Forest Ecology and Management 384 (2017) 100–109

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Assessing the long-term ecological effects of riparian management practices on headwater streams in a coastal temperate rainforest

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ARTICLE INFO

Article history:
Received 5 July 2016
Received in revised form 16 October 2016
Accepted 18 October 2016
Available online 26 October 2016

Keywords:
Forest harvesting
Riparian protection
Stream recovery
Logging legacies
Litter decomposition
Shredder community

ABSTRACT

Our understanding of how effective forestry Best Management Practices (BMPs) can mitigate logging impacts on the structure and functioning of temperate headwater streams tends to be based upon studies conducted within the first few years post-harvest. Little is known about how the affected biological parameters of streams change during riparian and upland forest regeneration, particularly the time taken to return to pre-harvest levels, or to within the range of reference conditions. By following up on an earlier study in southwestern British Columbia, Canada, we examined the post-logging recovery trajectories of stream attributes under multiple forest treatments. These treatments provided a gradient of riparian protection, including streamside clear-cutting with no reserves, and with fixed-width reserves (10 m and 30 m), and thinning with 50% basal area removal of riparian trees, which were compared with unharvested control sites. About 15 years after clear-cutting and 9 years after thinning, slower decomposition of red alder leaves (*Alnus rubra*) was reported in streams affected by forest harvesting, which was attributed to lower density of shredder invertebrates. Thinned reaches had lower litter decomposition rate than, but similar shredder density and richness to, unharvested reference sites. After a further 7 years of forest regrowth (time elapsed between the previous and present study), we found that litter decomposition rate and shredder density in logging-affected reaches converged with values in reference reaches. Stream functional integrity, as reflected by litter decomposition, increased across all forest treatments. Some differences in rarefied shredder richness among forest treatments emerged in this study. The legacy effects of thinning on some biotic variables likely diminished more quickly (2–9 years post-harvest) than those of clear-cutting with and without riparian reserves (8–15 years). Stream recovery from thinning to reference conditions should continue to warrant attention, as wider, larger-scale partial harvesting practices are recommended within emerging paradigms of forest management. Overall, our findings indicate time scales towards recovery of an important ecological process of streams under common forestry practices, which could be longer than other stream properties, such as water quality. Such differences in recovery time frames should be considered for the planning of forestry operations and monitoring of harvesting legacies.

1. Introduction

A range of management practices have been designed to address and mitigate the impacts of forest harvesting on watersheds, which operate on various spatial scales. These practices typically include the establishment of riparian reserve strips of fixed or variable widths and configurations (reach scale); and harvesting of various extent and species (e.g., partial harvesting, progressive harvesting, selective and shelterwood logging), re-routing of stream crossings and road networks, etc. (catchment scale). Many of these practices are now formulated as forestry best management practices (BMPs), and incorporated in forestry guidelines and regulations worldwide (e.g., Lee et al., 2004; McDermott et al., 2010; Cristan et al., 2016), as well as forest certification programs (Ice et al., 2010).

Contemporary forestry BMPs and other riparian protection measures are known to differ in the effectiveness of maintaining water quality, aquatic and riparian biodiversity, ecosystem functions and services (Cristan et al., 2016). Such effectiveness tends to increase with the width of riparian reserves, and fixed-width reserves of 30 m have been typically set to balance stream-riparian protection and timber production. Nevertheless, forest

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http://dx.doi.org/10.1016/j.foreco.2016.10.044
0378-1127/

harvesting even ⩾30 m beyond streamsides is sometimes shown to cause apparent abiotic (e.g., temperature and nitrate removal efficiency; see Sweeney and Newbold, 2014) and biotic changes in stream and riparian systems (e.g., Pearson and Manuwal, 2001; Kreutzweiser et al., 2008a; Lecerf and Richardson, 2010; Marczak et al., 2010). Partial harvesting of riparian vegetation (or thinning; usually affecting ⩽50% of the basal area) could elevate stream temperature (Macdonald et al., 2003; Guenther et al., 2014) and nutrient levels shortly after logging (Wang et al., 2006). The effects of thinning upland and riparian vegetation, or thinning upland forests while retaining riparian buffers, on stream habitats and communities may be evident (e.g., Martel et al., 2007; Moseley et al., 2008; Kara et al., 2014; Burton et al., 2016) or undetectable (e.g., Wilkerson et al., 2006; Olson and Rugger, 2007; Kreutzweiser et al., 2009; Chizinski et al., 2010), depending on the extent and methods of harvesting.

The effectiveness of riparian protection measures, such as fixed-width buffers and partial harvesting, has typically been evaluated based on short-term, post-harvest water quality data (e.g., within three years after harvesting; see Cristan et al., 2016). Post-harvest ecological recovery of streams, including biotic communities and their functions, has been much less studied, which can require longer time frames (but see Jackson et al., 2007; Gravelle et al., 2009). Many studies of ecological recovery adopted various sampling designs to minimize site-specific differences in ecological processes post-harvest, by studying streams affected by a gradient of logging history (Herlihy et al., 2005; Martel et al., 2007), multiple paired watersheds and three or more sites in treatment/control groups in replicated designs (e.g., Frady et al., 2007; Hemstad et al., 2008; Medhurst et al., 2010). Some studies detected signs of recovery for macroinvertebrate or shredder communities >10 years after harvesting (Davies et al., 2005; Frady et al., 2007; Medhurst et al., 2010), but did not address long-term changes in ecosystem processes, such as litter decomposition.

Measures of stream ecosystem processes are important to assess ecological integrity (Gessner and Chauvet, 2002). As forested headwater streams receive most of their energy inputs from allochthonous detritus, decomposition rates of leaf litter have been used to indicate forestry impacts on important ecosystem processes, with post-harvest increases (Griffith and Perry, 1991; Benfield et al., 2001; McKie and Malmqvist, 2009) and decreases (Kreutzweiser et al., 2008a; Lecerf and Richardson, 2010) being documented. The substantial variability of the post-harvest responses of litter decomposition rate (in terms of direction and magnitude) could be attributed to logging-induced alterations in stream habitats (Webster and Waide, 1982) and compositional shifts of riparian forest vegetation (Kominoski et al., 2011) (see also Richardson and Béraud, 2014). Several lines of evidence indicate that these changes affected the abundance and diversity of invertebrate shredders, as a key agent of organic matter breakdown in aquatic ecosystems (e.g., Griffith and Perry, 1991; McKie and Malmqvist, 2009; Lecerf and Richardson, 2010).

As part of the riparian management study at the University of British Columbia's Malcolm Knapp Research Forest (MKRF), near Vancouver, Canada, experimental harvests were executed across watersheds, with replicate streams for each harvesting practice (see Methods for detailed descriptions). The recovery of stream temperature and water chemistry in the logged sites to reference levels was detected within 5 years post-harvest (Gomi et al., 2006; Feller, 2010). In a study conducted in 2006, Lecerf and Richardson (2010) showed lower litter decomposition rates in streams 8 years after clear-cut logging with or without riparian reserves, and 2 years after thinning (i.e., logging 50% of the basal area of riparian trees) than in reference ones. The reduced decomposition rates in clear-cut reaches with or without riparian reserves were associated with lower densities of shredder invertebrates.

We conducted this study in 2013 (i.e., 15 years after logging and 9 years after thinning) by re-measuring litter decomposition rate, shredder density and richness, and water quality characteristics in the same study sites. This study thus investigated the post-logging recovery trajectories of headwater streams in the presence of experimental riparian management practices. After an additional 7-year period of forest regeneration, we predicted that the measured biological parameters in some of the logged reaches, especially those with wider riparian reserves, would become close to, or no longer be significantly different from, those in reference reaches. Such convergence would indicate signs of ecological recovery from forest harvests, and would likely be associated with the altered physical environment of streams approximating reference conditions. We noted that several hydro-climatic characteristics, including temperature, precipitation and stream discharge, could potentially influence the responses of the measured biological parameters, in addition to the legacy effects of forest harvesting. For instance, stream discharge and thermal regimes in the study period and the preceding summer could affect shredder recruitment and survival, and hence litter decomposition, which need to be considered when comparing them across forest treatments.

2. Material and methods

2.1. Study sites

The set of study sites were the same as used in Lecerf and Richardson (2010). The study area is located within the Coast Mountains of the Pacific Northwest and about 45 km east of Vancouver, British Columbia. A total of 16 stream reaches (up to 5 m wide) in MKRF (49°18′40″N, 122°32′40″W) were chosen and randomly assigned (with one exception) to various riparian management practices, including (1) clear-cutting where no reserves were left; (2) upland clear-cut logging with 30-m continuous riparian reserves on both sides of the study reach; (3) upland logging with 10-m riparian reserves on both sides; (4) upland and riparian thinning (50% basal area removal). There were 3 or 4 replicate stream reaches in each riparian management practice (for details, see Kiffney et al., 2003 and Lecerf and Richardson, 2010). Experimental streamside logging with manipulations of fixed-width riparian reserves (0, 10-m and 30-m wide) took place in 1998, whereas thinning occurred in 2004. Thinning involved uniform tree removals spanning the stream channel within a harvest unit, with the goal of removing a similar basal area of trees on a catchment scale as in earlier upland logging.

Prior to the experimental harvests, these reaches and the unharvested, reference reaches were located in second-growth forests which had not been logged since 1931. Early successional riparian forests in the clear-cut sites was primarily dominated by rapidly-growing, nitrogen-fixing red alder, *Alnus rubra* Bong. (Betulaceae) in 2006 (Lecerf and Richardson, 2010). At the time of this study, detrital inputs of red alder (and other deciduous broadleaves) likely continued to dominate riparian litterfall to streams (Bilby and Bisson, 1992; Hoover et al., 2011), and enhance the productivity of lower trophic levels in clear-cut sites (Kominoski et al., 2012). Some red alder trees were also present in the riparian vegetation in sites with riparian reserves and thinned sites, and much fewer in coniferous-dominated reference sites. Canopy openness in each site was determined from digital hemispherical pictures taken vertically upward about 1 m from the streambed in autumn 2013 (Nikon Coolpix 4500 with fisheye lens, Nikon USA Inc., Melville, NY, USA). Pictures were processed using the software package