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Wildfire in boreal forest catchments influences leaf litter subsidies and consumer communities in streams: Implications for riparian management strategies

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ABSTRACT

Applying the emerging paradigm of emulation of natural disturbances (END) to forest management requires understanding of how the riparian-aquatic interface responds to natural forest disturbances. A comparison of riparian forest condition and stream function was conducted across boreal, headwater streams with wildfire, harvest with minimum 30 m riparian buffers, and reference forested catchment histories. We assessed riparian vegetation characteristics, leaf litter inputs to streams, instream leaf litter decomposition rates using leaf packs, and aquatic macroinvertebrates that colonized the leaf packs. Riparian shrub and juvenile woody-stem community structure was significantly more taxonomically rich and compositionally different at fire than reference sites. Mature tree densities at reference sites were 1.7× and 4× higher than at harvested and fire, respectively. Leaf litter input from riparian forests to streams was significantly greater and compositionally dissimilar at fire compared to harvested and reference sites. Although decomposition of speckled alder (*Alnus icana* ssp. *rugosa*) in the leaf packs did not differ significantly among study reaches, the aquatic invertebrate communities found in the leaf packs at fire sites were characterized by significantly higher taxa richness and unique shredder taxa. Detectable differences in riparian forest condition and instream processes suggest that forest management under the END paradigm could sustain ecosystem services (the support of aquatic biodiversity) by inducing riparian forest succession, enhancing leaf litter inputs and organic matter processing, and promoting riparian habitat complexity.

1. Introduction

There are strong ecological linkages between forested headwater streams and their adjacent terrestrial landscapes (Kaushik and Hynes, 1971; Wallace et al., 1997; Kreutzweiser et al., 2008). On a local level, headwater and low-order streams are dependent on riparian forests for services such as flood mitigation, temperature regulation, nutrient and sediment retention, organic matter inputs and instream habitat formation (Richardson et al., 2010; Timonen et al., 2010; Jyväsjärvi et al., 2014). Forested headwater streams create a habitat of low primary production and high dependence on allochthonous energy subsidies compared to higher order streams and rivers due to their narrow channel width and closed canopies (Vannote et al., 1980). Consequently, allochthonous subsidies, including leaf litter and other particulate organic matter, are the primary energy sources for aquatic macroinvertebrates and microbial communities in small forested streams driving instream metabolism and foodweb structure (Benfield, 1997; Pozo et al., 1998; Webster et al., 1999; Kreutzweiser et al., 2008).

Headwater systems make up a major spatial extent (70–80%) of the total catchment area (Sidle et al., 2000; Meyer and Wallace, 2001; Gomi et al., 2002). Riparian forests and headwater streams support diverse biological communities (Meyer et al., 2007) and provide important ecosystem services such as water quantity and quality regulation, nutrient cycling, and energy transport for the support of downstream biodiversity and river functioning (Sweeney, 1993; Meyer and Wallace, 2001; Wipfli and Gregovich, 2002; Moore and Richardson, 2003; Wipfli et al., 2007; Hoover et al., 2010). However, the specific relationships between headwater streams and the adjacent riparian forest conditions that arise from natural and human disturbances remain poorly understood in boreal forests despite their critical role in influencing the structure and function of the connected downstream aquatic ecosystems.

Harvesting and headwater streams are unavoidably coupled and a multitude of studies have shown that harvesting can affect

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ground stability, nutrient cycling, biodiversity, riparian microclimate, stream temperature, and habitat availability within headwater catchments of watersheds (Webster et al., 1992; Rex et al., 2012) leading to direct effects on streams including reduced shading and canopy cover, altered leaf litter and instream large wood inputs, increased sediment deposition and nutrient concentrations, and obstructed fish passages (Prepas et al., 2003a,b; Fortino et al., 2004; Richardson et al., 2012; Kreutzweiser et al., 2013; Webster et al., 2015). Consequently, knowledge of the impacts of forest harvesting within headwater catchments have heavily influenced current forest management practices, which are designed to minimize negative aquatic impacts (Ice et al., 2010; Richardson et al., 2012).

Forest fires are, by far, the dominant natural disturbance in boreal forests, and can result in major vegetation structural shifts, from stands dominated with mature trees to stands dominated with early-successional species (Hunter, 1993). Fire-induced changes in forest composition significantly influence habitat diversity and complexity that can affect biodiversity at levels determined by the spatial extent of the disturbance (Esseen et al., 1997; Swanson et al., 2011; Brooks et al., 2012). Generally, the effects of forest fire on aquatic systems depend on the severity, frequency and location of the fire (Minshall, 2003) and can range from short-term effects on water chemistry and stream temperature to long term effects on aquatic invertebrate community diversity and fish community biomass (Jackson et al., 2012).

Ecologists have previously studied how terrestrial disturbances can exert immediate or short-term influences on riparian-stream connectivity (e.g., Arkle and Pilliod, 2010; Clinton, 2011; Kastendick et al., 2012; Rex et al., 2012), however, we have a weaker understanding of the longer-term effects of disturbance on the riparian-stream interface in boreal forest watersheds. Understanding both short-and-long-term effects of forest disturbance on riparian forest composition, and the quality and quantity of organic material fluxes across forest-stream boundaries is crucial in the establishment of effective riparian ecosystem management strategies (Kreutzweiser et al., 2008, 2012; Hoover et al., 2010). Over the past few decades, the development of Best Management Practices (BMPs) to mitigate the impacts of forest harvesting on streams and lakes has been a central focus for forest managers (Broadmeadow and Nisbet, 2004; Fortino et al., 2004; Vowell and Frydenborg, 2004). One of the most common mitigation strategies is the use of riparian buffers to protect forest-stream interactions and stream health. However, the application of fixed-width riparian buffers, while convenient from a management perspective, ignores that these systems evolved under, and are adapted to, periodic natural disturbances such as fire, which are essential for riparian forest regeneration and creating habitat complexity in riparian ecotones (Sibley and Gordon, 2010). The systematic usage of fixed-width riparian buffers surrounding water bodies create unnatural bands or "ribbons" of older-growth forest along the perimeter of streams in catchments that have undergone forest harvesting (Buttle, 2002; Kreutzweiser et al., 2010). Developing management strategies that recreate natural disturbance habitat patterns and conditions is one of the goals of modern forest management and serves as a theoretical basis for management strategies such as the emulation of natural disturbances (END) paradigm (Naylor et al., 2012; Sibley et al., 2012). One of the possible strategies to achieve management goals under the END paradigm would be to incorporate harvest patterns within riparian zones that emulate natural riparian disturbance patterns. However, prior to implementing such strategies it is critical to understand stream-riparian ecosystem responses to natural disturbance in forest catchments and their riparian areas (Kreutzweiser et al., 2010, 2012).

The objective of our research was to measure and compare riparian forest structure, using species composition and abundance metrics, and its influences on leaf litter input and decomposition, and the aquatic macroinvertebrate communities in headwater streams of forest catchments with fire, harvested and reference (minimally disturbed) conditions. Our particular interest was in the comparison between fire and reference catchments and their streams as it pertains to the application of END management principles to riparian forests. However, we also included harvested catchments with minimum 30 m riparian buffers to compare structural and functional differences in streams with and without riparian disturbances. We predicted that the greatest differences among our measured variables would be between the fire and reference streams relating to effects of fire on riparian forest structure. Differences were expected to be smaller in harvested catchments where riparian forests had been retained by including a 30 m riparian buffer. The magnitude and characteristics of effects among response variables at fire sites could provide targets and benchmarks for riparian management strategies designed to emulate natural disturbance patterns and processes. Our study was conducted in the Boreal Shield of Ontario, which could be a relevant forest type for the implementation of END strategies to riparian forest management because forest fires are the dominant natural disturbance agent in this region.

2. Methods

2.1. Study site characteristics

The study was conducted approximately 75 km inland from the northeastern shore of Lake Superior within Canada's Boreal Shield ecozone in the White River Forest Management Area (Fig. 1). This area consists primarily of mixed-wood boreal forests of black and white spruce (*Picea mariana* and *P. glauca*), balsam fir (*Abies balsamea*), jack pine (*Pinus banksiana*), white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides)* (MacDonald, 1995). Speckled alder (*Alnus icana ssp. rugosa)* and red osier dogwood (*Cornus sericea*) are commonly found in the riparian forests of the region (Muto et al., 2009). The geologic foundation of the region is Precambrian granite bedrock with Humo-Ferric Podzol soil (Gunn and Pitblado, 2004) and the climate is characterized by lengthy, cold winters with relatively short, warm summers. The mean annual air temperature is approximately 2 °C, and precipitation via rain and snow averages 1000 mm annually. Streams in this region are generally ice covered from November to May.

In our study we focussed on low-order (headwater) catchments because of their sensitivity to disturbance and the crucial influence they exhibit on downstream aquatic systems (Lowe and Likens, 2005). Forest fire effects decrease as stream size increases (Minshall et al., 1989), and consequently, fire (and disturbance in general) can have a greater influence on headwater streams than higher order rivers due to a higher degree of catchment burned and a similar ratio between approximate stream margin area and water volume (Minshall et al., 1989). The three catchment disturbance types we focused on were harvested (conventional clearcut harvesting 7–17 years prior to study initiation) with slope-dependent, minimum 30 m riparian buffers, fire (burned 12 years prior to study initiation by wildfire, no dead material removed) and reference (minimally disturbed, i.e., no fire or harvesting for at least 40 years). Within these disturbance types, our study sites consist of ~50 m stream reaches established in 25 catchments (10 harvest; 7 fire; 8 reference) for leaf decomposition and aquatic invertebrate communities, and a subset of reaches in 18 catchments (5 harvest, 7 fire, 6 reference) was used to measure riparian forest structure and leaf litter inputs due to logistical constraints. Harvested catchments were an average of 330 ha, fire catchments were an average of 350 ha, and reference catchments were an