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BRIDGES

Natural disturbance and forest management in riparian zones: comparison of effects at reach, catchment, and landscape scales

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Abstract. Forest disturbance agents, such as wildfire and windthrow, often differ in magnitude and frequency between upland and riparian zones. Riparian forests may be subject to additional disturbance agents that do not affect uplands, including debris flows, floods, bank erosion, and avulsions. Forest harvesting, with or without a streamside buffer, is an additional riparian disturbance agent in managed landscapes. The effects of riparian harvesting on stream habitat and ecology are qualitatively similar to those of wildfire, with the important exception of recruitment of large in-stream wood. For most other disturbance agents, current knowledge is insufficient to assess the degree to which natural disturbance can be emulated via riparian forest harvesting. In particular, the effects of the spatial patterns and frequencies of disturbance on the trajectories and rates of postdisturbance recovery are poorly understood for many landscapes and are complicated by the potential for propagation of effects down the stream network. Broadly based, long-term research on riparian disturbance regimes is needed to provide the scientific basis required for designing strategies for sustainable streamside forest management.

Key words: riparian forests, natural disturbance, wildfire, logging impacts, landscape management.

In forested catchments, streams and their riparian areas are subject to disturbances, such as wildfire and insect outbreaks, across a range of spatial and temporal scales. Riparian disturbances can have deleterious effects on water quality, habitat, and biota, at least over short and medium time scales. However, as is the case for natural disturbances in other ecosystems, stream and riparian disturbances are integral to the long-term function and evolution of riverine ecosystems and can play an important role in the spatial patterns of channel morphology and stream–riparian habitat complexity (Everett et al. 2003, Bigelow et al. 2007, Florsheim et al. 2008, Eaton and Giles 2009, Death 2010).

The objective of our paper is to compare the effects of natural disturbance and forest management on riparian–stream systems with a focus on in-stream habitat and ecology. First, we summarize the effects of forest management activities on riparian processes and stream environments and review the characteristics of riparian forest disturbance regimes in the context of catchment-scale and broader landscape-level processes of forest disturbance. Then, we use the specific example of wildfire, for which the greatest knowledge base exists (Nitschke 2005), to compare the effects of riparian harvesting and natural disturbance on riparian–stream interactions and aquatic habitat. Last, we identify some operational implications and research needs associated with the application of the Emulation of Natural Disturbance (END) paradigm for riparian management.

Forest Management as a Stream and Riparian Disturbance

Forestry operations influence a number of riparian and stream processes. Harvesting in the riparian zone can reduce shade and increase stream temperature

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TABLE 1. Forest disturbance agents and their geographic characteristics. Agents denoted with an asterisk are restricted to riparian forest. Others influence both upland and riparian zones.

Disturbance agent	Geographic characteristics
Crown fire	Drier forest types
Surface fire	Drier forest types with high fuel load or low ignition points
Windthrow	Exposed, or wind-prone areas; particularly significant along streams with riparian buffers
Insect disturbance	Most forest types; affected tree species depends on insect
Individual tree mortality	Predominantly in moist ecosystems dominated by gap dynamics
Treefall caused by snow loading	Areas subject to heavy falls of cohesive snow, particularly near the coast
Treefall caused by ice accumulation	Regions subject to freezing rain, such as Quebec and New England
Snow avalanching	Snow-dominated, steep landscapes
Debris flows*	Steep landscapes; initiation in headwaters with potential to propagate down to intermediate and larger streams
Floods*	Most significant in downstream reaches in larger catchments
Bank erosion*	Larger channels where streams are competent to move sediment
Avulsions*	Larger streams flowing in alluvium

(Moore et al. 2005), modify the recruitment of in-stream wood (Bilby and Ward 1991), decrease root strength and bank stability (Millar 2000), and influence the supply of allochthonous and autochthonous material (Kiffney et al. 2003, Kiffney and Richardson 2010). Effects of disturbance on water quality, such as increased water temperatures and suspended sediment concentrations, can propagate downstream and influence stream reaches flowing in undisturbed forest (Story et al. 2003, Feller 2005, Wilkerson et al. 2006).

Even where forested buffers are retained along a stream, upland forest removal influences riparian and stream processes. The presence of a riparian buffer typically has little effect on harvesting-related changes in stream flow (Moore and Wondzell 2005) and may not protect against increases in sediment input (Rivenbark and Jackson 2004). Removal of upland forest can increase windthrow in riparian zones, and thus, influence patterns of recruitment of in-stream wood (Grizzel and Wolff 1998). Upland forest harvesting also increases light penetration in riparian forest (Kiffney et al. 2003) and releases understory growth from shade limitation.

After harvest, the trajectory of riparian vegetation development will depend on ongoing silvicultural activities. In some instances, forest harvesting without riparian buffers can result in conversion of near-stream forest to N-fixing species, such as red alder (*Alnus rubra*) in western North America and black locust (*Robinia pseudoacacia*) in southeastern USA, resulting in a long-term increase in stream NO_3^- concentrations (Swank et al. 2001, Wipfli and Musslewhite 2004). In other cases, such as in western Oregon, silvicultural practices encouraged development of densely stocked coniferous stands in the riparian and upland zones of headwater streams (Anderson et al. 2007).

Roads and their drainage systems can be significant sources of sediment to streams even in the presence of riparian buffers (Gomi et al. 2005). In addition, removal of forest cover in road right-of-ways can increase solar radiation and wind penetration into the riparian zone, resulting in changes in riparian microclimate and stream temperature (Herunter et al. 2003). Increased penetration of solar radiation could affect vegetation growth within the buffer and in-stream primary productivity.

Natural Disturbance Regimes and Stream–Riparian Systems

Natural disturbance regimes in forests can be broadly described in terms of the disturbance agent (e.g., fire, windthrow, insects; Table 1), the spatial extent and pattern of disturbance, and the frequency and intensity of disturbance. These characteristics vary geographically as a function of climate, topography, vegetation, and their interactions. For example, in British Columbia, Canada (Fig. 1), natural disturbance regimes at a coarse scale differ between those in the wet coastal forests, where fire is rare and individual tree mortality, blowdown, and landslides are the dominant disturbance agents, and those in the drier interior forests, where frequent stand-replacing and stand-maintaining fires predominate (Wong et al. 2003, Daniels and Gray 2006). Within these coarse divisions, substantial finer-scale variability exists, including mixed-severity fire regimes (Klenner et al. 2008).

Riparian zones often differ from upland sites in terms of topography, microclimate, moisture dynamics, and vegetation, and therefore, should differ from

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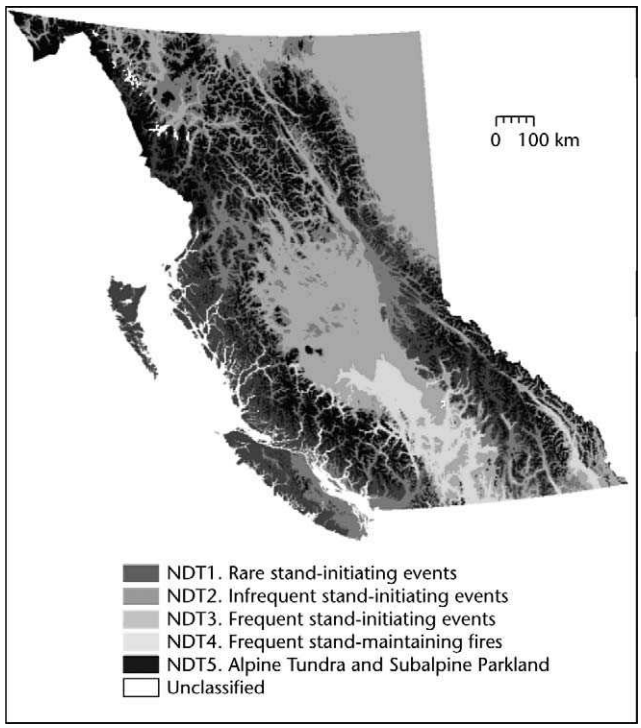


FIG. 1. Geographic distribution of natural disturbance types (NDTs) in British Columbia, Canada (Province of British Columbia 1995; http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/biodiv/biotoc.htm). This figure provides an example of the coarse-scale geographic variation in a single jurisdiction, with dominant disturbance agents ranging from infrequent tree death (NDT1) to frequent, stand-maintaining disturbances (NDT4).

upland sites in forest disturbance regime. The typically moister conditions in riparian zones can result in shallower rooting depths and, for some forest types, greater vulnerability of riparian forests to processes such as windthrow and falldown caused by snow loading. Wildfire disturbance may be less frequent in riparian zones than in upland sites (Everett et al. 2003, Pettit and Naiman 2007), although the disturbance frequencies may be similar in drier regions, such as eastern Oregon and Alberta (Macdonald et al. 2004, Olson and Agee 2005) and along intermittent headwater streams (Tollefson et al. 2004). However, wildfire disturbance may be more intense in riparian zones than on sideslopes because of greater accumulation of fuel between fires (Everett et al. 2003). The recent outbreak of mountain pine beetle (*Dendroctonus ponderosae*) in western North America, which has caused widespread mortality of pine trees (Fauria and Johnson 2009), is a good example of the contrasts in disturbance regimes between riparian and upland forest. In areas of central British Columbia identified as having pine-dominated forest stands, spruce is commonly the dominant species in riparian zones (Rex et al. 2009). Thus, riparian forests are likely to be less affected by mountain pine beetle than upland forests, where pine is typically the dominant species.

Some disturbance agents, such as debris flows and floods, are unique to riparian zones (Table 1). Debris flows in tributary reaches can contribute sediment and large wood to mainstem reaches (Hogan 1989, Bigelow et al. 2007). During floods, these pieces of large wood can be mobilized. Mobilization of large wood can increase disturbance to the channel and the riparian forest along the mainstem reach (Johnson et al. 2000) and can prompt stream avulsion. The legacy of past disturbance can be important. In a catchment in the Oregon Cascades, Johnson et al. (2000) inferred that logging in the 1940s and 1950s increased the wood available for transport during a major flood in 1964, which resulted in toppling and uprooting of old-growth conifers in the riparian zone. Subsequent forest harvesting decreased the availability of large wood for transport in a 1996 flood.

Stream and riparian disturbance regimes vary with catchment scale and stream size. Headwater reaches will be more strongly influenced by debris flows than floods, whereas floods can significantly influence larger, downstream channels flowing in floodplains (Johnson et al. 2000). For streams below a threshold bankfull width (~15–20 m in the Pacific Northwest), riparian forest can provide sufficient cohesion that bank erosion and lateral channel migration are minimal (Beechie et al. 2006). For larger streams, shear stress on the banks will exceed their shear strength on a more regular basis, promoting channel migration, disturbance to the riparian forest, and wood recruitment to the channel (Eaton and Giles 2009).

Stream channels and riparian zones exhibit a range of states across a landscape. These states reflect different disturbance histories and recovery trajectories and inherent intersite differences in conditions (Bigelow et al. 2007, Naiman et al. 2010). The spatial pattern of these states influences the resilience of the system to disturbance. For example, undisturbed tributary reaches can provide critical refugia that provide a source of colonists to promote recovery of downstream, disturbed reaches (Lamberti et al. 1991, Nakamura et al. 2000).

Comparison of Wildfire and Harvesting as Disturbance Agents

The body of available research on wildfire as a forest disturbance provides a basis for comparison with forest harvesting at the reach and catchment

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scales. Wildfire and harvesting influence catchment-scale generation of stream flow by affecting snow dynamics and snowmelt runoff. Reduction of canopy cover increases snow accumulation by reducing interception loss and increases melt rate by decreased shading (Winkler et al. 2005, Winkler 2011). However, following a wildfire, standing dead trees can provide substantial shading (Leach and Moore 2010), leading to lower melt rates than after clearcut harvesting (Burles and Boon 2011, Winkler 2011). Harvesting and wildfire both typically result in an earlier onset of snowmelt (Moore and Scott 2005, Eaton et al. 2010, Seibert et al. 2010). In addition, both types of disturbance reduce interception loss and transpiration, resulting in increased annual runoff (Cheng 1980, Moore and Wondzell 2005, Seibert et al. 2010). Most investigators have found that both harvesting and wildfire increase snowmelt-generated peak flows, although partial disturbance of a catchment can, in some circumstances, apparently result in desynchronized snowmelt and reduced peak flows (Verry et al. 1983, Eaton et al. 2010). The duration of these effects depends on the rate of hydrologic recovery, which, in turn, depends on the rate at which the regenerating stand grows after disturbance (Huggard and Lewis 2008).

Catchment-scale effects of wildfire and harvesting can differ significantly in cases where intense fire results in loss of soil organic matter and development of a hydrophobic layer within the soil (Huffman et al. 2001). In these cases, infiltration of rainfall is impeded and water runs over the soil surface, resulting in more intense peak flows, widespread surface erosion, and dramatically increased suspended sediment loads (Moody and Martin 2001, Silins et al. 2009). In contrast, reduced infiltration and increased overland flow are rarely observed after harvesting except from roads and areas where the soil has been disturbed by compaction (Moore and Wondzell 2005). In mountainous catchments, debris flows often occur after wildfire (Wondzell and King 2003). However, an increase in surface erosion and stream sediment concentrations does not follow wildfire in all cases (Eaton et al. 2010), especially where the duff layer is only partially consumed in a fire (Martin et al., in press).

Wildfire and harvesting both result in decay of tree roots and, thus, loss of soil cohesion. On steep slopes, the result can be increased risk of landslides during intense rain or snowmelt events (Benda and Dunne 1997). In riparian zones, decay of tree roots can result in loss of bank strength and increased rates of bank erosion (Millar 2000, Eaton et al. 2010). Eaton and Giles (2009) hypothesized that loss of bank strength after wildfire may strongly influence stream habitat complexity. For a stream that normally cannot erode its banks, loss of bank strength after riparian wildfire can trigger a period of lateral instability, leading to an increase in the frequency of pool–riffle units and formation of side channels, both of which provide habitat complexity on land and in the water. As the riparian forest regenerates over the following decades, lateral stability is re-established, leading to a gradual loss of complexity.

The severity of and potential for interactions between catchment-scale and riparian disturbances depend on the types and intensities of disturbance and on the nature of postdisturbance weather, which introduces an element of contingency. For example, the effects of catchment-scale harvesting are likely to be more benign than those of wildfire in cases where intense rainfall, which can trigger widespread overland flow on hydrophobic soils and debris flows, occurs in the first year or two after a fire. However, in cases where intense rain and overland flow do not occur, clearcut harvesting is likely to result in a greater increase in peak flow than fire in snow-dominated catchments. Increased peak flows combined with the loss of bank strength after riparian harvesting could promote increased bank erosion and channel instability.

In the first few years after disturbance, harvesting and wildfire can lead to increased nutrient export, which can promote increased primary production in stream ecosystems (Feller 2005, Bladon et al. 2008). Large-scale fire and forest harvesting have qualitatively similar effects on stream communities and often cause simplification of the community with increases in generalist species (e.g., *Baetis* spp.) and species with short-generation times (e.g., Chironomidae) (Minshall et al. 1997, Ely and Wallace 2010, Malison and Baxter 2010).

Wildfire and harvesting in the riparian zone differ importantly in their effect on recruitment of large wood. In the wake of fire, wood loading increases dramatically as a result of the toppling of trees as their roots fail and increased bank erosion. The legacy of this pulse of recruitment lasts for decades (Bragg 2000, Scherer 2008). In the case of riparian harvesting, recruitment is likely to decrease for several decades, decreasing in-stream wood load (especially of large pieces) and its associated fluvial and ecological functions (Scherer 2008).

The decrease in shading associated with harvesting and wildfire leads to increases in stream temperature (Minshall et al. 1997), which can influence many aspects of stream ecosystems. However, after a wildfire, standing dead trees function more like a

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TABLE 2. Comparison of harvest and wildfire impacts on the functions of riparian forest. Note that the effects of riparian wildfire depend on intensity and, especially, on the percentage of riparian trees that survive the fire.

Function of riparian forest	Effect of riparian wildfire	Effect of riparian harvest	Comment
Bank strength	Decreased	Decreased	Effects should be roughly equivalent
Recruitment of in-stream wood	Input rate increased in the short-to-medium term	No recruitment for up to several decades	In-stream loss rates not compensated by new recruitment, reducing habitat complexity
Shade	Decreased	Decreased	Dead standing trees can provide some shade; effect is equivalent to partial-harvest treatments
Allochthonous plant litter inputs from riparian forest	Decreased	Decreased	Roughly equivalent
Habitat for riparian obligate species	Remnant trees, hydrophobic soils	No residual trees remaining, possible compaction	Dead standing trees can provide habitat to cavity nesters and foraging sites for flycatchers; changes to soil may affect burrowers
Sediment interception and storage	Reduced, especially where organic matter is lost and soils become hydrophobic	Possibly reduced, depending on extent of soil disturbance	

partial-retention riparian buffer than a clearcut in terms of shading (Leach and Moore 2010). The thermal sensitivity of a stream to a decrease in canopy shading depends on channel characteristics. For example, Dunham et al. (2007) found that the thermal effects of wildfire were greater for channels that had experienced postfire geomorphic disturbance than for channels that experienced only a reduction in canopy cover.

Fire may have relatively little effect on riparian-dependent plant and animal species (Hossack and Corn 2007), may be highly detrimental (Hossack et al. 2006), or may increase habitat supply. In some cases, riparian areas provide a refuge from upslope wildfires that stop in the relatively moister riparian vegetation (Pettit and Naiman 2007). In some landscapes, the community structure of riparian plants does not differ significantly between sites that have been harvested and sites that have been burned to the stream's edge (Lamb et al. 2003). However, harvesting and fire do differ in their implications for animal species that are riparian obligates or riparian associates (Marczak et al. 2010). In the few studies that have compared the effects of wildfire and forest harvesting on terrestrial wildlife, responses have ranged from almost no difference (Macdonald et al. 2004, Kardynal et al. 2009) to relatively large changes (Hobson and Schieck 1999; but this latter study did not include riparian areas).

Implications for Forest Management

Application of the emulation of natural disturbance (END) paradigm for managing riparian forest rests on the assumption that the effects of harvesting can mimic those of natural disturbance agents. In the case of riparian wildfire, many of the effects are qualitatively similar to those of riparian harvesting (Table 2). However, an important difference between natural disturbances and riparian harvesting is the effect on recruitment of in-stream wood. This observation reinforces the motivation for at least partial retention of the riparian forest during harvesting along streams where fire is a dominant agent of disturbance and in-stream wood is an important structural component. Blowdown is often higher in riparian buffers than in intact stands (Grizzel and Wolff 1998, Bahuguna et al. 2010), and this increase in blowdown appears to mimic the pulsed input of wood to streams that typically follows wildfire (Bragg 2000). Retention of some riparian forest also would emulate the shading provided by standing dead trees after a fire.

In some cases, riparian forest harvesting could also be a tool for ecological restoration in a manner similar to the use of prescribed fire where fire suppression has led to undesirable ecological changes (Bêche et al. 2005). For example, reduced frequency of riparian wildfire could result in decreased complexity of the channel and riparian areas, with implications for aquatic and riparian habitats (Eaton and Giles 2009).

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In such a case, riparian harvesting could lead to a period of channel instability and the associated creation of side channels after re-establishment of riparian forest. However, potential short-term conflicts with other resource values, such as maintenance of fish populations, and potential downstream effects, should be considered before using riparian harvesting as a tool for restoration (Rieman et al. 2010).

Compelling reasons may exist for using riparian harvesting to mimic natural disturbances in some landscapes. However, if END is used as a hypothesis to guide riparian forest management, the scale and pattern of disturbance will have to be evaluated carefully with consideration of catchment- and landscape-scale contexts of each site. For example, how will reach-scale riparian harvesting interact with upstream and catchment-scale disturbances? To what extent will the effects of reach-scale disturbance propagate downstream? How will reach-scale harvesting influence the spatial distribution of stream habitat conditions, particularly the locations of refugia? How will riparian harvesting interact with other disturbance agents to influence the trajectory of this distribution? Progress has been made in understanding landscape-scale patterns of stream–riparian disturbance in the Pacific Northwest (Hogan 1989, Cissel et al. 1999, Johnson et al. 2000, Nakamura et al. 2000, Tollefson et al. 2004, Bigelow et al. 2007), but this knowledge may not be applicable in other landscapes, such as the boreal forest. Long-term research on riparian disturbance regimes is needed to provide the basis for addressing these questions. This research should include retrospective studies (e.g., using dendrochronology) to reconstruct disturbance histories for stream–riparian systems, adaptive-management trials to increase understanding of the short-term impacts and longer-term recovery dynamics following forest harvest, and landscape-scale modelling to understand the longer-term effects of different management approaches on the spatial pattern of stream and riparian habitat conditions.

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