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Fire and riparian ecosystems in landscapes of the western USA

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Abstract

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

Keywords: Riparian areas; Western USA; Fire behavior; Fire severity; Riparian fire regimes; Land use; Riparian-aquatic habitat; Postfire recovery

1. Introduction

Wildfire is a widespread natural disturbance in landscapes of the western USA (Turner and Romme, 1994; Agee, 1998), and the effects of fire on vegetation, soils, water yield, and erosion have been studied in different regions and numerous forest types (Gresswell, 1999; Brown, 2000; Arno and Allison-Bunnell, 2002). More recently, there has been increased interest in the effects of fire on aquatic habitats and stream biota (Minshall et al., 1989; Minshall et al., 1997; Gresswell, 1999; Bisson et al., 2003). Despite the recognized linkages between streams and riparian zones, however, few studies have directly addressed

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the effects of fire on riparian ecosystems. Although they may occupy only 0.5 to 2.0% of the landscape, riparian areas provide critical habitat for numerous terrestrial and aquatic species (Naiman et al., 1993; Kauffman et al., 1997; Kauffman et al., 2001), and may affect fire properties and patterns at local and landscape scales. The ecological diversity of riparian corridors is maintained by natural disturbance regimes (Naiman et al., 1993), including fire and fire-related flooding, debris flows and landslides, and little is known about the fire properties and fire history of most riparian areas of the western USA.

Riparian areas are defined as ''three-dimensional zones of direct physical and biotic interactions between terrestrial and aquatic ecosystems, with boundaries extending outward to the limits of flooding and upward into the canopy of streamside vegetation'' (Gregory et al., 1991). The first dimension of riparian areas is the longitudinal continuum from headwater streams to the oceans (Vannote et al., 1980). The second is the vertical dimension that extends upward into the vegetation canopy and downward into the subsurface and includes belowground interactions for the length of the stream-riparian corridor. The vertical dimension encompasses the distinct microclimates often associated with riparian areas. The third dimension is lateral, extending to the limits of flooding on either side of the stream or river (Stanford and Ward, 1993). Collectively, the three dimensions likely influence fire properties in riparian areas and contribute to differences in fire regimes between riparian areas and adjacent uplands.

The objectives of this paper are to: (1) synthesize the limited research conducted on fire regimes in riparian areas relative to uplands; (2) summarize the distinctive features of riparian zones that influence the properties of fire; (3) discuss the impacts of land use as they may affect fire behavior in riparian areas; and (4) describe the adaptations of riparian plant species to fire. Because data are limited on these topics, portions of the discussion are speculative, and some conclusions are tentative.

The fire terminology used in this paper is derived from Agee (1993) and Brown and Smith (2000). Fire frequency refers to the recurrence of fire in a given area over time. Mean fire-return interval is the average time interval between fires for a given area. Fire severity is a qualitative measure of the immediate effects of fire on the ecosystem, including vegetation and soil. Type of fire is related to the fuels that support the fire, namely surface fire, ground fires, and crown fires. Fire weather encompasses the climatic factors that influence the behavior and spread of fires including air temperature, relative humidity, winds, and precipitation patterns.

2. Properties and behavior of fire in riparian areas

2.1. Fire regimes in riparian areas

Fire regimes in western North America are described in terms of fire frequency, magnitude, fireline intensity, and spatial scale and pattern (Agee, 1993; Baker, 1989; Brown, 2000) and reflect characteristics of the vegetation and fuels, fire weather, and other environmental conditions (Agee, 1993; Agee, 1998). The severity, size, and frequency of fires exert strong influences on patterns of forest composition, structure, and successional dynamics (Agee, 1993; Halpern and Spies, 1995). Our understanding of fire frequency is based largely on retrospective studies of tree-rings, postfire stand ages, and analysis of fire scars. These techniques provide information about the recent past (last several hundred years) but generally do not incorporate the longer-term influence of climate (Whitlock et al., 2003).

Fire history studies in low- to mid-elevation forest types, such as those dominated by ponderosa pine (*Pinus ponderosa*), indicate that fires generally occurred more frequently prior to European-American settlement (Covington and Moore, 1994a,b; Covington et al., 1994; Arno et al., 1997). The longest fire-free intervals in many low- and mid-elevation forests and rangelands have occurred in the 20th century (Arno and Gruell, 1983). Fire suppression and landscape fragmentation due to multiple land uses have contributed to the reduction of fire frequencies (Baker, 1993; Peterson, 1998), accumulation of fuels, and alteration of fire regimes in much of the western USA (Arno, 2000). In the Pacific Northwest, increased disease and insect outbreaks appeared to be related to fire suppression (Hessburg et al., 1994; Swetnam et al., 1995). In forests that evolved with low- or mixed-severity fire regimes, vegetation and fuel structures are currently more conducive to high-severity fires (Arno et al., 1997; Pyne, 1997; Agee, 1998).

Research on fire regimes in riparian areas relative to adjacent uplands indicates that fire frequency and severity varies by region and forest type. For riparian forests of the western Cascade Mountains, Oregon, Morrison and Swanson (1990) suggested that fire frequency was generally lower and fire severity was more moderate than in adjacent uplands. In the eastern Cascade Mountains of Washington, areas least likely to burn (fire refugia) were frequently located near confluences of perennial streams (Camp et al., 1997). In Mount Rainier National Park, Washington, high intensity, stand-replacing fires have resulted in a mosaic of different age classes in upland forests (Hemstrom and Franklin, 1982). However, old-growth conifers occurred mostly along river valleys, suggesting a more moderate fire regime in riparian areas. In eastern Idaho, the mean fire return interval was estimated to be approximately 30 years for upland grand fir (*Abies grandis*) stands, and about 48 years in riparian communities, dominated by western red cedar (*Thuja plicata*) (Barrett, 1988). In the Klamath Mountains of northern California, Skinner (2003) found that the median fire return intervals were twice as long in riparian reserves as in upland sites, suggesting that fires occurred less frequently in riparian areas. Olson (2000) quantified the fire history of upland and riparian forests, (low-severity fire regime) dominated by ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and grand fir, and (mixed-severity fire regime) mesic forests, dominated by grand fir in the Blue Mountains and South Cascades of Oregon. In these drier forest types, fire return intervals were generally similar in upslope and riparian stands, indicating that fires typically burned the riparian areas with comparable frequency.

Fewer studies have investigated the relations between fire regimes in upland and riparian vegetation for semi-arid shrublands and grasslands (Paysen et al., 2000), where the riparian plant communities are dominated by deciduous hardwoods (Patten, 1998). In prairie grasslands, fire return intervals range from 10 to 30 years (Paysen et al., 2000), and fires burn periodically into the deciduous riparian woodlands. In a tree-ring analysis of riparian cottonwoods harvested on the Oldman River in Alberta, Canada, Mahoney et al. (1991) found up to four fire scars per century, suggesting the periodic occurrence of low-intensity surface fires rather than stand-replacing fires. This paucity of information underscores the need for better knowledge of fire frequency and the ecological role and importance of fire in riparian ecosystems, particularly for riparian communities dominated by deciduous hardwoods.

2.2. Physical characteristics of riparian areas that influence fire properties

Riparian areas generally differ from surrounding uplands in topography, microclimate, geomorphology, and vegetation (Table 1). However, limited research has been conducted on how riparian characteristics influence fire properties. Riparian areas are typically located at the lowest point in most landscapes, where slopes are often less steep than those in surrounding uplands. This topographic position, as well as proximity to surface water, presence of saturated soils, and provision of shade by riparian vegetation, contributes to the distinct microclimates that occur in many riparian areas. Riparian microclimates are generally characterized by cooler air temperature, lower daily maximum air temperature, and higher relative humidity than the microclimates of adjacent uplands (Brosofske et al., 1997; Danehy and Kirpes, 2000). In steep canyons, topographic shade may also influence the cooler microclimates along stream corridors. Moister, cooler microclimates likely contribute to higher moisture content of live and dead fuels and riparian soils relative to uplands, presumably lowering the intensity, severity, and frequency of fire in riparian areas.

Basin topography encompasses gradients in elevation and aspect that influence air movement patterns, such as seasonal cold air drainage through stream-riparian corridors. Wind speeds are generally lower in valleys that are protected by side slopes and are usually slowed and dispersed by trees in forested uplands. In montane riparian areas, disturbance from high winds may be lower than in surrounding uplands and along ridgelines, and consequently, the quantity of downed large wood fuels could potentially decrease. During fire events, if wind speeds are lower in riparian zones than surrounding uplands, fire behavior may be less severe, with decreased rate of spread, decreased flame lengths, and lower fireline intensities. Conversely, steep canyons may serve as wind tunnels and possibly increase wind speeds in narrow valley

Table 1
Riparian related characteristics that may influence fire behavior and spread in forest and rangeland landscapes of the western USA

Fire risk factor	Riparian characteristic	Fire effect
Fuel loads	High fuel loads due to high net primary productivity; accumulation of fuels due to low fire return intervals	High fuel loads can increase vulnerability to fire in drought conditions, and influence fire severity, intensity, and return intervals
Fuel moisture content	High fuel moisture content due to proximity to water, shallow water tables and dense shade	Fuel loads may remain too moist for sustained fire spread late into the fire season
Fuel continuity	Active channels, gravel bars, and wet meadows may function as natural fuel breaks	Breaks in fuel continuity can prevent or slow the spread of fire
Topographic position	Canyon bottoms; lowest points on the landscape	High fuel moisture, high relative humidity, and few lightning strikes may decrease fire frequency and severity; more human-caused ignitions may increase fire frequency
Microclimate	Topography, presence of water and dense shade can create cooler, moister conditions	High relative humidity and cool temperatures may lessen fire intensity and rate of spread

bottoms. Lightning-caused fire ignitions are less likely to occur in riparian areas due to higher moisture content of fine fuels, fuel types, topographic position, and characteristics of lightning (Latham and Williams, 2001). However, more intensive human use of riparian areas, including recreation, settlements, and transportation networks, may lead to more human-caused ignitions than in adjacent uplands.

Geomorphic features of stream-riparian corridors can also influence fire properties. The continuous stream channel may function as a natural firebreak, particularly along alluvial reaches where extensive, unvegetated gravel bars may slow or halt an advancing fire front. In unconstrained reaches, riparian soils are frequently deeper and have higher soil moisture and greater proximity to the water table than upland soils. Higher moisture content in vegetation and dead fuels, combined with higher soil moisture content, could reduce fire intensity and slow rates of spread as a fire moves across a riparian zone. For example, wet meadows, where moisture content of fuels and soils are generally higher than in surrounding uplands, may serve as fire breaks until late in the fire season.

The degree to which fire properties vary from riparian areas to uplands also depends on the topographic continuity of the landscape. In conifer dominated headwater streams, fire properties may be similar in riparian areas and uplands due to small differences in topography, microclimate, vegetation, and fuels (Agee et al., 2002). However, marked differences in physical characteristics and fuels may be expected in deep canyons occurring in an otherwise level landscape, or along wide alluvial reaches in a mountainous landscape. In the northern Great Plains, fires were frequent in open grasslands but thought to occur less frequently in rough and dissected terrain (Higgins, 1984). Under drought conditions, with the simultaneous occurrence of high temperatures, high wind speeds, and low relative humidity, fire weather would likely override local physical variables as the primary determinant of fire behavior. In this case fire may behave similarly in riparian areas and in uplands.

2.3. Influence of riparian vegetation on fire properties

The properties of fire are also affected by characteristics of vegetation, such as the quantity, chemistry, moisture content, and size distribution of fuels (Agee, 1993). In conifer-dominated riparian areas, the dominant tree species are frequently the same as those in surrounding uplands (Case, 1995). However, riparian forests generally have better access to moisture and may differ in understory vegetation, fuel loads, ratio of live-to-dead material (flammability), and fuel moisture (Table 1). Agee et al. (2002) measured late season foliar moisture in paired upland-riparian stands of Douglas-fir, grand fir, and sub-alpine fir (*Abies lasiocarpa*) in the Blue Mountains of northeastern Oregon. In the Douglas-fir and grand fir series, they observed no differences in conifer foliar moisture between the upland and riparian stands; however, understory shrub and herbaceous foliar moisture was considerably higher in the riparian stands. In addition, herbaceous foliar moisture was more variable in the riparian stands, a condition that the authors attributed to the diversity of herbaceous species occurring in the riparian understory. Understory fuel moisture has been shown to affect the rate of spread, fire line intensity, fuel consumption, and plant mortality in coniferous forests (Kauffman and Martin, 1989; Kauffman and Martin, 1990), and consequently higher moisture content of riparian fuels may reduce fire intensity and severity relative to uplands.

The extent to which a riparian area serves as a fire barrier depends on the size or extent of the stream and riparian area, topography, and characteristics of riparian fuels (Table 1). Agee (1998) described a situation where portions of the riparian area bordering Little French Creek, Payette National Forest, Idaho served as corridors of severe fire. The riparian vegetation contained multiple structural layers and large amounts of standing dead fuel and burned with a severe crown fire. In contrast, the surrounding upland forest, which had burned twice in the previous 100 years, was composed of widely spaced lodgepole pine (*Pinus contorta*) with little coarse woody debris; this area experienced low-intensity spot fires. In riparian areas bordering intermittent streams in the Klamath Mountains of California, Taylor and Skinner (1998) found that fires had been frequent and suggested that some headwater reaches may act as chutes where fires may spread readily and burn intensely. Fuel characteristics and potential for crown fire initiation (torching) were studied in paired upland—riparian stands of Ponderosa pine/Douglas-fir, grand fir, and sub-alpine fir, in the Blue Mountains, northeastern Oregon (Williamson, 1999). The potential for torching was high in both upland and riparian forests of all forest types, suggesting that the potential for high-severity fire could extend from uplands through the valley bottoms.

The limited research on the influence of riparian vegetation on fire properties has been conducted in areas of the Pacific Northwest where upland and riparian forests are dominated by the same conifer species. However, in much of the western USA, riparian plant communities are quite distinctive from surrounding vegetation. Riparian vegetation may be dominated by deciduous trees and shrubs, including alders (*Alnus* spp.), willows (*Salix* spp.), quaking aspen (*Populus tremuloides*), and cottonwoods (*Populus* spp.; Patten, 1998), and these areas can differ considerably in fuel characteristics (chemistry, fuel composition, and moisture content) from conifer, shrub, or grassland-dominated uplands. Montane meadows border a significant portion of streams in some parts of the western USA. Grass and sedge dominated meadows often produce high loads of fine fuels (3–11 Mg/ha; Otting, 1998; Dwire, 2001) that may burn late in the fire season. The distribution of riparian vegetation is patchy, frequently consisting of a mosaic of different plant communities and age classes that have developed as a result of multiple fluvial disturbances (Naiman et al., 1993; Tabacchi et al., 1998). Because fire behavior is influenced by fuel characteristics, the variation in riparian vegetation likely contributes to the tendency for many fires to burn in a patchy manner through riparian areas. These speculations are tentative, however, since few data are available on fuel loads, fuel chemistry, or fuel moisture for most common riparian plant communities, and on how the distribution of fuels influences fire behavior in stream-riparian corridors.

3. Interactions of land use and fire in riparian areas

Characteristics of riparian areas result from numerous complex interactions among climatic, biotic, and geomorphic influences (Fig. 1; Gregory et al., 1991; Naiman and Decamps, 1997; Kauffman et al., 1997). Human activities that alter one or more of these components will be reflected in other components over various time scales through feedback responses, leading to changes in riparian species composition, and affecting the structure and function of riparian ecosystems (Kauffman et al., 1997). Forest cutting, road building, and channel simplification can influence geomorphologic processes that are part of the natural disturbance regime for many watersheds (Nakamara et al., 2000). Elimination of beaver from western watersheds during the past two centuries likely decreased the zone of saturation in riparian zones and reduced the area of wet meadows, thus altering the lateral extent and composition of riparian vegetation (Naiman et al., 1994). Damming and flow regulation of rivers have also influenced the areal extent, structure, and species composition of riparian vegetation (Rood et al., 1995; Shafroth et al., 2002),

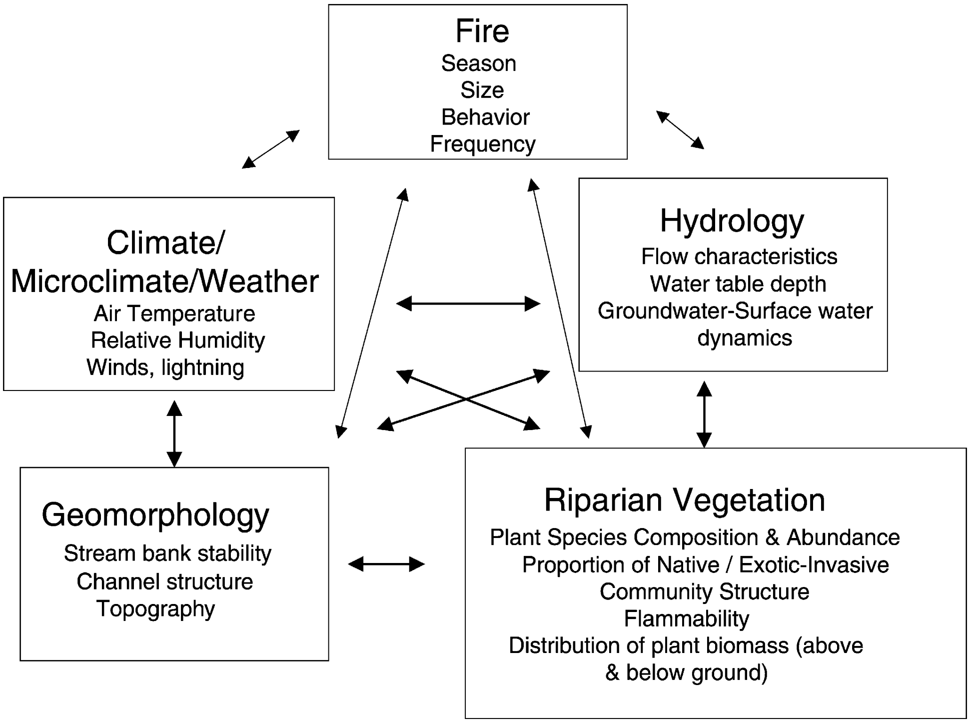

Fig. 1. Interactions (indicated by arrows) among fire, hydrology, geomorphology, climate/weather, and vegetation that contribute to the structure, function and composition of riparian ecosystems. Land-use impacts on one component may result in eventual changes in the other components.

affected channel characteristics (Shafroth et al., 2002), and altered hydrological and geomorphologic processes (Poff et al., 1997). Riparian ecosystems have also been altered due to livestock grazing (Kauffman and Krueger, 1984), urbanization, and agricultural and recreational development. Cumulative effects of multiple land uses can have dramatic consequences for the condition and functioning of riparian and aquatic ecosystems (Patten, 1998).

Impacts of land use and management may strongly influence the fire properties in some riparian areas. Where streams and riparian areas have been degraded by land and water use, fire properties may begin to resemble the drier uplands. As in uplands, fire suppression in forested riparian areas with low-severity fire regimes has resulted in increased fuel loads and changes in vegetation composition and structure (Arno and Allison-Bunnell, 2002). For example, quaking aspen, an important species for maintenance of biological diversity, is declining in abundance in the western USA largely because of fire exclusion and overgrazing by wildlife and livestock (Fig. 2; Bartos and Campbell, 1998). Shifts in riparian species composition related to hydrologic modification of watersheds and the introduction of invasive non-native species have also resulted in changes in fuel characteristics. In the southwestern US, for example, river damming, flow regulation, and water diversions have contributed to the transformation of native riparian gallery forests, dominated by Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*), to riparian scrub thickets, dominated by exotic tamarisk species (*Tamarix* spp.) (Graf, 1982; Busch and Smith, 1995; Everitt, 1998; Smith et al., 1998). Tamarisk produces large quantities of highly combustible fuels, and its dominance in riparian floodplains has apparently altered the role and influence of fire in structuring riparian communities (Busch and Smith, 1995; Shafroth et al., 2002).

In landscapes typified by low- or moderate-severity fire regimes, the cumulative impacts of land use on fire behavior may be most pronounced under conditions of

Fig. 2. Fire exclusion and land use have resulted in the degradation of many riparian communities throughout the western USA. In this aspen (*P. tremuloides*) dominated riparian area in eastern Oregon, fire suppression and grazing by livestock and wildlife have resulted in degradation of the stand and accumulation of fuels (photo by J.B. Kauffman).

extreme fire weather (Kauffman, 2001). The probability of high-severity fire can be conceptualized in terms of land-use alteration along the gradient of fire weather (Fig. 3). Extreme fire weather includes periods of high air temperatures, high wind speeds, low relative humidity, and very dry fuels. Although extreme fire events are more frequent as fire weather becomes extreme, the probability of extreme fire events also increases in landscapes altered by human impacts. As the degree of departure from the historical range of variability (Morgan et al., 1994) increases in relation to land-use activities, the probability of extreme fire events becomes greater (Fig. 3). For riparian-stream corridors, this conceptual model suggests that human alterations in vegetation, hydrology, and geomorphology increase the probability of high-severity fires (Fig. 3) and reduce the capacity of riparian features to act as natural firebreaks.

4. Recovery of riparian and aquatic ecosystems following fire

4.1. Adaptations of riparian vegetation to fire

Riparian species exhibit a range of adaptations to disturbance (Table 2) that contribute to the rapid recovery of streamside habitats following fire. These include adaptations that facilitate the survival of plants on site, such as sprouting and thick bark, and those that contribute to recolonization of burned sites, including wind and water dispersal, reproductive responses, and the capacity to establish in postfire environments (Stickney, 1986; Kauffman, 1990; Miller, 2000).

Clonal regeneration of quaking aspen (*P. tremuloides*) is promoted by light to moderate-severity fire (Jones and DeByle, 1985; Romme et al., 1995; Bartos and Campbell, 1998). When aspen trees are top-killed by fire, the roots are stimulated to produce numerous suckers (Schier, 1973; Shepperd and Smith, 1993). Most cottonwood and willow species respond to browsing by beaver and fluvial disturbances through coppice sprouting from stems, as well as production of root suckers (Rood et al., 1994). These adaptations also contribute to regeneration following fire (Fig. 4). In floodplain forests along the Oldman River in southern Alberta, Canada, 75% of the cottonwood trees sprouted vigorously from stumps within 5 months of an early spring fire (Gom and Rood, 1999). Root suckers were also common, demonstrating that fire stimulated clonal regeneration of native riparian cottonwoods. In south-central New Mexico, over 40% of Rio Grande cottonwoods (*Populus deltoides wislizenii*) that burned in two study sites produced shoots that

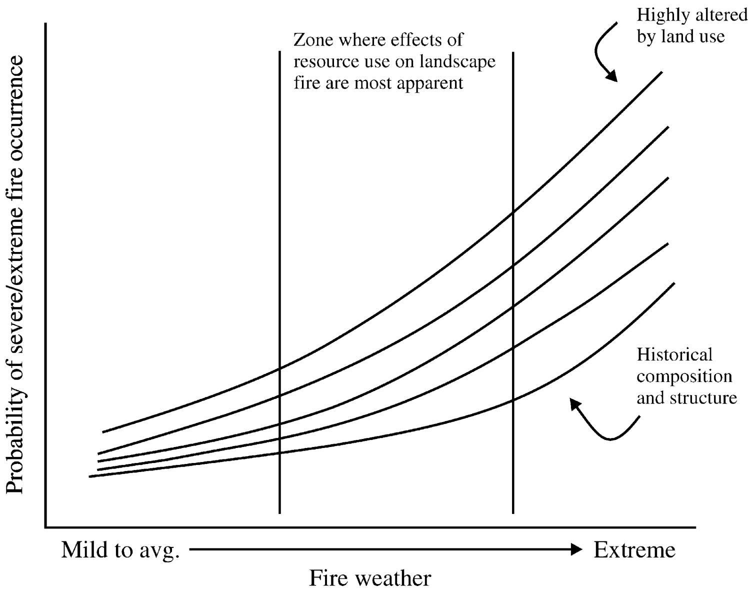

Fig. 3. Relationships among fire weather, fire severity and land use. Each curve represents a different degree of departure from the historical range of variability (Morgan et al., 1994) for a given landscape or watershed. The probability of extreme fire events increases as the degree of departure from natural conditions becomes greater. Land use and management activities that may increase the probability of high-severity fire events include fire exclusion in low-severity fire regimes, logging, and extensive livestock grazing (modified from Kauffman, 2001).

Table 2
Ecological adaptations that promote persistence and recovery of riparian plant species following fire

Adaptation	Function	Example[a]
Adaptations that facilitate survival		
Epicormic sprouting (coppice sprouting)	Regrowth from dormant buds on branches and stems protected by bark	Cottonwoods (*Populus* spp.), Oregon ash (*Fraxinus latifolia*), oaks (*Quercus* spp.), hawthorn (*Crataegus* spp.)
Basal sprouting	Regrowth from subterranean buds on root, bulbs, lignotubers, and rhizomes	Willows (*Salix* spp.), aspen (*P. tremuloides*), camas (*Camassia quamash*), sedges (*Carex* spp.), grasses
Thick bark	Protection of cambial tissues from heat damage	Ponderosa pine (*P. ponderosa*), redwood (*S. sempervirens*)
Adaptations that facilitate recolonization		
Windborne seeds	Deposition and establishment on post-fire soils	Willows, cottonwoods, willow herbs (*Epilobium* spp.)
Water-dispersed propagules	Dispersal of seeds or vegetative propagules to burned locations	Cottonwoods, willows, alders (*Alnus* spp.), sedges, rushes (*Juncus* spp.)
Fire-enhanced flowering and fruit production	Increased reproductive effort in the years following fire	Camas, blueberries (*Vaccinium* spp.), many shrubs, herbaceous dicots, and grasses
Refractory seed buried in soils	Resistant seed coat requires fire or scarification to germinate	Lupine (*Lupinus* spp.), manzanita (*Arctostaphylos* spp.), *Ceanothus* spp.
On-plant seed storage	Seed storage in cones in canopy released post-fire	Lodgepole pine (*P. contorta*)

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

Fig. 4. Recovery of riparian shrub community (includes *Salix* spp., *Alnus incana*, *Ribes* spp., and *Cornus sericea*), 5 years after the Teepee Butte fire in the Wallowa Mountains, northeastern Oregon (photo by J.B. Kauffman).

survived at least 2 years following fire (Ellis, 2001). About 73% of the native Goodding willow individuals produced shoot sprouts during the first 4 months following burning, but only 55% of the exotic tamarisk (*Tamarix ramosissima*) individuals sprouted (Ellis, 2001). Season of fire may be a critical factor in determining the capacity of cottonwoods and willows to survive fire. For example, severe summer fires in the southwestern US may kill some cottonwoods, particularly trees that are stressed or senescent (Busch and Smith, 1993; Busch, 1995).

Common riparian shrubs, such as alder, birch (*Betula* spp.), currant (*Ribes* spp.), rose (*Rosa* spp.), and snowberry (*Symphoricarpos* spp.) sprout from stumps, root crowns, and belowground stems following fire (Fig. 4; Adams et al., 1982; Stickney, 1986; Miller, 2000). In uplands, shrub survival is related to fuel consumption (Kauffman and Martin, 1990). Fire-caused tree and shrub mortality is highest when the litter layer and soil organic horizons are consumed by fire, and root crowns and other belowground tissue are killed (Stickney, 1986; Kauffman and Martin, 1990). In riparian areas, higher levels of soil moisture may prevent the combustion of soil organic matter and protect belowground tissues, thus increasing the probability of shrub survival. Most riparian sedge (*Carex* spp.) and grass species recover rapidly following light surface fires, through regeneration from roots and rhizomes (Fig. 5; Racine et al., 1987). Under low-severity fire regimes, thick bark protects the cambium of tree species that may occur in riparian areas, such as ponderosa pine, western larch (*Larix occidentalis*), and coastal redwood (*Sequoia sempervirens*) (Miller, 2000). Riparian species that grow on stream banks, in the channel, or on sparsely vegetated gravel bars may survive fire by persisting where fires generally cannot carry.

A number of riparian species display rapid postfire establishment in part because of water and wind dispersal of propagules and fire-enhanced flowering and fruit production (Table 2). Many riparian species, including willows, cottonwoods, and numerous herbaceous species can establish in high densities on burned riparian sites via postfire arrival of light, wind-borne seeds. In Hells Canyon, Idaho, Havlina (1995) found densities of Scouler's willow (*Salix scouleriana*) to be as high as 400,000/ha on burned upland sites 4 years following severe stand-replacing fires. Fluvial delivery of seeds and vegetative propagules to streamside sites during flood events can also increase recolonization of burned areas (Johansson et al., 1996; Shafroth et al., 2002). Several grasses and forbs increase reproductive output in the first few postfire years (Kauffman, 1990). The endangered Bradshaw's

Fig. 5. A montane riparian meadow (dominated by *Carex* spp.) and associated stream channel, 5 years after the Tanner Gulch Fire, northeastern Oregon (photo by J.B. Kauffman). The resilience of riparian plant communities is an important consideration in planning post-fire rehabilitation projects.

desert parsley (*Lomatium bradshawii*), a wetland-obligate species in western Oregon, was found to dramatically increase fruit production and seedling density following fire (Pendergrass et al., 1999; Kaye et al., 2001).

4.2. Interactions among physical processes and recovery of riparian and aquatic habitat

Fires interact with physical processes at both local and landscape scales to influence the form and dynamics of stream networks, hydrology, geomorphology, and riparian plant communities (Fig. 1; Arno and Allison-Bunnell, 2002). These interactions may be manifested in direct and immediate ecosystem changes, as well as indirect changes occurring over extended time periods (Yount and Niemi, 1990; Gresswell, 1999). Following fire, various sedimentation processes, including overland flow, debris flows, earthflows, and mudslides, may introduce sediment to the channel and floodplain (Meyer et al., 2001; Pierson et al., 2001; Wondzell and King, 2003). Postfire erosion is affected by geological substrate, severity of the fire, local and landscape impacts of the fire to vegetation and soil, and precipitation patterns (Moody and Martin, 2001). Fire-related flood and sedimentation events may result in localized removal or burial of riparian vegetation, alteration of floodplain surfaces, and deposition of various substrates, thus resetting successional dynamics in the plant communities. Existing riparian vegetation may retain finer sediment that will eventually be incorporated into the floodplain soils. Stand-replacing fires can facilitate a large pulse of large wood to the stream and floodplain, and existing riparian vegetation may capture and retain wood moving downstream. Although the condition and characteristics of riparian areas can influence the physical changes to stream channels following fire, limited research has been conducted on the role of riparian vegetation and geomorphology in woody debris recruitment and other postfire physical processes.

Most studies examining fire effects on lotic systems have focused on changes in streamflow, sediment transport, water chemistry, and fish habitat (Gresswell, 1999). Minshall et al. (1989) described the linkages between recovery processes in riparian and stream ecosystems following fire, noted the importance of riparian vegetation in providing increased shade and allochthonous inputs of organic matter over time, and suggested trajectories for consequent changes in benthic invertebrate communities. However, interactions between postfire recovery of aquatic and riparian ecosystems have rarely been directly investigated. Following the 1988 fires in Yellowstone National Park, Minshall and others initiated extensive studies on the effects of wildfire to stream properties and biota, particularly macroinvertebrate communities (Richards and Minshall, 1992; Minshall et al., 1995; Minshall et al., 2001). Comparing burned and reference streams in the first several years following fire, they reported changes in the relative abundance of certain invertebrate functional feeding groups, transport and storage of organic matter, and movement of large wood. Postfire recovery rates of aquatic biota were faster than expected and appeared to be related to the recovery of riparian vegetation (Minshall et al., 1997; Minshall et al., 2001). These observations suggest a high degree of ecological resilience in riparian and stream ecosystems, and recovery may be more rapid than in adjacent uplands. Coordinated research that addresses interactions and feedbacks among postfire physical processes, re-growth of riparian vegetation, and changes in aquatic communities is needed to prescribe effective rehabilitation projects following fire.

5. Summary

Limited data, the ecological importance of riparian areas, and the need to improve approaches for the conservation and restoration of riparian and aquatic habitats highlight the necessity for more extensive research on the history and ecological role of fire in riparian areas of the western USA. Fire regimes will often differ between riparian areas and uplands because of differences in geomorphology, hydrology, vegetation, and microclimate (Table 1). Studies on fire regimes in forested riparian areas indicate that fire frequency and severity are lower in some forest types (Hemstrom and Franklin, 1982; Barrett, 1988; Morrison and Swanson, 1990; Camp et al., 1997) but similar to uplands in other regions and forest types (Olson, 2000). Additional research is needed on fire return intervals of riparian areas dominated by deciduous trees and shrubs, and relations between upland and riparian fire regimes.

Tremendous variation often exists among riparian areas of a stream network, and fire behavior and effects will depend on local conditions and position in the watershed. Along elevational gradients, riparian vegetation may change from alpine wetlands to coniferous to mixed conifer-deciduous to deciduous vegetation (Patten, 1998). Geomorphic gradients along elevational gradients may range from broad alluvial floodplains dominated by montane meadows and hardwoods to narrow canyons with little or no riparian vegetation. To understand and predict fire behavior in riparian areas, increased understanding of fire spread and burn patterns is needed. For example, fuel loads and distribution, fuel chemistry and flammability, and fuel moisture in different riparian plant communities can influence fire at the local level.

Land use and management have frequently altered characteristics of riparian areas, including the presence of surface water, ground water tables, floodplain topography, and biotic diversity and productivity (Patten, 1998). Cumulative effects of human disturbance may also strongly influence fire properties and regimes in riparian areas, and these factors are likely to be most pronounced during periods of drought and under conditions of extreme fire weather (Fig. 3). Effects and properties of fire cannot be isolated from human activities, including water use and management and anthropogenic disturbances (Gresswell, 1999). Increased understanding of human influence on relationships between fire and riparian areas is needed, particularly at wildland-urban interfaces. In addition, riparian areas should be integrated into predictive models of fire behavior under different scenarios of land and water use and global climate change (Kauffman, 2001).

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