Cumulative Watershed Effects
of Fuel Management in the
Western United States

CHAPTER 10.

Potential Effects of Fuel Management Activities on Riparian Areas

Kathleen A. Dwire, *Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO*
Charles C. Rhoades

Michael K. Young, *Rocky Mountain Research Station, USDA Forest Service, Missoula, MT*

Introduction

A significant increase in fuel management treatments is underway as the Forest Service and other natural resource agencies implement the National Fire Plan (USDA USDI 2001), the Healthy Forests Restoration Act (GAO 2003; HFRA 2003), and the President's Healthy Forest Initiative (Dombeck and others 2004; Graham and others 2004; Stephens and Ruth 2005). One of the four goals of the National Fire Plan Comprehensive Strategy is to reduce hazardous fuel, thus potentially decreasing the risk of severe wildfire and modifying fire behavior so that some wildland fires may be more readily and safely suppressed (Graham and others 2004; USDA USDI 2002).

The general objective of this report is to provide resource managers and specialists with a summary of existing knowledge that they can use to evaluate the impacts of proposed fuel treatment projects, particularly the cumulative effects on watersheds. Cumulative watershed effects are defined as "the environmental changes that are affected by more than one land use activity…" (Reid 1998). Cumulative impacts can result from individually minor but collectively significant actions that occur over a period of time (Belt and others 1992). In other words, the effects may prove to be additive or interactive. Riparian areas can act as both moderators and integrators of activities that occur within a watershed. Consideration of the potential effects of fuel treatments on ecological functions of riparian areas is essential in determining cumulative watershed effects.

The objective of this chapter is to synthesize the current state of knowledge about the potential impacts of streamside and upland fuel management on the structure and function of riparian areas. Although research is underway, little has been published on these topics, and most examples from the literature are derived from studies that investigated the effects of forest harvest or wildland fire. Although findings from studies conducted throughout the nation are presented in this chapter, the focus is on riparian areas in mountainous regions of the western United States The influence of fuel management practices on surface water quality and aquatic biota are addressed elsewhere in this report (Chapter 8; Chapter 11; Chapter 12).

Riparian Areas: Definition, Natural Variability, and Management

Definition of Riparian Areas

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 and others 1991). The first dimension of riparian areas is the longitudinal continuum from headwaters to the mouths of streams and rivers and ultimately the oceans (Vannote and others 1980). The second is the vertical dimension that extends upward into the vegetation canopy and downward into the subsurface and includes hyporheic and belowground interactions for the length of the stream-riparian corridor (Edwards 1998; Stanford and Ward 1988). The third dimension is lateral, extending to the limits of flooding on either side of the stream or river (Stanford and Ward 1993). The vertical and lateral dimensions include the distinct microclimates often associated with riparian areas. 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 and others 1991; Naiman and Decamps 1997). In the scientific literature the terms "riparian habitat," "riparian area," and "riparian ecosystem" are used somewhat interchangeably, and pertain to the ecologically defined area adjacent to streams (Knutson and Naef 1997). In this chapter, we use the term "riparian area" when referring to the three dimensional streamside zone (Gregory and others 1991). We focus on riparian areas bordering streams, rivers, and springs, although much of the information presented in this chapter also pertains to vegetated areas surrounding lentic waters such as lakes and wetlands.

To assist in managing riparian areas, numerous administrative definitions have been developed along with terms such as "streamside management zones," "riparian habitat areas," "riparian buffers," and "riparian management zones". Most definitions are based on attributes that differentiate streamside areas from adjacent uplands (Belt and others 1992; Knutson and Naef 1997), such as moist soils and occurrence of plant species and communities that are adapted to them or may rely on somewhat arbitrary boundaries such as a fixed distance on each side of a stream channel (Belt and others 1992). We use the term "riparian buffer" when referring to any administratively defined area adjacent to flowing or lentic surface water, including those that are specified by a given distance from the stream or presence of certain ecological attributes.

As suggested by both ecological and some management definitions, riparian areas and influence do not stop at a uniform distance from the stream bank. Instead, they are composed of mosaics of land forms, plant communities, and environments that vary in width and shape within the larger landscape (Gregory and others 1991; Naiman and Decamps 1997) and are not always easily delineated. The Federal Interagency Stream Restoration Working Group recognized the following three components of the stream corridor: the *stream channel*, with flowing water at least part of the year; *the floodplain*, a highly variable area on one or both sides of the stream channel that is inundated by floodwaters at some interval; and the *transitional upland fringe*, a portion of the upland on one or both sides of the floodplain that serves as a transitional zone or edge between the floodplain and the surrounding landscape (Federal Interagency Stream Restoration Working Group 1998). In this chapter, we use the term "stream-riparian corridor" when referring to the stream channel, adjacent floodplains, and the transitional upland fringe. Each of these components should be considered in fuel management because of the linkages and feedbacks that occur among the channel, riparian area, and uplands (Federal Interagency Stream Restoration Working Group 1998).

Natural Variability Among Riparian Areas

Stream-riparian corridors are highly variable and characterized by multidimensional spatial gradients. The effects of fuel reduction treatments on riparian areas will depend largely on the location of the treatments within a watershed, that is, if they are adjacent to the channel or in the uplands or headwaters, middle or lower portion of the drainage, and positioned relative to 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 areas to fuel reduction treatments. Effects will also vary considerably depending on the type of treatment. Some treatments in close proximity to riparian areas may have little effect, such as a relatively cool prescribed fire with low flame length, whereas other treatments may significantly influence riparian areas.

The longitudinal profile of many streams in the western United States can be roughly divided into three zones, which are described based on a simple model of dominant erosion processes: the steep *headwaters*, central *transfer zone*, and low elevation *depositional zone* (Schumm 1977). Each zone is also characterized by riparian plant species, growth forms, and communities that reflect the elevation, geomorphic position, hydrologic and sediment regimes, and past disturbance within a watershed (Carsey and others 2003; Crowe and Clausnitzer 1997; Youngblood and others 1985). The three-zone model is frequently presented for mountain streams; however, the general erosion and geomorphic patterns are also applicable to drainages with less topographic relief. Other stream classifications based on physical processes also help to explain the interactions between the distribution of riparian vegetation and watershed variables and emphasize the role of temporal and spatial scales in understanding the interdependence of physical and biotic processes (Frissell and others 1986; Montgomery 1999; Montgomery and Buffington 1998; Poole 2002; Rosgen 1994; Ward and Stanford 1995).

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 along with the subsequent successional changes in riparian plant communities over time (Gecy and Wilson 1990; Naiman and others 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 plant communities evolved within the ecological context of regional fire regimes (Arno 2000). Studies in several parts of the western United States have revealed that historical fire frequencies in uplands and riparian areas were often comparable (Macdonald and others 2004; Olson and Agee 2005), whereas in others, riparian fires were less frequent but more severe than those in uplands (Arno 1996; Everett and others 2003). Moreover, dendrochronological analyses often detected the same fire events in upland forests and adjacent riparian areas. The decline in fire frequencies in both areas corresponded with the onset of effective fire suppression (Everett and others 2003). Effects of both wildland fire and fire suppression have likely influenced riparian vegetation and functions and should be acknowledged during planning and implementation of fuel reduction treatments. Predicting the potential impacts of fuel treatments on riparian areas requires consideration of the fire history and natural fire regime along elevation gradients throughout the treated watershed and surrounding landscape (Agee 1991, 1993; Arno 2000).

Current attributes and condition of riparian plant communities reflect the historically recent (approximately 100 to 200 years) physical conditions of the landscape as well as land management activities (NCASI 2005). Forest harvest, livestock grazing, road construction, inadequate road maintenance, flow alteration (dams and diversions), and recreation have altered composition and structure of riparian plant communities (Kauffman 2004; NCASI 2005). Removal of beaver has changed stream and floodplain hydrology in watersheds throughout the western United States and directly and indirectly influenced riparian vegetation and nutrient and organic matter dynamics. Mining activities, particularly dredging and hydraulic mining, have left a lasting legacy on the geomorphology and hydrology of many western stream riparian corridors (Wohl 2001).

Although portions of many riparian areas along perennial streams are currently protected, the lingering effects of land management prior to the establishment of buffers are likely to influence the structure and composition of riparian areas for decades to centuries (Young and others 1994). Legacies of past management within watersheds could potentially confound responses to fuel reduction treatments.

Best Management Practices and Protection of Riparian Areas

Riparian areas cover a relatively small area, yet they are disproportionately important for maintenance of water quality and quantity (water storage and aquifer recharge), habitat for aquatic and terrestrial biota, sediment retention, stream bank building and maintenance, and provision of services of economic and social value such as livestock grazing and recreation (table 1) (Gregory and others 1991; Naiman and Decamps 1997; Naiman and others 2005; Prichard and others 1998). On National Forest lands, protection of riparian areas is often governed by special rules, stated as Standards and Guidelines in the Forest Plan for each National Forest, which frequently include sets of best management practices (BMPs) (Belt and others 1992; Gregory 1997; Mosley and others 1997). BMPs are officially approved practices and techniques that are generally cost effective and practicable means of reducing management impacts on streams, valued riparian functions, or ecosystem services (Belt and others 1992; Mosley and others 1997). The management of riparian areas can generally be defined as custodial, in which the riparian areas are protected to maintain specific functions (table 1) (Gregory 1997). The general objective of most BMPs is to protect water quality and habitat along streams from timber harvest, road construction, grazing, recreation, and other land use activities (Belt and others 1992; Mosley and others 1997) and is often accompanied by the designation of riparian buffers (Norris 1993).

Riparian buffers contribute to watershed protection by restricting management activities and other human caused disturbances that alter ecological conditions of stream riparian corridors (Norris 1993). Riparian influence decreases with distance from the stream channel (fig. 1) (FEMAT 1993). Depending on stream width, location within a drainage basin, and management concerns, the required riparian buffer width may vary from 5 ft to 300 ft on each side of the stream (Belt and others 1992; Lee and others 2004). Streams used for domestic water supplies are accorded wider riparian buffers to protect downstream reservoirs from non-point pollution resulting from forest management (Belt and others 1992). Many federally listed plant and animal species (frequently selected as management indicator species) require riparian areas as habitat. Streams that are important for spawning, rearing, or migration of sensitive fish species often receive additional protection in the form of wider buffers (USDA 1995). Existence of a riparian buffer, however, does not preclude all types of management activities. Lee and others (2004) noted that about 80 percent of state and provincial jurisdictions permitted riparian timber harvest. Regulations on public lands are somewhat more restrictive but still allow active riparian management.

The effectiveness of BMPs in mitigating the impacts of land management varies considerably depending on local conditions, management guidance and practices, and the stream or riparian feature of concern (Belt and others 1992; Weller and others 1998). Implementation of BMPs and establishment of riparian buffers have generally decreased the negative effects of forest harvest activities on surface water quality (Belt and others 1992; Norris 1993; Osborne and Kovacic 1993). However, less is known regarding BMP effectiveness in protecting other riparian functions (table 1). For example, in western Washington, Brosofske and others (1997) found that forest harvest strongly affected the riparian microclimate despite designated buffers (mean buffer width, 72 ft; range, 40 to 236 ft). Whereas riparian buffers and BMPs will likely assist in mitigating some impacts of upland fuel reduction treatments, additional precautions and actions may be necessary to protect particular riparian functions. In burned watersheds or areas that have experienced insect caused mortality, riparian buffers may consist of mostly dead trees, and streamside fuel loads may cause concern about fire risk and potential fire behavior. Although the utility of such buffers is questionable for functions such as

Table 1. Functions of riparian areas and key relationships to ecological service (modified from NRC 2002; Naiman and others 2005).

Riparian functions	Indicators of riparian functions	On-site or off-site effects of functions	Valued goods and services provided
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, & mesic plant species	Maintenance of 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
Biogeochemistry and nutrient cycling			
Riparian vegetation provides source of organic carbon (allochthonous inputs to streams; organic matter inputs to soils)	Healthy mosaic of riparian vegetation	Maintenance of aquatic and terrestrial food webs	Supports terrestrial and aquatic biodiversity
Transformation and retention of nutrients and pollutants	Water quality and biotic indicators	Interception of nutrients and toxicants from runoff; water quality	Improvement and maintenance of water quality
Sequestration of carbon in riparian soils	Occurrence, extent, & distribution of organic-rich soils	Contributes to nutrient retention and carbon sequestration	Potentially ameliorates global warming; provides source of dissolved carbon to streams via subsurface flow paths
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, others)
Contribution to aquatic habitat; provision of large wood (CWD/LWD inputs)	Aquatic habitat complexity (pool-riffle sequences, debris dams); maintenance of aquatic biota	Maintenance of aquatic biota	Maintenance of fisheries, recreation
Provision of structural diversity	Availability of nesting/rearing habitat; presence of appropriate indicator wildlife species (for example, neotropical migrants)	Maintenance of global biodiversity; provides migratory corridors for terrestrial and aquatic species	Recreation: bird watching, wildlife enjoyment, and game hunting

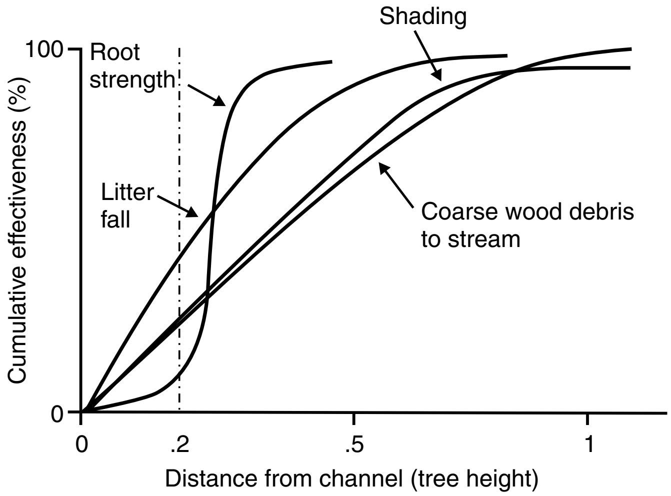

Figure 1. Generalized curves indicating cumulative percent effectiveness of riparian ecological functions occurring with varying distance from the stream channel (FEMAT 1993).

maintenance of stream water quality, they may provide critical wildlife habitat and an important source of large wood for streams and floodplains. In these cases, as well as for prescriptions that are being planned and conducted within riparian areas, managers may need to develop and implement additional on-site BMPs and riparian-specific prescriptions to protect streams and valued riparian functions.

Potential Effects of Fuel Management Activities on Riparian Areas

Fuel Management Treatments

Fuel reduction treatments are being planned and implemented throughout the western United States (http://www.fireplan.gov). Most treatments have the overall goal of decreasing the risk of high severity fire by fragmenting the forest canopy, removing ladder fuel, and reducing the abundance of ground fuel (Peterson and others 2005). Forest fuelbeds can be categorized into six strata:

1. forest canopy,
2. small trees and shrubs,
3. low vegetation,
4. dead wood,
5. moss, lichens, and litter, and
6. duff (Sandberg and others 2001).

Fuel reduction treatments typically target crown, ladder, and surface fuel (Peterson and others 2003) and include prescribed fire, thinning and other silvicultural operations, and chemical and biological treatment (Graham and others 2004). There is considerable variation within each treatment type. For example, a controlled burn prescription may include different burn intensities and different preparation procedures. Also, various combinations of different treatments are used to modify vegetation in each stratum and depend on project objectives, targeted fuel, current condition of the vegetation, past management, and logistics (Peterson and others 2005) (Chapter 4). Each treatment type and combination could have very different individual and cumulative environmental effects on ecosystems processes and attributes, ranging from negative to positive to benign. Also, fuel reduction projects usually require a sequence of multiple treatments staged over a period of time. Discussion of the variation in fuel reduction treatments and potential impacts of each type are beyond the scope of this review chapter. However, the effectiveness of projects in reducing site specific fire hazard and minimizing negative environmental consequences will depend on knowledge of natural fire regimes and existing data on current and historical forest structure and fuel distribution (Peterson and others 2005). The current management of natural ignitions or wildland fire use must also be integrated into planning for fuel reduction treatments and considered in assessment of cumulative impacts.

For most riparian plant communities, few data are available on fuel loads, characteristics, or distribution (Dwire and Kauffman 2003); however, there is a perception that current fuel quantities in some riparian areas are hazardous and constitute a fire risk. This has likely resulted from the recognition that fire in some riparian areas was historically common and that fire suppression has contributed to the accumulation of fuel in riparian areas as it has in uplands, particularly in forest types that historically supported low intensity, high frequency fire (Everett and others 2003; Olson and Agee 2005). Given data limitations on historical composition and structure of riparian vegetation, managers are encouraged to consider the natural fire regime and fire history of the watersheds to be treated when they define target fuel loads for riparian areas.

Despite the uncertainty, fuel reduction treatments are underway in riparian areas (http://www.fireplan.gov/reports) and for some projects objectives extend beyond the reduction of fire risk. For example, prescribed fire has been used to control invasive species along streams and rivers (*Tamarix* spp. in the Bighorn River Basin, Wyoming, Bureau of Land Management Worland Field Office) and enhance wildlife habitat through the regeneration of willows (Bridger-Teton National Forest and Grand Teton National Park, Wyoming). Mechanical methods have been employed to protect structures (for example, restrooms, interpretive displays, and developed campsites) at riparian recreational sites such as picnic areas and campgrounds (for example, along the Colorado River near Moab, Utah, Bureau of Land Management Moab Field Office). These projects are generally quite small (less than 5 acres), and the ecological effects are likely to be fairly local. Most projects are being implemented in riparian areas that have undergone considerable management and disturbance, including wildfire, infestation by exotic species, timber harvest, and road and recreational development. These fuel reduction projects are providing managers with opportunities to reduce fire risk, remove invasive species, and restore streamside areas to conditions that support valued riparian species.

Riparian Vegetation

Riparian plant communities frequently constitute the most floristically and structurally diverse vegetation in a given region (Naiman and others 1993, 1998, 2005; Pollock and others 1998; Tabacchi and others 1998). Because of their transitional location at the land water ecotone, riparian plant communities may include upland, riparian, and wetland species, and thus maintain high levels of beta and gamma diversity (Pollock and others 1998), and a range of life forms and functional groups (NCASI 2005; Pabst and Spies 1999). Numerous vascular plant species of concern occur in riparian habitats (CNPS 1997; Eastman 1990). Riparian plant species have an array of morphological, physiological, and reproductive adaptations for survival in variable and frequently disturbed environments. Specific adaptations include those related to flooding, erosion, sediment deposition, seasonally saturated soil environments, physical abrasion, and stem breakage. Patterns of riparian plant community development and structure are driven by responses to disturbance, hydrologic and geomorphic variables, soil and substrate characteristics, and biological attributes related to succession (Baker 1989). Characteristics of vegetation structure are similar to those used to categorize fuelbed strata (Peterson and others 2005) and include age class, structural type, size, shape, and spatial distribution (vertical and horizontal) of vegetation components (Spies 1998).

Limited research has been conducted on the effects of fuel reduction treatments on riparian vegetation. However, results from studies of prescribed fire and more extensive forest harvest treatments in upland and riparian areas may be helpful in evaluating potential impacts (table 2) (NCASI 2005). Bêche and others (2005) sampled riparian vegetation before and after a fall prescribed burn along stream segments in the central Sierra Nevada Mountains of California. They found that ground cover taxa richness decreased more in the burned plots than unburned plots, diversity (Simpson's D) decreased in both, and ordination results showed little difference in community composition between burned and unburned riparian plots (table 2) (Bêche and others 2005). Similar results have been observed in other locations following prescribed fire (Elliott and others 1999) and may partly be due to patchy burning. In the Oregon Coast Range, riparian herbaceous plant diversity did not differ significantly between unharvested riparian buffers surrounded by logged uplands and undisturbed riparian forests located in unharvested watersheds (table 2) (Hibbs and Giordano 1996; Hibbs and Bower 2001). 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 others 1992; Halpern and Spies 1995). It should be noted, however, that certain rare species have been locally extirpated by forest harvest (Halpern and Spies 1995; Hansen and others 1991). As expected, plant cover and structure were dramatically reduced in

Table 2. Effects of wildfire, prescribed burning, and forest harvest treatments on diversity of forest and riparian vegetation.

Source	Time scale[a] (years)	Treatment and study type	Location	Findings
Andrus and Froehlich 1988	+2 to + 135	Logging, wildfire, logging + wildfire; retrospective sampling in riparian plots	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
Nierenberg and Hibbs 2000	+ 145	Stand-replacing wildfire; retrospective sampling in riparian plots	Western hemlock–Douglas fir forest type; Oregon Coast Oregon (9 streams)	Understory shrubs and red alder dominate initially; eventually replaced by conifers
Bêche and others 2005	-1 to +1 (with unburned controls)	Fall prescribed burn in riparian plots; experimental study	Mixed-conifer forest type; Sierra Nevada, CA;	No clear treatment effects in riparian community composition; diversity decreased in both burned and unburned plots
Elliott and others 1999	-1 to +2	Spring prescribed fire on hillslope gradient including riparian cove; experimental study	Mixed-oak and pine/ hardwood forest types; No. Carolina	No change in riparian species composition
Hibbs and Giordano 1996	+1 to + 32 (with controls)	Unharvested alder-dominated buffers across chronosequence of upland harvest compared to alder-dominated riparian forests undisturbed by upland logging; retrospective sampling in riparian plots	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 Bower 2001 Pabst and Spies 1999	+1 to +33	Unharvested riparian buffers across chronosequence since upland harvest; retrospective sampling in riparian buffers; compared buffer results to those from unmanaged riparian areas	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.
Halpern and Spies 1995	Varied; for most plots, before (-1) and after (+2 to +20) logging	Clear-cut logging, slash burning, thinning; permanent plot and chronosequence sampling in managed and unmananged upland forests	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

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

the first few years following prescribed burning and forest harvest treatments (Bêche and others 2005; Halpern and Spies 1995).

Management activities have also increased the vulnerability of riparian areas to invasion by nonnative species (DeFerrari and Naiman 1994; Fleischner 1994; Parks and others 2005; Planty-Tabacchi and others 1996). Following forest harvest, the occurrence of nonnative species has increased at some sites (Andrus and Froehlich 1988; Halpern and Spies 1995). Livestock grazing has led to the introduction of both non-indigenous pasture species and noxious range weeds throughout the western United States, including riparian areas (Fleischner 1994; Hessburg and Agee 2003). Many stream valleys serve as transportation corridors, and roads and trails—known to be major conduits for dispersal of nonnative plants—are frequently located within floodplains (Forman and Alexander 1998; Gelbard and Belnap 2003; Trombulak and Frissell 2000). The potential for introduction or increased cover of invasive species is an important consideration in the planning and implementation of fuel reduction treatments (Harrod 2001).

An immediate goal of most fuel reduction treatments in upland and riparian areas is to change vegetative structure, although the longer term changes on plant community composition, as well as other ecological consequences, are difficult to predict. In many cases, fire managers are able to implement controlled burns by prescription to obtain the desired effects (for example, no tree mortality or mortality of certain size classes). Reports of successful implementation of prescribed burns are not yet generally available. Monitoring has been minimal and little is known about meeting the longer term project objectives, particularly for riparian areas. Many riparian species appear to be fairly resilient to disturbance, particularly fire (Dwire and Kauffman 2003). Because of the ecological importance of riparian vegetation and the experimental nature of most fuel reduction treatments in riparian areas, monitoring before and after treatment to evaluate achievement of objectives, including the response of streamside plant communities, will assist in advancing our understanding and avoiding litigation.

Terrestrial and Aquatic Habitat in Stream-Riparian Corridors

Terrestrial Habitat

The critical importance of riparian areas for wildlife, particularly in arid portions of the western United States, is well recognized (Kauffman and others 2001; Kelsey and West 1998; Raedeke 1988; Thomas and others 1979). Characteristics of stream-riparian corridors that are important for wildlife are related to the transitional nature of the interface between upland and aquatic habitats, the resulting microclimates and provision of water, food, and cover, and the generally linear shapes with high edge to area ratios that serve as routes of seasonal migration for many vertebrate species (table 1) (Kauffman and others 2001; Kelsey and West 1998). Structurally and spatially complex riparian vegetation provides important habitat for some species, including large and small wood on the ground, snags, multiple and diverse vegetative strata and canopy layers (cover), and complex branching patterns (Steel and others 1999).

Managers designing fuel reduction treatments need to consider the riparian features required by wildlife species of concern as well as potential conditions that might promote increases in undesirable nonnative species (Pilliod and others 2006; Strohmaier 2000; Tiedemann and others 2000; Wales 2001). 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 are likely to be locally extirpated with loss of riparian habitat. Such species include some amphibians, reptiles, and small mammals and numerous 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 and others 2001; McComb and others 1993; Raedeke 1988). Riparian areas support nonnative animal species, such as introduced game birds, as well as undesirable exotic wildlife species, such as nutria (*Myocastor coypus*) (Hayes and Jennings 1986). The fragmentation of native riparian cover types influences the distribution of certain wildlife species, often favoring opportunistic species over those with more specific habitat requirements (Knopf and others 1988; Raedeke 1988). In some regions, breaks in riparian corridor continuity can impact animal movement (Smith 2000). Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators (Knopf 1986; Knopf and others 1988).

Research on the influence of prescribed fire, wildland fire, and forest harvest on wildlife species and habitat has shown mixed results that vary considerably for different taxa and by region (table 3) (Raedeke 1988; Smith 2000). Forest management practices primarily affect fauna in the ways that they affect habitat, including nesting, rearing, and food availability (Lyon and others 2000; Tiedemann and others 2000). Some wildlife taxa (or certain life stages of some taxa) may benefit from a particular forest management practice while others may be harmed. For example, certain mammals and birds have been shown to increase in species numbers with forest harvest, while reptiles and

Table 3. Effects of wildfire, prescribed burning and forest harvest treatments on riparian and aquatic habitat and biota.

Source	Time scale[a] (years)	Treatment and study type	Location	Findings
Pilliod and others 2003	Review of monitoring and research results	Wildland fire, prescribed fire	Range of vegetation types, largely conifer or hardwood forests; USA and Australia;	Limited research; declines in several amphibian species following wildland and prescribed fire
Bury 2004	Review of monitoring and research results	Wildland fire, various fuel treatments	Mixed conifer; Pacific Northwest forests	Limited effects on terrestrial amphibian species and riparian generalists; negative effects on riparian obligates
Bury and Corn 1988	Review of monitoring and research results	Various forest harvest practices	Mixed conifer; Pacific Northwest forests	Declines in amphibian populations following logging; severity of decline depended on species
Hicks and others 1991	Review of research results	Removal of trees from riparian areas and various upland harvest practices	Mixed conifer; Pacific Northwest forests	Negative impacts on native salmonid species; degradation of habitat and reduction in number of fish
Smith (ed.) 2000	Review of monitoring and research results	Wildland fire, prescribed fire	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
Bêche and others 2005	-1 to +1 (with unburned controls)	Fall prescribed burn in riparian plots; experimental study	Mixed-conifer forest type; Sierra Nevada, CA	Periphyton biomass initially lower in the burned stream, but exceeded biomass in unburned streams within 1 year; Aquatic macroinvertebrate communities showed no detectable response
Huntzinger 2003	+1 to +10	Wildland fire, prescribed fire; experimental study	Mixed-conifer forest types; Yosemite National Park, California; Southern Oregon	More butterfly species in burned areas (wildfire and prescribed fire) relative to controls
Hawkins and others 1983	+2 to +25	Clearcut logging	Mixed conifer; Pacific Northwest forests	Initial increases in fish and salamander populations, followed by declines
Brosofske and others 1997	-2 to +2	Hillslope clearcut/ harvest	Douglas–fir dominated; West Cascades, Washington	Harvesting affected riparian microclimate gradients; increased air temperature, decreased relative humidity; riparian environments became more similar to uplands
Li and others 1994	Review of multiple management impacts on aquatic habitat	Multiple—cumulative effects	Range of vegetation types, mostly mixed conifer; Northeast Oregon	Cumulative effects of grazing, forest harvest, water diversions result in increased stream temperature, degraded fish habitat

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

amphibians have decreased (Raedeke 1988; Salo and Cundy 1987; Thomas and others 1979). In addition, beneficial effects of forest management on wildlife are sometimes difficult to separate from those that are detrimental (Raedeke 1988) and may change over successional time. Recent reviews have summarized the general patterns of bird responses to fire (Pilliod and others 2006; Saab and Dudley 1998; Saab and Powell 2005). Our understanding of forest harvest on wildlife species is limited, but even less is known about the potential effects of fuel reduction treatments (Bury 2004). Thinning and prescribed burning may significantly impact some wildlife by reducing the amount of down wood (cover), reducing numbers of older snags (nesting sites), and altering the plant species composition of the treated stands (cover and food) (Tiedemann and others 2000). However, fuel reduction treatments may also benefit certain species or multiple species at certain times. For example, riparian burning and thinning resulted in increased butterfly species richness and diversity along streams in the Sierra Nevada Mountains of California (table 3) (Huntzinger 2003).

As land managers proceed with fuel reduction prescriptions, wildlife habitat issues may be among the most contentious and vulnerable to litigation (Bury 2004). The presence of threatened or endangered wildlife species will likely preclude fuel reduction treatments in particular areas, including some riparian areas. However, if goals for treatments include both reduction of fire risk and the return to more historically natural conditions that support riparian habitat (Arno 1996), potential impacts to a range of wildlife species need to be evaluated. The basic life history traits and riparian habitat elements required by rare wildlife species need to be considered at different spatial and temporal scales. Wildlife species will likely respond differently to various prescriptions and successional changes following fuel reduction treatments, as has been observed with other management practices (Bury 2004; Knopf and others 1988; Pilliod and others 2006; Raedeke 1988). Although there may be short-term risks to some riparian habitat, fuel reduction treatments (and the reintroduction of fire to riparian areas) may result in a more spatially diverse range of habitat components with long-term benefits for certain species. Given limitations of current knowledge on the effects of prescribed fire and mechanical treatments on wildlife, monitoring the response of species of concern before and after fuel treatments may be essential to avoiding litigation in some locations.

Aquatic Habitat

Streambank stability: Riparian vegetation can directly affect stream channel characteristics, particularly streambank stability (Davies-Colley 1997; Gregory and Gurnell 1988; Pollen and others 2004; Simon and Collison 2002). Root systems can armor stream banks (Stokes and Mattheck 1996; Abernathy and Rutherford 2001) and bind bank sediment, thus contributing to bank stabilization, reduction of sediment inputs to streams (Dunaway and others 1994), and development and maintenance of undercut banks (Sedell and Beschta 1991). Studies have shown marked differences among riparian species and vegetation types in root characteristics and their influence on bank stability (Lyons and others 2000; Simon and Collison 2002; Wynn and others 2004). 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). Local alterations to riparian vegetation that affect bank stability and other geomorphic processes may have effects that extend downstream.

The contribution of woody roots to streambank stabilization was modeled for forested reaches and predicted to extend approximately one-half the average crown diameter (fig. 1) (Wu 1986). 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. Prescribed fire may top kill certain riparian trees and shrubs but is unlikely to negatively affect belowground structure (Dwire and Kauffman 2003). In planning fuel reduction treatments in riparian areas, managers need to consider rooting characteristics of the plant species treated and the likely replacement species, the nature of streambank sediments, and potential impacts on streambank stability.

Aquatic foodwebs: By altering riparian vegetation, fuel reduction treatments have the potential to influence stream-riparian organic matter dynamics and aquatic trophic pathways. Autochthonous organic matter is generated through photosynthetic production by autotrophic organisms of the aquatic community (vascular plants, bryophytes, algae, bacteria, and protists) and is driven by the amount of light reaching the stream surface. Removal of riparian vegetation can result in increases in stream temperature and light, thus promoting autotrophic production (Bisson and Bilby 1998). In contrast, allochthonous organic matter originates directly from riparian or upland vegetation in the form of leaves, twigs, and other fine litter and indirectly as terrestrial invertebrates (Bisson and Bilby 1998). The input, use, retention, and transport of allochthonous organic matter in streams may drive carbon and nutrient dynamics and affect biota (Webster and Meyer 1997). For most low order streams in forested watersheds, much of the energy for aquatic food webs is derived from allochthonous inputs (Fisher and Likens 1973; Sedell and others 1978; Vannote and others 1980; Newbold and others 1982). Different plant sources vary widely in nutritional quality, and require different degrees of in-stream processing and conditioning by microbes and invertebrates (Allen 1995; Webster and Benfield 1986). In some areas, seasonal inputs of terrestrial insects from riparian areas are an important food source for drift feeding fish species (Young and others 1997). Such inputs are highest from closed canopy riparian areas dominated by deciduous plant species (Baxter and others 2004, 2005; Edwards and Huryn 1995; Nakano and others 1999). For floodplain forests, it has been suggested (FEMAT 1993) that the effectiveness of riparian vegetation in providing allochthonous inputs to streams declines at distances greater than approximately one-half a tree height away from the channel (fig. 1).

Research from studies on the impacts of fire and forest harvest on aquatic food webs have shown mixed results, depending on location, season, and species of interest (Bisson and Bilby 1998). 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. Aquatic macroinvertebrate communities showed no detectable response to prescribed burning (table 3) (Bêche and others 2005). Significant alteration in the quality or quantity of allochthonous inputs—such as those occurring following fire (prescribed fire of wildfire) and forest harvest—has led to changes in aquatic trophic pathways that affect fish productivity (Bisson and Bilby 1998; Bisson and others 2003a; Edwards and Huryn 1996). In forested watersheds of the Pacific Northwest, the removal of riparian trees has had negative consequences for some native salmonid species (Hicks and others 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, that is, by invertebrate groups that ingest algae and algal conditioned organic matter. Increased productivity in summer populations of salmonids have 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). In locations where fish bearing streams are management priorities, resource managers need to consider potential impacts of fuel reduction prescriptions on riparian vegetation that influences aquatic food webs and stream-riparian nutrient and organic matter dynamics.

Stream temperature: Fuel reduction treatments could potentially affect water temperature by altering vegetative shade that attenuates the input of solar radiation to streams. Direct sunlight warms streams, particularly during periods of low flow. During winter, lack of cover can affect stream temperature by permitting radiant cooling to the sky, potentially resulting in the formation of anchor ice (Ashton 1989). For many low order streams, riparian shading moderates these thermal fluctuations. Stream temperature has tremendous ecological importance for aquatic biota and ecosystem processes such as productivity and nutrient cycling (Allan 1995; Sweeney 1992). Water temperature strongly influences growth, development, and behavioral patterns of aquatic biota both directly and because of its influence on dissolved oxygen concentrations (Sweeney 1993). Stream temperature is an important factor determining the distribution of fish in freshwater streams, and most species of concern have limited temperature tolerances (Torgersen and others 1999).

Stream water temperature varies markedly within and among stream systems (Poole and Berman 2001). Natural drivers of water temperature include topographic shade, upland and riparian vegetation, ambient air temperature and relative humidity, altitude, latitude, discharge, water source, and solar angle and radiation (Poole and Berman

2001; Sweeney 1993). Streams in different regions and stream segments in different parts of a drainage basin vary in response and sensitivity to specific human activities that alter these drivers (Poole and Berman 2001). In addition, effectiveness of vegetation in providing stream shade varies with topography, channel size and orientation, extent of canopy cover above the channel, and vegetation structure. However, stream shading by riparian and upland vegetation is one of the few factors that can be actively managed to achieve stream temperature targets. The curve presented in figure 1 generalizes the relationship between distance from the channel and shade provided by riparian trees. In western Oregon and Washington, riparian buffer width has been designed to correlate with degree of shade (Beschta and others 1987), and riparian buffers of 100 ft or more have been reported to provide as much shade as undisturbed late successional/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 short- and long-term impacts of fuel reduction treatments on shade (provided by both upland and riparian vegetation) and adequacy of buffer width need to be explicitly addressed.

Large wood dynamics: Fuel reduction treatments could potentially affect aquatic habitat by altering recruitment of large wood to streams. The role of large wood in aquatic ecosystems has become increasingly recognized over the last several decades (Bilby and Bisson 1998; Gregory and others 2003; Harmon 2002). Large wood affects geomorphic, hydrological, and ecological processes in streams and rivers, and its numerous roles link aquatic, riparian, and upland portions of watersheds (Gregory 2003; Lienkaemper and Swanson 1987). Large wood strongly influences channel form in small streams, creating pools and waterfalls and affecting channel width and depth (Montgomery and others 2003). Many species use pools formed by large wood as habitat and in-stream wood for cover (Bilby and Bisson 1998; Dolloff and Warren 2003; Wondzell and Bisson 2003). The presence of large wood in streams affects erosion, transport, and deposition of sediment, the creation and growth of gravel bars, and channel and floodplain sedimentation (Montgomery and others 2003). Dams formed by accumulations of large wood increase channel complexity and facilitate deposition of organic matter, thus providing a food source for numerous invertebrate species and contributing to nutrient cycling and retention (Bilby and Bisson 1998; Wondzell and Bisson 2003). 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 and others 1990). Large pulses of wood may originate from near channel sources following fire, windthrow, or insect infestations, or be transported from distant sites by debris torrents, avalanches, or landslides (Benda and others 2003; Bilby and Bisson 1998; Bragg 2000). In forested landscapes, riparian areas are important sources of large wood for streams and floodplains. However, riparian forest stands are frequently patchy, and variation from all these sources can lead to spatial variability in large wood distribution that is often not recognized in management prescriptions for a given amount of large wood per unit length of stream (Young and others 2006).

The temporal variation in large wood loads creates additional complexity. Following disturbance such as fire, contributions of large wood to channels and riparian areas can be very high in the first few decades thereafter, but the storage in each area may differ substantially. In stream channels, peaks in large wood transport may coincide with increases in contributions because of declines in stream channel stability and increases in discharge following fire, leading to rapid depletion of large wood loads during early phases of post disturbance succession. As riparian trees age, they become large enough to resist transport and breakage once they fall, and large wood loads can slowly build to pre-disturbance levels (Bragg 2000; Minshall and Brock 1991). In riparian areas, the decay of fallen trees can be surprisingly swift (Spies and others 1998; Mackensen and others 2003). In addition, recurrent fire may consume some riparian large wood (Skinner 2002) but leave pieces in the stream channel largely unaffected. Because large wood dynamics in streams and riparian areas are complex and remain poorly understood, we suggest that managers proceed with caution in altering fuel loads near streams, particularly in watersheds that have been logged.

Land use and management practices have led to marked decreases in the quantity of large wood in channels in some forested regions. Historical practices, such as removal of wood from rivers for navigation and fish passage, splash damming, tie drives, and clearing of riparian trees has resulted in simplification of stream channels and streambanks, reduction in the areal extent of riparian areas, and local decreases in amounts of large wood (Sedell and Froggatt 1984; Young and others 1994). More recent research has focused on the consequences of streamside logging (table 4). Studies conducted in forested portions of the western United States have shown marked long-term reduction in recruitment of large wood to streams in basins where forest harvest has been conducted (Lisle 2002). 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 (fig. 1) (McDade and others 1990; Van Sickle and Gregory 1990). Similarly, the effectiveness of upland forests to deliver large wood to riparian areas is expected to decline at distances greater than about one tree height from the upland forested edge and depends on steepness of slope. However, 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 Montana, researchers also found differences in features of large wood in logged and reference streams that provide important habitat for bull trout, a federally threatened species (Hauer and others 1999). These included difference in ratios of large to small pieces of large wood, the proportion of pieces attached to the stream channel or bank, and the proportion of large wood pieces with root wads. The role of large wood is so valuable in structuring aquatic habitat that numerous efforts are underway to restore streams by adding large wood (Bisson and others 2003b; Reich and others 2003).

Table 4. Effects of fire and forest harvest on large wood (LW) inputs to streams.

Source	Time scale[a] (years)	Treatment and study type	Location	Findings
Bragg 2000	+10 to +250	Comparative simulation study of large wood inputs to streams following clear-cutting and slash removal, relative to wildfire and insect-caused mortality	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
Bilby and Ward 1991	+5 to +100	Retrospective sampling of near-stream areas in clearcuts, second-growth and old growth	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
Hauer and others 1999	Not specified	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	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.
Ralph and others 1994	+3 to +40	Retrospective sampling of streams draining watersheds with unharvested old-growth forests, and intensively and moderately harvested forests	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
Chen and others 2005	+10 to +40	Retrospective sampling of streamside areas with harvested riparian forest, burned riparian forest, and undisturbed old-growth riparian forest	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

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

The influence of fuel treatments on large wood is a sensitive issue because of the many management actions that have reduced its abundance in stream channels. There is little ecological justification for the direct removal of large wood from riparian areas or riparian trees or snags that would create it. Prescribed fire, however, will not necessarily remove large wood from riparian areas or stream channels. Prescribed burns are typically conducted in spring or fall when fire severity is likely to be low to moderate because air temperatures are low and humidities and fuel moisture are relatively high (Knapp and others 2005). Under these conditions, large, sound boles of fallen trees do not readily ignite (especially those in and over the stream channel), although rotten pieces are consumed (Bêche and others 2005; Brown and others 2003; Stephens and Moghaddas 2005). Whereas decomposing large wood may contribute to soil formation and provide wildlife habitat in riparian areas (Chen and others 2005), only sound pieces are likely to resist breakage, promote local erosion and sediment storage, and form habitat in stream channels (Montgomery and others 2003). In addition, tree mortality caused by riparian prescribed fire is likely to contribute coarse wood in the riparian area and stream channel (Bêche and others 2005; Chen and others 2005).

Given the historical prevalence of fire in montane riparian areas (Everett and others 2003; Macdonald and others 2004), the effects of prescribed burns may emulate those of low to moderate severity wildfires that were part of the historical disturbance regime that maintained the structural and functional diversity of streams and riparian areas (Reeves and others 1995). Nevertheless, the historical interaction between fire, forest type, and large wood varied regionally (Agee 2002; Skinner 2002). It is likely that the impacts of riparian burning will also vary considerably throughout the western United States. Reports on the effects of riparian burning are few (for example, Bêche and others 2005), and we urge that these management experiments be widely shared in the literature.

Riparian Soils

Chemical, physical, and biological processes occurring within riparian soil profiles have the potential to filter, buffer, degrade, immobilize, and detoxify organic and inorganic compounds before they enter streamwater. The likely effects of upland management on down slope hydrologic and biogeochemical fluxes will impact processes that regulate nutrient, carbon, and sediment retention within riparian areas (table 5). The influence of fuel reduction treatments on compaction and productivity of upland soils are described elsewhere in this report (Chapter 9). In this section, we discuss how management of upland areas may modify riparian soil processes and contribute to their watershed effects.

The intersections of near surface hydrologic flowpaths with carbon and nutrient rich soils form "hotspots" of biogeochemical activity in riparian areas (McClain and others 2003; Wagener and others 1998). Riparian soils are frequently moist because of their lower landscape position and proximity to streams and shallow water tables. Water movement from upslope areas and hyporheic zones controls the flux of nutrients and carbon through riparian areas and regulates the soil moisture conditions that influence biogeochemical processes (Triska and others 1989). The finer textured soils found in many riparian areas have higher water holding capacity and their greater exchange capacity increases nutrient retention relative to upslope landscape positions. Especially in arid environments, increased soil moisture availability in riparian areas enhances the productivity of streamside vegetation and may support unique or more diverse plant associations as compared to upland areas (Carsey and others 2003). Root production, soil nutrient uptake and turnover, and litter production (above and belowground) also tend to be higher in streamside plant communities. In lower gradient reaches that are seasonally wet and support productive vegetation, riparian soils may be high in organic matter (Crowe and Clausnitzer 1997).

Biogeochemical processes within riparian soils regulate nitrogen transfer from terrestrial to aquatic ecosystems. Groundwater discharge represents the largest source of dissolved nitrogen delivered to forest streams (McClain and others 1998), yet plant

Table 5. Effects of prescribed burning and forest harvest treatments on soil resources and sediment movement.

Source	Time scale[a]	Treatment	Location	Comments - Findings
Covington and Sackett 1992	-1 wk to + 1 yr	Broadcast burn	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
Monleon and Cromack 1996	+ 0.3, 5, 12 years	Low-intensity broadcast burn	Ponderosa pine, Central Oregon	Burning increased release of N & P from litter & reduced litter decomposition rates
Covington and others 1991	1 to 25 years	Slash pile burn	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.
Korb and others 2004	0 to 2 years	Slash pile burn	Ponderosa pine, Coconino NF near Flagstaff, Arizona	Higher soil pH, NH_4 and NO_3 and lower total C and N inside burn scars
Reuss and others 1997 Starr 2004	1 to 10 years +20 years	Clearcut	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
Giardina and Rhoades 2001	5 year after cutting 1 year after burning	Clearcut + slash retention; clearcut followed by surface fire	Lodgepole pine, Medicine Bow NF, S. Wyoming	Clearcuts had higher NH_4, NO_3, net mineralization, and soil moisture than uncut forest. Slash burning doubled soil N availability compared to unburned cut.
Swanson and others 1987 Brown 1983 Binkley and Brown 1993	Reviews of research and monitoring results	Clearcut	Pacific Northwest Pacific Northwest North America	Increase in suspended sediment concentrations associated with forest roads
Binkley and others 2003	1 year	Application of chipped harvest residue	Lodgepole pine-dominated subalpine forest, Fraser Experimental Forest, central Colorado	Soil NH_4, NO_3 declined beneath chips. Soil moisture increased.
Benson 1982	5 years	Application of chipped harvest residue	Lodgepole pine, Bridger Teton NF, western Wyoming	Surface runoff and soil erosion less than residue removal or undisturbed forest.

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

nutrient uptake and microbial transformations occurring within riparian soils can remove 90 percent of dissolved nitrate from near surface groundwater prior to its release into surface water (Gilliam 1994; Haycock and Pinay 1993; Peterjohn and Correll 1984). 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 and others 1992; Hedin and others 1998; Hill 1996). In contrast to most upland forest soils where denitrification rates are low (Groffman and others 1992), frequent saturation of riparian soils provides a redox environment that favors denitrification (Lowrance and others 1997; Peterjohn and Correll 1984; Vidon and Hill 2004). Denitrying bacteria also requires labile carbon and nitrate within the anoxic soil layer. These compounds move along groundwater flowpaths from uplands into riparian soils and denitrification releases significant amounts of nitrogen from undisturbed (Duff and Triska 1990; Hussey and others 1985) and disturbed (Davidson and Swank 1987; Rich and Myrold 2004; Waide and others 1988) watersheds.

Soil variability regulates groundwater flux and riparian biogeochemical processes. In subalpine forest watersheds, greater than 95 percent of snowmelt passes along shallow groundwater flowpaths (Troendle and Reuss 1997) and through riparian areas before entering streams. The depth and seasonal patterns of these flows determine their chemical composition and the magnitude of nutrient transformation, retention, or export (Simmons and others 1992). Soil texture and porosity control the hydraulic conductivity of near surface groundwater flow paths, exchange with labile nitrogen and carbon sources, and rates of denitrification (Hedin and others 1998; Vidon and Hill 2004). Riparian soils develop from and upon alluvial, colluvial, and aeolian parent materials and are highly variable. Fine and coarse-textured lenses and buried organic layers common to riparian soil profiles (Crowe and Clausnitzer 1997; Youngblood and others 1985) modify vertical and lateral water and nutrient movement into and through riparian areas (Groffman and others 1992; Jacinthe and others 1998; Simmons and others 1992). These sources of soil and groundwater heterogeneity form biogeochemically reactive zones imbedded within relatively inert regions. Improved ability to identify biogeochemical hotspots would help guide efforts to buffer the areas most crucial for water quality protection.

Riparian areas are vulnerable to both compaction and physical disturbance during ground harvesting operations due to areas of high moisture and low soil strength that are common within streamside zones. These concerns, along with riparian and aquatic habitat protection, provide the basis for limiting mechanical harvesting activities within streamside zones. Beyond designation of riparian buffers, land managers should consider how upland fuel reduction operations may influence nutrient and sediment retention in riparian areas and potential water quality impairment. Both vegetation removal and the actions of harvesting equipment alter site nutrient and water balances (Bormann and Likens 1979; Swank 1988). The linkages between upland management and riparian processes depend on a variety of landscape, vegetation, soil, and hydrogeologic factors that determine the flux of water, nutrients, and sediment into riparian areas, as well as specifics of the fuel management activities.

In subalpine forests of the Fraser Experimental Forest (northern Colorado), clearcutting increased snow accumulation and peak water equivalent by 36 percent and increased flow along subsurface flowpaths four-fold (Troendle and Reuss 1997). The export of nitrate from undisturbed subalpine forest hillslopes is negligible. In comparison, harvesting increases mineral nitrogen availability (table 5) (Giardina and Rhoades 2001), leaching (Fahey and Yavitt 1988; Parsons and others 1994), and groundwater flux (Reuss and others 1997; Stottlemyer and Troendle 1999). Greater subsurface water flux and nitrate concentrations may promote denitrification, if adequate labile carbon is available to fuel microbial activity (Groffman and others 1992; Simmons and others 1992). Nutrient and water uptake by riparian and residual upland vegetation will also respond to harvesting and may contribute to nutrient retention and water quality protection.

Disturbance of organic and mineral soil layers during harvesting operations can alter soil structure, infiltration, and bulk density and may lead to channelized runoff and erosion (table 5) (Binkley and Brown 1993; Brown 1983). Overland flow and sheet erosion are typically minimal in undisturbed forests, but steep slopes of many forest watersheds are susceptible to sediment transport via channelized flow (Megahan and others 1992). Loss of surface litter also increases surface runoff and decreases infiltration. Clearcutting has been shown to increase suspended sediment yield from Rocky Mountain and Pacific Northwest watersheds (Binkley and Brown 1993; Leaf 1966; Swanson and others 1987; Wondzell 2001). Similar impacts result from other ground disturbing activities such as road and fire break construction associated with fuel management activities (Wondzell 2001). The potential impact of fuel reduction treatments on the ability of riparian areas to retain sediment depends on the geomorphic setting, soil properties of the basin, and condition of the riparian vegetation.

The impact of upland prescribed burning on the capacity of riparian soils and vegetation to retain nutrients and sediment depends on fire severity and extent and distribution within a watershed (DeBano and others 1998; Fisher and Binkley 2000; Neary and others 1999). Low and moderate severity controlled burns have smaller consequences (both positive and negative) than high severity wildfires (Wondzell 2001). Fuel consumption and fireline intensity determine nutrient loss and nutrient and sediment movement following combustion. Effects can be comparable between high severity wildfire and controlled slash (Feller 1988; Giardina and others 2000) and broadcast burns (Covington and Sackett 1992; Knoepp and Swank 1993; Johnson and others 1998; Monleon and others 1997). Combustion of standing or surface fuel coupled with decreased plant uptake and fluctuating microbial activity often results 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 and others 1991; Korb and others 2004). Elevated soil nutrient pools can lead to greater nitrate and cation leaching (Knoepp and Swank 1993; Trammell and others 2004) and in some cases, higher streamwater export (Chorover and others 1994). In uplands, high severity prescribed burns 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 may 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 within riparian ecosystems are likely to be similar, though we are not aware of comparable published results for streamside areas.

Mechanical chipping and mastication operations are being widely prescribed to treat hazardous fuel, yet the implications of these practices on riparian and watershed conditions are largely unknown. As compared to typical harvesting operations and unharvested stands, these fuel management prescriptions rearrange the amount, size, and orientation of surface woody materials. Similar to other upland management activities, these mechanical treatments are likely to influence soil processes and nutrient retention within riparian areas. A recent review of published findings relating to woody debris additions reported that implementation of chipping and mastication treatments varies considerably among sites depending on equipment and operational differences (Resh and others 2006). The influence of the treatments on soil properties varied as well, although some generalizations emerged. Soil carbon and moisture increased following the mechanical fuel reduction operations. Maximum soil temperature and understory vegetation declined. Woody debris additions had variable effects on soil nutrients. In some cases, soil nitrogen availability decreased as carbon rich woody material stimulated microbial nitrogen immobilization (Binkley and others 2003; Blumfield and Xu 2003; Lalande and others 1998). For example, in Colorado lodgepole pine stands, addition of wood chips reduced soil nitrogen availability by ~ 65 percent (Binkley and others 2003). There is some evidence that logging residue and chip additions may depress sediment movement (Benson 1982). 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. To date, there are no completed studies that directly assess the linkages between these new mechanical fuel management strategies and riparian processes or watershed conditions.

Cumulative Watershed Effects of Fuel Management Activities on Riparian Areas

Most land management activities contribute to cumulative watershed effects, and fuel reduction treatments being conducted anywhere within a watershed could potentially influence riparian functions. Because stream-riparian corridors are located at the lowest point within drainage basins, they can act as integrators of entire watersheds and may be particularly vulnerable to effects of fuel reduction treatments conducted upslope and upstream. In the past, undesirable changes in riparian areas have resulted from the failure to recognize linkages among streams, riparian areas, and uplands. To minimize negative cumulative effects on riparian functions, integrative planning and assessment of all management activities, including fuel reduction treatments, grazing, forest harvest, and recreation, should occur at both watershed and larger landscape scales. The management of wildfires, including location of back burns, cutting lines and natural ignitions that have been allowed to burn, may have very direct and cumulative effects. Wildland fire use (managed wildfire) is increasingly common, and portions of the landscape that have been allowed to burn are likely to be much larger than areas treated with prescribed fire and mechanical fuel removal. The management history, hydrologic and sediment regimes, and the role of natural disturbance all need to be considered in planning fuel treatments (Chapter 12).

The watershed approach of assessing additive and interactive impacts on riparian areas is conceptually simple. However, the actual evaluation of cumulative watershed effects on riparian functions is technically difficult because of limited knowledge of many biological and physical processes, interactions among processes for which impacts may accumulate through space and time, and time lags in the expression of effects. Another limitation is the lack of reference conditions and limited baseline data for comparison and evaluation of environmental changes, including measures of impact severity (Reid 1998). Despite these difficulties, an analysis of cumulative watershed effects on riparian functions must evaluate potentially important impacts on valued riparian functions, downstream impacts, and impacts accumulating through space and time within the watershed using the best available analysis methods and information. Relative risks of severe wildfire versus impacts of fuel treatments need to be weighed (O'Laughlin 2005). In addition, information needs should be acknowledged and monitoring goals clearly identified (REO 1995).

Analysis methods for assessment of cumulative effects have been developed to fulfill requirements of the National Environmental Policy Act and require a non-traditional approach to information (Reid 1998) (Chapter 14). The ecosystem analysis method used on federal lands in much of the Pacific Northwest provides a model that integrates background information about ecosystem and landscape interactions that can be used for later cumulative effects assessments during project planning (FEMAT 1993; Reid 1998). In addition, landscape analysis tools, such as Landscape Management System (LMS), have been developed to assist in planning of fuel treatments (McCarter and others 1998; Peterson and others 2003). These tools display spatial patterns of forest structure and fuel across a landscape for current conditions and compare them to patterns produced by various fuel treatment scenarios. When possible, spatial delineation of riparian areas should be incorporated into landscape level planning of fuel treatments and may contribute to effects analysis as well as integrate riparian protection and management into fuel reduction programs.

Management Implications

1. **Riparian areas are spatially diverse and variously defined. Attention to ecological context within a drainage basin and the larger landscape is critical, as is the connectivity between upslope and upstream management and condition of streams and riparian areas.** Impacts of fuel treatment activities will vary depending on their locations within a watershed, the natural fire regimes, and the fire and management history of the treated basins. Stream-riparian corridors are dynamic and planning should allow for continuous change, including successional processes and natural disturbance.
2. **During planning and implementation of fuel reduction treatments, consideration of potential impacts on key riparian functions is essential to minimize local and immediate effects as well as cumulative, longer term effects.** Riparian areas provide valued ecological functions (table 1) that have been altered by land management (tables 2-5) (Hessburg and Agee 2003). Local and regional issues will dictate which riparian functions are priorities for management goals and critical for protection.
3. **Riparian buffers and BMPs may not protect all riparian functions during fuel reduction treatments.** Although BMPs and the establishment of riparian buffers have mitigated the effects of forest harvest activities on stream water temperature and

quality, current BMPs may not be effective in protecting all valued riparian functions, particularly in watersheds that have been recently burned by severe wildfire. With multiple fuel reduction treatments (including consecutive entries over time), BMP effectiveness may vary and additional conservation practices may be necessary.

4. **Objectives for fuel reduction treatments should include the return to fuel loads that support ecosystem processes and natural disturbance regimes and incorporate short- and long-term targets for the vegetation condition of uplands and riparian areas (Rieman and others 2003).** Using concepts such as natural or historical range of variability (Landres and others 1999), reference areas, and desired future condition, the planning and implementation of fuel reduction treatments may be regarded as opportunities to restore certain ecological conditions, especially in riparian areas (Arno 1996). 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 fuel management, are encouraged. In addition, follow up monitoring for achievement of project objectives (short- and long-term) is critical to expand our knowledge of fuel management.
5. **Current knowledge on the effects of fuel reduction treatments on riparian areas is very limited. Potential environmental effects need to be assessed in a landscape context that includes relative influences of all management influences, including past fire suppression and current wildland fire use.** We have summarized potential effects of fuel reduction treatments on riparian vegetation, the provision of terrestrial and aquatic habitat (contributions to streambank stability, aquatic food webs, maintenance of stream temperature, and large wood dynamics), and the filtering and sediment retention capacity of riparian areas (tables 2-5). We emphasize that very little is actually known about either specific or cumulative impacts of specific fuel reduction treatments. Our understanding of cumulative watershed effects is largely derived from a handful of watershed scale studies of past practices (Reid 1998). Results from these studies are quite variable and confounded by local effects of other past and current management activities (Wondzell 2001). Much of the site level research cited in this chapter was conducted in the Pacific Northwest and may be difficult to extrapolate to other regions in the western United States. Explicit recognition of uncertainty is encouraged during planning and implementation of treatments, with an adaptive management approach to changing direction if the desired outcome is not achieved. We regard each individual fuel reduction project as an experiment and emphasize the need for monitoring to track the impacts of prescribed burning, tree removal, chipping and mastication, and salvage logging.
6. **Research is needed to address the impacts of fuel treatments on watershed processes, riparian functions, and aquatic resources.** Although studies are underway (http://jfsp.nifc.gov/JFSP_Project_Info.htm), we have noted numerous research needs throughout this review, as well as regions with limited data (for example, many Rocky Mountain ecosystems). Fuel reduction treatments are highly variable, and each treatment, sequence, or combination of treatments may have significantly different environmental effects. For assessment of cumulative effects, research on impacts of multiple stage projects is key, particularly in relation to other active management, including that of wildland fire.

References

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

Agee, J.K. 1991. Fire history along an elevational gradient in the Siskiyou Mountains, Oregon. Northwest Science. 65: 188-199.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press. Washington, DC. 505 p.

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 Jr., W.F.; 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. PSW-GTR-181. Albany, CA. USDA Forest Service, Pacific Southwest Research Station: 359-368.

Allen, J.D. 1995. Stream ecology: Structure and function of running waters. Chapman and Hall. New York. 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.

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. INT-GTR-341. Ogden, UT. USDA 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. RM-GTR-42. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station: 97-120.

Ashton, G.D. 1989. Thin ice formation. Water Resources Research. 25: 564-566.

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

Baxter, C.V.; Fausch, K.D.; Murakami, M.; Chapman, P.L. 2004. Nonnative stream fish invasions restructure stream and forest food webs by interrupting reciprocal prey subsidies. Ecology. 85: 2656-2663.

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.

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. Idaho Forest. Wildlife and Range Policy Analysis Group. Report No. 8. 35 p.

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. 2003. Wood recruitment processes and wood budgeting. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 49-73.

Benson, R.E. 1982. Management consequences of alternative harvesting and residue treatment practices—lodgepole pine. INT-GTR-132. USDA Forest Service. Intermountain Forest Range Experimental Station. Ogden, UT. 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. Seattle, Washington. University of Washington. Institute of Forest Resources. Contribution Number. 57: 191-232.

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. Springer-Verlag, New York, Inc: 324-346.

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.; Ward, J.W. 1991. Characteristics and function 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 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. Springer-Verlag, New York, Inc.: 373-398.

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

Bisson, P.A.; Wondzell, S.M.; Reeves, G.H.; Gregory, S.V. 2003b. Trends in using wood to restore aquatic habitats and fish communities in western North American rivers. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 391-406.

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. American Institute of Fisheries Research Biologists. Juneau, Alaska: 121-129.

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

Bormann, F.H.; Likens, G.E. 1979. Pattern and process in a forested ecosystem. Springer-Verlag New York. 253 p.

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.

Brosofske, K.D.; Chen, J.; Naiman, R.J.; Franklin, J.F. 1997. Effects of harvesting on microclimate from small streams to uplands in western Washington. Ecological Applications. 7: 1188-1200.

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

Brown, J.K.; Reihhardt, E.D.; Kramer, K.A. 2003. Coarse woody debris: Managing benefits and fire hazard in the recovering forest. RMRS-GTR-105. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station. 16 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. University of Washington, Seattle. Contribution No. 59: 165-181.

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

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.

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.

Colorado Native Plant Society [CNPS]. 1997. Rare plants of Colorado. Falcon Press, Helena, MT, and the Rocky Mountain Nature Association. Estes Park, CO. 107 p.

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.

Crowe, E.A.; Clausnitzer, R.R. 1997. Mid-montane wetland plant associations of the Malhuer, Umatilla, and Wallowa-Whitman National Forests. U.S. Department of Agriculture, Forest Service. R6-NR-ECOL-TP-22-97.

Davies-Colley, R.J. 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research. 31: 599-608.

Davidson, E.A.; Swank, W.T. 1987. Factors limiting denitrification in soils from mature and undisturbed southeastern hardwood forests. Forest Science. 33: 135-144.

DeBano, L.F. 2000. The role of fire and soil heating on water repellency in wildland environments: A review. Journal of Hydrology. 231-232: 195-206.

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

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.

Dolloff, C.A.; Warren, M.L., Jr. 2003. Fish relationships with large wood in small streams. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 179-193.

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.

Duff, J.H.; Triska, F.J. 1990. Denitrification in sediments from the hyporheic zone adjacent to a small forested stream. Canadian Journal of Fisheries and Aquatic Science. 47: 1140-1147.

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.

Dwire, K.A.; Kauffman, J.B. 2003. Fire and riparian ecosystems in landscapes of the western USA. Forest Ecology and Management. 178 (1-2): 61-74.

Eastman, D.C. 1990. Rare and endangered plants of Oregon. Beautiful America Publishing Company. Wilsonville, OR. 194 p.

Edwards, E.D.; Huryn, A.D. 1995. Annual contribution of terrestrial invertebrates to a New Zealand trout stream. New Zealand Journal of Marine and Freshwater Research. 29: 465-475.

Edwards, E.D.; Huryn, A.D. 1996. Effect of riparian land use on contributions of terrestrial invertebrates to streams. Hydrobiologia. 337: 151-159.

Edwards, R.T. 1998. The Hyporheic Zone. In: River Ecology and Management. Naiman R.J.; Bilby, R.E. [Eds.]. Springer-Verlag: 399-429.

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.

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.

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 Stream Restoration Working Group. 1998. Stream corridor restoration: Principles, processes, and practices. National Technical Information Service. U.S. Department of Commerce. Washington, DC.

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

Forest Ecosystem Management Assessment Team (FEMAT). 1993. Forest ecosystem management: An ecological, economic, and social assessment. USDA Forest Service. U.S. Department of Commerce. National Oceanic and Atmospheric Administration. National Marine Fisheries Service. USDI Bureau of Land Management. Fish and Wildlife Service. National Park Service. Environmental Protection Agency. Portland, OR. [Irregular pagination].

Fisher, R.F.; Binkley, D. 2000. Ecology and management of forest soils. Third edition. Wiley and Sons, New York. 489 p.

Fisher, S.G.; Likens, G.E. 1973. Energy flow in Bear Brook, New Hampshire: An integrative approach to stream ecosystem metabolism. Ecological Monographs. 43: 421-39.

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

Forman, R.T.T.; Alexander, L. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics. 29: 207-231.

Frissell, C.A.; Liss, W.J.; Warren, C.E.; Hurley, M.D. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management. 10: 199-214.

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.

Gelbard, J.L.; Belnap, J. 2003. Roads as conduits for exotic plant invasions in a semi-arid landscape. Conservation Biology. 17: 420-432.

Giardina, C.P.; Rhoades, C.C. 2001. Clearcutting 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.

Giardina, C.P.; Sanford, R.L., Jr.; Dockersmith, I.C.; Jaramillo, V.J. 2000. The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. Plant and Soil. 220: 247-260.

Gilliam, J.W. 1994. Riparian wetlands and water quality. Journal of Environmental Quality. 23: 896-900.

Graham, R.T.; McCaffrey, S.; Jain, T.B. Tech. Eds. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. RMRS-GTR-120. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station. 43 p.

Gregory, K.J. 2003. The limits of wood in world rivers: Present, past, and future. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 1-19.

Gregory, K.J.; Gurnell, A.M. 1988. Vegetation and river channel form and process. In: Viles, H. [Ed.]. Biogeomorphology. Basil Blackwell, Oxford, UK: 11-42.

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. Island Press. Washington, DC: 69-85.

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

Gregory, S.V.; Boyer, K. L.; Gurnell, A.M. [Eds.]. 2003. The ecology and management of wood in world rivers. American Fisheries Society 37. Bethesda, MD.

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.

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.

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

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

Harrod, R.J. 2001. The effect of invasive and noxious plants on land management in Oregon and Washington. Northwest Science. 75: 85-90.

Harmon, M.E. 2002. Moving towards a new paradigm for woody detritus management. 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. PSW-GTR-181. Albany, CA. USDA Forest Service. Pacific Southwest Research Station: 929-944.

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.

Haycock, N.E.; Pinay, G. 1993. Groundwater nitrate in grass and poplar vegetated riparian buffer strips during the winter. Journal of Environmental Quality. 22: 273-278.

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.

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.

Healthy Forests Restoration Act of 2003 [HFRA]. 2003. [Online]. Part 1. 28 p. http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_reports&docid=f:hr096p1.108.pdf. Part 2. 84 p. http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_reports&docid=f:hr096p2.108.pdf. [July 2009].

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.

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

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

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.

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

Hussey, M.R.; Skinner, Q. D.; Harvey, A.J. 1985. Denitrification and bacterial numbers in riparian soils of a Wyoming mountain watershed. Journal of Range Management. 38: 492-496.

Jacinthe, P.A.; Groffman, P.M.; Gold, A.J.; Mosier, A. 1998. Patchiness in microbial nitrogen transformations in groundwater in a riparian forest. Journal of Environmental Quality. 27: 156-164.

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.

Kauffman, J.B. 2004. Death rides the forest: perceptions of fire, land use, and ecological restoration of western forests. Conservation Biology. 18: 878-882.

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. Oregon State University Press. Corvallis, OR: 361-388.

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

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. Springer-Verlag, New York, Inc.: 235-258.

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. Washington Department of Fish and Wildlife. Olympia, WA. 181 p.

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.

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.

Leaf, C.F. 1966. Sediment yields from high mountain watersheds, central Colorado. USDA Forest Service Research Paper RM-23: 15 p.

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.

Li, H.W.; Lamberti, G.A.; Pearsons, 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.

Lienkaemper, G.W.; Swanson, C.D. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Canadian Journal of Forest Research. 17: 150-156.

Lisle, T.E. 2002. How much dead wood in stream channels is enough? In: Laudenslayer Jr., W.F.; 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. PSW-GTR-181. Albany, CA. USDA Forest Service. Pacific Southwest Research Station: 85-93.

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.

Lyon, L.J.; Huff, M.H.; Smith, J.K. 2000. Fire effects on wildlife foods. In: Smith, J.K. [Ed.]. 2000. Wildland fire in ecosystems: Effects of fire on fauna. RMRS-GTR-42. Ogden, UT. USDA Forest Service. Rocky Mountain Research Station. 1: 51-58.

Lyons, J.; Trimble, S.W.; Paine, L.K. 2000. Grass versus trees: Managing riparian areas to benefit streams of North America. Water Resources Bulletin. 36: 919-930.

Macdonald, E.; Burgess, C.J.; Scrimgeour, G.J.; Boutin, S.; Reedyk, S.; Kotak, B. 2004. Should riparian buffers be part of forest management based on emulation of natural disturbance? Forest Ecology and Management. 187: 185-196.

Mackensen, J.; Bauhus, J.; Webber, E. 2003. Decomposition rates of coarse woody debris—A review with particular emphasis on Australian tree species. Australian Journal of Botany. 51: 27-37.

McCarter, J.M.; Wilson, J.S.; Baker, P.J.; Moffett, J.L.; Oliver, C.D. 1998. Landscape management through integration of existing tools and emerging technologies. Journal of Forestry. 96: 17-23.

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. Springer-Verlag, New York, 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-fire stands, western Oregon. Northwest Science. 67: 7-15.

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.

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. Springer-Verlag, New York: 401-414.

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. New Haven, Connecticut: 123-135.

Monleon, V.J.; Cromack, Jr. K. 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: 369-378.

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association. 35: 397-410.

Montgomery, D.R.; Buffington, J.M. 1998. Channel processes, classification, and response potential. In: Naiman, R.J.; Bilby, R.E. [Eds.]. River Ecology and Management: Lessons from the Pacific Coastal Region. Springer-Verlag, New York, Inc.: 13-42.

Montgomery, D.R.; Collins, B.D.; Buffington, J.M.; Abbe, T.B. 2003. Geomorphic effects of wood in rivers. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 21-47.

Mosley, J.C.; Cook, P.S.; Griffis, A.J.; O'Laughlin, Jay. 1997. Guidelines for managing cattle grazing in riparian areas to protect water quality: Review of research and best management practices policy. Idaho Forest, Wildlife and Range Policy Analysis Group. Report No. 15. 67 p.

Naiman, R.J.; Decamps, H. 1997. The ecology of interfaces: Riparian zones. Annual review of Ecology and Systematics. 28: 621-658.

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

Naiman, R.J.; Fetherston, K.L.; Mckay, S.J.; Chen, J. 1998. Riparian forests. In: Naiman, R.J.; Bilby, R.E. [Eds.]. River ecology and management: Lessons from the Pacific Coastal Region. Springer-Verlag, New York, Inc.: 289-323.

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

Nakano, S.; Miyasaka, H.; Kuhara, N. 1999. Terrestrial-aquatic linkages: Riparian arthropod inputs alter trophic cascades in stream food webs. Ecology. 80: 2435-2441.

National Council for Air and Stream Improvement [NCASI]. 2005. Riparian zone management and the protection of biodiversity: A problem analysis. Technical Bulletin No. 908. 107 p. + appendices.

National Research Council (NRC). 2002. Riparian areas. National Academy Press. Washington, DC.

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.

Newbold, J.D.; Mulholland, P.S.; Elwood, J.W.; O'Neill, R.J. 1982. Organic carbon spiraling in stream ecosystems. Oikos. 38: 266-272.

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.

O'Laughlin, J. 2005. Conceptual model for comparative ecological risk assessment of wildfire effects on fish, with and without hazardous fuel treatment. Forest Ecology and Management. 211: 59-72.

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.

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: 1557-573.

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. 9 p.

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.

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.; Johnson, M.C.; Agee, J.K.; Jain, T.B.; McKenzie, D.; Reinhardt, E.D. 2003. Fuels planning: Managing forest structure to reduce fire hazard. In: Proceedings of the second international wildland fire ecology and fire management congress and fifth symposium on fire and forest meteorology. November 16-20, 2003. Orlando, FL. American Meteorological Society.

Peterson, D.L.; Johnson, M.C.; Agee, J.K.; Jain, T.B.; McKenzie, D.; Reinhardt, E.D. 2005. Forest structure and fire hazard in dry forests of the western United States. USDA Forest Service. Portland, OR. PNW-GTR-628. Pacific Northwest Research Station. 30 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.

Pilliod, David S.; Bull, Evelyn L.; Hayes, Jane L.; Wales, Barbara C. 2006. Wildlife and invertebrate response to fuel reduction treatments in dry coniferous forests of the Western United States: A synthesis. RMRS-GTR-173. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station. 34 p.

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. American Geophysical Union. 8: 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.

Poole, G.C. 2002. Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. Freshwater Biology. 47: 641- 660.

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.

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. Bureau of Land Management. Denver, CO. BLM/SC/ST-93/003+1737+REV95+REV98. 60 p.

Raedeke, K.J. [Ed.]. 1988. Streamside management: Riparian wildlife and forestry interactions, Contribution No. 59. Institute of Forest Resources. University of Washington, Seattle.

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. In: Nielsen, J.L. [Ed.]. Evolution and the aquatic ecosystem: Defining unique units in population conservation. American Fisheries Society Symposium. Bethesda, Maryland. 17: 334-349.

Regional Ecosystem Office (REO). 1995. Ecosystem analysis at the watershed scale, version 2.2. U.S. Government Printing Office. Portland, OR. 1995 - 689-120/21215 Region 10. 26 p.

Reich, M.; Kershner, J.L.; Wildman, R.C. 2003. Restoring streams with large wood: A synthesis. In: Gregory, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 355-366.

Reid, L.M. 1998. Cumulative watershed effects and watershed analysis. In: Naiman, R.J.; Bilby, R.E. [Eds.]. River ecology and management: Lessons from the Pacific Coastal Region. Springer-Verlag, New York, Inc.: 476-501.

Resh, S.C.; Ryan, M.G.; Joyce, L.; Binkley, D. 2006. Chipping and mastication in forest ecosystems-a synthesis (unpublished manuscript).

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

Rieman, B.E.; 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.

Rich, J.J.; Myrold, D.D. 2004. Community composition and activities of denitrifying bacteria from adjacent agricultural soil, riparian soil, and creek sediment in Oregon, USA. Soil Biology and Biochemistry. 36: 1431-1441.

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.

Rosgen, D. 1994. A classification of natural rivers. Catena. 22: 169-199.

Saab, V.A.; Dudley, J. 1998. Responses of cavity-nesting birds to stand-replacement fire and salvage logging in ponderosa pine/Douglas-fir forests of southwestern Idaho. Res. Pap. RMRS-RP-11. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station. 17 p.

Saab, V.A.; Powell, H.D.W. 2005. Fire and avian ecology in North America: Process influencing pattern. Studies in Avian Biology. 30: 1-30.

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

Sandberg, D.V; Ottmar, R.D.; Cushion, G.H. 2001. Characterizing fuels in the 21st century. International Journal of Wildland Fire. 10: 381-387.

Schumm, S.A. 1977. The Fluvial System. John Wiley and Sons, New York. 338 p.

Sedell, J.R.; Froggatt, J.L 1984. Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon from its floodplain by snagging and streamside forest removal. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie. 22: 1828-1834.

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. Bethesda, MD. 10: 160-175.

Sedell, J.R.; Naiman, R.J.; Cummins, K.W.; Minshall, G.W.; Vannnote, R.L. 1978. Transport of particulate organic matter in streams as a function of physical processes. Verhandlungen der Internationalen Vereinigung für theoretische und Angewandte Limnologie. 20: 1366-1375.

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.

Simmons, R.C.; Gold, A.J.; Groffman, P.M. 1992. Nitrate dynamics in riparian forests: Groundwater studies. Journal of Environmental Quality. 21: 659-665.

Skinner, C.N. 2002. Influence of fire on the dynamics of dead woody material in forests of California and southwestern Oregon. In: Laudenslayer Jr., W.F.; 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. PSW-GTR-181. Albany, CA. USDA Forest Service. Pacific Southwest Research Station: 445-454.

Smith, J.K. [Ed.]. 2000. Wildland fire in ecosystems: Effects of fire on fauna. RMRS-GTR-42. Vol. 1. Fort Collins, CO. USDA Forest Service. Rocky Mountain Research Station. 83 p.

Spies, T.A. 1998. Forest structure: A key to the ecosystem. Northwest Science. 72: 34-39.

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. M.S. Thesis. Colorado State University. Fort Collins, Colorado. 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, 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.

Strohmaier, D.J. 2000. The ethics of prescribed fire: A notable silence. Ecological Restoration. 18: 5-9.

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

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.

Swank, W.T. 1988. Stream chemistry response to disturbance. In: Swank, W.T.; Crossley Jr., D.A. [Eds.]. Forest Hydrology and Ecology at Coweeta. Springer-Verlag, New York: 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. Institute of Forest Resources. Contribution #59. University of Washington. Seattle, WA: 9-38.

Sweeney, B.W. 1992. Streamside forests and the physical, chemical, and trophic characteristics of piedmont streams in eastern North America. Water Science Technology. 26: 1-12.

Sweeney, B.W. 1993. Effects of streamside vegetation on macroinvertebrate communities of White Clay Creek in eastern North America. Stroud Water Resources Center. Academy of Natural Sciences. Philadelphia. 144: 291-340.

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.

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. Handbook 553. USDA Forest Service: 40-47.

Thorne, C.R. 1990. Effects of vegetation on riverbank erosion and stability. In: J.B. Thornes (Ed.). Vegetation and erosion: Processes and environments. John Wiley and Sons. Chichester, UK: 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 clearcutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Sciences. 1: 325-332.

Trombulak, S.C.; Frissell, C.A. 2000. Review of the ecological effects of roads on terrestrial and aquatic communities. Conservation Biology. 14: 18-30.

U.S. Department of Agriculture [USDA]. 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. USDA Forest Service. Region 1. Missoula, MT.

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

USDA Forest Service; U.S. Department of the Interior [USDA USDI]. 2002. National Fire Plan. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy implementation plan. Washington, DC. 27 p. [Online]. http://www.westgov.org/wga/initiatives/fire/implem_plan.pdf. [July 2009].

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

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, John; Gregory, Stanley V. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research. 20: 1593-1601.

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.

Waide, J.B.; Caskey, W.H.; Todd, R.L.; Boring, L.R. 1988. Changes in soil nitrogen pools and transformations following forest clearcutting. In: Swank, W.T.; Crossley Jr., D.A. [Eds.]. Forest hydrology and ecology at Coweeta. Springer-Verlag, New York: 221-232.

Wales, B.C. 2001. The management of insects, diseases, fire, and grazing and implications for terrestrial vertebrates using riparian habitats in eastern Oregon and Washington. Northwest Science. 75: 119-127.

Ward, J.V.; Stanford, J.A. 1995. The serial discontinuity concept: Extending the model to floodplain rivers. Regulated Rivers: Research and Management. 10: 159-168.

Webster, J.R.; Benfield, E.F. 1986. Vascular plant breakdown in freshwater ecosystems. Annual Review of Ecology and Systematics. 17: 567-594.

Webster, J.R.; Meyer, J.L. 1997. Stream organic matter budgets—introduction. Pages 3-13. In: Webster, J.R.; Meyer, J.L. [Eds.]. Stream organic matter budgets. Journal of the North American Benthological Society. 16: 3-161.

Weller, D.E.; Jordan, T.E.; Correll, D.L. 1998. Heuristic models for material discharge from landscapes with riparian buffers. Ecological Applications. 8: 1156-1169.

Wohl, E.E. 2001. Virtual rivers: Lessons from the mountain rivers of the Colorado Front Range. Yale University Press. New Haven, Connecticut. 224 p.

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, Stanley V.; Boyer, Kathryn L.; Gurnell, Angela M. [Eds.]. The ecology and management of wood in world rivers. American Fisheries Society. Bethesda, MD. 37: 249-264.

Wu, T.H. 1986. Root geometry model and simulation. Unpublished final report. National Science Foundation Grant CEE-811253. USDA Forest Service Grant PNW-83-317. Department of Civil Engineering. Ohio State University. 62 p.

Wynn, T.M.; Mostaghimi, S.; Burger, J.A.; Harpold, A.A.; Henderson, M.B.; Henry, L. 2004. Variation in root density along stream banks. Journal of Environmental Quality. 33: 2030-2039.

Young, M.K.; Haire, D.; Bozek, M.A. 1994. The impact and extent of railroad tie drives in streams of southeastern Wyoming. Western Journal of Applied Forestry. 9: 125-130.

Young, M.K.; Mace, E.A.; Ziegler, E.T.; Sutherland, E.K. 2006. Characterizing and contrasting instream and riparian coarse wood in western Montana basins. Forest Ecology and Management. 226: 26-40.

Young, M.K.; Rader, R.B.; Belish, T.A. 1997. Influence of macroinvertebrate drift and light on the activity and movement of Colorado River cutthroat trout. Transactions of the American Fisheries Society. 126: 428-437.

Youngblood, A.P.; Padgett, W.G.; Winward, A.H. 1985. Riparian community type classification of eastern Idaho—western Wyoming. USDA Forest Service. Intermountain Region. R4-Ecol-85-01.