Ecosystems (2007) 10: 673–687
DOI: 10.1007/s10021-007-9048-5

Fire in the Riparian Zone: Characteristics and Ecological Consequences

Neil E. Pettit,[1,2,*] and Robert J. Naiman[1]

[1]*School of Aquatic and Fishery Sciences, University of Washington, Campus Box 355020 Seattle, Washington 98195, USA;*
[2]*School of Environmental Science, Murdoch University, Perth, Western Australia 6027, Australia*

Abstract

We review the current understandings of the frequency, spatial distributions, mechanisms, and ecological consequences of fire in riparian zones. Riparian zones are well known for influencing many ecological processes at local to landscape scales, and fire can have an important ecosystem-scale influence on them. Riparian zones differ from surrounding uplands in their biophysical templates, moisture regimes and disturbance regimes; as a consequence the characteristics and effects of fire are different than in adjacent uplands. Fire impacts on riparian zones vary proportionally with the severity and extent of burning in the catchment and are affected by stream size. Riparian zones can act as a buffer against fire and therefore as a refuge for fire-sensitive species. However, under some circumstances, such as dry pre-fire climatic conditions and the accumulation of dry fuel, riparian areas become corridors for fire movement. Fire incursion into riparian zones creates canopy gaps and drier conditions, which allow subsequent build up of dead wood and establishment of fire adapted species. In concert, this increases fuel loads and the probability of another fire. Secondary effects of riparian fire include altering nutrient fluxes and cycling, increasing sediment loads, and stimulating erosion. We conclude that riparian fires are potentially important in shaping ecological characteristics in many regions, but this is poorly quantified. A better understanding of riparian fire regimes is essential to assess the effects of fire in helping shape the complex ecological characteristics of riparian zones over the longer-term.

Key words: riparian fire; vegetation; kruger National park; Pacific northwest; ecological processes and consequences.

Introduction

Fire and riparian zones may seem like an oxymoron to many people. As a result, fire in riparian zones is a subject that does not receive much attention but, when it occurs, has long-lasting and often far-reaching ecological consequences. It is well known that riparian zones—transitional areas between water bodies and upland terrestrial communities—are influential in integrating interactions between these systems throughout the landscape (Malanson 1993; Naiman and others 2005b). Riparian systems usually differ from surrounding uplands in moisture regime, topography, micro-climate, soils and vegetative structure and productivity—reflecting the fact that organisms occurring there are well adapted to the dynamic water regimes inherent in river systems (for example, floods and drought; Junk and others 1989; Naiman and others 2005a). As a consequence, riparian zones are often characterized as

Received 30 October 2006; accepted 6 March 2007; published online 14 April 2007.
**Corresponding author; e-mail:* N.Pettit@murdoch.edu.au

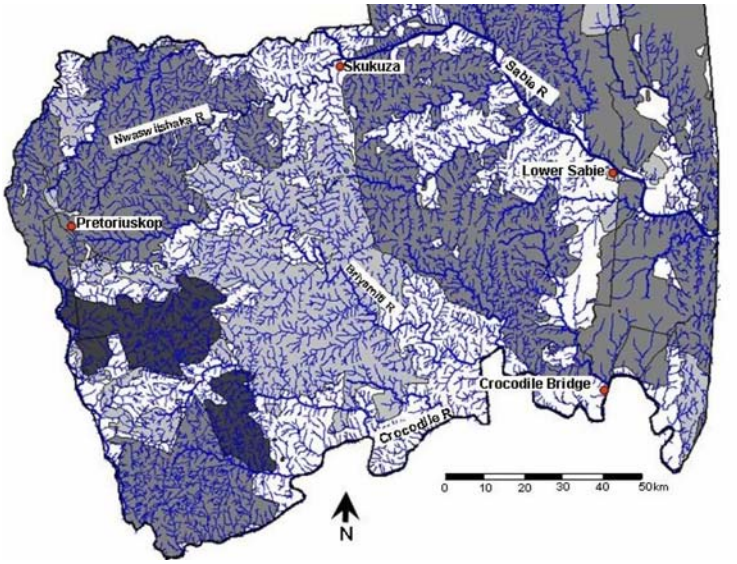

Figure 1. Network of streams and riparian areas across the landscape and the spatial extent of fires over three years (2002 *grey*, 2003 *dark grey*, 2004 *light grey*) in the southern section of Kruger National Park, South Africa.

being highly heterogeneous in time and space (Naiman and others 1993, 2005a, b), with complex biophysical structures and disturbance regimes (Pettit and Naiman 2005; Gurnell and others 2005). Fire adds another important layer of complexity.

Riparian zones, as linear systems penetrating throughout the landscape (Figure 1), are ecologically influential in regulating the movement of species and propagules as well as water and nutrients. Fire directly affects landscape features including riparian areas embedded within catchments. Most riparian areas are small but nonetheless important. In wet regions there are approximately 2.5 km of stream corridor per km^2 of land; in drier regions stream density declines to approximately 1.5 km/km^2 (Naiman and others 2005b). Further, riparian systems have a large edge-to-surface ratio making them highly susceptible to edge effects from upland-based fire. Therefore, because streams and rivers are a pervasive and embedded part of landscapes, the effects of fire on riparian zones have implications for the whole catchment.

Fire effects on ecosystems are related to their frequency, severity and timing of occurrence which are, in-turn, affected by climate conditions, vegetation type, fuel loads and landscape features (Agee 1993; Pyne and others 1996). Nevertheless, the majority of landscape management and research does not treat riparian zones as separate or special ecosystem types. An ecological understanding of the frequency-of-occurrence and consequences of fire, as well as fire suppression, in contrasting riparian systems is essential to forming a better understanding of factors underpinning the unusual complexity, resilience and biodiversity of riparian systems.

The ecological effects of fire in riparian zones are the result of interactions between fire characteristics and the riparian biophysical environment (Figure 2). Climate has strong influences on specific fire characteristics (Agee 1993; Whelan 1998) as well as on the riparian physical environment; together their interaction determines the ultimate effects of fire on riparian vegetation (Figure 2). The location of the riparian zone, in relation to watershed position and elevation (that is stream order), are also likely to determine their vulnerability to fire. This article reviews current understandings of the frequencies, spatial distributions, mechanisms, and ecological consequences of fire in riparian zones, and highlights topics where additional knowledge is needed. This article deals only with stream riparian zones and therefore some conclusions may not hold in lake or wetland riparian zones. The general propositions that provide the framework for this review include:

1. Fires are generally less frequent and of lower or higher intensity in the riparian zone, as compared with adjacent uplands.
2. Streams form linear landscape features that are influenced by upland fires but also influence fire spread across the landscape. This is also related to stream order.
3. Fire interacts with flooding to provide a major system-scale driver in shaping riparian characteristics, particularly after a large infrequent disturbance.
4. Riparian fires influence in-stream ecology and geomorphology by altering the physical nature of the riparian and in-stream environment.

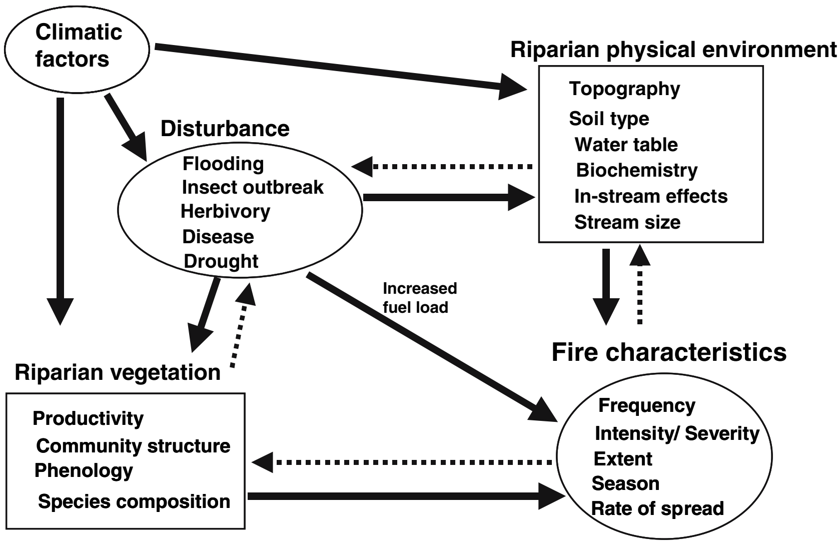

Figure 2. Conceptual model of the processes of fire in the riparian zone. Climate has a strong influence on the particular characteristics of a fire as well as the riparian physical environment which will determine the effects of fire on the riparian vegetation. The riparian vegetation in-turn affects the characteristics of a fire and the riparian physical environment. Other disturbances create synergistic fire characters via increased fuel load which will increase fire intensity and severity.

5 Nutrients in riparian soils vary unpredictably in response to fire due to spatial variability in fire characteristics, climate and landscape topography.
6 Plant adaptations for living in an environment with a high frequency of disturbance and topographic heterogeneity combine to make the vegetative community in the riparian zone relatively resilient to fire.

Fire Frequency and Intensity as Applied to Riparian Areas

In general terms, fire regimes in riparian areas are considered to be of lower intensity and to occur less frequently than in the surrounding uplands (Agee 1988; Benda and others 1998; Patten 1998; Dwire and Kauffman 2003). In the majority of instances tongues of fire enter the riparian area from uplands, creating burnt and unburnt patches and contributing to the establishment of the upland/riparian boundary. For example, following a prescribed fire in temperate forest in the southern Appalachian Mountains (USA), which had not burnt for 70 years, there was no tree mortality in the riparian zone compared with 37% mortality upslope, with no observed change in riparian species diversity (Elliot and others 1999). In a tropical riparian forest within a savanna matrix in Central America, fire scarred trees were concentrated on gentler slopes near the savanna-forest boundary (Kellman and Tackaberry 1993) indicating that fire rarely penetrates far into the riparian forest as it is stalled at the boundary. Penetration of upland fires appears to depend, to a large extent, on the intensity of the fire and the width of the riparian zone (Agee 1988). Therefore riparian zones, as part of the landscape topography can act as a filter to fire, stopping some but allowing others to pass (Taylor and Skinner 2003).

Under some circumstances climatic pre-fire conditions can drive large and intense fires in riparian zones with significant ecological impacts. Over longer time scales, prolonged droughts lower the watertable and dry out riparian vegetation, increasing fire risk. The 'terrestrialization' of riparian areas through extended (for example, decadal) low rainfall periods can also result in the riparian vegetation community more closely resembling upland communities and consequently sharing a similar fire regime (Naiman and others 2005b).

After the application of an ignition source (such as lightening or anthropogenic), whether flaming combustion is achieved will depend on the state of the fuel, including moisture content, fuel size and oxygen levels (Neary and others 1999). Foliar moisture content of needles will affect the likelihood of crown fire of conifers in Pacific Northwest forests of the US (Agee and others 2002) and leaf litter moisture levels of greater than 20% will prevent ignition in eucalypt forests in Australia (Cheney 1981). Fine fuels are generally involved in active flaming combustion whereas larger fuels are important for residual combustion and smoke production. The size distribution of fuels can affect the rate of spread as well as intensity of fire. In a fire in mixed conifer riparian forest in Sierra Nevada, California, around 90% of small size fuel, including litter and duff, was consumed, whereas only 6% of large sized fuel was consumed, unless it was partly decomposed in which case 100% was consumed (Bêche and others 2005). In this study it was also shown that riparian fires were generally patchy and most severe where there were large accumulations of small sized fuel such as conifer litter and debris. Fire fuels also relate to the different strata within a riparian forest from tree crowns to organic soil layers, including both live and dead biomass.

The general aspects of fire regimes—frequency, season, intensity, severity, fuel loads and spread—are obviously also relevant to fires in riparian zones but with some strong, as well as more subtle but important differences. Collectively, factors affecting fire characteristics are interrelated and all are greatly influenced by climate.

Fire frequency Fire return interval is generally a function of how quickly fuel accumulates, of climate conditions and of the frequency of ignition. Less frequent and milder fires in riparian areas as compared with adjacent uplands are, to a large extent, due to higher fuel moisture content and relative humidity in the riparian areas. This is particularly associated with understorey shrubs and herbs (Agee and others 2002). The frequency of fire intrusion into stream corridors is also affected by local topography, particularly bank slope, so that in general, steeper bank gradients restrict the ability of fire to burn through riparian zones. In contrast, for a riparian area of low topographic incision in Douglas fir (*Pseudotsuga menziesii*) forest in Oregon, Olsen and Agee (2005) found no difference in fire return intervals between riparian and upland areas. In first and second order gravel bed streams in Canada no difference was found in fire frequency between upland and riparian areas (Charron and Johnson 2006). Riparian fire frequency is therefore likely to decrease with increasing stream size (Benda and others 1998) so that headwater channels have a much greater fire frequency than wider channels and wider riparian zones downstream. However, in some areas differences in vegetation structure between riparian zones and adjacent areas govern the occurrence of fire (van Wilgen and others 1990). Aspect is another important topographic feature of riparian areas in determining the spatial variation in fire frequency with fires (in the northern hemisphere) generally less frequent on north facing slopes (Taylor and Skinner 2003).

Intensity Fire intensity usually refers to the energy released during fire but probably a more useful term in the context of this review is fire severity, which is broadly defined as the measure of ecosystem impact, such as tree death or consumption of above ground biomass (Bond and Keeley 2005). Micro-climate conditions, particularly temperature and humidity influence fire severity. High relative air humidity prevents fuel from drying sufficiently to carry a fire, or at least reduces fire intensity. Riparian plant communities exert considerable influences on local microclimates (for example, Chen and others 1999) with the usually dense, closed canopies reducing evaporation and maintaining a high relative humidity—keeping fuel moisture levels high. Additionally, the close proximity of water often sustains mesic vegetation in riparian zones by keeping surface soils moister, thereby contributing to higher humidity. Finally, shading lowers air temperatures, reducing drying rates of fuel, and the dense riparian vegetation reduces wind speeds thus helping to maintain high humidity and therefore lowering fire severity.

Season The seasonal timing of burning has strong effects on riparian and in-stream processes, principally through fire severity. In sub-tropical savannas late dry season fires are generally larger and more severe than those at the beginning of the dry season (Andersen and others 2003; Govender and others 2006). In a long-term experiment in a wet tropical savanna in northern Australia, season of burning (early or late dry season) had large effects on riparian vegetation in terms of species composition. There was higher species richness, density and cover of woody species and vines in unburnt riparian areas as compared with late dry season (hot) burn areas, with early dry season (cool) fire effects intermediate (Douglas and others 2003). The effect of season of fires in the riparian zone can be related to annual flooding patterns as well as to the phenological characteristics of the vegetation (for example, growth, flowering, seed set and dispersal).

Fuel loads Accumulation of fuel in riparian zones occurs through a variety of mechanisms not always found in uplands. Particularly in drier regions, primary production is generally higher in riparian zones, due primarily to the ready availability of water, which is a major contributor to high fuel loads. Also, as riparian trees are uprooted and deposited in channels and particularly in the riparian zone during large floods, the risk of high severity riparian fires increases in response to the accumulation and concentration of wrack and woody fuels (Figure 3; Pettit and others 2005). Additionally, harvesting trees in riparian zones increases fuel loads as well as creating canopy gaps allowing faster drying of fuel, thereby increasing

Figure 3. **a** Large woody debris deposited in the riparian zone after a flood increases fuel load and can accumulate around surviving trees. **b** The wood accumulations are subsequently consumed in a high intensity fire.

fire frequency and severity (Uhl and Kauffman 1990). It appears that there is a lagging relationship between fire, flood frequency and forest practices with the accumulation of woody debris and litter increasing fire severity (Ellis 2001; Reeves and others 2006).

Fire extent and rate of spread Fire extent and spread are both generally related to landscape heterogeneity. Riparian landscapes are considered to be highly heterogeneous (Malanson 1993; Naiman and others 2005a) and several aspects of this heterogeneity affect fire characteristics and behavior. In particular topography is usually diverse in riparian zones with low and high terraces, levy banks and banks with variable slopes such as in constrained and unconstrained reaches. The rate of spread is further complicated by the patchiness of vegetation type and density, as well as soil and plant moisture content, which are also related to local topography. Fuel loads are generally spatially and temporally heterogeneous in riparian zones—due to flood-related accumulation of debris piles and flood regimes, respectively—which contribute to highly variable rates of spread (Cary and others 2006). Large increases in fuel are likely to increase fire residence times (and therefore the residence time of lethal temperatures), which can have important ecological consequences.

Streams as Linear Landscape Features

Most riparian areas are linear, dendritic landscape features and, as such, are biophysically influential throughout the catchment. The size and spatial position of streams within the catchment, as well as stream type, have strong interactions with fire (Figure 4). The penetration of upland fires into riparian zones along higher order streams is often patchy or completely absent in all but the most intense fires (Kellman and Tackaberry 1993). In contrast, on lower order streams, fires of moderate intensity are able to move through entire riparian zones, although in some instances headwater springs, seeps, and small wetlands can mediate local fire effects. Fire interactions with streams are also more frequent in lower order streams simply because of the greater abundance of these lower order streams in the landscape (Figure 1). Drainage density tends to be concentrated in the lower order streams so that over 80% of the stream kilometres within a catchment can be small first and second order streams (Dunne and Leopold 1978). Fire effects on streams are greatest in headwaters and dissipate progressively downstream (Minshall and others 1989), therefore fire frequency and severity in the riparian zone usually decreases as channel size increases. In low-order gravel bed streams in the Canadian Rocky Mountains, Charron and Johnson (2006) found that fire was of greater importance for riparian tree establishment than flooding except for trees establishing on lateral and point bars.

Fire effects in low order streams are likely to have consequences for the riparian environment throughout the downstream system. Fire in headwater streams can lead to pulses of nutrients, sediment, plant propagules, and increased wood debris being delivered downstream. Alternatively the consumption of woody debris by fires in low order streams may deprive downstream reaches of this important ecological asset (Gregory and others 2003; Gurnell and others 2005; Pettit and Naiman 2005; Latterell and Naiman 2007). Therefore, although fire may be less frequent in higher order

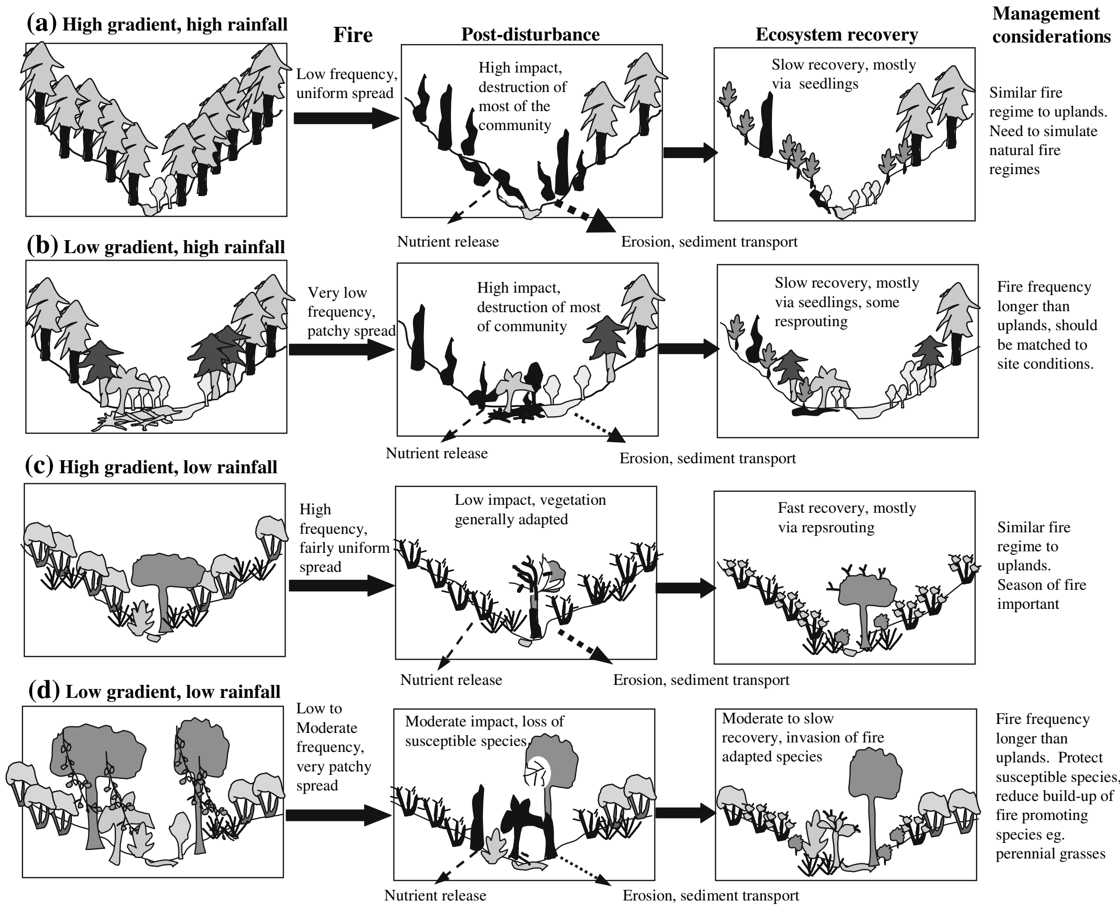

Figure 4. Examples of fire effects on the riparian zone in the four generalized cases in terms of the location of the riparian zone according to extremes of watershed position and climate. **a** High elevation and high rainfall, **b** Low elevation and high rainfall, **c** High elevation and low rainfall, **d** Low elevation and low rainfall.

streams, fire effects at the top of the catchment may still have consequences for the ecosystems downstream.

Riparian areas, as they criss-cross the landscape, also act as natural fire breaks to limit the spatial extent of wildfires. Features of the riparian zone described above (for example, high humidity, high fuel moisture levels) can have a retardant effect on fires as they spread. This effect can be used by land managers to limit terrestrial fires by creating a buffer zone to protect the stream ecosystems from fire (Bisson and others 2003). However, under certain circumstances, such as through fuel accumulation and a hot dry period, riparian zones can act as passages for fire leading to the spread of fire to unburnt uplands (Agee 1998). Also, under particular conditions steep sided stream banks can act to funnel winds increasing wind speeds that may increase fire rate of spread and operate as a conduit for fire to different parts of the landscape (Dwire and Kauffman 2003).

Higher frequency of fires on lower order streams can lead to the loss of some elements of the riparian plant community such as fire-sensitive species (Douglas and others 2003). Through system-scale feedbacks, fires entering the riparian zone can open up the canopy leading to an increase in fire tolerant life-forms such as grasses, which in-turn increase fire frequency. Unravelling the influence of fire on riparian vegetation composition in both wet and dry environments, and interactions with stream size and gradient, will improve landscape-scale management of these systems.

Relationship between Fire and Flooding

Flooding, a major system-scale driver in shaping riparian characteristics interacts with fire to provide an important element of the disturbance regime and to the ecosystem-scale outcomes. For example, flooding can lead to the accumulation of wrack and woody fuel (Pettit and others 2005) and the destruction of riparian forest. This opens the area to greater radiant heat (Cochrane 2003), thereby increasing the drying-out of fuels including the surviving vegetation, ground litter and woody debris. This combination of increased fuel load from flood debris and the drying out of fuels increases the likelihood of subsequent fires. In the riparian zone of the Rio Grande River in New Mexico, fire severity is related to the amount of organic debris present—a reflection of flooding history (Ellis 2001). The deposition of wood debris piles after a large flood on a river in semi-arid South Africa created conditions for fire that was spatially patchy in terms of intensity with subsequent effects on vegetation and soil nutrients (Pettit and Naiman 2007). In a low rainfall savanna in Botswana, fire frequency was higher on floodplains than uplands due to higher biomass production and associated fuel loads (Heinl and others 2006). However frequent flooding will inhibit vegetation growth and the build up of fuel, thus reducing the risk and intensity of fire. Therefore we suspect fire and flood frequency have a non-linear relationship with fire frequency being highest at intermediate flooding frequencies.

Post-fire, the trajectory of stream ecosystem succession may depend to a large extent on the levels of stream flooding in years immediately after the fire (Minshall and others 1989). In fact flooding shortly after a riparian fire increases stream bank erosion and damages vegetation recovering from loss of numbers and foliage in the fire. Occurrence of fire in the immediate post-flooding period also affects the regeneration dynamics of vegetation through the destruction of regenerating plants. The life history adaptations of riparian vegetation to flooding, however, may also ameliorate the effects of fire on plants. Conifer forests in Canada generally reveal no serious impact of fire in riparian zones—when compared to uplands—as riparian forest are considered pre-adapted to fire by having an open canopy and subject to frequent flooding disturbance (Lamb and others 2003).

Riparian Fires, Geomorphology and In-stream Ecology

Floods and riparian fires create and maintain complex and productive in-stream aquatic habitat (Bisson and others 2003). Depending on stream size, fire effects include changes to nutrient fluxes and cycling, input of sediment and wood load, litter input and consequently the general ecology of aquatic organisms (Minshall and others 1989). Fire effects on streams can be immediate and generally short-lived such as when pulses of sediment and woody debris are delivered to streams after fires, which will have obvious effects on in-stream habitat. Fire can also create short-term effects on stream nutrient levels. In first order streams in a mixed conifer forest in Sierra Nevada, California total N and total P increased immediately post-fire but decreased to pre-fire levels within 1–2 weeks (Bêche and others 2005). Fire effects on streams also can be long-term. For example, changes to channel form in a stream that was burnt 11 years previously in Yellowstone National Park, Wyoming lead to greater mobility of wood and therefore a lower frequency of wood accumulations, compared to an unburnt stream (Zelt and Wohl 2004). Changes in channel form and reduction in riparian canopy cover due to fire lead to elevated stream temperatures for extended periods of up to 10 years in a British Columbia headwater stream (Moore and others 2005). In smaller streams riparian fires can defoliate trees, resulting in more light reaching the stream thereby increasing water temperature as well as growth of aquatic and emergent plants. Although fire can kill and injure riparian trees the resultant opening of the canopy, together with increases in nutrients, can alter in-stream diversity and productivity by adding woody structure and augmenting the light and nutrient regimes (Douglas and others 2003).

Fire affects stream channel geomorphology by increasing sediment flux as well as the movement of wood, leading to changes in channel shape and flow patterns. The major physical effects of riparian fire are an increasing likelihood of bank erosion and the large fluctuations in the delivery of woody debris in the riparian zone and in the stream. Fire increases erosion in the riparian area by removing vegetation, increasing surface run-off and reducing soil infiltration rates—thereby increasing the potential for landslides and debris flows (Shakesby and Doerr 2006). Fire can reduce water infiltration rates by creating a hard soil surface crust which is often hydrophobic and, combined with loss of ground cover (vegetation, litter or wood debris), leads to sheet or gully erosion (Shakesby and Doerr 2006). The net result is the loss of nutrients and soil from riparian areas to the stream. High severity fires destroy vegetation that is important in maintaining bank stability (that is through roots binding the soil). In this case the fire is more likely to result in eroded stream banks during subsequent high flows. This can lead to further loss of trees, channel widening and the input of additional sediment into the stream. Wood pieces can also form channel dams, and if burned, these release large amounts of stored sediment downstream. In a comparison of a burnt and unburnt stream corridor in Wyoming (USA), Zelt and Wohl (2004) found stream channel width increased in burnt streams due to increased bank erosion and sediment movement. This led to a loss of large woody debris as the wider channel transported wood more readily during high flows. Intense fires resulting in the death of many trees, coupled with increased bank instability, can lead to a large amount of wood being deposited in the stream (Bêche and others 2005). However severe fires can also lead to the consumption of most of the dead wood, particularly in lower order streams (Figure 3). For a second order stream in Wyoming, Bragg (2000) found that fire greatly increased woody debris fluxes to streams; more so than normal annual mortality or episodic events such as tree death through insect outbreaks or clear-cutting. Whether woody debris increases or decreases in riparian areas after fires depends—to a large extent—on fire characteristics, existing composition of the vegetation, position in the catchment and channel geomorphology.

Riparian Soil Nutrients and Fire

Fire effects on soil nutrients are complex and variable, with the fire-vegetation interaction leading to either nutrient increases or shortages (Neary and others 1999). Specific effects depend to a large extent on the fire characteristics and the fire regime (Wan and others 2001; Certini 2005). In general, low severity fires increase plant available nutrients whereas severe fires result in the volatilization of soil nutrients and losses through ash entrainment, erosion, leaching and denitrification (Cook 1994; Neary and others 1999; Aranibar and others 2003).

Although riparian areas occupy the lower part of the landscape and are therefore run-on zones where water and soil nutrients tend to accumulate, changes in nutrient dynamics brought about by fire in riparian zones are likely to be similar to those documented for uplands, and therefore depend to a great extent on the fire regime. However, high water tables in riparian zones may minimize the fire effect on nutrients with loss of carbon and nitrogen during fires reduced on sites with high water tables compared with low water table sites (Blank and others 2003). Additionally, soil moisture has a strong influence on mineralization rates (Austin and others 2004) so that riparian zones with typically high soil moisture content suggest a pattern of soil nitrogen levels increasing quickly after fire due to relatively higher levels of nitrogen mineralization. In contrast, high soil moisture levels and accumulations of fine fuel material will increase soil heating in fire which may lead to greater volatilization of some soil minerals and the death of soil organisms (Neary and others 1999). High water tables and humidity levels in riparian zones as well as periodic accumulations of fine debris material during flooding can create such conditions.

Nutrients from upland fires also reach the riparian zone. Fire generated ash and modified soil are mobilized in the uplands during subsequent rainstorms and deposited in the lower slopes, including the riparian zone. Surface runoff is increased through the reduction of vegetation cover and soil structure via fire (Beeson and others 2001; Johansen and others 2001). Nutrient influxes in rainfall run-off after a fire is also likely to be more pronounced in the numerous low order streams with smaller riparian buffers.

In addition to the effects of fire on individual soil nutrients, fire is likely to have a strong effect on element interactions. Elements released by fire are mobilized differently, which is likely to contrast with the elemental ratio requirements of organisms (Sterner and Elser 2002). How the ratios of elements are redistributed following a fire will depend on pathways in which they are mobilized, which will be influenced in-turn by the make-up of the biological community. In a simulation of carbon–nitrogen–phosphorus interactions under various frequencies and intensities of fire, high frequency fire reduced nitrogen pools to only 25% of levels seen without fire (Hungate and others 2003). However where nitrogen-fixing plants were present, fire increased phosphorus availability, which in-turn enhanced the rates of nitrogen fixation. In the riparian zone, floods also mobilize elements to varying degrees. Knowledge of how flooding and fire interact with element ratios in the riparian zone and their effects on in-stream processes would enhance our understanding of the ecosystem consequences of fire in the riparian zone.

Riparian Vegetation and Adaptation to Fire

Riparian fires shape vegetative community composition and plant structure via the responses and adaptations of individual species. In fire-prone upland environments, such as savanna, fire is a major controller of tree/grass dynamics (Scholes and Walker 1993; Higgins and others 2000) with annual fires promoting grasses and preventing the establishment of woody plants (Heisler and others 2004). However, in most riparian zones environmental factors such as moisture, flow regime, herbivory and geomorphology are likely to be the key drivers of plant community characteristics (Naiman and others 2005b). For example, in Californian conifer forests, distance from the stream was a stronger influence than time since the last fire on vegetative composition suggesting—as one would expect—that the effects of fire declines with proximity to water (Russell and McBride 2001). Southwestern US riparian communities are generally structured along gradients related to moisture, fire and community age (Busch and Smith 1995). However, fire can play an important role in the structuring of riparian communities in headwater streams by reducing plant cover and species richness and by altering composition (Bêche and others 2005). In savannas, fire can also influence tree densities in the riparian zone. Fire interval needs to be sufficiently long for saplings resprouting from the root collar to grow tall enough to survive a subsequent fire (Bond and Keeley 2005). Lower fire frequencies and higher growth rates means that tree seedlings in the riparian zone are more readily able to escape from the firetrap. Along with higher moisture regimes this will contribute to riparian seedlings having higher survival rates than in upland areas that will contribute to high tree densities in riparian communities.

In many situations the fire retardant effect of the riparian zone and the patchy nature of riparian fires create refugia for fire-sensitive species in a matrix of more fire-prone uplands (Meave and others 1991). These refugia can then act as focal points from which plants and animals can recolonize the post-fire landscape. For example in tropical lowland rainforest in Indonesia large diameter trees characteristic of climax vegetation are more common in the riparian forest where fire is rare (Slik and Eichhorn 2003). Gallery forest along streams in savannas includes fire sensitive tree species that occur only in protected areas away from the savanna boundary where fire is uncommon (Kellman and others 1998). Consequently an ecotone of fire tolerant trees along the savanna boundary develops, which acts as protection for fire sensitive species in the interior. Even where fire encroaches into the riparian zone, fire protected patches such as moist gullies may exist which offer some protection for fire sensitive species.

There are few examples of fire responses by specific riparian plants but examples from uplands give important insights about potential riparian responses. In fire-adapted savanna communities there is a relationship between fire history and plant life history so that the phenology of the vegetation becomes an important determinant of subsequent fire impacts (Williams and others 2002). This is seen in key phenological phases such as leaf flush, flowering and seed set, which tend to occur in the late dry season when the majority of fires occur. The implications are that the reproductive characteristics of riparian plants can be differentially affected by fires occurring outside the normal period. For example, burning late in the dry season greatly reduces flowering and fruiting of a common riparian tree (*Eucalyptus alba*) in northern Australia (Douglas and others 2003). Additionally, the combination of fire and flooding may also affect seed germination and seedling development by riparian plants. Fires in southeastern Australia enhance the germination of soil-stored seed of the riparian shrub *Grevillea rivularis* by helping break seed dormancy. Seedlings of this species emerge after fires that are followed by local flooding (Pickup and others 2003).

Plants with the ability to resprout after the loss of all or most of the aboveground biomass are favored in environments with a high frequency of disturbance such as flooding (Bellingham and Sparrow 2000) or fire (Bond and Midgley 2003). The ability to resprout from broken stems or from the rootstock after defoliation can be seen as an adaptation of riparian species in flood zones (Naiman and others 2005b) but also may provide riparian plants an ability to recover quickly after fire. This has been reported in southern Californian streams (USA) where fire history influenced riparian community composition so that sites with high fire frequency are dominated by resprouting species (Bendix 1994). In the Pacific Northwest (USA) the most common riparian species, willow (*Salix* spp) and poplar (*Populus* spp) resprout readily after flood damage whereas Sitka spruce (*Picea sitchnesis*) does not (Naiman and others 1998). On the Sabie River in South Africa, after a 1:100 year flood, 30% of the regenerating riparian plants originated from resprouting residual plants (M. Parsons, University of the Witwatersrand, personal communication).

Riparian vegetation of seasonal streams in wet tropical savanna in northern Australia have features that are more characteristic of rainforest than savanna and consequently unburnt riparian areas have twice as many tree species and three times the stem density of sites burnt in the late dry season (Andersen and others 2005). Some riparian species are particularly sensitive to fire such as trees with thin bark (Cochrane 2003) as well as many species of liana (Douglas 1999; Laurance 2003). In contrast, many plants that are adapted to a fire-prone environment have hard fruit or thick walled seed and thick bark that are better able to withstand the heat from fires (Bond and van Wilgen 1996; Bond and Midgely 2003).

Riparian Fire: Examples from Two Contrasting Environments

Semi-arid savanna: Kruger National Park, South Africa. Kruger National Park is situated in a semi-arid subtropical region of north-eastern South Africa. The area, locally described as the lowveld, consists principally of a grassy woodland savanna and is considered to be a highly fire adapted ecosystem with a large proportion of plants able to withstand repeated and frequent defoliation by fire (van Wilgen and others 2003, 2004). Several major rivers, supported by a vast network of smaller tributaries, run through Kruger (Figure 1; O'Keeffe and Rogers 2003). Prescribed burning within Kruger has concentrated on the extensive terrestrial ecosystems whereas, from 1957 to 1975, fire was excluded from some areas considered fire sensitive including vleis (wetlands) and riparian areas (Brynard 1971). However, fires were probably not completely absent from these areas and analyses of fire records suggest that management had little effect on the total area burnt which is controlled by rainfall—a major driver of grass biomass (van Wilgen and others 2004; Govender and others 2006). Fire policy since 1975 has allowed management or wildfires to burn into riparian areas (N. Govender, personal communication).

Fire in the riparian zones of higher order streams in Kruger is generally considered relatively uncommon, only likely when fuel loads build-up sufficiently and fuel moisture contents are low. On the Sabie River in Kruger, after a approximately 100 year return interval flood in 2000, large numbers of riparian trees and shrubs were uprooted and redistributed, resulting in an open riparian canopy and the accumulation of substantial amounts of large woody debris and wrack material in the riparian zone (Pettit and others 2005). Prior to the flood, woody debris was scarce or absent from most of the riparian corridor (Parsons and others 2006). Deposited wood piles are likely to create a particularly acute fire hazard to remnant trees, especially those where wood has accumulated around the trunk (Figure 3). A flood of comparable size last occurred on the Sabie River in March 1925 (Heritage and others 2001). Historical accounts of the aftermath of this flood describe large accumulations of wood that were considered a fire risk to surviving trees. Indeed the then warden of the Kruger Game Reserve, J. Stevenson-Hamilton, described:

''On subsidence of the flood huge piles of reeds and uprooted trees were left far away from the river, piled in heaps often 10–12 feet high... I found this to be the case at many places along the Sabie River, and it is clear that at the next grass fire these masses of tinder would form the funeral pyre of many beautiful trees... I had found places where fire had already done their work, and where only a few charred trunks, their surroundings covered 2 feet deep in wood ashes, remained to tell a tale of furious conflagration. Of course no trees, however hardy, can withstand bonfires of this kind.'' (Stevenson-Hamilton 1929)

After the February 2000 flood on the Sabie River several fires have taken place, burning sections of the riparian zone. These fires were not necessarily of high intensity. For example a riparian fire in October 2004 occurred on a cool, high humidity day where the fire slowly burnt across the sparse grass ground cover before reaching debris piles where high severity spot fires were responsible for the death of many trees in close proximity (Pettit and Naiman 2007; Figure 3). These fires can alter pathways of succession after floods causing the destruction of survivors as well as the regenerating vegetation and create a mosaic of alternate successional states (Pettit and Naiman 2007).

Current fire management in Kruger is a combination of patch burning, burning according to range condition and lightning fires. This approach is taken with the aim of maximizing landscape heterogeneity (van Wilgen and others 2003). As riparian fires usually originate in the uplands the fire regime created there will have an impact on riparian areas. The distinct vegetation community that exists in the riparian zone and the relationship that exists between flooding and fire suggests that there is some case for the management of fire in riparian zones as a separate and distinct ecosystem, at least for higher order streams.

Temperate Forest: Pacific Northwest, USA. The Pacific Northwest of North America, extending from northern California to south-eastern Alaska, is an area of temperate climate characterized by generally high precipitation with cool, dry summers and wet winters. The forest cover is a complex mixture of coniferous and hardwood forest reflecting topographic and rainfall patterns. In this region there is a high diversity of vegetation types, riparian systems, and fire regimes with fires generally frequent and of low intensity in the eastern dry forests and infrequent and of high intensity in western moist forests.

Fire is an important disturbance process in Pacific Northwest forests but is generally less frequent in the riparian areas due to high humidity and moisture levels and to more common deciduous vegetation that is less flammable than upslope conifers (Agee 1988). Periodic drought, drying easterly winds and the build-up of wood debris create favorable conditions for fire (Agee 1993)—and the frequency and magnitude of fires strongly influences stand ages in the southern, drier regions (Benda and others 1998). Fire frequency has a wide range (10 to >500 years) and mid to late summer is the most common season for fires (Agee 1998). Simulation models suggest substantial differences in fire return interval for different parts of the landscape. For example, even though the average interval for southwest Washington is approximately 300 years, it is approximately 500 years for valley floors whereas, on ridge tops and along low order streams, it is only about 150 years (Benda and others 1998). Riparian areas usually have a more complex forest structure than uplands, which allows faster post-fire recovery from fires that may be less frequent and severe (Agee 1998). Eventually unravelling the intricate interactions of fire regime with site conditions in the riparian zone will require more in-depth understanding of the basic characteristics and processes associated with the riparian areas.

The riparian zone is frequently protected from fire to 'preserve' aquatic ecosystems important to salmonids in the Pacific Northwest (Agee 1998; Bisson and others 2003) and, as well, the riparian zone acts as a buffer between moderate intensity fires in the upland and the in-stream environment (Bêche and others 2005). However, under conditions of severe drying weather and inherently high fuel loads (Gregory and others 2003; Latterell and Naiman 2007) riparian areas can act as a corridor for fire too (Segura and Snook 1992; Agee 1998). Riparian areas can then carry a more severe fire than upland areas, particularly when upland fuels have been depleted by a recent fire. Inherently high fuel loads are maintained continuously in Pacific Northwest riparian zones by the death of large numbers of trees through such mechanisms as severe flooding or intense insect outbreaks or storms (Camp and others 1997; Agee 1998; Bragg 2000). The synergy of conditions required for a severe riparian fire therefore suggests that these fires are highly episodic.

Forestry practices in the Pacific Northwest have generally been one of fire exclusion, which has dramatically altered the forest ecosystem so that increased fuel loads in areas of low severity fire now have severe fire impacts (Agee 1998). Simulating natural disturbance patterns has been proposed as an alternate management strategy to maintain broadly defined ecosystem processes (Swanson and others 1997) and in particular to maintain structures in aquatic ecosystems (Bisson and others 2003). This would require extensive knowledge of past fire regimes in these forests (Agee 1998) as well as understanding of the highly variable spatial and temporal nature of the riparian ecosystems in this region (Naiman and Bilby 1998; Bisson and others 2003; Naiman and others 2005b).

Despite the very different ecosystems described in this section there are several similarities in preferred approaches to fire management. This includes the desire to replicate natural fire regimes as well as producing a mosaic of fire patches to create and maintain biodiversity and, thereby, ecosystem resilience. Also, for each bioregion, knowledge of fire regime effects on riparian ecosystems as well as individual riparian species, or what the natural fire regimes are, is incomplete. Therefore an adaptive management approach to fire management is advocated (van Wilgen and others 2003; Bisson and others 2003) whereby management decisions are based on a thorough ecological understanding and outcomes from management prescriptions that are continuously refined through feedback from monitoring.

Summary and Conclusions

There is vast variation in the nature of riparian zones. This occurs within a catchment, from headwater streams to high order rivers, as well as among rivers, and depends on the physical template including geology, topography, soils, geomorphology, hydrology and climate. The heterogeneous fire conditions found in riparian zones—those created largely by topography, canopy gaps, moisture gathering areas, distribution of wood fuel and viability in fuel moisture content—create a mix of crown fires, surface fires and unburnt patches—thus contributing to a high degree of heterogeneity within the riparian zone. Also, the episodic nature of riparian fires, depending on the confluence of particular conditions of fuel load and climate, is evident across riparian ecosystems in vastly different bioregions (Figure 4). Due to the connectivity of stream networks, fire effects in low order streams will be conveyed downstream and have ecological consequences for the riparian environments in valley bottoms (Wipfli and others 2007). Therefore, when establishing policy for managing fire in riparian zones we need to understand differences in the ecological effects of riparian fire for different stream order and elevation, under different climatic regimes (Figure 4).

Riparian areas and their associated streams are pervasive landscape features, suggesting that fire will have spatially broad consequences extending beyond the actual location of the fire—as well as for riparian areas themselves. Therefore disruption of the natural fire regime can lead to adverse affects for riparian areas and the wider landscape. Activities such as logging, construction of fire access routes along rivers and road construction along riparian corridors may lead to fires of greater frequency and severity in riparian areas (Reeves and others 2006). Other changes to river function such as flow regulation also can have indirect consequences on the riparian fire regime, such as reducing the accumulation of wood debris by reduced flooding. Protecting riparian buffers from fire is likely to change the structure and possibly the function of riparian areas (Agee 1998) as fire exclusion can eventually lead to extreme, high severity fires through the accumulation of fuels. We believe that a greater understanding of the link between the riparian zone and the surrounding upland matrix, together with the relationship to disturbance regimes such as fire and flooding, will improve landscape and watershed management overall.

Alternatively, rare natural disturbance events, such as extreme flooding, can lead to the rapid build up of fuel, as occurred on the Sabie River, South Africa. This increases fire risk as well as fire severity in riparian zones that rarely experience severe fires. Thus there is a link between these two infrequent disturbance events which can act as catalysts for sudden change in ecosystems and may result in the development of alternate successional states (Turner and Dale 1998) in the regenerating riparian community (Pettit and Naiman 2007). Acknowledgement that rare large-scale disturbances are inevitable—and required for the long-term ecological stability—is important for fire management in riparian systems (Bisson and others 2003).

In considering appropriate management of fires for riparian zones there first needs to be a general assessment of the role of fire in local riparian ecosystem processes. Further, most knowledge on riparian fires relates to short-term responses to fires but there is also a need to consider long-term fire regimes with a focus on variability within and between habitats, on resultant habitat quality and diversity, as well as on acknowledging elements and processes important for ecosystem resilience (Andersen and others 2003). Management for riparian fires also needs to consider habitat quality as well as habitat diversity at the landscape scale while considering the historic range of variability. For higher order streams at least, because riparian areas represent different vegetation community types, they should be considered separately in terms of fire management. Implicit in this is a requirement for improved understanding of the natural recovery processes of riparian areas after fire.

ACKNOWLEDGMENTS

We thank the Andrew W. Mellon Foundation for financial support, Professor James Agee (University of Washington) for informative discussions on fire ecology and fire in forests of the USA Pacific Northwest, and Navashni Govender (Kruger National Park, South Africa) for discussions and access to data and photographs of fires in Kruger. Also, we thank Professor James Agee, Dr Josh Latterell (University of Washington), Dr Alan Andersen (CSIRO) and Dr David Peterson (USDA-Forest Service) for highly constructive and comprehensive comments on earlier drafts.

REFERENCES

Agee JK. 1993. Fire ecology of Pacific Northwest forests. Washington DC: Island Press.

Agee JK. 1988. Successional dynamics in forest riparian zones. In: Raedeke KJ (Ed). Streamside management: Riparian wildlife and forestry interactions. Contribution No. 59. Seattle: University of Washington Institute of Forest Resources. pp 31–43.

Agee JK. 1998. The landscape ecology of western forest fire regimes. Northwest Sci 72:24–34.

Agee JK, Wright CS, Williamson N, Huff MH. 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. For Ecol Manage 167:57–66.

Andersen AN, Cook GD, Williams RJ (Eds). 2003. Fire in tropical Savanna: the Kapalga experiment. New York: Springer.

Andersen AN, Cook GD, Corbett LK, Douglas MM, Eager RW, Russell-Smith J, Setterfield SA, Williams RJ, Woinarski JCZ. 2005. Fire frequency and biodiversity conservation in Australian tropical savannas: implications from the Kapalga fire experiment. Austral Ecol 30:155–67.

Aranibar JN, Macko SA, Anderson IC, Potgieter AL, Sowry R, Shugart HH. 2003. Nutrient cycling responses to fire frequency in the Kruger National Park (South Africa) as indicated by stable isotope analysis. Isotopes Environ Health Stud 39:141–58.

Austin AT, Yahdjian L, Stark JM, Belnap J, Porporato A, Norton U, Ravetta DA, Schaeffer S.M. 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141:221–35.

Bêche LA, Stephens SL, Resh VH. 2005. Effects of prescribed fire on a Sierra Nevada (California, USA) stream and its riparian zone. For Ecol Manage 218:37–59.

Bellingham PJ, Sparrow AD. 2000. Resprouting as a life history strategy in woody plant communities. Oikos 89:409–16.

Beeson PC, Martens SN, Breshears DD. 2001. Simulating overland flow following wildfire: mapping vulnerability to landscape disturbance. Hydrolog Processes 15:2917–30.

Benda LE, Miller DJ, Dunne T, Reeves GH, Agee JK. 1998. Dynamic landscape systems. In: Naiman RJ, Bilby RE (Eds). River ecology and management: lessons from the pacific coastal ecoregion. New York: Springer. pp 261–88.

Bendix J. 1994. Among-site variation in riparian vegetation of the southern California transverse ranges. Am Midl Nat 132:136–51.

Bisson PA, Rieman BE, Luce C, Hessberg PF, Lee DC, Kershner JL, Reeves GH, Gresswell RE. 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. For Ecol Manage 178:213–29.

Blank RR, Chambers JC, Zamudio D. 2003. Restoring riparian corridors with fire: Effects on soil and vegetation. J Range Manage 56:388–96.

Bond WJ, Midgley JJ. 2003. The evolutionary ecology of sprouting in woody plants. Int J Plant Sci 164:103–14.

Bond WJ, Keeley JE. 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. Trends Ecol Evol 20:387–94.

Bond WJ, van Wilgen BW. 1996. Fire and plants. London: Chapman and Hall.

Bragg DC. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology 81:1383–94.

Brynard AM. 1971. Controlled burning in the Kruger National Park—History and development of a veld burning policy. In: Tall timbers fire ecology conference—fire in Africa. Tallahassee Florida: Tall Timbers Research Station. pp 219–31.

Busch DE, Smith SD. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern US. Ecol Monogr 65:347–70.

Camp A, Oliver C, Hessburg P, Everett R. 1997. Predicting latesucessional fire refugia pre-dating European settlement in the Wenatchee Mountains. For Ecol Manage 95:63–77.

Cary GJ, Keane RE, Gardner RH, Lavorel S, Flannigan MD, Davies IA, Li C, Lenihan JM, Rupp TS, Mouillot F. 2006. Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. Landscape Ecol 21:121–37.

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

Charron I, Johnson EA. 2006. The importance of fires and floods on tree ages along mountainous gravel-bed streams. Ecol Appl 16:1757–70.

Chen J, Saunders S, Crow T, Naiman RJ, Brosofske K, Mroz G, Brookshire B, Franklin JF. 1999. Microclimate in forest ecosystem and landscape ecology. Bioscience 49:288–97.

Cheney NP. 1981. Fire behaviour. In: Gill AM, Groves RH, Noble IR (Eds). Fire and the Australia biota. Canberra: Australian Academy of Science. pp 151–75.

Cochrane MA. 2003. Fire science for rainforests. Nature 421:913–19.

Cook GD. 1994. The fate of nutrients during fires in a tropical savanna. Aust J Ecol 19:359–65.

Douglas M. 1999. The effect of fire regime on riparian vegetation. PhD thesis. Darwin: Charles Darwin University.

Douglas MM, Townsend SA, Lake PS. 2003. Streams. In: Andersen AN, Cook GD, Williams RJ (Eds). Fire in tropical Savanna: the Kapalga experiment. New York: Springer. pp 59–78.

Dwire KA, Kauffman JB. 2003. Fire and riparian ecosystems in landscapes of the western USA. For Ecol Manage 178:61–74.

Dunne T, Leopold L. 1978. Water in environmental planning. New York: W.H. Freeman and Company.

Elliott KJ, Hendrick RL, Major AE, Vose JM, Swank WT. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. For Ecol Manage 114:199–213.

Ellis LM. 2001. Short-term response of woody plants to fire in a Rio Grande riparian forest, central New Mexico, USA. Biol Conserv 97:159–70.

Govender N, Trollope SW, van Wilgen BW. 2006. The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. J Appl Ecol 43:748–58.

Gregory SV, Boyer K, Gurnell A (Eds). 2003. The ecology and management of wood in world rivers. Bethesda (MD): American Fisheries Society.

Gurnell A, Tockner K, Edwards P, Petts G. 2005. Effects of deposited wood on biocomplexity of river corridors. Front Ecol Environ 3:377–82.

Heisler JL, Briggs JM, Knapp AK, Blair JM, Seery A. 2004. Direct and indirect effects of fire on shrub density and above ground productivity in a mesic grassland. Ecology 85:2245–57.

Heritage GL, Moon BP, Jewitt GP, Large ARG, Rountree M. 2001. The February 2000 floods on the Sabie River, South Africa: an examination of their magnitude and frequency. Koedoe 44:37–44.

Heinl M, Neuenschwander A, Sliva J, Vanderpost C. 2006. Interactions between fire and flooding in a southern African floodplain system (Okavango Delta, Botswana). Landscape Ecol 21:699–709.

Higgins SI, Bond WJ, Trollope WSW. 2000. Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna. J Ecol 88:213–29.

Hungate BA, Naiman RJ, Apps M, Cole JJ, Moldan B, Satake K, Stewart JWB, Victoria R, Vitousek PM. 2003. Disturbance and element interactions. In: Melillo JM, Field CB, Moldan B (Eds). Interactions of the major biochemical cycles. Washington: Island Press. pp 47–62.

Johansen MP, Hakonson TE, Breshears DD. 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. Hydrolog Processes 15:2953–65.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river floodplain systems. In: Dodge DP (Ed). International large river symposium, vol 106. Canada Fisheries and Aquatic Sciences Special Publication. pp 110–27.

Kellman M, Tackaberry R. 1993. Disturbance and tree species coexistence in tropical riparian forest fragments. Glob Ecol Biogeogr Lett 3:1–9.

Kellman M, Tackaberry R, Rigg L. 1998. Structure and function in two tropical gallery forest communities: implications for forest conservation in fragmented systems. J Appl Ecol 35:195–206.

Latterell JJ, Naiman RJ. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecol Appl (in press).

Lamb EG, Mallik AU, Mackereth RW. 2003. The early impact of adjacent clearcutting and forest fire on riparian zone vegetation in northwestern Ontario. For Ecol Manage 177:529–538.

Laurance WF. 2003. Slow burn: the insidious effects of surface fires on tropical forests. Trends Ecol Evol 18:209–12.

Malanson GP. 1993. Riparian landscapes. Cambridge: Cambridge University Press.

Meave J, Kellman M, MacDougall A, Rosales J. 1991. Riparian habitats as tropical forest refugia. Glob Ecol Biogeogr Lett 1:69–76.

Minshall GW, Brock JT, Varley JD. 1989. Wildfires and Yellowstone's stream ecosystems. Bioscience 39:707–15.

Moore RD, Sunderland P, Gomi T, Dhakal A. 2005. Thermal regime of a headwater stream within a clearcut, coastal Britsh Columbia, Canada. Hydrolog Processes 19:2591–608.

Naiman RJ, Décamps H, Pollock M. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecol Appl 3:209–12.

Naiman RJ, Bilby RE, (Eds). 1998. River ecology and management: lessons from the Pacific coastal ecoregion. New York: Springer.

Naiman RJ, Fetherston KL, McKay SJ, Chen J. 1998. Riparian forests. In: Naiman RJ, Bilby RE (Eds). River ecology and management: lessons from the Pacific coastal ecoregion. New York: Springer. pp 289–323.

Naiman RJ, Bechtold JS, Drake D, Latterell JJ, O'Keefe TC, Balian EV. 2005a. Origins, patterns, and importance of heterogeneity in riparian systems. In: Lovett G, Jones CG, Turner MG, Weathers KC (Eds). Ecosystem function in heterogeneous landscapes. New York Springer. pp 279–309.

Naiman RJ, Décamps H, McClain ME. 2005b. Riparia: ecology, conservation and management of streamside communities. Boston: Elsevier Academic.

Neary DG, Klopatek CC, DeBano LF, Folliott PF. 1999. Fire effects on belowground sustainability: a review and synthesis. For Ecol Manage 122:51–71.

Olsen DL, Agee JK. 2005. Historical fires in Douglas-fir dominated riparian forests of the southern Cascades, Oregon. Fire Ecol 1:50–74.

O'Keeffe J, Rogers KH. 2003. Heterogeneity and management of the lowveld rivers. In: Du Toit JT, Rogers KH, Biggs HR (Eds). The Kruger experience: ecology and management of savanna heterogeneity. Covelo (CA): Island Press. pp 445–66.

Parsons M, McLouglin CA, Rountree MW, Rogers KH. 2006. The biotic and abiotic legacy of a large infrequent flood disturbance in the Sabie River, South Africa. River Res Appl 22:187–201.

Patten DT. 1998. Riparian ecosystems of semi-arid North America: diversity and impacts. Wetlands 18:498–512.

Pettit NE, Naiman RJ. 2005. Flood-deposited wood debris and its contribution to heterogeneity and regeneration in a semi-arid riparian landscape. Oecologia 145:434–44.

Pettit NE, Naiman RJ. 2007. Post-fire response of riparian vegetation and soils and the effect of flood-deposited wood in a semi-arid landscape. Ecology (in press).

Pettit NE, Naiman RJ, Rogers KH, Little JE. 2005. Post-flooding distribution and characteristics of large woody debris piles along the semi-arid Sabie River, South Africa. River Res Appl 21:27–38.

Pickup M, McDougall KL, Whelan RJ. 2003. Fire and flood: Soil-stored seed bank and germination ecology in the endangered Carrington Falls Grevillea (Grevillea rivularis, Proteace). Austral Ecol 28:128–36.

Pyne SJ, Andrews PL, Laven RD. 1996. Introduction to wildland fire. New York: Wiley.

Reeves GH, Bisson PA, Rieman BE, Benda LE. 2006. Postfire logging in riparian areas. Conserv Biol 20:994–1004.

Russell WH, McBride JR. 2001. The relative importance of fire and watercourse proximity in determining stand composition in mixed conifer riparian stands. For Ecol Manage 150:259–65.

Scholes RJ, Walker BH. 1993. An African savanna: synthesis of the Nylsvlei study. Cambridge: Cambridge University Press.

Segura G, Snook LC. 1992. Stand dynamics and regeneration patterns of a pinyon pine forest in east-central Mexico. For Ecol Manage 47:175–94.

Slik JWF, Eichhorn KAO. 2003. Fire survival of lowland tropical rain forest trees in relation to stem diameter and topographic position. Oecologia 137:446–55.

Sterner RW, Elser JJ. 2002. Ecological stoichiometry: the biology of elements from elements to the biosphere. Princeton: Princeton University Press.

Shakesby RA, Doerr SH. 2006. Wildfire as a hydrological and geomorphical agent. Earth Sci Rev 74:269–307.

Stevenson-Hamilton J. 1929. The lowveld: it's wildlife and it's people. London: Cassel and Company Ltd.

Swanson FJ, Jones JA, Grant GE. 1997. The physical environment as a basis for managing ecosystems. In: Kohm KA, Franklin JE (Eds). Creating a forestry for the 21st Century. Washington DC: Island Press.

Taylor AH, Skinner CN. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecol Appl 13:704–19.

Turner MG, Dale VH. 1998. Comparing large infrequent disturbances: what have we learned?. Ecosystems 1:493–96.

Uhl C, Kauffman JB. 1990. Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. Ecology 71:437–49.

Van Wilgen BW, Higgins KB, Bellstedt. 1990. The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone Fynbos shrublands of South Africa. J Ecol 78:210–22.

van Wilgen BW, Trollope WSW, Biggs HC., Potgieter ALF, Brockett BH. 2003. Fire as a driver of ecosystem variability. In: du Toit JT, Rogers KH, Biggs (Eds). The Kruger experience: ecology and management of savanna heterogeneity. Washington: Island Press. pp 149–70.

van Wilgen BW, Govender N, Biggs HC, Ntsala D, Funda XN. 2004. Response of savanna fire regimes to changing fire-management polices in a large African national park. Conserv Biol 18:1533–540.

Wan S, Hui D, Luo Y. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. Ecol Appl 11:1349–65.

Whelan RJ. 1998. The ecology of fire. Cambridge: Cambridge University Press.

Williams RJ, Griffiths AD, Allan GE. 2002. Fire regimes and biodiversity in the savannas of northern Australia. In: Bradstock RA, Williams JE, Gill AM (Eds). Flammable Australia: the fire regimes and biodiversity of a continent. Cambridge: Cambridge University Press. pp 281–304.

Wipfli MS, Richardson JS, Naiman RJ. 2007. Ecological linkages between headwaters and downstream ecosystems: transport of organic matter, invertebrates, and wood down headwater channels. J Am Water Res Assoc (in press).

Zelt RB, Wohl EE. 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. Geomorphology 57:217–33.