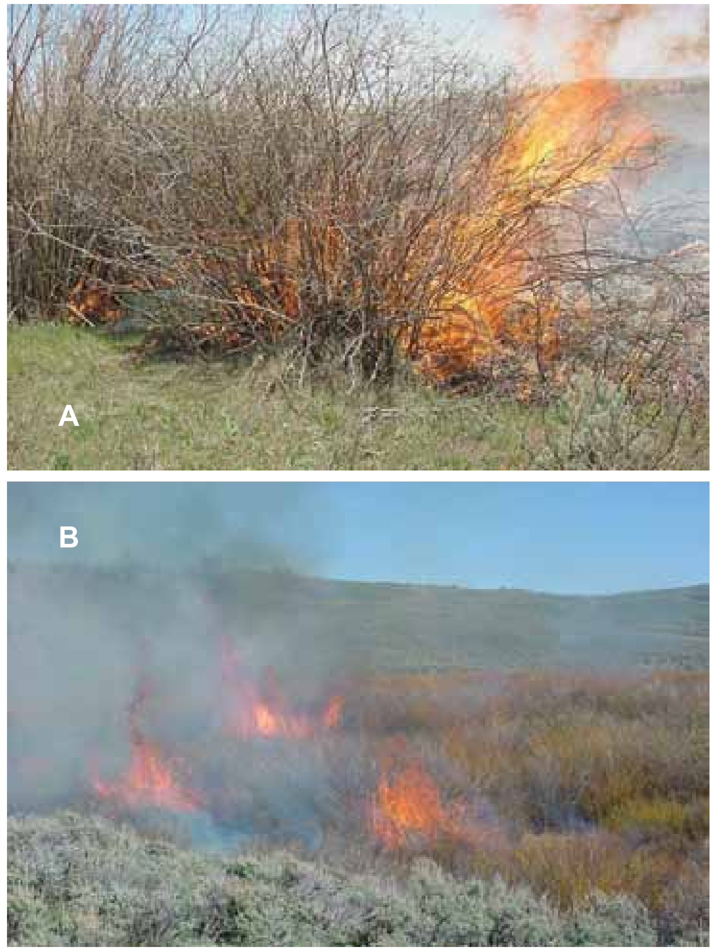


Figure 26—Ignited willows during the Fontenelle Willows Prescribed Burn project (May 2003), Bridger-Teton National Forest, Wyoming. The treatment was conducted before bud-break when soils were moist.

the unit burned intensely with flame heights of more than 15 feet in some portions of the treated area (fig. 26 a,b). The postburn evaluation showed that approximately 51 percent of the unit was blackened, 18 percent burned with low intensity, and approximately 33 percent burned with moderate intensity (fig. 27). Due to the short duration of low- to moderate-intensity fire, there was minimal damage to the soil with organic matter still present across most portions of the treated area. Willows, forbs, and grasses began re-sprouting within weeks of the treatment (fig. 28). To evaluate achievement of ecological objectives, percentage of cover and height of willows (live and dead) were sampled along five transects (25 m long) before the treatment, 1 year posttreatment, and 5 years post-treatment. Posttreatment monitoring indicated that willow growth exceeded expectations. The 2003 Fontenelle Creek burn achieved project implementation treatment objectives as well as ecological objectives (Banister and Lockwood 2010; Meyer et al. 2012).

Another portion (approximately 570 acres) of the Fontenelle Creek Grazing Allotment was scheduled for similar treatment in spring 2010. However, high flow in Fontenelle Creek and muddy roads prevented vehicle access, and saturated soils and ground fuel moisture conditions were not conducive to the ignition and spread of fire across the unit; therefore, the treatment was postponed. The inability to successfully implement a prescribed burn in spring 2010 demonstrated the role of soil and fuel moisture content, which can frequently confound the treatment of riparian fuels. The preferred season for burning deciduous-dominated riparian vegetation is spring, before leaf-out

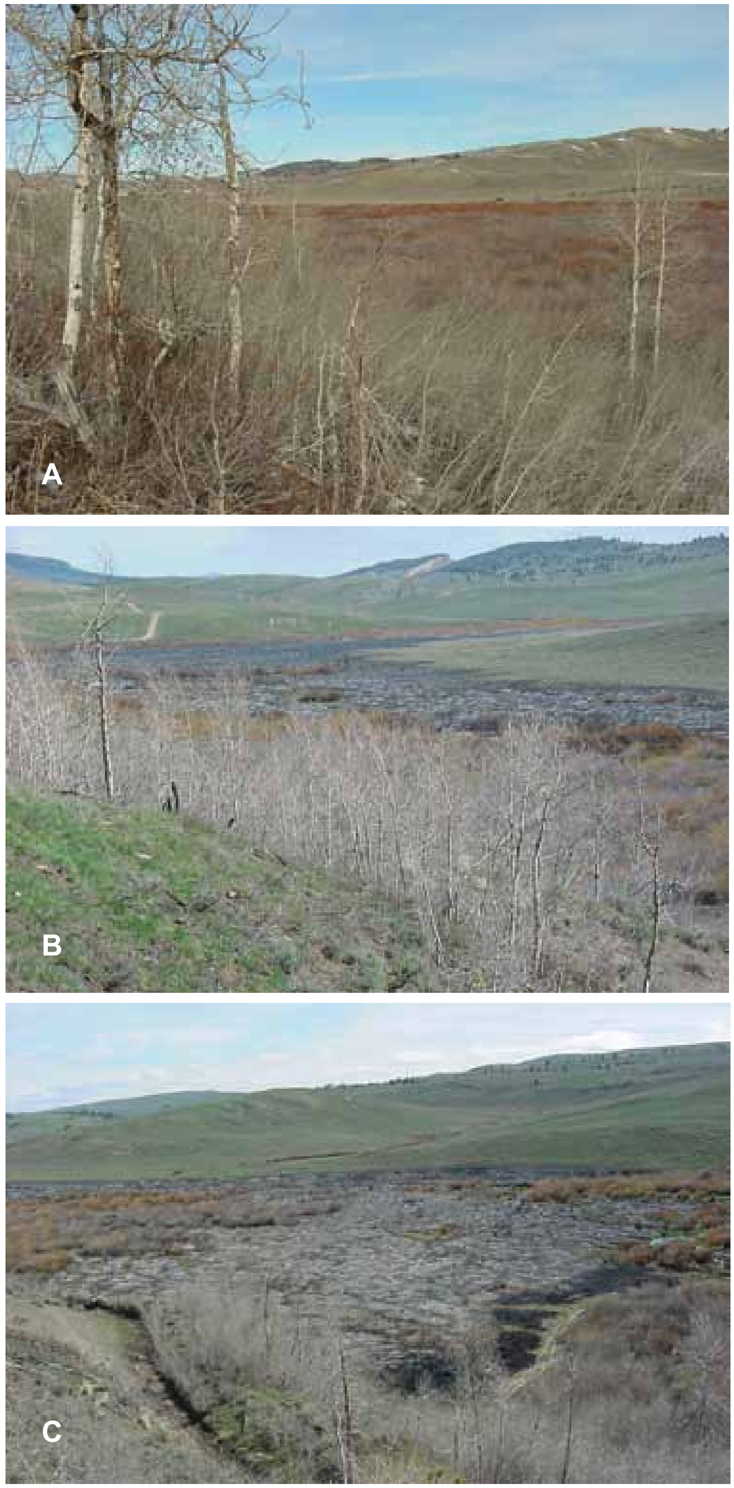


Figure 27—Overview of the Fontenelle Willows Prescribed Burn project area before treatment (A), and immediately following treatment in May 2003 (B,C), showing a mosaic of portions burned with low to moderate intensity.

and most bud-break, thus reducing the overall vulnerability of the plants to fire. Later in summer, moisture conditions may be more favorable for burning, but the plants are potentially more vulnerable to damage, some nesting birds may be more severely impacted, and the fires may be more difficult to control. Scheduling restrictions are critical in planning for all fuel reduction treatments but require additional consideration in streamside areas.

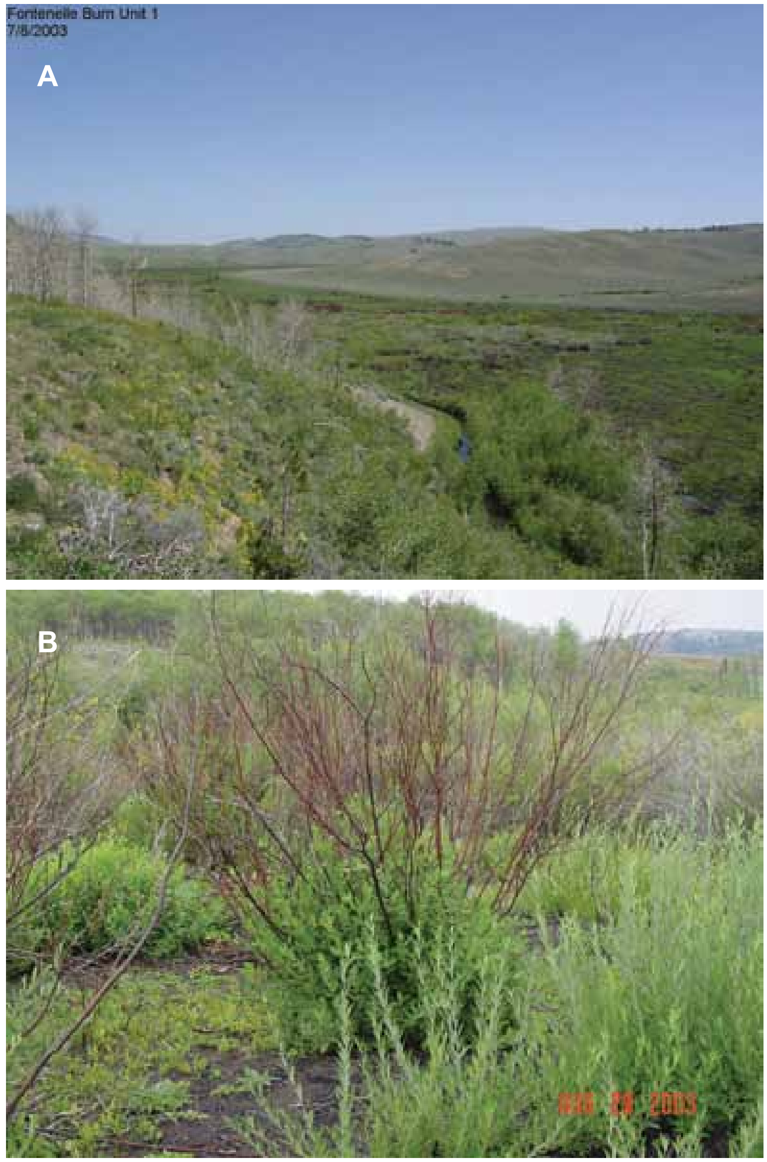


Figure 28—Regrowth of both willows and the herbaceous understory exceeded expectations. Overview of the Fontenelle Willows Prescribed Burn project area approximately 5 weeks following treatment (A; July 2003) showing the regrowth of willows and the herbaceous understory. Burned willows resprouted vigorously within approximately 5 weeks of treatment (B).

6.1.2 Prescribed Burns in Willow Stands, Bridger-Teton National Forest and Teton National Park, Wyoming

In the Buffalo River Valley, located in the Blackrock Ranger District of the Bridger-Teton National Forest, resource managers from the National Park Service and Wyoming Game and Fish Department have been using prescribed fire to manage willow-dominated areas for wildlife benefit since the mid-1980s (fig. 29). In spring 1994, a low-severity burn was conducted in a portion of the Buffalo Valley where willow and aspen were severely suppressed by combined herbivory from moose, elk, and cattle; most plants were essentially browsed to snow height every winter. Monitoring has indicated that the spring burns rejuvenated the treated willow stands, which resprouted vigorously, providing critical winter forage for moose in the area. It was also observed that moose and elk tended to select Booth's willow (*Salix boothii*) over Geyer's willow (*Salix geyeri*) following treatment.

In the eastern portion of Grand Teton National Park, adjacent to Wolff Ridge, resource managers installed exclosures in a small riparian area following a prescribed

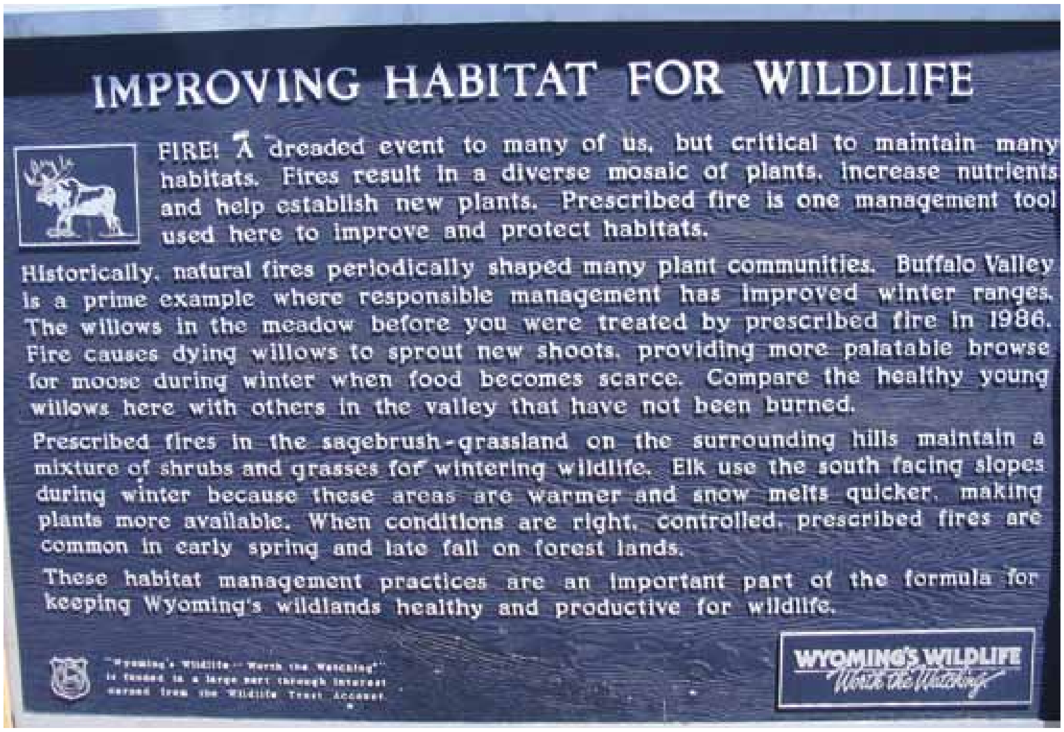


Figure 29—Interpretive sign posted along Wyoming State Highway 26/287 in the Buffalo River Valley. The sign explains the role of prescribed fire in habitat management of willows as winter browse for moose and other wildlife.

fire in 1997 to determine the effects of livestock and wildlife (moose, elk, bison [*Bison bison*], and deer) exclusion on posttreatment growth of willows and aspen (willow height and aspen stem density; fig. 30). As expected, plants recovered most rapidly in the exclosures that excluded both livestock and wildlife. Postfire growth was slower in the exclosures that excluded only livestock and most reduced in the unfenced 'control' areas, which were impacted by wildlife and livestock herbivory. Resource managers advised that caution be used in managing vegetation recovering from prescribed burn treatments, particularly in the first 2 to 5 years posttreatment. In locations where browsing pressure is exceptionally heavy, herbivory by livestock or native ungulates or both can set back growth and productivity (Kaczynski and Cooper, 2015) and limit reproduction of some willow species (Case and Kauffman 1997), particularly where resprouting shrubs are exposed, accessible, and highly visible (Dwire et al. 2006). Although the treatment at Wolff Ridge was considered successful over the extensive burn unit dominated by sagebrush and aspen, resource managers noted that some individual willow plants were killed in the prescribed burn (fig. 30).

Spring prescribed fire treatment has also been applied to willow stands west of the historic Jackson Lake Lodge in Grand Teton National Park (fig. 31), in an area referred to as 'Willow Flats.' In 2002, a controlled burn was implemented primarily to reduce potentially hazardous fuels near the Lodge in addition to stimulating growth in willows to improve winter browse for moose and elk. The fuel type was tall, dense willows (*Salix geyeri, Salix boothii,* and other species) with a high proportion of dead stems. This treatment resulted in a mosaic of predominantly low- to medium-burn severity (less than 20 percent blackened), with smaller patches of complete willow consumption, as assessed

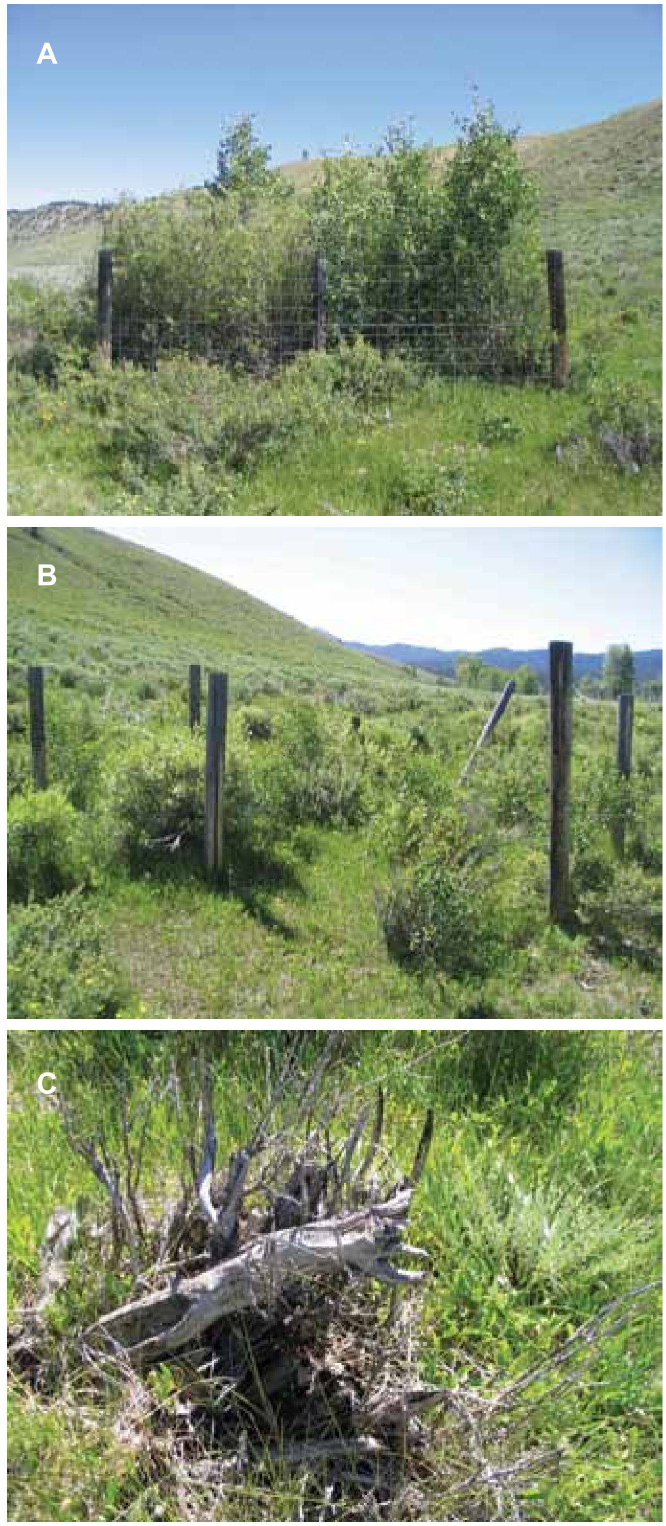


Figure 30—Near Wolff Ridge, Grand Teton National Park, Wyoming, exclosures were constructed to evaluate the effects of herbivory by livestock and wildlife (moose [*Alces alces*], elk [*Cervus elaphus*], bison [*Bison bison*], and deer [*Odocoileus hemionus*]) on willows (*Salix* spp.) and aspen (*Populus tremuloides*) following prescribed fire treatments (A). The effects of cattle grazing were observed for 2 years; the fencing was removed each season when the cows were removed (B). Some individual willow plants were killed in the prescribed fire (C).

through analysis of aerial photos taken within days of the treatment. Ten years post-treatment, most willows range between approximately 1 meter to more than 2 meters in height, and there is little evidence of the burn, with the exception of blackened standing dead stems in some stands, due to the treatment (fig. 31). Browsing by elk and moose does not appear to be limiting willow growth.

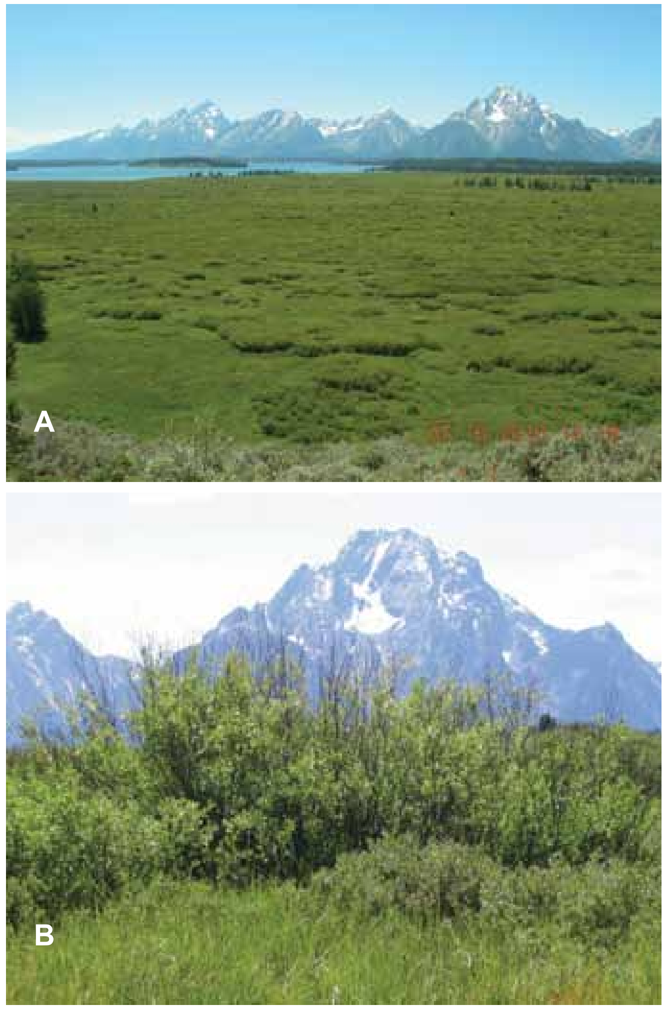


Figure 31—Portions of the extensive area between Jackson Lake Lodge and Jackson Lake (A) were treated with prescribed fire in spring 2002 to reduce hazardous fuels and improve wildlife habitat (improve browse quality; A). Eight years after treatment, there is little evidence of the burn. Although most willow stems range in height from 0.5 meter to over 2 meters, the controlled burn treatment left many standing dead stems, possibly killed by the fire (B).

6.2 Habitat Restoration and Invasive Plant Management; Bighorn Canyon National Recreation Area and Yellowtail Wildlife Habitat Management Area, Wyoming

The Bighorn Canyon National Recreation Area was established in 1966 following the construction of the Yellowtail Dam, which dammed the Bighorn River and formed Bighorn Lake. The lake extends 71 miles (114 km) across the border between northeast Wyoming and southeast Montana; approximately 55 miles (89 km) of Bighorn Lake occur within the national recreation area. Portions of the Bighorn Canyon National Recreation Area are included in the Yellowtail Wildlife Habitat Management Area (YWHMA), a 19,424-acre unit managed by the Wyoming Game and Fish Department in cooperation with the NPS, Bureau of Reclamation, and BLM (fig. 32). The YWHMA includes wetlands associated with Bighorn Lake as well as 16 smaller constructed wetlands and extensive riparian cottonwood gallery forests along the Bighorn and Shoshone rivers. These features provide protected resting area for migrating waterfowl (primary management goal); critical spring nesting habitat for numerous bird species, including turkeys (*Meleagris gallopavo*), pheasants (primarily *Phasianus colchicus*), and waterfowl; and yearlong habitat for white-tailed deer (*Odocoileus virginianus*) and other big game. The YWHMA is designated as an Important Bird Area by the

National Audubon Society (http://web4.audubon.org/bird/iba/). The gallery forests are dominated by plains cottonwood (*Populus deltoides*) with some narrowleaf cottonwood (*Populus angustifolia*) but are extensively infested with invasive woody species, notably Russian olive (*Elaeagnus angustifolia*) and saltcedar (*Tamarix* spp.) as well as herbaceous weed species such as whitetop (*Cardaria draba* (L.) Desv.), Russian knapweed (*Acroptilon repens* L.), and Canada thistle (*Cirsium arvense* (L.) Scop.). Dams upstream of the YWHMA alter the flow regimes of both the Bighorn and Shoshone rivers, and the cottonwood stands are primarily comprised of older, larger size classes. The larger Russian olive trees at the site are estimated to be approximately 40 to 50 years old.

In 2003, the Yellowtail Area Coordinated Resource Management (CRM) group was formed to address the issue of invasive plants on the YWHMA and surrounding

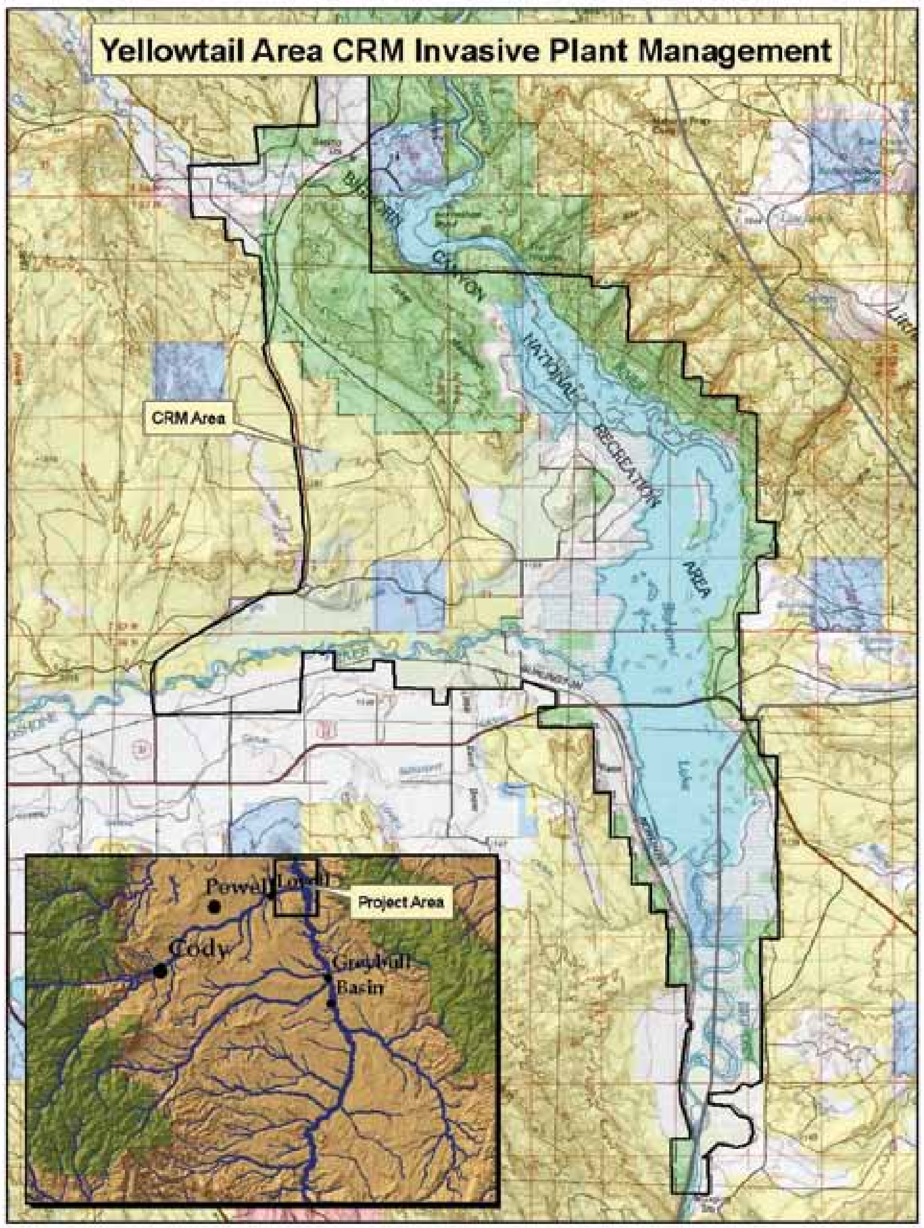


Figure 32—Map of the Yellowtail Area Coordinated Resource Management (CRM) project area, Wyoming (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007; map by Jerry Altermatt, Wyoming Game and Fish Department, used with permission).

private lands along the Shoshone and Big Horn rivers. The persistence and spread of both woody and herbaceous noxious weeds were considered to pose serious threats to wildlife habitat and agricultural production. The CRM mission statement is "to manage the CRM Area for healthy, desirable plant communities that promote wildlife habitat, sustainable recreation and agriculture and educational opportunities" (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007). The Yellowtail CRM is a highly collaborative effort among the Wyoming Wildlife and Natural Resource Trust Board, National Fish and Wildlife Foundation, National Wild Turkey Federation, Wyoming Game and Fish Department, National Park Service, and Bureau of Land Management. In 2006, CRM obtained a grant from the Wyoming Wildlife and Natural Resource Trust (WWNRT) to actively manage invasive plants within the YWHMA; proposed management activities included the reduction of fine fuels within portions of the unit. The project goal was to "reduce the acres infested with invasive species by 20 percent within 5 years using a combination of integrated pest management methods including chemical, biological and mechanical (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007)." Since 2006, CRM has received several additional grants from WWNRT and other funding sources to continue projects on invasive plant management.

Several approaches to eliminating or controlling different invasive plant species have been employed over time, including planned sequences of mechanical mulching, application of herbicides, grazing by cattle, and browsing by goats (table 23; Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007, 2012). Treatments have been adjusted over time to better achieve management objectives. An early step (2006–2007) was an invasive plant inventory to determine the distribution of woody and herbaceous invasive species across ~32,000 acres in the Bighorn Canyon National Recreation Area. The mapped distributions of different species facilitated planning for application of various treatments in the most heavily infested areas.

Areas with high cover and stem densities of Russian olive and saltcedar were cut and mulched using a tracked excavator with a mulching attachment (Janaury to March 2009; fig. 33 a,b). The excavator/mulcher that was used cuts down trees and mulches the woody stem and branch biomass on site (Harrod et al. 2009; Rummer, 2010). To minimize ground disturbance, the mechanical treatment was conducted from January to March 2009 while the ground was protected by some snow cover. Russian olive can resprout strongly after cutting and other disturbances, so stumps were treated with an herbicide (triclopyr®), mixed with basal bark oil. When applied immediately after cutting, the triclopyr®-oil mix is drawn into the stump to the roots, thereby killing the tree. Following the first mulch-herbicide treatments, many of the stumps resprouted (fig. 33c). This was attributed to conservative application of the herbicide. In following years, the amount of herbicide applied was increased, resulting in higher tree mortality and less resprouting. An alternate herbicide (imazilpyr®) was also tried and proved to be more effective in reducing the amount of sprouting. However, the use of imazilpyr® was later discontinued because it seemed to cause nontarget mortality of understory plant species. After trying different approaches, CRM is using the following approach to control Russian olive: mechanical treatment using boom-mounted mastication heads on hydrobunchers in winter (with no herbicide stump treatments) followed by foliar treatments with 4 percent triclopyr® or basal (or both) treatments with 2.5:1 triclopyr® to basal bark oil.

Table 23—Approaches to eliminating or controlling different invasive plant species in riparian floodplains of the Yellowtail Wildlife Habitat Management Area (Bighorn National Recreation Area), Wyoming. A range of different treatments were used; several treatments were sequentially applied over time (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007).

Treatment	Objective	Outcome
Conduct mechanical treatments on Russian olive and saltcedar	Mechanically remove woody invasive species or reduce stem density in designated areas; treat stumps with herbicide and basal bark oil to reduce re-sprouting	Considerable re-sprouting of Russian olive occurred in the spring following treatment; herbicide treatments were intensified
Five treatment trials were tested to control saltcedar	Determine the most effective treatments for reducing cover of saltcedar. Treatment were: (1) mechanical mulching, chemical (trichlopyr®), insects (*Diorhabda elongata*), and goat browsing; (2) mechanical mulching, insects (*Diorhabda elongata*), and goat browsing; (3) mechanical mulching, chemical (trichlopyr®), and insects (*Diorhabda elongata*); (4) mechanical mulching, and insects (*Diorhabda elongata*); (5) mechanical mulching alone.	1st year results indicated that mechanical mulching followed by chemical treatment (trichlopyr®) resulted in highest saltcedar mortality
Conduct herbicide treatments (using backpack sprayers, boom sprayers)	Control Russian knapweed, whitetop, saltcedar, Canada thistle through targeted 'spot-spraying.'	Successfully treated most areas; targeted saltcedar plants showed 100% mortality
Winter cattle grazing on selected pastures to remove fine fuels	Reduce the risk of wildfire, rejuvenate grass and forb communities, and create areas of high quality brood-rearing habitat for upland birds.	Reduction in fine fuels in grazed pastures
Browsing by Boer goats in designated areas to control invasive species	Reduce cover of Russian olive, saltcedar, Russian knapweed, whitetop by sequential browsing by goats	Goats show preference for Russian olive, Russian knapweed and avoidance of grasses. Constraints included expense (management of goats) and limited treatment time due to overlap in bird-hunting season

Herbicide was also applied in areas that were not mechanically treated using backpack sprayers and boom sprayers. Spot treatments of herbicide application were applied in low-density infestations of saltcedar. In other locations, spot treatments targeted Russian knapweed, whitetop, Russian olive, and Canada thistle. Treated areas were revisited in following years to treat missed plants.

A winter cattle grazing program was conducted from 2002 to 2011 in small pastures along the Shoshone River floodplain in the Yellowtail CRM. Objectives of the grazing treatment were to "reduce the risk of wildfire, rejuvenate grass and forb communities, and create areas of high-quality brood-rearing habitat for upland birds" (table 23; Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007). It was discontinued due to changes in the management of lake levels in Bighorn Lake by the U.S. Bureau of Reclamation that caused overbank winter flooding onto the Shoshone River floodplains.

Boer goats (*Capra hircus*) were introduced into designated areas with high cover of invasive species—particularly Russian olive and Russian knapweed—to consume non-native forage and reduce ladder fuels. Their movement was controlled by either electric fencing or through intensive herding. However, the goats had to be moved before the start of bird-hunting season, limiting the duration of the goat-browsing treatment. In small

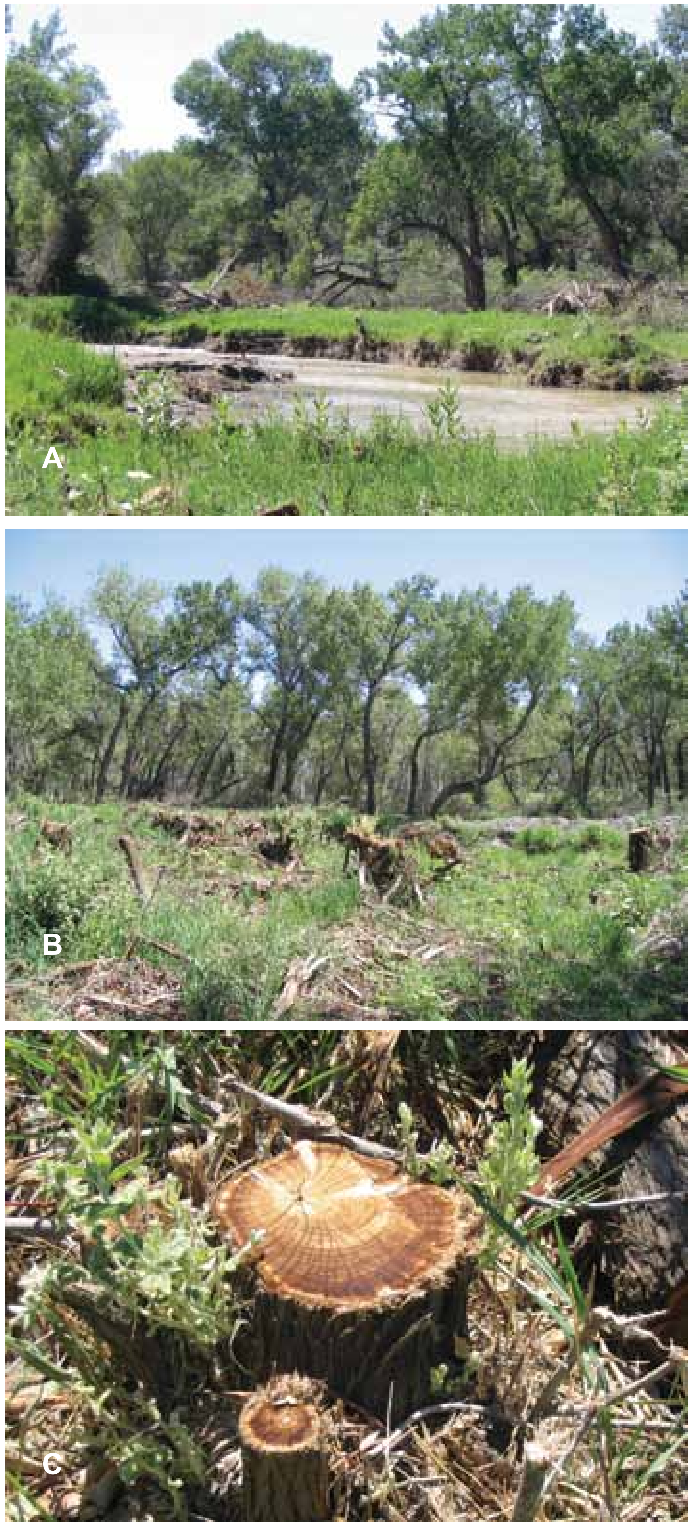


Figure 33—Area along the Shoshone River that had been mechanically treated (2009; excavator-mulcher) to control Russian olive (A,B). Following mechanical treatments, Russian olive stumps were individually treated with an herbicide (triclopyr®) penetrating oil mix to kill the tree; however, many stumps resprouted (B).

areas, browsing by goats appeared to be effective, as they showed foraging preference for Russian olive and Russian knapweed and tended to avoid grasses.

In addition to the mechanical, chemical, and browsing treatments described above, use of a biological insect (*Diorhabda elongate*) control agent was also tested to control saltcedar. In 1999, the USDA Agricultural Research Service (ARS) released the insect into field cages in the Yellowtail CRM; in 2001, the insects were released in open field trials. After 6 years of monitoring permanently marked saltcedar plants distributed across the habitat area, it was determined that 11 percent of tagged saltcedar plants were killed by insect herbivory. The biocontrol insects continue to disperse over the Yellowtail CRM area. Long-term monitoring and experimental studies have assisted in determining rates of population growth, dispersal, and impact of *Diorhabda elongate* on saltcedar and other plants. The first notable increases in populations of the insect were detected in 2003; by 2006, insects had dispersed to more than 50 percent of the CRM area. In 2007, the insect population began declining (cause unknown); this trend continued for the next 2 years. A slight increase in population numbers was observed in 2010, followed by another decline in 2011 (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2012). USDA ARS is considering another release of the insect to the site.

The effectiveness of the insect was also tested in combination with other treatments. The following five treatment combinations were tested: (1) mechanical mulching plus chemical (Trichlopyr) plus insects (*Diorhabda elongata*) plus goat browsing; (2) mechanical mulching plus insects (*Diorhabda elongata*) plus goat browsing; (3) mechanical mulching plus chemical (Trichlopyr) plus insects (*Diorhabda elongata*); (4) mechanical mulching plus insects (*Diorhabda elongata*); (5) mechanical mulching alone. Monitoring results have shown that mechanical mulching followed by foliar herbicide (trichlopyr) and insects resulted in the highest mortality of saltcedar (Shoshone Conservation District and Yellowtail Area Coordinated Resource Management 2007).

In May 2013, approximately 1,500 acres of the riparian floodplain in the YWHMA burned along the Shoshone River. The Big Fork Fire began as a controlled agricultural burn but went out of control due to changing wind conditions. The loss of spring nesting habitat for turkeys, pheasants, and waterfowl was an immediate concern, although vegetative recovery is expected. However, many large cottonwood trees were burned and likely killed. As noted above, plains cottonwood is the dominant native riparian tree in the YWHMA and is known to be a weak sprouter after fire (Taylor 2001). Some individuals may sprout from roots, root crowns, or the main stem, but generally sprouts are few and most die. In a study conducted in Alberta, Canada, 5 years after a spring fire, Gom and Rood (1999) showed that only 10 percent of plains cottonwood boles still supported live sprouts. In addition, natural replacement of the killed cottonwood trees in YWHMA is unlikely. Cottonwoods generally require flooding that occurs during the natural spring runoff to establish new individuals. The natural flow regime of the Shoshone River has been altered by the upstream Buffalo Bill Dam and no longer provides the spring flow events required for extensive cottonwood establishment.

6.3 Management of Woody Encroachment into Riparian Meadows: Fremont-Winema National Forests, Oregon

The encroachment of montane meadows by conifers is occurring throughout the western States and has been attributed to several factors (Lepofsky et al. 2003), including fire suppression (Arno and Gruell 1986) and changes in climate and land use (Haugo and Halpern 2007). The ecological consequences of woody encroachment can be extensive, ranging from changes in soil characteristics (Griffiths et al. 2005) and vegetation structure (Haugo and Halpern 2007) to decrease of native plant diversity (Moore and Huffman

2004), thus influencing wildlife habitat and ecosystem processes. Although woody encroachment of upland meadows occurs in grasslands, montane forests (Magee and Antos 1992; Haugo and Halpern 2007), and alpine areas, recent increases in conifer cover have also been notable in many riparian meadows (Lepofsky et al. 2003).

In national forests of central Oregon, resource managers have used a combination of thinning and prescribed fire to reduce the cover and stem density of invading lodgepole pine (*Pinus contorta*) in riparian meadows. The purpose of these projects is to increase available habitat for native and sensitive plant species found in meadow environments, as well as improve the quality of wildlife habitat for Rocky Mountain elk (*Cervus canadensis nelsonii*) and nesting and brood rearing of bird species dependent on open meadows (e.g., sandhill cranes[*Grus canadensis*]). In central Oregon, native meadow habitats were historically maintained by periodic low-intensity wildfires that occurred on a 1–35-year occurrence cycle. These fires controlled the number and extent of encroaching trees and other forest vegetation while maintaining the native grass and forbs favored by a variety of bird species and Rocky Mountain elk. The combination of fire suppression and aggressive fire control efforts in the last century has apparently limited the periodic, low-intensity fires and contributed to the encroachment of lodgepole pine into meadow habitats.

On the Fremont-Winema National Forest, Bullfrog Meadow was treated in 2000–2001 (fig. 34). The desired area for tree removal—that is, the area that was historically open and free of trees—was determined using an aerial photo of the meadow from the 1960s. First, the numerous, dense, small-diameter (average diameter at breast height was approximately 10 cm) trees were cut using chainsaws; no mechanized harvest equipment was used. Trees were severed at the base, left in place, and allowed to cure for approximately 1 year (fig. 34a). The fuel bed was approximately 1.2 m deep, but the trees were not sectioned or limbed, and remained braced by their branches to allow air circulation throughout the fuel profile (fig. 34a). In November 2001, the unit was burned (nearly 5 acres; fig. 34b,c). The prescribed fire was implemented as planned, burned very quickly with little smoke and low emissions. The clean burn was partly attributed to the arrangement of the fuels, which allowed air and flames to flow under and around the downed trees, lifting the heat up and away from the soil. Fire residence time was minimal, and no soil damage occurred. A similar treatment combination (chain-saw thinning, followed by prescribed fire) has been implemented at nearby Rider's Camp Meadow with similar results.

The meadows have been largely restored as open meadows (fig. 35). However, lodgepole pine has continued to invade portions of the meadow, as can be seen by patches of high conifer stem density in figure 35. It appears that maintenance of open meadows will require periodic treatment over time, such as cutting out the saplings that have recruited since treatment. Additional research is needed on the ecology and management of riparian meadows to improve understanding of the causes and consequences of conifer encroachment and to continue testing methods for controlling encroachment and restoring meadow habitats.

Figure 34—Treatment of conifer encroachment of Bullfrog Meadow, Fremont-Winema National Forest Oregon (November 2001). Dense, small-diameter lodgepole pine trees were cut with chainsaws, left in place, and allowed to cure for 1 year; the depth of the fuel bed was approximately 1.2 m (A). The prescribed fire was implemented as planned; fuels burned quickly, with minimal smoke, low emissions, and no detectable soil damage (B,C). The size and density of lodgepole stands surrounding the meadow are evident (photos by Edwin Brown, Fremont-Winema National Forest, used with permission).

Figure 35—Treatment of conifer encroachment of Bullfrog Meadow, Fremont-Winema National Forest, Oregon (October 2015, 14 years after treatment). The meadow was opened with the thinning and prescribed fire treatments, but remains vulnerable to continued encroachment by lodgepole pine (photos by Faith Brown, Fremont-Winema National Forest, used with permission).

References

Abernathy, B.; Rutherford, I.D. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrological Processes. 15: 63–79.

Adams, D.E.; Anderson, R.C.; Collins, S.L. 1982. Differential response of woody and herbaceous species to summer and winter burning in Oklahoma grassland. The Southwestern Naturalist. 27: 55–61.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press.

Agee, J.K. 1998. The landscape ecology of western forest fire regimes. Northwest Science. 72 (Special Issue): 24–34.

Agee, J.K. 2002. Fire as a coarse filter for snags and logs. In: Laudenslayer, W.F., Jr.; Shea, P.J.; Valentine, B.E.; Weatherspoon, C.P.; Lisle, T.E., eds. Proceedings of the symposium on the ecology and management of dead wood in western Forests. Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 359–368.

Agee, J.K.; Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83–96.

Agee, J.K.; Wright, C.S.; Williamson, N.; Huff, M.H. 2002. Foliar moisture of Pacific Northwest vegetation and its relation to wildland fire behavior. Forest Ecology and Management. 167: 57–66.

Ager, A.A.; Day, M.A.; McHugh, C.W.; Short, K.; Gilbertson-Day, J.; Finney, M.A.; Calkin, D.E. 2014. Wildfire exposure and fuel management on western US national forests. Journal of Environmental Management. 145: 54–70.

Allen, J.D. 1995. Stream ecology: Structure and function of running waters. Chapman and Hill. 388 p.

Andrus, C.; Froehlich, H.A. 1988. Riparian forest development after logging or fire in the Oregon Coast Range: Wildlife habitat and timber value. In: Raedeke, K.J., ed. Streamside management: Riparian wildlife and forestry interactions. University of Washington, Institute of Forest Resources, Contribution No. 59:139–152.

Archer, E.K.; Hough-Snee, N.; Van Wagenen, A.; Lokteff, R.; Roper, B.B. 2012a. The PACFISH INFISH Biological Opinion (PIBO) Effectiveness Monitoring Program and Invasive Plant Species Detection: A retrospective summary 2003–2011. Logan, UT: U.S. Department of Agriculture, Forest Service, PACFISH/INFISH Biological Opinion Effectiveness Monitoring Program.

Archer, E.K.; Van Wagenen, A.R.; Coles-Ritchie, M.; Ebertowski, P.; Becker, A.D.; Uhler, K.B.; Eskandari, P.G.; Babich, L.; Leary, R.J. 2012b. Effectiveness monitoring for streams and riparian areas: Sampling protocol for vegetation parameters. Unpublished paper on file at: http://www.fs.fed.us/biology/fishecology/emp.

Arkle, R.S.; Pilliod, D.S. 2010. Prescribed fires as ecological surrogates for wildfires: A stream and riparian perspective. Forest Ecology and Management. 259: 893–903.

Arkle, R.S.; Pilliod, D.S.; Strickler, K. 2010. Fire, flow, and dynamic equilibrium in stream macroinvertebrate communities. Freshwater Biology. 55: 299–314.

Armstrong, J.B.; Schindler, D.E. 2013. Going with the flow: spatial distributions of Juvenile Coho salmon track an annually shifting mosaic of water temperature. Ecosystems. 16: 1429–1441.

Arno, M.K. 1996. Reestablishing fire-adapted communities in the ponderosa pine zone. In: Arno, S.F.; Hardy, C.C., eds. The use of fire in forest restoration. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 42–43.

Arno, M.K. 2000. Fire regimes in western forest ecosystems. In: Brown, J.K., ed. Effects of fire on flora. Gen. Tech. Rep. GTR-RM-42. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 97–120.

Arno, S.F.; Allison-Bunnell, S. 2002. Flames in our forest: Disaster or renewal? Washington, DC: Island Press. 227 p.

Arno, S.F.; Gruell, G.E. 1986. Douglas-fir encroachment into mountain grasslands in southwestern Montana. Journal of Range Management. 39: 272–276.

Arno, S.F.; Smith, H.Y.; Krebs, M.A. 1997. Old growth ponderosa pine and western larch stand structures: Influences of pre-1900 fires and fire exclusion. Res. Pap. INT-495. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 20 p.

Baker, M.B. 1990. Hydrologic and water quality effects of fire. In: Krammes, J.S., ed. Effects of fire management of southwestern natural resources. Gen. Tech. Rep. GTR-RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 31–42.

Baker, W.L. 1989. Classification of the montane and subalpine zones of western Colorado. Great Basin Naturalist. 9: 214–228.

Baker, W.L. 1992. Effects of settlement and fire suppression on landscape structure. Ecology. 73: 1879–1887.

Banister, B.; Lockwood, P. 2010. Fontenelle Willow Rx Prescribed Fire Plan. Internal report on file at: U.S. Department of Agriculture, Forest Service, Bridger-Teton National Forest, Jackson, WY. 58 p.

Barrett, S.W. 2000. Fire history and fire regimes, South Fork Salmon River drainage, central Idaho. Unpublished report No. 43-0256-9-0651 on file at: U.S. Department of Agriculture, Forest Service, Payette National Forest, Krassel Ranger District, McCall, ID.

Barrett, S.W.; Arno, S.F.; Menakis, J.P. 1997. Fire episodes in the inland Northwest (1540–1940) based on fire history data. Gen. Tech. Rep. INT- GTR-370. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Barrett, S.W.; Havlina, D.; Jones, J.A. 2010. Interagency fire regime condition class guidebook Version 3.0. National Interagency Fuels, Fire, and Vegetation Technology Transfer. 26 p. http://www.fire.org/niftt/released/FRCC_Guidebook_2010_final.pdf.

Barrows, J.S. 1951a. Fire behavior in Northern Rocky Mountain forests. Station Paper 29. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 134 p.

Barrows, J.S. 1951b. Forest fires in the northern Rocky Mountains. Res. Pap. RM-28. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 252 p.

Bartos, D.L.; Campbell, R.B., Jr. 1998. Decline of quaking aspen in the interior west, examples from Utah. Rangelands. 20: 17–24.

Battaglia, M.A.; Dodson, J.M.; Shepperd, W.D.; Platten, M.J.; Tallmadge, O.M. 2005. Colorado Front Range fuel photo series. Gen Tech Rep. RMRS-GTR-155WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39 p.

Battaglia, M.A.; Rocca, M.E.; Rhoades, C.C.; Ryan, M.G. 2010. Surface fuel loadings within mulching treatments in Colorado coniferous forests. Forest Ecology and Management. 260: 1557–1566.

Baxter, C.V.; Fausch, K.D.; Saunders, W.C. 2005. Tangled webs: Reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology. 50: 201–220.

Bêche, L.A.; Stephens, S.L.; Resh, V.H. 2005. Effects of prescribed fire on a Sierra Nevada (California, USA) stream and its riparian zone. Forest Ecology and Management. 218: 37–59.

Beever, E.A.; Pyke, D.A.; Chambers, J.C.; Landau, F.; Smith, S.D. 2005. Monitoring temporal change in riparian vegetation of Great Basin National Park. Western North American Naturalist. 65(3): 382–402.

Belsky, A.J.; Matzke, A.; Uselman, S. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation. 54: 141–158.

Belt, G.H.; O'Laughlin, J.; Merrill, T. 1992. Design of forest riparian buffer strips for the protection of water quality: Analysis of scientific literature. Report No. 8. Idaho Forest, Wildlife and Range Policy Analysis Group.

Benavides-Solorio, J.; MacDonald, L.H. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes. 15: 2877–2892.

Benda, L.; Miller, D.; Sias, J.; Martin, D.; Bilby, R.; Veldhuisen, C.; Dunne, T. 2003a. Wood recruitment processes and wood budgeting. In: Gregory, S.V.; Boyer, K.L.; Gurnell, A.M., eds. The ecology and management of wood in world rivers. Symposium 37. Bethesda, MD: American Fisheries Society: 49–73.

Benda, L.; Miller, D.; Bigelow, P.; Andrus, K. 2003b. Effects of post-wildfire erosion on channel environments, Boise River, Idaho. Forest Ecology and Management. 178: 105–120.

Bendix, J. 1994. Among-site variation in riparian vegetation of the Southern California Transverse Ranges. American Midland Naturalist. 132(1): 136–151.

Bendix, J.; Cowell, C. 2010. Fire, floods and woody debris: Interactions between biotic and geomorphic processes. Geomorphology. 116: 297–304.

Benson, R.E. 1982. Management consequences of alternative harvesting and residue treatment practices—lodgepole pine. INT-GTR-132. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 132 p.

Beschta, R.L.; Bilby, R.E.; Brown, G.W.; Holtby, L.B.; Hofsta, T.D. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. In: Salo E.O.; Cundy, T.W., eds. Forestry and Fisheries Interactions. Contribution Number 57. Seattle, WA: University of Washington, Institute of Forest Resources: 191–232.

Bessie, W.C.; Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in a subalpine forest. Ecology. 76: 747–762.

Bilby, R.E.; Bisson, P.A. 1992. Allochthonous versus autochthonous organic matter contributions to the trophic support of fish populations in clear-cut and old-growth forested streams. Canadian Journal of Fisheries and Aquatic Sciences. 49: 540–551.

Bilby, R.E.; Bisson, P.A. 1998. Function and distribution of large woody debris. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: Lessons from the Pacific Coastal Region. New York: Springer-Verlag, Inc.: 324–346.

Bilby, R.E.; Ward, J.W. 1991. Characteristics and functions of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences. 48: 2499–2508.

Binkley, D.; Brown, T.C. 1993. Forest practices as nonpoint sources of pollution in North America. Water Resources Bulletin. 29: 729–740.

Binkley, D.; Bird, S.; Ryan, M.G.; Rhoades, C.C. 2003. Impact of wood chips on forest soil temperature, moisture, and nitrogen supply. Report to: Colorado State University, Interior West Center for the Innovative Use of Small Diameter Wood.

Bisson, P.A.; Bilby, R.E. 1998. Organic matter and trophic dynamics. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: Lessons from the Pacific Coastal Region. New York: Springer-Verlag, Inc.: 373–398.

Bisson, P.A.; Sedell, J.R. 1984. Salmonid populations in streams in clearcut vs. old-growth forests of western Washington. In: Meehan, W.R.; Merrell, Jr., T.R.; Hanley, T.A., eds. Fish and wildlife relationships in old-growth forests. Juneau, AK: American Institute of Fisheries Research Biologists: 121–129.

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 ecosystems of the western USA: Current knowledge and key questions. Forest Ecology and Management. 178: 213–229.

Bixby, R.J.; Cooper, S.D.; Gresswell, R.E.; Brown, L.E.; Dahm, C.N.; Dwire, K.A. 2015. Fire effects on aquatic ecosystems: An assessment of the current state of the science. Freshwater Science. 34(4): 1340–1350. http://www.treesearch.fs.fed.us/pubs/50479.

Blanton, P.; Marcus, W.A. 2009. Railroads, roads, and lateral disconnection in the river landscapes of the continental United States. Geomorphology. 112: 212–227.

Bledsoe, B.P.; Watson, C.C. 2001. Effects of urbanization on channel instability. Journal of the American Water Resources Association. 37: 255–270.

Blumfield, T.J.; Xu, A.H. 2003. Impact of forest residues on soil mineral nitrogen dynamics following clearfall harvesting of a hoop pine plantation in subtropical Australia. Forest Ecology and Management. 179: 55–67.

Bock, C.E.; Block, W.M. 2005. Fire and birds in the southwestern United States. In: Saab, V.; Powell, H.D.W., eds. Fire and avian ecology in North America. Studies in Avian Biology 30. Cooper Ornithological Society: 14–32.

Boggs, K.; Hansen, P.; Pfister, R.; Joy, J. 1990. Classification and management of riparian and wetland sites in northwestern Montana. Missoula, MT: University of Montana, School of Forestry, Montana Forest and Conservation Experiment Station, Montana Riparian Association.

Bragg, D.C. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology. 81: 1383–1394.

Bragg, D.C.; Kershner, J.L. 2004. Sensitivity of a riparian large woody debris recruitment model to the number of contributing banks and tree fall pattern. Western Journal of Applied Forestry. 19: 117–122.

Bragg, D.C.; Kershner, J.L.; Roberts, D.W. 2000. Modeling large woody debris recruitment for small streams of the central Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-55. Fort Collins, CO: U.S. Department of Agriculture, Rocky Mountain Research Station.

Brass, J.A.; Ambrosia, V.G.; Riggan, P.J.; Sebesta, P.D. 1996. Consequences of fire on aquatic nitrate and phosphate dynamics in Yellowstone National Park. International Journal of Wildland Fire. 6: 53–57.

Brooks, M.L. 2008. Plant invasions and fire regimes. In: Zouher, K.; Smith, J.K.; Sutherland, S.; Brooks, M.L. eds. Wildland fire in ecosystems: fire and nonnative invasive plants. Gen. Tech. Rep. RMRS-GTR-42-vol 6. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 33–46.

Brooks, M.L.; D'Antonio, C.M., Richardson, D.M.; Grace, J.B.; Keeley, J.E.; DiTomaso, J.M.; Hobbs, R.J.; Pellant, M.; Pyke, D. 2004. Effects of invasive plants alien plants on fire regimes. BioScience 54: 677–688.

Brosofske, K.D.; Chen, J.; Naiman, R.J.; Franklin, J.F. 1997. Harvesting effects on microclimate gradients from small streams to uplands in western Washington. Ecological Applications. 7: 1188–1200.

Brown, G.W. 1983. Forestry and water quality. 2nd ed. Corvallis, OR: Oregon State University, College of Forestry.

Brown, J.K. 2000. Introduction and fire regimes. In: Brown, J.K.; Smith; J.K. eds. Wildland fire in ecosystems: Effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 1–8.

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

Bull, E.L.; Parks, C.G.; Torgersen, T.R. 1997. Trees and logs important to wildlife in the interior Columbia River basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Burton, T.A. 2005. Fish and stream habitat risks from uncharacteristic wildfire: Observations from 17 years of fire-related disturbances on the Boise National Forest, Idaho. Forest Ecology and Management. 211: 140–149.

Burton, T.A.; Smith, S.J.; Cowley, E.R. 2008. Monitoring stream channels and riparian vegetation—multiple indicators. Interagency Technical Bulletin Version 5.0. BLM/ID/GI-08/001+1150. U.S. Department of Agriculture, Forest Service, Intermountain Region; U.S. Department of the Interior, Bureau of Land Management; Idaho State Office.

Burton, T.A.; Smith, S.J.; Cowley, E.R. 2011. Multiple indicator monitoring of stream channels and streamside vegetation. TR 1737-23. U.S. Department of the Interior, Bureau of Land Management. 170 p.

Bury, R.B. 2004. Wildfire, fuel reduction, and herpetofaunas across diverse landscape mosaics in northwestern forests. Conservation Biology. 18: 968–975.

Bury, R.B.; Corn, P.S. 1988. Responses of aquatic and streamside amphibians to timber harvest: A review. In: Raedeke, K.J., ed. Streamside management: Riparian wildlife and forestry interactions. Institute of Forest Resources. Seattle: University of Washington. Contribution No. 59: 165–181.

Busch, D.E. 1995. Effects of fire on southwestern riparian plant community structure. The Southwestern Naturalist. 40: 259–267.

Busch, D.E.; Smith, S.D. 1993. Effects of fire on water and salinity relations of riparian woody taxa. Oecologia. 94: 186–194.

Busch, D.E.; Smith, S.D. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. Ecological Monographs. 65: 347–370.

Caissie, D. 2006. The thermal regime of rivers: A review. Freshwater Biology. 51: 1389–1406.

Camp, A.; Oliver C.; Hessburg, P.; Everett, R. 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. Forest Ecology and Management. 95: 63–77.

Cannon, S.H.; Bigio, E.R.; Mine, E. 2001. A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico. Hydrological Processes. 15(15): 3011–3023.

Canterbury, G.E.; Martin, T.E.; Petit, D.R.; Petit, L.J.; Bradford, D.F. 2000. Bird communities and habitat as ecological indicators of forest condition in regional monitoring. Conservation Biology. 14: 544–558.

Carsey, K.; Kittel, G.; Decker, K.; Cooper D.J.; Culver, D. 2003. Field guide to the wetland and riparian plant associations of Colorado. Fort Collins, CO: Colorado Natural Heritage Program. 466 p.

Case, R.L.; Kauffman, J.B. 1997. Wild ungulate influences on the recovery of willows, black cottonwood and thin-leaved alder following cessation of cattle grazing in northeastern Oregon. Northwest Science. 71: 115–126.

Caskey, S.T.; Blaschak, T.S.; Wohl, E.; Schnackenberg, E.; Merritt, D.M.; Dwire, K.A. 2015. Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA. Earth Surface Processes and Landforms. 40: 586–598.

Certini, G. 2005. Effects of fire on properties of forest soils: A review. Oecologia. 143: 1–10.

Chambers, J.C.; Miller, J.R., eds. 2004. Great Basin riparian ecosystems: Ecology, management, and restoration. Island Press. 305 p.

Chambers, J.C.; Roundy, B.A.; Blank, R.R.; Meyer, S.E.; Whittaker, A. 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecological Monographs. 77: 117–145. http://dx.doi.org/10.1890/05-1991

Chapman, D.W.; Knudsen, E. 1980. Channelization and livestock impacts on salmonid habitat and biomass in western Washington. Transactions of the American Fisheries Society. 109: 357–363.

Chen, X.; Wei, X.; Scherer, R. 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. Forest Ecology and Management. 208: 101–114.

Chin, A.; Daniels, M.D.; Urban, M.A.; Piegay, H.; Gregory, K.J.; Bigler, W.; Boyer, K.; Butt, A.; Grable, J.; Gregory, S.V.; LaFrenz, M.; Laurencio, L.R.; Wohl, E. 2008. Perceptions of wood in rivers and challenges for stream restoration in the United States. Environmental Management. 41(6): 893–903.

Chorover, J.; Vitousek, P.M.; Everson, D.A.; Esperanza, A.M.; Turner, D. 1994. Solution chemistry profiles of mixed-conifer forests before and after fire. Biogeochemistry. 26: 115–144.

Converse, S.J.; Block, W.M.; White, D.C. 2006. Small mammal population and habitat responses to forest thinning and prescribed fire. Forest Ecology and Management. 228: 263–273.

Cooper, D.J.; Merritt, D.M. 2012. Assessing the water needs of riparian and wetland vegetation in the western United States. Gen. Tech. Rep. RMRS-GTR-282. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 125 p.

Cooper, S.D.; Page, H.M.; Wiseman, S.W.; Klose K.; Bennnett, D.; Even, T.; Sadro, S.; Nelson, C.E.; Dudley, T.L. 2015. Physicochemical and biological responses of streams to wildfire severity in riparian zones. Freshwater Biology. 60: 2600–2619. doi:10.1111/fwb.12523.

Corn, P.S.; Bury, R.B. 1989. Logging in western Oregon: Response of headwater habitats and stream amphibians. Forest Ecology and Management. 29: 39–57.

Countryman, C.M. 1971. Fire whirls…why, when, and where. Station Paper. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 11 p.

Coutant, C.C. 1999. Perspective on temperature in the Pacific Northwest's fresh water. Environmental Sciences Division. Publication No. 4849. ORNL/TM–1999/44. Oak Ridge, TN: Oak Ridge National Laboratory. 109 p.

Covington, W.W.; Moore M.M. 1994. Postsettlement changes in natural fire regimes and forest structure: Ecological restoration of old-growth ponderosa pine forest. In: Sampson, R.N.; Adams, D.L., eds. Assessing forest ecosystem health in the Inland West. New York. The Haworth Press Inc.: 153–181.

Covington, W.W.; Sackett, S.S. 1992. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. Forest Ecology and Management. 54: 175–191.

Covington, W.W.; DeBano, L.F.; Huntsberger, T.G. 1991. Soil nitrogen changes associated with slash pile burning in pinyon-juniper woodlands. Forest Science. 37: 347–355.

Cowardin, L.M.; Carter, V.; Golet, F.C.; LaRoe, E.T. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. Washington, DC: U.S. Department of the Interior, U.S. Fish and Wildlife Service.

Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P.; Ayres, M.P.; Flannigan, M.D.; Hanson, P.J.; Irland, L.C.; Lugo, A.E.; Peterson, C.J.; Simberloff, D.; Swanson, F.J.; Stocks, B.J.; Wotton, B.M. 2001. Forest disturbances and climate change. BioScience. 51: 723–734.

Danehy, R.J.; Kirpes, B.J. 2000. Relative humidity gradients across riparian areas in eastern Oregon and Washington forests. Northwest Science. 74: 224–233.

DeBano, L.F. 2000. The role of fire and soil heating on water repellency in wildland environments: A review. Journal of Hydrology. 231: 195–206.

DeBano, L.F.; Neary, D.G.; Ffolliott, P.F. 1998. Fire's effects on ecosystems. New York: John Wiley and Sons.

DeFerrari, C.M.; Naiman, R.J. 1994. A multi-scale assessment of the occurrence of non-indigenous plants on the Olympic Peninsula, Washington. Journal of Vegetation Science. 5: 247–258.

Derr, T.; Moote, A.; Savage, M.; Schumann, M.; Abrams, J.; Lowe, K. 2005. Handbook two: Developing a multiparty monitoring plan. Collaborative Forest Restoration Program: The Multiparty Handbook Series. Flagstaff, AZ: Northern Arizona University, Ecological Restoration Institute. 19 p.

Dombeck, M.P.; Williams, J.E.; Wood, C.A. 2004. Wildfire policy and public land: Scientific understanding with social concerns across landscapes. Conservation Biology. 18: 883–889.

Dunaway, D.; Swanson, S.R.; Wendel, J.; Clary, W. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. Geomorphology. 9: 47–56.

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.

Dunham, J.B.; Young, M.K.; Gresswell, R.E.; Rieman, B.E. 2003. Effects of fire on fish populations on fish populations: Landscape perspectives on persistence of native fishes and nonnative fish invasions. Forest Ecology and Management. 178: 183–196.

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

Dwire, K.A.; Bazan, R.; Hubbard, R. 2015b. Forest attributes and fuel loads of riparian vs. upland stands in mountain pine beetle infested watersheds, southern Rocky Mountains. In: Potter, K.M.; Conkling, B.L., eds. Forest health monitoring: National status, trends and analysis 2013. Gen. Tech. Rep. SRS-207. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 177–185. http://fhm.fs.fed.us/pubs/index.shtml.

Dwire, K.A.; Hubbard, R.; Bazan, R. 2015a. Comparison of riparian and upland forest stand structure and fuel loads in beetle infested watersheds, southern Rocky Mountains. Forest Ecology and Management. 335: 194–206. doi: 10.1016/j.foreco.2014.09.039.

Dwire, K.A.; Kauffman, J.B.; Baham, J. 2006a. Plant species distribution in relation to water table depth and soil redox potential in montane riparian meadows. Wetlands. 26(1): 131–146.

Dwire, K.A.; Kauffman, J.B.; Brookshire, E.N.J.; Baham, J. 2004. Plant biomass and species composition along an environmental gradient in montane riparian meadows. Oecologia. 139(2): 309–317.

Dwire, K.A.; McIntosh, B.A.; Kauffman, J.B. 1999. Ecological influences of the introduction of livestock on Pacific Northwest ecosystems. In: Goble, D.D.; Hirt, P.W., eds. Northwest lands and peoples: Readings in environmental history. Seattle, WA: University of Washington Press: 313–335.

Dwire, K.A.; Rhoades, C.C.; Young, M.K. 2010. Potential effects of fuel management activities in riparian areas. In: Elliot, W.J.; Miller, I.S.; Audin, L. eds. Cumulative watershed effects of fuel management in the western United States. Gen.Tech.Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 176–205.

Dwire, K.A.; Ryan, S.E.; Shirley, L.J.; Lytjen, D.; Otting, N.; Dixon, M.K. 2006b. Influence of herbivory on regrowth of riparian shrubs following a wildland fire. Journal of the American Water Resources Association. 42: 201–212.

Ebersole, J.L.; Liss, W.J.; Frissell, C.A. 2001. Relationship between stream temperature, thermal refugia and rainbow trout *Oncorhynchus mykiss* abundance in arid-land streams of the northwestern United States. Ecology of Freshwater Fish. 10: 1–10.

Elliott, K.J.; Hendrick, R.L.; Major, A.E.; Vose, J.M.; Swank, W.T. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. Forest Ecology and Management. 114: 199–213.

Ellis, L. 2001. Short-term response of woody plants to fire in a Rio Grande riparian forest, Central New Mexico, USA. Biological Conservation. 97: 159–170.

Elliott, K.J.; Hendrick, R.L.; Major, A.E.; Vose, J.M.; Swank, W.T. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. Forest Ecology and Management. 114: 199–213.

Elzinga, C.L.; Salzer, D.W.; Willoughby, J.W. 1998. Measuring and monitoring plant populations. Tech Reference 1730-1, BLM/RS/ST-98/005+1730. Denver, CO: Bureau of Land Management, National Business Center.

Everest, F.H.; Reeves, G.H. 2006. Riparian and aquatic habitats of the Pacific Northwest and Southeast Alaska: Ecology, management history and potential management strategies. Gen. Tech. Rep. PNW-GTR-692. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

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.

Everitt, B.L. 1998. Chronology of the spread of tamarisk in the central Rio Grande. Wetlands. 18: 658–668.

Fahey, T.J.; Yavitt, J.B. 1988. Soil solution chemistry in lodgepole pine (*Pinus contorta* ssp. *latifolia*) ecosystems, southeastern Wyoming, USA. Biogeochemistry. 6: 91–118.

Federal Interagency Committee for Wetland Delineation. 1989. Federal manual for identifying and delineating wetlands. Coop. Tech. Pub. Washington, DC: Department of Defense, U.S. Army Corps of Engineers; U.S. Environmental Protection Agency; Department of the Interior, U.S. Fish and Wildlife Service; U.S. Department of Agriculture, Soil Conservation Service.

Feller, M.C. 1988. Relationships between fuel properties and slashburning-induced nutrient losses. Forest Science. 34: 998–1015.

Finlay, J.C. 2001. Stable-carbon-isotope ratios of river biota, implications for energy flow in lotic food webs. Ecology 82: 1052–1064.

Fisher, R.F.; Binkley, D. 2000. Ecology and management of forest soils. 3rd ed. New York: Wiley and Sons.

Fisk, H.; Megown, K.; Decker, L. 2004. Riparian burn area analysis: Process and applications. RSAC-57-TIP1. Salt Lake City, UT: U.S. Department of Agriculture, Forest Service, Remote Sensing Applications Center. 4 p.

Forest Ecosystem Management Assessment Team (FEMAT). 1993. Forest ecosystem management: An ecological, economic, and social assessment. U.S. Department of Agriculture, Forest Service; U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service; U.S. Department of the Interior, Bureau of Land Management, Fish and Wildlife Service, National Park Service. Environmental Protection Agency.

Fornwalt, P.J.; Rhoades, C.C. 2011. Rehabilitating slash pile burn scars in upper montane forests of the Colorado Front Range. Natural Areas Journal. 31: 177–182.

Foster, R.D.; Wetzel, P.R. 2005. Invading monotypic stands of Phalaris arundinacea: A test of fire, herbicide, and woody and herbaceous native plant groups. Restoration Ecology. 13(2): 318–324.

Friedman, J.M.; Auble, G.T.; Shafroth, P.B.; Scott, M.L.; Merigliano, M.F.; Freehling, M.D.; Griffin, E.R. 2005. Dominance of non-native riparian trees in the western USA. Biological Invasions. 7(4): 747–751.

Fulé; P.Z.; Covington,W.; Moore, M.M. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications. 7(3): 895–908.

Fulé, P.Z.; Heinlein, T.A.; Covington, W.W.; Moore, M.M. 2003. Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. International Journal of Wildland Fire. 12(2): 129–145.

Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology. 8: 629–644.

Gabet, E.J.; Bookter, A. 2008. A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA. Geomorphology. 96: 298–309.

Gage, E.A.; Cooper, D.J. 2013. Historical range of variation assessment for wetlands and riparian ecosystems, U.S. Forest Service Rocky Mountain Region. Gen. Tech. Rep. RMRS-GTR-286. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 239 p.

GAO [U.S. General Accounting Office]. 2003. Forest service fuels reduction. Report GAO-03-689R. Washington, DC: U.S. General Accounting Office.

Gartner, J.E.; Cannon, S.H.; Santi, P.M.; Dewolfe, V.G. 2008. Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S. Geomorphology. 96: 339–354.

Gecy, J.L.; Wilson, M.V. 1990. Initial establishment of riparian vegetation after disturbance by debris flows in Oregon. American Midland Naturalist. 123: 282–291.

Giardina, C.P.; Rhoades, C.C. 2001. Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodgepole pine forest. Forest Ecology and Management. 140: 19–28.

Gom, L.A.; Rood, S.B. 1999. Fire induces clonal sprouting of riparian cottonwoods. Canadian Journal of Botany. 77(11): 1604–1616.

Gomi, T.; Sidle, R.C.; Richardson, J.S. 2002. Understanding processes and downstream linkages of headwater systems. BioScience. 52(10): 905–916.

Graham, R.T.; Jain, T.B.; Loseke, M. 2009. Fuel treatments, fire suppression, and their interactions with wildfire and its effects: The Warm Lake experience during the Cascade Complex of Wildfires in central Idaho, 2007. Gen. Tech. Rep. RMRS-GTR-229. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 36 p.

Graham, R.T.; Jain, T.B.; Matthews, S. 2010. Fuel management in forests of the Inland West. In: Elliot, W.J.; Miller, I.S.; Audin, L. eds. Cumulative watershed effects of fuel management in the western United States. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 19–68.

Graham, R.T.; McCaffrey S.; Jain, T.B., eds. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Gregory, S.V. 1997. Riparian management in the 21st century. In: Kohm, K.A.; Franklin, J.F., eds. Creating a forestry for the 21st Century: The science of ecosystem management. Washington, DC: Island Press: 69–85.

Gregory, S.V.; Boyer, K.L.; Gurnell, A.M., eds. 2003. The ecology and management of wood in world rivers. Symposium 37. Bethesda, MD: American Fisheries Society. 431 p.

Gregory, S.V.; Swanson, F.V.; McKee W.A.; Cummins. K.W. 1991. An ecosystem perspective of riparian zones. BioScience. 41: 540–551.

Gresswell, R.E. 1999. Fire and aquatic ecosystems in forested biomes of North America. Transactions of the American Fisheries Society. 128: 193–221.

Griffiths, R.; Madritch, M.; Swanson, A. 2005. Conifer invasion of forest meadows transforms soil characteristics in the Pacific Northwest. Forest Ecology and Management. 208: 347–358.

Grizzel, J.D.; Wolff, N. 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in northwestern Washington. Northwest Science. 72: 214–223.

Groffman, P.M.; Gold, A.J.; Simmons, R.C. 1992. Nitrate dynamics in riparian forests: Microbial studies. Journal of Environmental Quality. 21: 666–671.

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.

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

Halofsky, J.E.; Hibbs, D.E. 2009b. Relationships among indices of fire severity in riparian zones. International Journal of Wildland Fire. 18: 584–593.

Halpern, C.B.; Spies, T.A. 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecological Application. 5: 913–934.

Halpern, C.P.; Franklin, J.F.; McKee, A. 1992. Changes in plant species diversity after harvest of Douglas-fir forests. Northwest Environmental Journal. 8: 205–207.

Hansen, A.J.; Spies, T.A.; Swanson, F.J.; Ohmann, J.L. 1991. Conserving biodiversity in managed forests. BioScience. 41: 382–392.

Harrod, R.; Ohlson, P.; Flatten, L.; Peterson, D.; Ottmar, R. 2009. A user's guide to thinning with mastication equipment. U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Okanogan-Wenatchee National Forest.

Harrod, R.J.; Reichard, S. 2001. Fire and invasive species within the temperate and boreal coniferous forests of western North America. In: Galley, K.E.M.; Wilson, T.P., eds. Proceedings of the invasive species workshop: The role of fire in the control and spread of invasive species; fire conference 2000: The first national congress on fire ecology, prevention, and management; 2000 Nov 27–Dec 1; San Diego, CA. Misc. Publ. No. 11. Tallahassee, FL: Tall Timbers Research Station: 95–101.

Hauer, F.R.; Poole, G.C.; Gangemi, J.T.; Baxter, C.V. 1999. Large woody debris in bull trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watersheds in northwest Montana. Canadian Journal of Fisheries and Aquatic Sciences. 56: 915–924.

Haugo, R.D.; Halpern, C.B. 2007. Vegetation responses to conifer encroachment in a western Cascade meadow: A chronosequence approach. Canadian Journal of Botany. 85: 285–298.

Hawkins, C.P.; Murphy, M.L.; Anderson, N.H.; Wilzbach, M.A. 1983. Density of fish and salamanders in relation to riparian canopy and physical habitat in streams of the northwestern United States. Canadian Journal of Fisheries and Aquatic Sciences. 40: 1173–1185.

Hayes, M.P.; Jennings, M.R. 1986. Decline of ranid frog species in western North America: Are bullfrogs (*Rana catesbeiana*) responsible? Journal of Herpetology. 20: 490–509.

Hedin, L.O.; von Fischer, J.C.; Ostrom, N.E.; Kennedy, B.P.; Brown, M.G.; Robertson, G.P. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology. 79: 684–703.

Hemstrom, M.A.; Franklin, J.F. 1982. Fire and other disturbances of the forest in Mount Rainier National Park. Quaternary Research. 18: 32–51.

Hessburg, P.F.; Agee, J.K. 2003. An environmental narrative of inland northwest United States forests, 1800–2000. Forest Ecology and Management. 178: 23–59.

Hibbs, D.E.; Bower, A.L. 2001. Riparian forests in the Oregon Coast Range. Forest Ecology and Management. 154: 201–213.

Hibbs, D.E.; Giordano, P.A. 1996. Vegetation characteristics of alder-dominated riparian buffer strips in the Oregon Coast Range. Northwest Science. 7: 213–223.

Hicks, B.J.; Hall, J.D.; Bisson, P.A.; Sedell, J.R. 1991. Response of salmonids to habitat changes. American Fisheries Society Special Publication. 19: 83–138.

Hill, A.R. 1996. Nitrate removal in stream riparian zones. Journal of Environmental Quality. 25: 743–754.

Howard, J. L. 2004. *Ailanthus altissima*. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/ [2014, February 7].

Hunter, M.E.; Shepperd, W.D.; Lentile, L.B.; Lundquist, J.E.; Andreu, M.G.; Butler, J.L.; Smith, F.W. 2007. A comprehensive guide to fuels treatment practices for ponderosa pine in the Black Hills, Colorado Front Range, and Southwest. Gen. Tech. Rep. RMRS-GTR-198. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 93 p.

Huntzinger, M. 2003. Effects of fire management practices on butterfly diversity in the forested western United States. Biological Conservation. 113: 1–12.

Hutchison, M. 1992. Vegetation management guideline: reed canary grass (*Phalaris arundinacea* L.). Natural Areas Journal. 12(3): 159.

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

Jackson, B.K.; Sullivan S.M.P. 2009. Influence of wildfire severity on riparian plant heterogeneity in an Idaho, USA wilderness. Forest Ecology and Management. 259: 24–32.

Jackson, B.K.; Sullivan, S.M.P.; Malison, R.L. 2012. Wildfire severity mediates fluxes of plant material and terrestrial invertebrates to mountain streams. Forest Ecology and Management. 278: 27–34.

Jain, T.B.; Battaglia, M.A.; Han, A.S.; Graham, R.T.; Keyes, C.R.; Fried, J.S.; Sandquist, J.E. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. Gen.Tech. Rep. RMRS-GTR-292. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 331 p.

Jain, T.B.; Juillerat, M.; Sandquist, J.; Ford, M.; Sauer, B.; Mitchell, R.; McAvoy, S.; Hanley, J.; David, J. 2007. Photographic handbook for comparing burned and unburned sites within a dry forested and grassland mosaic: A tool for communication, calibration, and monitoring post-fire effects. Gen. Tech. Rep. RMRS-GTR-197. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 57 p.

Jarrett, R.D. 1987. Flood hydrology of foothill and mountain streams in Colorado. Thesis, Colorado State University, Fort Collins, CO.

Jarrett, R.D. 1990. Hydrologic and hydraulic research in mountain rivers. Water Resources Bulletin. 28: 419–429.

Johansson, M.E.; Nilsson, C. 2002. Responses of riparian plants to flooding in free flowing and regulated rivers: An experimental study. Journal of Applied Ecology. 39: 917–986.

Johnson, D.W.; Susfalk, R.B.; Dahlgren, R.A.; Klopatek, J.M. 1998. Fire is more important than water for nitrogen fluxes in semi-arid forest. Environmental Science and Policy. 1: 79–86.

Johnson, S.L.; Swanson, F.J.; Grant, G.E.; Wondzell, S.M. 2000. Riparian forest disturbances by a mountain flood: The influence of floated wood. Hydrological Processes. 14: 3031–3050.

Jones, J.R.; DeByle, N.V. 1985. Fire. In: DeByle, N.V.; Winokur, R.P., eds. Aspen: Ecology and management in the western United States. Gen. Tech. Rep. RM-119. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 77–81.

Kaczynski, K.M.; Cooper, D.J. 2015. Post-fire response of riparian vegetation in a heavily browsed environment. Forest Ecology and Management 338: 14–19.

Kauffman, J.B. 1990. Ecological relationships of vegetation and fire. In: Walstad, J.D.; Radosevich, S.R.; Sandberg, D.V., eds. Prescribed fire in Pacific Northwest forests. Corvallis, OR: Oregon State University Press: 39–51.

Kauffman, J.B.; Martin, R.E. 1989. Fire behavior, fuel consumption, and forest floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. Canadian Journal of Forest Research. 19: 455–462.

Kauffman, J.B.; Martin, R.E. 1990. Sprouting shrub response to varying seasons and fuel consumption levels of prescribed fire in Sierra Nevada mixed conifer ecosystems. Forest Science. 36: 748–764.

Kauffman, J.B.; Mahrt, M.; Mahrt, L.A.; Edge, W.D. 2001. Wildlife of riparian habitats. In: Johnson, D.H.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 361–388.

Kauffman, J.B.; Thorpe, A.S.; Brookshire, E.N.J. 2004. Livestock exclusion and belowground ecosystem responses in riparian meadows of eastern Oregon. Ecological Applications. 14: 1671–1679.

Kaye, J.P.; Hart, S.C. 1998. Ecological restoration alters nitrogen transformations in a ponderosa pine-bunchgrass ecosystem. Ecological Applications. 8: 1052–1060.

Keane, R.E.; Agee, J.; Fulé; P.; Keeley, J.E.; Key, C.; Kitchen, S.G.; Miller, R; Schulte, L.A. 2008. Ecological effects of large fires on the US landscapes: Benefit or catastrophe? International Journal of Wildland Fire. 17: 696–712.

Keane, R.E.; Ryan, K.C.; Veblen, T.T.; Allen, C.D.; Logan, J.A.; Hawkes, B. 2002. The cascading effects of fire exclusion in Rocky Mountain ecosystems. In: Jill S. Baron, ed. Rocky Mountain Futures: An ecological perspective. Island Press: 133–152.

Keeley, J.E. 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. International Journal of Wildland Fire. 18: 116–126.

Kelsey, K.A.; West, S.D. 1998. Riparian wildlife. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: Lessons from the Pacific Coastal Region. New York: Springer-Verlag, Inc.: 235–258.

Kershner, J.L. 2002. Effectiveness monitoring of aquatic and riparian resources in the areas of PACFISH/INFISH and the biological opinions for bull trout, salmon, and steelhead. Final Plan. Logan, UT: U.S. Department of Agriculture, Forest Service. 56 p.

Kershner, J.L.; Cowley, E.; Henderson, R.; Kratz, K.; Martin, D.; Quimby, D.; Stein, K.; Turner, D.; Ulmner, L.; Vison, M.C.; Young, D. 2001. Effectiveness monitoring of aquatic and riparian resources in the areas of PACFISH/INFISH and the biological opinions for bull trout, salmon, and steelhead. Draft Plan. Logan, UT: U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management. 50 p.

Kilbride, K.M.; Paveglio, F.L. 1999. Integrated pest management to control reed canarygrass in seasonal wetlands of southwestern Washington. Wildlife Society Bulletin. 27(2): 292–297.

Kluber, M.R.; Olson, D.H.; Puettmann, K.J. 2008. Amphibian distributions in riparian and upslope areas and their habitat associations on managed forest landscapes on the Oregon Coast Range. Forest Ecology and Management. 256: 529–535.

Knapp, E.E.; Estes, B.L.; Skinner, C.N. 2009. Ecological effects of prescribed fire season: A literature review and synthesis for managers. Gen. Tech. Rep. PSW-GTR-224. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 80 p.

Knapp, E.E.; Keeley, J.E.; Ballenger, E.A.; Brennan, T.J. 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. Forest Ecology and Management. 208: 383–397.

Knoepp, J.D.; Swank, W.T. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: Nitrogen responses in soil, soil water, and streams. Canadian Journal of Forest Research. 23: 2263–2270.

Knopf, F.L. 1986. Changing landscapes and the cosmopolitanism of the eastern Colorado avifauna. Wildlife Society Bulletin. 14: 132–142.

Knopf, F.L.; Johnson, R.R.; Rich, T.; Samson, F.B.; Szaro, R.C. 1988. Conservation of riparian systems in the United States. Wilson Bulletin. 100: 272–284.

Knutson, K.L.; Naef, V.L. 1997. Management recommendations for Washington's priority habitats: Riparian. Olympia, WA: Washington Department of Fish and Wildlife. 181 p.

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

Korb, J.E.; Johnson, N.C.; Covington, W.W. 2004. Slash pile burning effects on soil biotic and chemical properties and plant establishment: Recommendations for amelioration. Restoration Ecology. 12: 52–62.

Kushla, J.D.; Ripple, W.J. 1997. The role of terrain in a fire mosaic of a temperate coniferous forest. Forest Ecology and Management. 95: 97–107.

Lalande, R.; Furlan, V.; Angers, D.A.; Lemieux, G. 1998. Soil improvement following addition of chipped wood from twigs. American Journal of Alternative Agriculture. 13: 132-137.

Landres, P.B.; Morgan, P.; Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications. 9: 1179–1188.

Lee, P.; Smyth, C.; Boutin, S. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management. 70: 165–180.

Lentile, L.B.; Holden, Z.A.; Smith, A.M.S.; Falkowski, M.J.; Hudak, A.T.; Morgan, P.; Lewis, S.A.; Gessler, P.E.; Benson, N.C. 2006. Remote sensing techniques to assess active fire and post-fire effects. International Journal of Wildland Fire. 15: 319–345.

Lentile, L.B.; Morgan, P.; Hudak, A.; Bobbitt, M.J.; Lewis, S.A.; Smith, A.M.S.; Robichaud, P.R. 2007. Burn severity and vegetation response following eight large wildfires across the western US. Fire Ecology. 3: 91–108.

Lepofsky, D.; Heyerdahl, E.K.; Lertzman, K.; Schaepe, D.; Mierendorf, B. Historical meadow dynamics in southwest British Columbia: A multidisciplinary analysis. Conservation Ecology. 7(3): 5. http://www.consecol.org/vol7/iss3/art5/.

Li, H.W.; Lamberti, G.A.; Persons, T.N.; Tait, C.K.; Li, J.L.; Buckhouse, J.C. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society. 123: 627–640.

Lowrance, R.; Altier, L.S.; Newbold, J.D.; Schnabel, R.R.; Groffman, P.M.; Denver, J.M.; Correll, D.L.; Gilliam, J.W.; Robinson, J.L.; Brinsfield, R.B.; Staver, K.W.; Lucas, W.; Todd A.H. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environmental Management. 21: 687–712.

Luce, C.; Morgan, P.; Dwire, K.A.; Isaak, D.; Rieman B. 2012. Climate change, forests, fire, water, and fish: Building resilient landscapes, streams and managers. Gen. Tech. Rep. RMRS-GTR-290. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 207 p. http://www.treesearch.fs.fed.us/pubs/41932.

Lutes, D.C.; Keane, R.E.; Caratti, J.F.; Key, C.H.; Benson, N.C.; Sutherland, S.; Gangi, L.J. 2006. FIREMON: Fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 1 CD.

Lyon, L.J.; Huff, M.H.; Smith, J.K. 2000. Fire effects on wildlife foods. In: Smith, J.K., ed. Wildland fire in ecosystems: Effects of fire on fauna. Gen. Tech. Report RMRS-GTR-42-vol. 1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 51–58.

Mack, M.C.; D'Antonio, C.M. 1998. Impacts of biological invasions on disturbance regimes. Trends in Ecology and Evolution. 13: 195–198.

Magee, T.K.; Antos, J.A. 1992. Tree invasion into a mountain-top meadow in the Oregon Coast Range, USA. Journal of Vegetation Science. 3: 485–494.

Mahoney, J.M.; Koegler, P.; Rood, S.B. 1991. The accuracy of tree ring analysis for estimating the age of riparian poplars. In: Proceedings of the biology and management of southern Alberta's cottonwoods conference; 1990 May. Lethbridge, Alberta: University of Lethbridge.

Malison, R.L.; Baxter, C.V. 2010a. Effects of wildfire of varying severity on benthic stream insect assemblages and emergence. Journal of the North American Benthological Society. 29: 1324–1338.

Malison, R.L.; Baxter, C.V. 2010b. The fire pulse: Wildfire stimulates flux of aquatic prey to terrestrial habitats driving increases in riparian consumers. Canadian Journal of Fisheries and Aquatic Sciences. 67: 570–579.

May, C.L. 2002. Debris flows through different forest age classes in the central Oregon Coast Range. Journal of the American Water Resources Association. 38(4): 1097–1113.

May, C.L.; Gresswell, R.E. 2003a. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, U.S.A. Canadian Journal of Forest Research. 33: 1352–1362.

May, C.L.; Gresswell, R.E. 2003b. Processes and rates of sediment and wood accumulation in headwater streams of the central Oregon Coast range. Earth Surface Processes and Landforms. 28: 409–424.

McAllister, L.S. 2008. Reconstructing historical conditions of two river basins in Eastern Oregon, USA. Environmental Management. 42: 412–425.

McClain M.E.; Bilby, R.E.; Triska, F.J. 1998. Nutrient cycles and responses to disturbance. In: Naiman, R.J.; Bilby, R.E., eds. River ecology and management: Lessons from the Pacific Coastal Region. New York: Springer-Verlag, Inc.: 347–372.

McClain, M.E.; Boyer, E.W.; Dent, C.L.; Gergel, S.E.; Grimm, N.B.; Groffman, P.M.; Hart, S.C.; Harvey, J.W.; Mayorga, E.; McDowell, W.H.; Pinay, G. 2003. Biogeochemical hot spots and hot moments at the interface of aquatic and terrestrial ecosystems. Ecosystems. 6: 301–312.

McComb, W.C.; McGarigal, K.; Anthony, R.G. 1993. Small mammal and amphibian abundance in streamside and upslope habitats of mature Douglas-fir stands, western Oregon. Northwest Science. 67: 7–15.

McCormick, F.H.; Rieman, B.E.; Kershner, J.L. 2010. Biological responses to stressors in aquatic ecosystems of western North America: Cumulative watershed effects of fuel treatments, wildfire, and post-fire remediation. In: Elliot, W.J., Miller, I.S.; Audin, L., eds. Cumulative watershed effects of fuel management in the western United States. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 206–233.

McDade, M.H.; Swanson, F.J.; McKee, W.A.; Franklin, J.F.; Van Sickle, J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research. 20: 326–330.

McIntosh, B.A.; Sedell, J.R.; Smith, J.E.; Wissmar, R.C.; Clarke, S.E.; Reeves, G.H.; Brown, L.A. 1994a. Historical changes in fish habitat for select river basins of eastern Oregon and Washington. Northwest Science. 68: 36–52.

McIntosh, B.A.; Sedell, J.R.; Smith, J.E.; Wissmar, R.C.; Clarke, S.E.; Reeves, G.H.; Brown, L.A. 1994b. Management history of eastside ecosystems: Changes in fish habitat over 50 years, 1935–1992. Gen. Tech. Rep. PNW-GTR-321. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Megahan, W.F.; Potyondy, J.P.; Seyedbagheri, K.A. 1992. Best management practices and cumulative effects from sedimentation in the South Fork Salmon River: An Idaho case study. In: Naiman, R.J., ed. Watershed management: Balancing sustainability and environmental change. NewYork: Springer-Verlag: 401–414.

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

Merritt, D.M.; Bateman, H.L. 2012. Linking stream flow and groundwater to avian habitat in a desert riparian system. Ecological Applications. 22 (7): 1973–1988.

Merritt, D.M.; Poff, N.L. 2010. Shifting dominance of riparian *Populus* and *Tamarix* along gradients of flow alteration in western North American rivers. Ecological Applications. 20(1): 135–152.

Messier, M.S.; Shatford, J.P.A.; Hibbs, D.E. 2012. Fire exclusion on riparian forest dynamics in southwestern Oregon. Forest Ecology and Management. 264: 60–71.

Meyer, G.A.; Pierce, J.L.; Wood, S.H.; Jull, A.J.T. 2001. Fire, storms, and erosional events in the Idaho batholith. Hydrologic Processes. 15: 3025–3038.

Meyer, G.A.; Wells, S.G.; Balling, R.C., Jr.; Jull, A.J.T. 1992. Response of alluvial systems to fire and climate change in Yellowstone National Park. Nature. 357: 147–150.

Meyer, K.E.; Dwire, K.A.; Champ, P.; Ryan, S.E.; Riegel, G.; Burton, T. 2012. Burning questions for managers: Fuels management practices in riparian areas. Fire Management Today. 72: 16–23.

Mihuc, T.B.; Minshall, G.W. 1995. Trophic generalists vs. trophic specialists: Implications for food web dynamics in post-fire streams. Ecology. 76: 2361–2372.

Miller, M. 2000. Fire autecology. In: Brown, J.K., Smith, J.K., eds. Wildland fire and ecosystems: Effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 9–34.

Miller, S. 2015. Slash from the past: Rehabilitating pile burn scars. Science You Can Use Bulletin. Issue 15, July/August 2015. Fort Collins, CO: U.S. Department of Agriculture, Rocky Mountain Research Station.

Minshall, G.W. 2003. Responses of stream benthic macroinvertebrates to fire. Forest Ecology and Management. 178: 155–161.

Minshall, G.W.; Brock, J.T. 1991. Observed and anticipated effects of forest fire on Yellowstone stream ecosystems. In: Keiter, R.B.; Boyce, M.S., eds. The Greater Yellowstone ecosystem: Redefining America's wilderness heritage. Yale University Press: 123–135.

Minshall, G.W.; Brock, J.T.; Varley, J.D. 1989. Wildfires and Yellowstone's stream ecosystems: A temporal perspective shows that aquatic recovery parallels forest succession. BioScience. 39: 707–715.

Minshall, G.W.; Robinson, C.T.; Lawrence, D.E. 1997. Immediate and mid-term responses of lotic ecosystems in Yellowstone National Park, USA to wildfire. Canadian Journal of Fisheries and Aquatic Science. 54: 2509–2525.

Minshall, G.W.; Robinson, C.T.; Royer, T.V.; Rushforth, S.R. 1995. Benthic community structure in two adjacent streams in Yellowstone National Park 5 years after the 1988 wildfires. Great Basin Naturalist. 55: 193–200.

Minshall, G.W.; Royer, T.V.; Robinson, C.T. 2001. Response of Cache Creek macroinvertebrates during the first 10 years following disturbance by the 1988 Yellowstone wildfires. Canadian Journal of Fisheries and Aquatic Science. 58: 1077–1088.

Minshall, G.W.; Royer, T.V.; Robinson, C.T. 2004. Stream ecosystem responses following the Yellowstone wildfires: The first 10 years. In: Wallace, D., ed. After the fires: The ecology of change in Yellowstone National Park. New Haven, CT: Yale University Press: 87–97.

Monleon, V.J.; Cromack, K., Jr. 1996. Long-term effects of prescribed underburning on litter decomposition and nutrient release in ponderosa pine stands in central Oregon. Forest Ecology and Management. 81:143–152.

Monleon, V.J.; Cromack, K., Jr.; Landsberg, J.D. 1997. Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Canadian Journal of Forest Research. 27: 369–378.

Montgomery, D.R.; Collins, B.D.; Buffington, J.M.; Abbe, T.B. 2003. Geomorphic effects of wood in rivers. In: Gregory, S.V.; Boyer, K.L.; Gurnell, A.M., eds. The ecology and management of wood in world rivers. Symposium 37. Bethesda, MD: American Fisheries Society: 21–47.

Moody, J.A.; Martin, D.A. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms. 26(10): 1049–1070.

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

Morrison, P.H.; Swanson, F.J. 1990. Fire history and pattern in a Cascade Range landscape. Gen. Tech. Rep. PNW-GTR-254. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 77 p.

Mosley, J.C.; Cook, P.S.; Griffis, A.J.; O'Laughlin, J. 1997. Guidelines for managing cattle grazing in riparian areas to protect water quality: Review of research and best management practices policy. Report No. 15. Moscow, ID: Idaho Forest, Wildlife and Range Policy Analysis Group.

Murphy, K.; Rich, T.; Sexton T. 2007. An assessment of fuel treatment effects on fire behavior, suppression effectiveness, and structure ignition on the Angora Fire. R5-TP-025. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region.

Naiman, R.J.; Décamps, H. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics. 28: 621–658.

Naiman, R.J.; Décamps, H.; McClain, M.E. 2005. Riparia: Ecology, conservation, and management of streamside communities. London, UK: Elsevier, Inc. 430 p.

Naiman, R.J.; Décamps, H.; Pollock, M. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications. 3: 209–212.

National Research Council. 1995. Wetlands: Characteristics and boundaries. Washington, DC: National Academy Press.

National Research Council. 2002. Riparian areas: Functions and strategies for management. Washington, DC: National Academy Press. 436 p.

Neary, D.G.; Klopatek, C.C.; DeBano, L.F.; Ffolliott, P.F. 1999. Fire effects on belowground sustainability: A review and synthesis. Forest Ecology and Management. 122: 51–71.

Nierenberg, T.R.; Hibbs, D.E. 2000. A characterization of unmanaged riparian areas in the central Coast Range of western Oregon. Forest Ecology and Management. 129: 195–206.

Norris, V. 1993. The use of buffer zones to protect water quality: A review. Water Resources and Management. 7: 257–272.

Nowakowski, A.L.; Wohl, E. 2008. Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. Environmental Management. 42: 557–571.

Olson, D.H.; Leirness, J.B.; Cunningham, P.G.; Steel, E.A. 2014. Riparian buffers and forest thinning: Effects on headwater invertebrates 10 years after thinning. Forest Ecology and Management. 321: 81–93.

Olson, D.L. 2000. Fire in riparian zones: A comparison of historical fire occurrence in riparian and upslope forests in the Blue Mountains and southern Cascades of Oregon. Thesis. Seattle, WA: University of Washington. 274 p.

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.

Osborne, L.L.; Kovacic, D.A. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology. 29: 243–258.

Otting, N.J. 1998. Ecological characteristics of montane floodplain plant communities in the Upper Grande Ronde River Basin, Oregon. Thesis. Corvallis, OR: Oregon State University. 71 p.

Pabst, R.J.; Spies, T.A. 1998. Distribution of herbs and shrubs in relation to landform and canopy cover in riparian forests of coastal Oregon. Canadian Journal of Botany. 76: 289–315.

Pabst, R.J.; Spies, T.A. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, USA. Canadian Journal of Forest Research. 29: 1557–1573.

Pannkuk, C.K.; Robichaud, P.R. 2003. Effectiveness of needle cast at reducing erosion after forest fires. Water Resources Research. 39(12): 1333. doi:10.1029/2003WRR002318.

Parks, C.G.; Radosevich, S.R.; Endress, B.A.; Naylor, B.J.; Anzinger, D.; Rew, L.J.; Maxwell, B.D.; Dwire, K.A. 2005. Natural and land-use history of the Northwest mountain ecoregions (USA) in relation to patterns of plant invasions. Perspectives in Plant Ecology, Evolution and Systematics. 7: 137–158.

Parsons, W.F.J.; Knight, D.H.; Miller, S.L. 1994. Root gap dynamics in lodgepole pine forest: Nitrogen transformations in gaps of different sizes. Ecological Applications. 4: 354–362.

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: Diversity and human impacts. Wetlands. 18: 498–512.

Paysen, T.E.; Ansley, R.J.; Brown, J.K.; Gottfried, G.J.; Haase, S.M.; Harrington, M.G.; Narog, M.G.; Sackett, S.S.; Wilson, R.C. 2000. Fire in western shrubland, woodland, and grassland ecosystems. In: Brown, J.K., Smith, J.K., eds. Wildland fire and ecosystems: Effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 121–159.

Perry, D.A.; Hessburg, P.F.; Skinner, C.N.; Spies, T.A.; Stephens, S.L.; Taylor, A.H.; Franklin, J.F.; McComb, B.; Riegel, G. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. Forest Ecology and Management. 262: 703–717.

Peterjohn, W.T.; Correll, D.L. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology. 65: 1466–1475.

Peterson, D.L. 1998. Large-scale fire disturbance: From concepts to models. Northwest Science. 72; 1–3 (special issue).

Peterson, D.L.; Evers, L.; Gravenmier, R.; Eberhardt, E. 2007. A consumer guide: Tools to manage vegetation and fuels. Gen. Tech. Rep. PNW-GTR-690. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 151 p. www.treesearch.fs.fed.pubs/25953.

Pettit, N.E.; Naiman, R.J. 2007. Fire in the riparian zone: Characteristics and ecological consequences. Ecosystems. 10: 673–687.

Piegay, H.; Gregory, K.J.; Bondarev, V.; Chin, A.; Dahlstrom, N.; Elosegi, A.; Gregory, S.V.; Joshi, V.; Mutz, M.; Rinaldi, M.; Wyzga, B.; Zawiejska, J. 2005. Public perception as a barrier to introducing wood in rivers for restoration purposes. Environmental Management. 36(5): 665–674.

Pierce, J.L.; Meyer, G.A.; Jull, A.J.T. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. Nature. 432: 87–90.

Pierson, F.B.; Robichaud, P.R.; Spaeth, K.E. 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. Hydrological Processes. 15: 2905–2916.

Pilliod, D.S.; Bull, E.L.; Hayes, J.L.; Wales, B.C. 2006. Wildlife and invertebrate response to fuel reduction treatments in dry coniferous forests of the Western United States: A synthesis. Gen. Tech. Rep. RMRS-GTR-173. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 34 p.

Pilliod, D.S.; Bury, R.B.; Hyde, E.J.; Pearl, C.A.; Corn, P.S. 2003. Fire and amphibians in North America. Forest Ecology and Management. 178: 163–181.

Planty-Tabacchi, A.; Tabacchi, E.; Naiman, R.J.; DeFerrari, C.; Decamps, H. 1996. Invasibility of species-rich communities in riparian zones. Conservation Biology. 10: 598–607.

Pollen, N.; Simon, A.; Collison, A.J.C. 2004. Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability. In: Bennett, S.; Simon, A., eds. Riparian vegetation and fluvial geomorphology. Water Science and Applications 8. American Geophysical Union: 125–139.

Pollock, M.M.; Naiman, R.J.; Hanley, T.A. 1998. Plant species richness in riparian wetlands—A test of biodiversity theory. Ecology. 79: 94–105.

Polvi, L.E.; Wohl, E.E.; Merritt, D.M. 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology. 125: 504–516.

Poole, G.C.; Berman, C.H. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management. 27: 787–802.

Popp, J.B.; Lundquist, J.E. 2006. Photo series for quantifying forest residues in managed lands of the Medicine Bow National Forest. Gen Tech Rep. RMRS-GTR-172. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 105 p.

Prichard, D.; Barrett, H.; Cagney, J.; Clark, R.; Fogg, J.; Gebhardt, K.; Hansen, P.; Mitchell, B.; Tippy, D. 1993; revised 1995, 1998. Riparian area management: Process for assessing proper functioning condition. Technical Reference 1737-9. Denver, CO: Bureau of Land Management. BLM/SC/ST-93/003+1737+REV95+REV98. 60 p.

Racine, C.H.; Johnson, L.A.; Viereck, L.A. 1987. Patterns of vegetative recovery after tundra fires in northwestern Alaska, USA. Arctic and Alpine Research. 19: 461–469.

Raedeke, K.J., ed. 1988. Streamside management: riparian wildlife and forestry interactions, Contribution No. 59. Seattle: University of Washington, Institute of Forest Resources.

Ralph, S.C.; Poole, G.C.; Conquest, L.L.; Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Canadian Journal of Fisheries and Aquatic Sciences. 51: 37–51.

Reeves, G.H.; Benda, L.E.; Burnett, K.M.; Bisson, P.A.; Sedell, J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17: 344–349.

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

Reich, M.; Kershner, J.L.; Wildman, R.C. 2003. Restoring streams with large wood: A synthesis. In: Gregory, S.V.; Boyer, K.L.; Gurnell, A.M., eds. The ecology and management of wood in world rivers. Symposium 37. Bethesda, MD: American Fisheries Society: 355–366.

Reid, L.M. 2010. Cumulative effects of fuel treatments on channel erosion and mass wasting. In: Elliot, W.J., Miller, I.S.; Audin, L., eds. Cumulative watershed effects of fuel management in the western United States. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 101–125.

Reuss, J.O.; Stottlemyer, R.; Troendle, C.A. 1997. Effect of clear cutting on nutrient fluxes in a subalpine forest at Fraser, Colorado. Hydrology and Earth System Sciences. 1: 333–344.

Rhoades, C.C.; Entwistle, D.; Butler, D. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. International Journal of Wildland Fire. 20: 430–442.

Rhoades, C.R.; Battaglia, M.A.; Rocca, M.E.; Ryan, M.G. 2012. Short-and-medium-term effects of fuel reduction mulch treatments on soil nitrogen availability in Colorado conifer forests. Forest Ecology and Management. 276: 231–238.

Rhoades, C.R.; Fornwalt, P.J. 2015. Pile burning creates a fifty-year legacy of openings in regenerating lodgepole pine forests in Colorado. Forest Ecology and Management. 336: 203–209.

Rhoades, C.R.; Fornwalt, P.J.; Paschke, M.W.; Shanklin, A.; Jonas, J.L. 2015. Recovery of small pile burn scars in conifer forests of the Colorado Front Range. Forest Ecology and Management. 347: 180–187.

Rieman, B.E.; Clayton, J.L. 1997. Fire and fish: issues of forest health and conservation of native fishes. Fisheries. 22(11): 6–15.

Rieman, B.; Lee, D.; Burns, D.; Gresswell, R.; Young, M.; Stowell, R.; Rinne, J.; Howell, P. 2003. Status of native fishes in the western United States and issues for fire and fuels management. Forest Ecology and Management. 178: 197–211.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology. 231/232: 220–229.

Robichaud, P.R.; Beyers, J.L.; Neary, D.G. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech. Rep. RMRS-GTR-63. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p.

Robichaud, P.R.; MacDonald, L.H.; Foltz, R.B. 2010. Fuel management and erosion. In: Elliot, W.J.; Miller, I.S.; Audin, L., eds. Cumulative watershed effects of fuel management in the western United States. Gen.Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 79–100.

Robichaud, P.R.; Wagenbrenner, J.W.; Brown, R.E.; Spigel, K.M. 2009. Three years of hillslope sediment yields following the Valley Complex fires, western Montana. Res. Pap. RMRS-RP-77. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 8 p.

Romme, W.H.; Knight, D.H. 1981. Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. Ecology. 62: 319–326.

Romme, W.H.; Turner, M.B.; Wallace, L.L.; Walker, J.S. 1995. Aspen, elk, and fire in northern Yellowstone National Park. Ecology. 76: 2097–2106.

Rood, S.B.; Hillman, C.; Sanche, T.; Mahoney, J.M. 1994. Clonal reproduction of riparian cottonwoods in southern Alberta. Canadian Journal of Botany. 72: 1766–1774.

Ruff, C.P.; Schindler, D.E.; Armstrong, J.B.; Bentley, K.T.; Brooks, G.T.; Holtgrieve, G.W.; McGlauflin, M.T.; Torgersen, C.E.; Seeb, J.E. 2011. Temperature-associated population diversity in salmon confers benefits to mobile consumers. Ecology. 92: 2073–2084.

Ruffing, C.; Daniels, M.; Dwire, K.A. 2015. Disturbance legacies of historic tie-drives persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. Geomorphology. 231: 1–14.

Rummer, B. 2010. Tools for fuel management. In: Elliot, W.J., Miller, I.S.; Audin, L., eds. Cumulative watershed effects of fuel management in the western United States. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 69–78.

Russell, W.H.; McBride, J.R. 2001. The relative importance of fire and watercourse proximity in determining stand composition in mixed conifer riparian forests. Forest Ecology and Management. 150: 259–265.

Ryan, K.C. 2001. Global change and wildland fire. In: Brown, J.K.; Smith, J.K., eds. Wildland fire in ecosystems: Effects of fire on flora. Gen.Tech. Rep. RMRS-GTR-42-vol 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 175–184.

Ryan, S.E.; Dwire, K.A.; Dixon, M.K. 2011. Impacts of wildfire on runoff and sediments loads, Little Granite Creek, western Wyoming. Geomorphology. 129: 113–130.

Saab, V.; Block, W.; Russell, R.; Lehmkuhl, J.; Bate, L.; White, R. 2007. Birds and burns of the interior West: descriptions, habitats, and management in western forests. Gen. Tech. Rep. PNW-GTR-712. Portland, OR: U.S. Department of Agriculture, Pacific Northwest Research Station. 23 p.

Saab, V.; Powell, H.D.W., eds. 2005. Fire and avian ecology in North America. Studies in Avian Biology. 30.

Saab, V.; Powell, H.D.W.; Kotliar, N.B.; Newlon, K.R. 2005. Variation in fire regimes of the Rocky Mountains: implications for avian communities and fire management. In: Saab, V.; Powell, H.D.W., eds. Fire and avian ecology in North America. Studies in Avian Biology. 30: 76–96.

Safford, H.D.; Schmidt, D.A.; Carlson, C. 2009. Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe basin, California. Forest Ecology and Management. 258: 773–787.

Salo, E.O.; Cundy, T.W., eds. 1987. Forestry and fisheries interactions. Contribution Number 57. Seattle, WA: University of Washington, Institute of Forest Resources.

Santi, P.M.; deWolfe, V.G.; Higgins, J.D.; Cannon, S.H.; Gartner, J.E. 2008. Sources of debris flow material in burned areas. Geomorphology. 96: 310–312.

Sarr, D.; Odion, D.C.; Hibbs, D.E.; Weikel, J.; Gresswell, R.E.; Burry, R.B.; Czarnomski, N.M.; Pabst, R.J.; Shatford, J.; Moldenke, A.R. 2005. Riparian zone management and the protection of biodiversity: A problem analysis. Tech. Bull. No. 908. Research Triangle Park, NC: National Council for Air and Stream Improvement. 107 pages + appendices.

Scheidt, N.E. 2006. Stream succession: Channel changes after wildfire disturbance. Thesis. Boise, ID: Boise State University. 60 p.

Schier, G.A. 1973. Origin and development of aspen root suckers. Canadian Journal of Forest Research. 3: 45–53.

Schoennagel, T.; Veblen, T.T.; Romme, W.H. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience. 54: 661–676.

Sedell, J.R.; Beschta, R.L. 1991. Bringing back the "bio" in bioengineering. In: Colt, J.; Dendall, S., eds. Fisheries bioengineering: Proceedings of the symposium. American Fisheries Society 10 Bethesda, MD: 160–175.

Sensenig, T.S. 2002. Development, fire history, and current and past growth of old-growth and young-growth forest stands in the Cascade, Siskiyou and mid-coast mountains of southwestern Oregon. Corvallis, OR: Oregon State University. Dissertation.

Sestrich, C.M.; McMahon, T.E.; Young, M.K. 2011. Influence of fire on native and nonnative salmonid populations and habitat in a western Montana basin. Transactions of the American Fisheries Society. 140(1): 136–146.

Shafroth, P.B.; Stromberg, J.C.; Patten, D.T. 2002. Riparian vegetation response to altered disturbance and stress regimes. Ecological Applications. 12: 107–123.

Shepperd, W.D.; Smith, F.W. 1993. The role of near-surface lateral roots in the life cycle of aspen in the central Rocky Mountains. Forest Ecology and Management. 61: 157–170.

Shlisky, A.; Waugh, J.; Gonzalez, P.; Gonzalez, M.; Manta, M.; Santoso, H.; Alvarado, E.; Nuruddin, A.A.; Rodriguez-Trejo, D.A.; Swaty, R.; Schmidt, D.; Kaufmann, M.; Myers, R.; Alencar, A.; Kearns, F.; Johnson, D.; Smith, J.; Zollner, D. 2007. Fire ecosystems and people: Threats and strategies for global biodiversity conservation. GFI Tech. Rep. 2007-2. Arlington, VA: The Nature Conservancy. 28 p.

Shoshone Conservation District and Yellowtail Area Coordinated Resource Management. 2007. Yellowtail Area Coordinated Resource Management (CRM) Invasive Plant Management. Unpublished Project Completion Report on file with: Wyoming Wildlife and Natural Resource Trust Board, Cheyenne, WY. 24 p.

Shoshone Conservation District and Yellowtail Area Coordinated Resource Management. 2012. Yellowtail Area Coordinated Resource Management (CRM) Invasive Plant Management. Unpublished Project Completion Report on file with: Wyoming Wildlife and Natural Resource Trust Board, Cheyenne, WY. 21 p.

Simon, A.; Collison, A. 2002. Quantifying the mechanical and hydrological effects of riparian vegetation on streambank stability. Earth Surfaces Processes and Landforms. 27: 527–546.

Skinner, C.N. 2002. Influence of fire on the dynamics of dead woody material in forests of California and southwestern Oregon. In: Laudenslayer, W.F., Jr.; Shea, P.J.; Valentine, B.E.; Weatherspoon, C.P.; Lisle, T.E., eds. Proceedings of the symposium on the ecology and management of dead wood in western forests. Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 445–454.

Skinner, C.N. 2003. A tree-ring based fire history of riparian reserves in the Klamath Mountains. In: Faber, P.M., ed. Proceedings, California riparian systems: Processes and floodplains management, ecology, and restoration; 2001 March 12–15; Sacramento, CA. Sacramento, CA: Riparian Habitat Joint Venture: 116–119.

Smith, J.K., ed. 2000. Wildland fire in ecosystems: Effects of fire on fauna. Gen. Tech. Rep. RMRS-GTR-42 Vol. 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

Smith, S.D.; Devitt, A.; Sala, A.; Cleverly, J.R.; Busch, D.E. 1998. Water relations of riparian plants from warm desert regions. Wetlands. 18: 687–696.

Spencer, C.N.; Gabel, K.O.; Hauer, F.R. 2003. Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. Forest Ecology and Management. 178: 141–153.

Squires, J.R.; Reynolds, R.T. 1997. Northern goshawk (*Accipiter gentilis*). In: Pool, A.; Gill, F., eds. The birds of North America. No. 298. Washington, DC: The American Ornithologists' Union, The Academy of Natural Sciences. 31 p.

Stanford, J.A.; Ward, J.V. 1988. The hyporheic habitat of river ecosystems. Nature. 335: 64–66.

Stanford, J.A.; Ward, J.V. 1993. An ecosystem perspective of alluvial rivers: Connectivity and the hyporheic corridor. Journal of the North American Benthological Society. 12: 48–60.

Starr, B. 2004. Long-term effects of clear-cutting on N availability and soil solution chemistry in the Fraser Experimental Forest, Colorado. Thesis. Fort Collins, CO: Colorado State University. 33 p.

Steel, E.A.; Naiman, R.J.; West, S.D. 1999. Use of woody debris piles by birds and small mammals in a riparian corridor. Northwest Science. 73: 19–26.

Stephens, J.L.; Alexander, J.D. 2011. Effects of fuel reduction on bird density and reproductive success in riparian areas of mixed-conifer forest in southeast Oregon. Forest Ecology and Management. 261: 43–49.

Stephens, S.L.; Moghaddas, J.J. 2005. Fuel treatment effects on snags and coarse woody debris in a Sierra Nevada mixed conifer forest. Forest Ecology and Management. 214: 53–64.

Stephens, S.L.; Ruth, L.W. 2005. Federal forest-fire policy in the United States. Ecological Applications. 15: 532–542.

Stickney, P.F. 1986. First decade plant succession following the Sundance Forest Fire, northern Idaho. Gen. Tech. Rep. GTR-INT-197. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. 26 p.

Stohlgren, T.J.; Bull, K.A.; Otsuki, Y.; Villa, C.; Lee, M. 1998. Riparian zones as havens for nonnative plant species. Plant Ecology. 138: 113–125.

Stokes, A.; Mattheck, C. 1996. Variation of wood strength in tree roots. Journal of Experimental Botany. 47: 693–699.

Stone, K.R.; Pilliod, D.S.; Dwire, K.A.; Rhoades, C.C.; Wollrab, S.P.; Young, M.K. 2010. Fuel reduction management practices in riparian areas of the western USA. Environmental Management. 46: 91–100. doi10.1007/s00267-010-9501-7.

Stottlemyer, R.; Troendle, C.A. 1999. Effect of subalpine canopy removal on snowpack, soil solution, and nutrient export, Fraser Experimental Forest, CO. Hydrological Processes. 13: 2287–2299.

Stratton, R.D. 2006. Guidance on spatial wildland fire analysis: Models, tools, and techniques. Gen. Tech. Rep. RMRS-GTR-183. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station 15 p. www.treesearch.fs.fed.us/pubs/25139.

Suzuki, N.; Olson, D.H. 2007. Options for biodiversity conservation in managed forest landscapes of multiple ownerships in Oregon and Washington, USA. Biodiversity Conservation. 16: 3895–3917.

Swank, W.T. 1988. Stream chemistry response to disturbance. In: Swank, W.T.; Crossley, D.A., Jr., eds. Forest hydrology and ecology at Coweeta. New York: Springer-Verlag: 339–358.

Swanson, F.J.; Benda, L.E.; Duncan, S.H.; Grant, G.E.; Megahan, W.F.; Reid, L.M.; Ziemer, R.R. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. In: Salo, E.O.; Cundy, T.W., eds. Streamside management: Forestry and fishery interactions. Contribution #59. Seattle, WA: University of Washington, Institute of Forest Resources: 9–38.

Tabacchi, E.; Correll, D.L.; Hauer, R.; Pinay, G.; Planty-Tabacchi, A.; Wissmar, R.C. 1998. Development, maintenance and role of riparian vegetation in the river landscape. Freshwater Biology. 40: 497–516.

Taylor, A.H.; Skinner, C.N. 1998. Fire history and landscape dynamics in a late successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management. 111: 285–301.

Taylor, J.L. 2001. *Populus deltoides*. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/ [2015, September 27].

Thomas, J.W.; Maser, C.; Rodiek, J.E. 1979. Riparian zones. In: Thomas, J.W., ed. Wildlife habitat in managed forests: The Blue Mountains of Oregon and Washington. Agric. Handb. 553. Washington, DC: U.S. Department of Agriculture, Forest Service: 40–47.

Thorne, C.R. 1990. Effects of vegetation on riverbank erosion and stability. In: Thornes, J.B., ed. Vegetation and erosion: Processes and environments. Chichester, UK: John Wiley and Sons: 125–144.

Tiedemann, A.R.; Klemmedson, J.O.; Bull, E.L. 2000. Solution of forest health problems with prescribed fire: Are forest productivity and wildlife at risk? Forest Ecology and Management. 127: 1–8.

Torgersen, C.E.; Price, D.M.; Li, H.W.; McIntosh, B.A. 1999. Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. Ecological Applications. 9: 301–319.

Trammell, T.L.E.; Rhoades, C.C.; Bukaveckas, P.A. 2004. Effects of prescribed burns on nitrogen, phosphorus, and base-cation loss from forest-glade habitats in central Kentucky. Restoration Ecology. 12: 596–603.

Triska, F.J.; Kennedy, V.C.; Avanzino, R.J.; Zellweger, G.W.; Bencala, K.E. 1989. Retention and transfer of nutrients in a third-order stream in Northwestern California: Hyporheic processes. Ecology. 70: 1893–1905.

Troendle, C.A.; Reuss, J.O. 1997. Effect of clear cutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Sciences. 1: 325–332.

Turner, M.G.; Romme, W.H. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology. 9(1): 59–77.

USDA Forest Service. 1995. Decision Notice/Decision Record, FONSI. Ecological analysis and appendices for the inland fish strategy (INFISH). Interim strategies for managing fish-producing watersheds in eastern Oregon and Washington, Idaho, western Montana, and portions of Nevada. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region.

USDA Forest Service. 2011. Watershed condition framework: A framework for assessing and tracking changes to watershed condition. USDA Forest Service. FS-977. 24 p.

USDA Forest Service. 2012. National Best Management Practices for Water Quality Management on National Forest System Lands. Volume 1: National Core BMP Technical Guide. 165 p.

USDA Forest Service; USDI. 2001. Managing the impact of wildfires on communities and the environment: A report to the President in response to the wildfires of 2000, September 8, 2000. Washington, DC: U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior.

USDA Forest Service; USDI. 2002. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy: Implementation plan. Washington, DC: U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior. 27 p. https://www.forestsandrangelands.gov/resources/plan/documents/11-23-en.pdf. [07 June 2016].

USDA Forest Service; USDI. 2008. Healthy Forests Report: FY 2008 Accomplishments. https://www.forestsandrangelands.gov/resources/reports/documents/healthyforests/2008/healthy_forests_report_fy2008.pdf.

USDI Fish and Wildlife Service. [n.d.] [Draft]. Fuel and fire effects monitoring guide. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service. http://www.fws.gov/fire/downloads/monitor.pdf

USDI National Park Service. 2001. Fire monitoring handbook. Boise, ID: National Interagency Fire Center. 283 p.

Van de Water, K.; North, M. 2011. Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA: A comparison of current and reconstructed conditions. Forest Ecology and Management. 262: 215–228.

Van Mantgem, P.; Schwartz, M.; Keifer, M. 2001. Monitoring fire effects for managed burns and wildfires: Coming to terms with pseudoreplication. Natural Areas Journal. 21(3): 266–273.

Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R.; Cushing, C.E. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences. 37: 130–137.

Van Sickle, J.; Gregory, S.V. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research. 20: 1593–1601.

Vaz, P.G.; Merten, E.C.; Warren, D.R.; Robinson, C.T.; Pinto, P.; Rego, F.C. 2013. Which stream wood becomes functional following wildfires? Ecological Engineering. 53: 82–89.

Verkaik, I.; Rieradevall, M.; Cooper, S.D.; Melack, J.M.; Dudley, T.L.; Prat, N. 2013. Fire as a disturbance in Mediterranean climate streams. Hydrobiologia. 719: 353–382.

Vidon, P.G.F.; Hill, A.R. 2004. Landscape controls on nitrate removal in stream riparian zones. Water Resources Research. 40: 1–14.

Wagener, S.M.; Oswood, M.W.; Schimel, J.P. 1998. Rivers and soils: Parallels in carbon and nutrient processing. BioScience. 48: 104–108.

Waggy, Melissa A. 2010. *Phalaris arundinacea*. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/ [accessed 2013, August 10].

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increases western U.S. forest wildfire activity. Science. 313: 940–943. doi: 10.1126/science.1128834.

Whitlock, C.; Shafer, S.L.; Marlon, J. 2003. The role of climate and vegetation in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management. 178: 5–21.

Williamson, N.M. 1999. Crown fuel characteristics, stand structure, and fire hazard in riparian forests of the Blue Mountains, Oregon. Thesis. Seattle, WA: University of Washington. 98 p.

Wimberly, M.C.; Spies, T.A. 2001. Influences of environment and disturbance on forest patterns in coastal Oregon watersheds. Ecology. 82: 1443–1459.

Winward, A.H. 2000. Monitoring the vegetation resources in riparian areas. Gen. Tech. Rep. RMRS-GTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Wohl, E. 2001. Virtual rivers: Lessons from the mountain rivers of the Colorado Front Range. New Haven, CT: Yale University Press. 210 p.

Wohl, E. 2006. Human impacts to mountain streams. Geomorphology. 79: 217–248.

Wohl, E.; Jaeger, K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surface Processes and Landforms. 34(3): 329–344.

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.

Wondzell, S.M.; Bisson, P.A. 2003. Influence of wood on aquatic biodiversity. In: Gregory, S.V.; Boyer, K.L.; Gurnell, A.M., eds. The ecology and management of wood in world rivers. Symposium 37. Bethesda, MD: American Fisheries Society: 249–265.

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

Wright, J.M.; Chambers, J.C. 2002. Restoring riparian meadows currently dominated by Artemisia using alternative state concepts—Above-ground vegetation response. Applied Vegetation Science. 5: 237–246.

Wu, T.H. 1986. Root geometry model and simulation. National Science Foundation Grant CEE-811253. USDA Forest Service Grant PNW-83-317. Unpublished final report on file at: Department of Civil Engineering, Ohio State University. 62 p.

Young, M.K. 1994. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. Canadian Journal of Forest Research. 24: 1933–1938.

Young, M.K.; Haire, D.; Bozek, M.A. 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. Western Journal of Applied Forestry. 9(4): 125–130.

Zelt, R.B.; Wohl, E. 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. Geomorphology. 57: 217–233.

Appendix—A Guide to Fuels Management in Riparian Areas of the Interior West

[Note: This is the survey as it appeared online, with the exception of page breaks, which have been removed. Also, referenced page numbers won't match with this document.]

Section 1: Background Information
Prescribed fire and other types of fuels treatments are being used more frequently by local, state, and federal government agencies to reduce the risk of wildfire throughout the western United States. Little is known about the extent and degree to which fuels management practices are carried out in riparian areas or wetlands. In this survey we will ask about fuel treatment projects that have been conducted or proposed in riparian areas in the administrative unit that you manage.

Please use the definition below to determine whether a particular fuel treatment was in a riparian area. We recognize that your agency may be operating under a different administrative definition of riparian areas, but ask you to consider the ecological definition below as riparian areas may extend beyond administrative boundaries. For wetlands, we use the classification developed by Cowardin and others (1979; USACOE 1987).

Riparian and Wetland Definitions
A *riparian area* is a three-dimensional area of direct physical and biotic interactions between terrestrial and aquatic ecosystems; the riparian area extends laterally from the active stream channel to include the limits of flooding and upward into the canopy of streamside vegetation (Gregory at al. 1991). Wetlands may be isolated or occur as part of a riparian area. *Wetlands* are areas that are inundated or saturated by surface or ground water (hydrology) at a frequency and duration sufficient to support hydrophytic vegetation adapted to saturated soil conditions (hydric soils). Wetlands must have one or more of the following attributes: (l) the wetland supports hydrophytic vegetation, (2) the substrates are primarily hydric soils, and (3) the substrate is saturated or covered by shallow water during all or part of the growing season (Cowardin and others 1979).

1.1 Please enter the information for your work location and position in the spaces provided below.

State: ____

Agency (USFS, NPS, BLM, USFWS, etc.): ______________________

Administrative unit (National Forest Ranger District, National Park, National Park Group [list parks in group], National Park District, BLM District Office/Field Office):

____

Your name: ____

Your position: ____

Number of years in current position: __________________________

Number of fuels management projects personally involved in planning: _________

1.2 Under your forest / fire management plan, are prescribed fires permitted to backburn into riparian or wetland areas? *Check one box*.

☐ Yes

☐ No

☐ Not specified / not sure

1.3 Under your forest / fire management plan, are fires designated as "Wildland Fire Use for Resource Benefit" permitted to burn into riparian or wetland areas? *Check one box*.

☐ Yes

☐ No

☐ Not specified / not sure

1.4 During what months of the year are fires most likely to **ignite** and **spread naturally** in your administrative unit? *Check all months that apply.*

☐ January

☐ February

☐ March

☐ April

☐ May

☐ June

☐ July

☐ August

☐ September

☐ October

☐ November

☐ December

Section 2: Project Information (*Page 1*)
In this section, we ask if you have completed fuels projects in riparian areas and / or wetlands. If so, we ask for detailed background information on the project that you selected for this survey. If not, you will be automatically directed to another section.

2.1 In the past ten years, have you been involved in any fuels treatment projects in riparian areas or wetlands that were completed in the administrative unit where you currently work? Also include projects that extended into riparian or wetland areas. *Check one box*.

☐ Yes (proceed to **question 2.2** on page 4 below)

☐ No (skip to **question 2.1, under "if no", on page 22**)

☐ Not sure (skip to **question 2.1, under "if no", on page 22**)

Section 2: Project Information (*Page 2*)

2.2 How many projects in riparian / wetland areas have you completed in the last 10 years? *Check one box*.

- ☐ One project completed
- ☐ Two projects completed
- ☐ Three projects completed
- ☐ More than three projects completed

Section 2: Project Information (*Page 3*)

Please select the most recent fuels project or the fuels project completed in your administrative unit that contained the largest riparian / wetland component. You will need detailed information on the selected project, including the project name, project objectives, treatments used and timing of treatment implementations, size and dimensions of the project area, other agencies involved in the project, project monitoring activities and reports, and the general physical and biological characteristics of the project area.

Definitions

The *Wildland Urban Interface* is defined as areas where human habitation and development meet or intermix with undeveloped wildland vegetation and fuels

2.3 Provide the project name, the year the project was completed, and list other collaborators, if any, in the appropriate boxes below.

Project name ____

Year project was completed __________________________________

Other agencies involved (list agencies or type "none" if no other agencies were involved ___________

____

2.4 For this project, please rate the importance of the objectives listed below. *Note: you will be asked to provide ratings of how effective the project was at meeting the project objectives at a later point in this survey, so it will be helpful to keep track of your responses to this question. Check one box* for each objective.

Project objectives	Primary Objective	Secondary Objective	Tertiary Objective	Not a priority / Not Applicable
Hazardous fuels reduction	☐	☐	☐	☐
Restore historical fire regime	☐	☐	☐	☐
Habitat restoration / enhancement	☐	☐	☐	☐
Invasive / noxious plant species	☐	☐	☐	☐
Protection of values at risk	☐	☐	☐	☐
Other	☐	☐	☐	☐

If objectives were "other", please list the objectives in the space provided below.

____

2.5 Complete the table below by identifying the treatments that were used in the project. Select the starting and ending month within each year for when the majority of the treatment was implemented to indicate the season that the treatment took place. Also, select the year that the treatment was initiated and the year that the treatment was completed. Only complete the rows for the treatments that were used.

Treatment	Treatment used?	Start month	End month	Year treatment was initiated	Year treatment was completed
Prescribed fire	Y/N in pull-down menu	List of 12 months will be in a pull-down menu	List of 12 months will be in a pull-down menu	List of years will be in a pull-down menu (1998-2010)	List of years will be in a pull-down menu (1998-2010)
Mechanical Thinning (using chainsaws and crews)					
Mechanical Thinning (using heavy equipment)					
Lopping and pruning					
Pile burning					
Mastication					
Other					

If "other" treatments were used, please list those treatments in the space provided below.

2.6 Please indicate if the entire project was specific to the riparian/wetland area, or if the riparian / wetland portion was part of a larger upland project. *Check one box*.

☐ Specific to riparian area

☐ Took place in riparian as a portion of a larger upland project

2.7 Was any part of the project in the Wildland Urban Interface? *Check one box*.

☐ Part or all of the project was in the Wildland Urban Interface

☐ No part of the project was in the Wildland Urban Interface

☐ Not sure

2.8 Using your best estimate, please fill in the information about the size and dimensions of the project in the spaces provided below. *Note: you can only enter positive whole numbers in the space provided. Do not use commas, decimals, text, fractions, etc*.

Overall project size (acres)	______________________________
Size of area within riparian / wetland area (acres)	______________________________
Estimated length of riparian / wetland area being treated (meters)	______________________________
Estimated average width of riparian/wetland area being treated (meters)	______________________________

2.9 What are the approximate Universal Transverse Mercator Coordinates (UTMs) for your project area? Note: If you do not know the UTMs for the project area, write unknown in the spaces provided.

Zone ______________________________

Easting ______________________________

Northing ______________________________

Section 3: Features of the Project Area (*Page 1*)
Each administrative unit or project area has unique physical and biological characteristics that can influence fire occurrence and behavior. These characteristics may also determine the need for an area to be treated, depending on management objectives. In this section, we request information on the physical and biological features of the area that was treated by the fuels project. Use the definitions below to assist with the questions in this section.

Definitions
Freshwater wetlands and deepwater habitats can be classified into three general types . *Riverine Habitats* include wetlands associated with stream or river channels *Lacustrine Habitats* include wetlands that are situated in topographic depressions, dammed river channels, or are associated with lakes. *Palustrine Habitats* include wetlands dominated by trees, shrubs and persistent emergents, such as swamps and marshes (Mitsch and Gosselink 2007).

Stream order is a simple classification of the position of a stream within the hierarchy of a drainage network. Each order is a numeric assignment; first order streams are unbranched headwaters; a second order stream is formed at the junction of any two first-order streams; third order by the junction of any two second-order streams (Strahler 1952).

Channel slope is the up-valley slope (in percent slope) of a stream reach or segment.

Drainage area (also referred to as watershed area or catchment area) includes all of the upstream land and water surface area that drains to a specific location on a stream (Gordon et al. 2008).

The *Rosgen Classification System* is a widely-used method for classifying streams and rivers based on common patterns of channel morphology (Rosgen 1996).

Fire Regime Condition Class (FRCC) is an approach for estimating the relative degree of departure from reference or historic conditions of an ecosystem or landscape. The classes are FRCC 1 (low [<33 percent] departure from reference conditions); FRCC2 (moderate [33 to 66 percent] departure from reference conditions); or FRCC3 (high [>66 percent] departure from reference conditions) (Hann and others 2004).

3.1 In what elevation range was the project located? *Check one box*.

☐ 0 to 900 meters (0 to 3,000 feet)

☐ 900 to 1,800 meters (3,000 to 6,000 feet)

☐ 1,800 to 2,700 meters (6,000 to 9,000 feet)

☐ Greater than 2,700 meters (9,000 feet)

3.2 Please select the predominant wetland habitat classification for the **riparian / wetland area** where the project was conducted. *Check one box*.

☐ Riverine Habitat (streams, rivers)

☐ Lacustrine Habitat (lakes, ponds)

☐ Palustrine Habitat (wetlands, marshes)

3.3 Please rate the presence of vegetation types within the riparian / wetland area treated at the time the project was implemented. *Check one box* for each vegetation type.

	Not present	Occasionally Present	Subdominant	Dominant
Willows / riparian shrubs	☐	☐	☐	☐
Cottonwood / hardwood forests	☐	☐	☐	☐
Coniferous forests	☐	☐	☐	☐
Upland Shrub / Woodland	☐	☐	☐	☐
Meadow	☐	☐	☐	☐
Other	☐	☐	☐	☐

3.4 Please indicate the stream orders that were included in the project area. Check all that apply.

☐ 1st Order

☐ 2nd Order

☐ 3rd Order

☐ 4th Order

☐ Not sure / not applicable

3.5 What is the estimate of the predominant channel slope within the project area? Check all that apply.

☐ Less than 1 percent

☐ 1 to 2 percent

☐ 2 to 4 percent

☐ 4 to 8 percent

☐ Greater than 8 percent

☐ Not sure / not applicable

3.6 Please indicate the approximate drainage area for the watershed in which the project was conducted. *Check one box*.

☐ Less than 1 km^2 (0.5 mi^2)

☐ 1 to 10 km^2 (0.5 to 5 mi^2)

☐ 10 to 50 km^2 (5 to 20 mi^2)

☐ 50 to 100 km^2 (20 to 40 mi^2)

☐ 100 to 500 km^2 (40 to 190 mi^2)

☐ Greater than 500 km^2 (190 mi^2)

☐ Not sure / not applicable

3.7 Within the project boundaries, what were the most prevalent stream types using the Rosgen Classification System? Check all that apply.

☐ A channel (cascade to step-pool)

☐ B channel (plane bed)

☐ C channel (pool-riffle)

☐ D channel (braided or bar-braided)

☐ E channel (consistent series of pool-riffle reaches)

☐ F channel (meandering, moderated pool-riffle sequence)

☐ G channel (entrenched, narrow, and deep step-pool)

☐ Not sure / not applicable

3.8 For the stream channels within the project area, what is the predominant grain (particle) size in the channel? Check all that apply.

☐ Boulder

☐ Cobble

☐ Cobble-gravel

☐ Gravel

☐ Gravel-sand

☐ Sand

☐ Fines

☐ Not sure / not applicable

3.9 For the streams within the project area, what is the degree of channel constraint? Check all that apply.

☐ Highly constrained (cannot move laterally)

☐ Moderately constrained (limited horizontal restriction)

☐ Wide valley bottom (channel free to move laterally)

☐ Not sure / not applicable

3.10 Within the project area, rate the presence of vegetation types of the **surrounding uplands** at the time the project was implemented. *Check one box* for each vegetation type.

	Not present	Occasionally Present	Subdominant	Dominant
Ponderosa Pine	☐	☐	☐	☐
Lodgepole Pine	☐	☐	☐	☐
Spruce/fir	☐	☐	☐	☐
Mixed Conifer	☐	☐	☐	☐
Piñon-Juniper / Woodland / Shrubland	☐	☐	☐	☐
Shrub Steppe	☐	☐	☐	☐
Grassland	☐	☐	☐	☐
Other	☐	☐	☐	☐

3.11 Are Fire Regime Condition Classes (FRCCs) applicable to the **riparian or wetland areas** within your project area? *Check one box*.

☐ Yes (continue to question 3.12 on page 13 below)

☐ No (go to question 3.13 on page 14)

☐ Not sure (go to question 3.13 on page 14)

Section 3: Features of the Project Area (Page 2)

3.12 What was the FRCC of the **riparian / wetland areas** in the project area at the time it was implemented? *Check one box*.

☐ FRCC 1 (low [<33 percent] departure from reference conditions)

☐ FRCC 2 (moderate [33 to 66 percent] departure from reference conditions)

☐ FRCC 3 (high [>66 percent] departure from reference conditions)

☐ Not sure

Section 3: Features of the Project Area (Page 3)

3.13 Select the FRCC applicable to the **surrounding uplands** at the time the project was implemented. *Check one box*.

☐ FRCC 1 (low [<33 percent] departure from reference conditions)

☐ FRCC 2 (moderate [33 to 66 percent] departure from reference conditions)

☐ FRCC 3 (high [>66 percent] departure from reference conditions)

☐ Not sure

3.14 Were invasive/noxious plant species prevalent in riparian / wetland habitats within the project area at the time of project implementation? *Check one box*.

☐ Yes

☐ No

☐ Not sure

3.15 Were invasive/noxious plant species prevalent in uplands within the project area at the time of project implementation? *Check one box*.

☐ Yes

☐ No

☐ Not sure

3.16 Were insects and disease prevalent in riparian / wetland habitats within the project area at the time of project implementation? *Check one box*.

☐ Yes

☐ No

☐ Not sure

3.17 Were insects and disease prevalent within uplands within the project area at the time of project implementation? *Check one box*.

☐ Yes

☐ No

☐ Not sure

Section 4: Monitoring (*Page 1*)
Monitoring is frequently used by land managers to determine the condition of riparian / wetland resources, to track trends in response to management, and to determine if projects are meeting objectives. In this section, we ask if and what types of monitoring have taken place, including ongoing monitoring not related to a fuels project and monitoring to track the effectiveness of the fuels project.

4.1 Following project implementation, did you monitor **the project's** effectiveness at meeting management objectives in riparian or wetland areas (using either visual or quantitative sampling methods)? *Check only one box.*

☐ Yes (continue to question 4.2 on page 16 below)

☐ No (Skip to question 4.3 on page 17)

☐ Not sure (Skip to question 4.3 on page 17)

Section 4: Monitoring (Page 2)

4.1 Please complete the table below to indicate the ecological components that were / are being monitored **to track the effectiveness of the fuels management project.** Select all that apply and complete the information in the table for each component that applies. *Only complete the rows for components being monitored.*

Ecological component	Monitored?	Monitoring methods	Protocols and / or sampling design?	Duration of monitoring	Frequency of monitoring	Pre- and post- data collected?
water quality and / or quantity	Pull-down menu Y/N	Pull-down menu list methods	Pull-down menu Y/N	Pull-down menu years (< 1month, 1-2 months,	Pull-down menu years or months	Pull-down menu
Erosion / runoff		(Visual / rapid assessment, Photopoints, Sample collection, Data collection from		3-6 months, 1 year, 2 years,…10 years,	between monitoring (< 1/month, every month,	Pre- and post- treatment, Post-treamtment
stream biota (fish, amphibians, macroinvertebrates)		transects/points/plots/ sediment fences, Measurements from instruments or sensors		More than 10 years)	Every 6 months, Annually,	only, or Pre-treatment only?
vegetation		Other)			Every 2 years)	
fuel types and loads						
terrestrial wildlife						
other						

Please describe any "other" selections in this table. *Note: if your administrative unit uses existing monitoring protocols such as PACFISH-INFISH Biological Opinion Monitoring (PIBO), Multiple Indicators Monitoring (MIM), or Proper Functioning Condition (PFC).* ________________________

____

Section 4: Monitoring (*Page 3*)

4.2 How effective was the project at meeting the project objectives? The response to this question should relate back to the management objectives you selected in question 2.4 in Section 2 of this survey. *Check one box for each objective.*

Project objectives	Not at all effective	Somewhat ineffective	Don't know or unsure	Somewhat effective	Very effective	Not applicable
Hazardous fuels reduction	☐	☐	☐	☐	☐	☐
Restore historical fire regime	☐	☐	☐	☐	☐	☐
Habitat restoration / enhancement	☐	☐	☐	☐	☐	☐
Invasive / noxious plant species	☐	☐	☐	☐	☐	☐
Protection of values at risk	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐

Section 4: Monitoring (*Page 4*)

Apart from monitoring that is specifically for fuels projects, we are also interested in ongoing monitoring taking place in **riparian / wetland areas** in your **administrative unit** (for example, monitoring that is part of an inventory and monitoring program).

4.3 Is ongoing monitoring, not associated with fuels projects, being conducted in any riparian or wetland areas within your administrative unit? Check only one box.

☐ Yes (continue to question 4.5 on page 19 below)

☐ No (Skip to question 5.1 under Section 5 on page 20)

☐ Not sure (Skip to question 5.1 under Section 5 on page 20)

Section 4: Monitoring (*Page 5*)

4.1 For the monitoring that is **not associated with fuels projects**, please complete the table below. Select all that apply and complete the information in the table for each ecological component that applies. Only complete the rows for components being monitored.

Ecological component	Monitored?	Monitoring methods	Protocols and / or sampling design?	Duration of monitoring	Frequency of monitoring
water quality and / or quantity	Pull-down menu Y/N	Pull-down menu list methods	Pull-down menu Y/N	Pull-down menu years (> 1 month, 1-2 months,	Pull-down menu years or months
Erosion / runoff		(Visual / rapid assessment, Photopoints, Sample collection, Data collection from		3-6 months, 1 year, 2 years,…10 years,	between monitoring (< 1/month, every month,
stream biota (fish, amphibians, macroinvertebrates)		transects/points/plots/sediment fences, Measurements from instruments or sensors		More than 10 years)	Every 6 months, Annually,
vegetation		other)			Every 2 years)
fuel types and loads					
terrestrial wildlife					
other					

Please describe any "other" selections in this table. *Note: if your administrative unit uses existing monitoring protocols such as PACFISH-INFISH Biological Opinion Monitoring (PIBO), Multiple Indicators Monitoring (MIM), or Proper Functioning Condition (PFC).*

____

Section 5: Proposed Projects (*Page 1*)
You may also have projects that are being proposed, in the planning process, or being implemented at the current time. In this section, we ask if other projects are in process and if there are constraints or concerns that inhibit your ability to conduct treatments in riparian or wetland areas.

5.1 Are any riparian or wetland fuels treatments other than the project described above, being **proposed** or **in process** within your administrative unit? *Check only one box*.

☐ Yes

☐ No

☐ Not sure

5.2 How many projects are proposed or in process in riparian areas and / or wetlands? *Check one box*.

☐ One project

☐ Two projects

☐ Three projects

☐ More than three projects

5.3 What are the constraints/concerns for conducting treatments in riparian / wetland areas in the administrative unit where you work? *Check all that apply from the list below*.

☐ Potential litigation

☐ Threatened / endangered or sensitive species

☐ Cultural resources

☐ Administrative policies

☐ Limited / lack of line officer support

☐ Limited / lack of agreement among resource specialists and/or FMOs

☐ Other

☐ N/A

"Other" (please specify)

____

Section 5: Proposed Projects (Page 2)

We would like to know what your experiences have been. If you have recommendations on fuels treatments in riparian or wetland areas please complete the question below.

5.4 Please use the space below if you have any recommendations for techniques that were highly effective or not effective.

____

____

____

____

____

____

____

____

Section 5: Future Monitoring (*Page 1*)

The following question is in regards to monitoring the effects of future riparian / wetland projects.

5.1 Do you plan to monitor the effectiveness of proposed fuels projects in relation to management objectives in riparian / wetland areas (using either visual or quantitative sampling methods)? *Check only one box.*

☐ Yes (continue to question 5.2 on page 32)

☐ No (Skip to question 5.3 on page 33)

☐ Not sure (Skip to question 5.3 on page 33)

Section 5: Future Monitoring (*Page 2*) The following question is in regards to monitoring the effects of future projects.

5.2 Please complete the table below to indicate the ecological components that will be monitored when future projects are implemented. Select all that apply and complete the information in the table for each component that applies. Only complete the rows for components that will be monitored.

Ecological component	Monitored?	Monitoring methods	Protocols and / or sampling design?	Duration of monitoring	Frequency of monitoring	Pre- and post-data collected?
water quality and / or quantity	Pull-down menu Y/N	Pull-down menu list methods	Pull-down menu Y/N	Pull-down menu years (< 1 month, 1-2 months,	Pull-down menu years or months	Pull-down menu

Erosion / runoff		(Visual / rapid assessment, Photo-points, Sample collection, Data collection from		3-6 months, 1 year, 2 years,…10 years,	between monitoring (< 1/month, every month,	Pre- and post-treatment, Post-treatment only, or Pre-treamtment
stream biota (fish, amphibians, macroinverte-brates)		transects/points/plots/sediment fences, Measure-ments from instru-ments or sensors		More than 10 years)	Every 6 months, Annu-ally,	only?
vegetation		Other)			Every 2 years)	
fuel types and loads						
terrestrial wildlife						
other						

Please describe any "other" selections in this table. Note: if your administrative unit uses existing monitoring protocols such as PACFISH-INFISH Biological Opinion Monitoring (PIBO), Multiple Indicators Monitoring (MIM), or Proper Functioning Condition (PFC). ____

____

Section 5: Future Monitoring (Page 3)

The following question is in regards to ongoing riparian / wetland monitoring in your administrative unit.

5.3 Is ongoing monitoring, not associated with fuels projects, being conducted in any riparian or wetland areas within your administrative unit? Check only one box.

- ☐ Yes (continue to question 5.4 on page 34)
- ☐ No (Skip to end of the survey on page 35)
- ☐ Not sure (Skip to end of the survey on page 35)

Section 5: Future Monitoring (*Page 4*)

The following question is in regards to ongoing riparian / wetland monitoring in your administrative unit.

5.4 For monitoring that is not associated with fuels projects, please complete the table below. Select all that apply and complete the information in the table for each ecological component that applies. Only complete the rows for components being monitored.

Ecological component	Monitored?	Monitoring methods	Protocols and / or sampling design?	Duration of monitoring	Frequency of monitoring
water quality and / or quantity	Pull-down menu Y/N	Pull-down menu list methods	Pull-down menu Y/N	Pull-down menu years (< 1 month, 1-2 months,	Pull-down menu years or months
Erosion / runoff		(Visual / rapid assessment, Photopoints, Sample collection, Data collection from		3-6 months, 1 year, 2 years,…10 years,	between monitoring (> 1/month, every month,
stream biota (fish, amphibians, macroinvertebrates)		transects/ points/plots/ sediment fences, Measurements from instruments or sensors		More than 10 years)	Every 6 months, Annually,
vegetation		Other)			Every 2 years)
fuel types and loads					
terrestrial wildlife					
other					

Please describe any "other" selections in this table. *Note: if your administrative unit uses existing monitoring protocols such as PACFISH-INFISH Biological Opinion Monitoring (PIBO), Multiple Indicators Monitoring (MIM), or Proper Functioning Condition (PFC).*

____

____

Thank you!

Thank you for your time and willingness to participate in this survey! We greatly appreciate your feedback.

References

Cowardin, L.M.; Carter, V.; Golet, F.C.; LaRoe, E.T. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. Washington, DC: U.S. Department of the Interior, U.S. Fish and Wildlife Service, 103 p.

Gordon, N.D.; McMahion, T.A.; Finlayson, B.L.; Gippel, C.J.; Nathan, R.J. 2008. Stream hydrology: An introduction for ecologists. 2nd ed. Hoboken, NJ: John Wiley and Sons, Ltd.

Hann, W.; Shlisky, A.; Havlina, D.; Schon, K.; Barrett, S.; DeMeo, T.; Pohl, K.; Menakis, J.; Hamilton, D.; Jones, J.; Levesque, M.; Frame, C. 2004. Interagency fire regime condition class guidebook. Updated January 2008: Version 1.3.0. U.S. Department of the Interior, Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, National Park Service; U.S. Department of Agriculture, Forest Service, U.S. Geological Service; The Nature Conservancy; Systems for Environmental Management. https://www.frames.gov/documents/frcc/documents/FRCC+Guidebook_2008.10.30.pdf.

Mitsch, W.J.; Gosselink, J.G. 2007. Wetlands. 4th ed. Hoboken, NJ: John Wiley and Sons, Inc.

Rosgen, D.L. 1996. Applied river geomorphology. Pagosa Springs, CO: Wildland Hydrology. 843 p.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin of the Geologic Society of America. 63: 1117–1142.

U.S. Army Corps of Engineers. 1987. Corps of Engineers wetlands delineation manual. Tech. Rep. Y-87-1. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station. 100 p. and appendices.

Federal Recycling Program Printed on Recycled Paper

To learn more about RMRS publications or search our online titles:

www.fs.fed.us/rm/publications

www.treesearch.fs.fed.us/

This is the spine text. Center text on spine.

Riparian Fuel Treatments in the Western USA: Challenges and Considerations

RMRS-GTR-352