Forest Ecology and Management 341 (2015) 45–58

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Differentiating mixed- and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera

Hélène M. Marcoux [a,*], Lori D. Daniels [a], Sarah E. Gergel [a], Eric Da Silva [b], Ze'ev Gedalof [b], Paul F. Hessburg [c]

[a] Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, Canada
[b] Department of Geography, University of Guelph, Guelph, ON, Canada
[c] USDA-FS, PNW Research Station, 1133 N. Western Ave., Wenatchee, WA, USA

ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form 22 December 2014
Accepted 23 December 2014
Available online 23 January 2015

Keywords:
Fire history
Forest age structure
Fire exclusion
Larix occidentalis
Snag dynamics
Stand dynamics

ABSTRACT

Mixed-severity fire regimes are important drivers of forest dynamics, stand structural attributes, and regional and local landscape heterogeneity, but they remain poorly understood. We reconstructed site-level fire histories using fire scars and even-aged cohorts at 20 sites in two contiguous watersheds in southeastern British Columbia, Canada, a region that is particularly understudied. We compared stand composition and structural attributes (i.e., snag and veteran tree densities, tree size variability, and maximum tree size) at sites found to be mixed-severity, as well as those found to be high-severity after recent (<150 years) and older ($\geqslant$150 years) stand-replacing fires. We developed two forest indices capturing age-structure complexity and continuity to refine these comparisons.

Eleven of 20 sites displayed mixed-severity fire histories and were located at elevations 600 m higher than previously described for this landscape. Tree species composition varied with disturbance history. Mixed-severity sites were dominated by Douglas-fir and western larch that regenerated after frequent low- to moderate-intensity fires, which created fire scars. Periodic moderate-severity fires generated some even-aged cohorts with surviving veteran trees. At higher-elevations, intense fires generated cohorts dominated by lodgepole pine. Subalpine fir dominated high-severity sites that last burned >250 years ago.

Age structures at mixed- and older high-severity sites were of similar complexity, but could be differentiated using our index of age structure continuity. We found western larch to be a strong indicator of historical mixed-severity fire regimes. Western larch trees and stumps were only found at mixed-severity sites, and 84% of these individuals established within 15 years of antecedent fire scars. Snag densities were greatest at high-severity sites that burned >150 years ago, in contrast to expectations that mixed-severity sites would be more structurally complex. Tree size attributes were indistinguishable between mixed- and high-severity sites, although, subcanopy densities were particularly high (upwards of 5600 ha^{-1}) having persisted since the last fire at most sites. Selective harvesting and fire suppression during the 20th century have homogenized contemporary forest structures in mid-elevation forests. An improved understanding of mixed-severity fire regimes is vital to determining whether forest resilience is compromised and where ecological restoration is warranted.

1. Introduction

Wildland fires are a keystone disturbance shaping forested landscapes in western North America (Agee, 1993; Hessburg and Agee, 2003). Increasing recognition of the historical prevalence of mixed-severity fire regimes has ushered in a new paradigm of fire ecology and management (Hessburg et al., 2007; Halofsky et al., 2011; Perry et al., 2011). Until the last decade, most fire history research focused on quantifying the frequency of low-severity and high-severity fire regimes, with less attention paid to variations in fire severity (Amoroso et al., 2011; Perry et al., 2011). Although the prevalence and importance of mixed-severity fire regimes in many mixed-conifer forests is increasingly recognized, many aspects of these fire regimes remain poorly understood (Halofsky et al., 2011; Perry et al., 2011). For example, the relative importance of low- versus high-severity fires and their spatio-temporal variation is a vital component of mixed-severity fire regimes

* Corresponding author at: Sustainable Resource Management Program, British Columbia Institute of Technology, 3700 Willingdon Ave., Burnaby, BC V5G 3H2, Canada.
E-mail address: marcouxhelene@gmail.com (H.M. Marcoux).

http://dx.doi.org/10.1016/j.foreco.2014.12.027
0378-1127/

(Agee, 1998). Understanding variation within and among forest types is key for identifying fire regimes that have been significantly altered by fire exclusion and suppression during the 20th century. Knowledge of fire regime variability is also critical for determining where forest resilience is compromised and ecological restoration is justified (Stephens et al., 2013; Odion et al., 2014; Stine et al., 2014). Knowledge gaps related to fire regime variability pose substantial challenges to managers who are responsible for sustainable harvest planning and biodiversity conservation. Hence, new research approaches are needed to better understand the spatio-temporal complexities of mixed-severity fire regimes and their influences on forest dynamics.

A fire regime describes the spatial and temporal dimensions of many fires for a defined area and time period (Agee, 1993, 1998; Turner, 2010). In forest ecosystems, low-severity fire regimes are characterized by frequent, low-intensity surface fires that burn at short intervals, consume surface fuels and understory vegetation, and kill a minority of the overstory trees (Agee, 1993; Schoennagel et al., 2004). Thick-barked trees mostly survive surface fires, often forming cambial scars, and resulting in open-canopied stands with few subcanopy trees. Traditionally, the resulting fire scars were used to quantify historical fire frequency of individual stands, or of larger areas (Swetnam et al., 1999). In contrast, high-severity fire regimes are characterized by infrequent, high-intensity active or passive crown fires that kill understory vegetation and most overstory trees (Agee, 1993), initiating new even-aged cohorts dominated by early-successional tree species (Kipfmueller and Baker, 1998). Fire frequency in these forests has been reconstructed using landscape-level time-since-fire maps combined with age-class modeling, a method that requires assigning a single age to each patch of forest and does not account for variation in historical fire severity (Johnson and Gutsell, 1994; Van Wagner et al., 2006). It is now recognized that classifying fire regimes as solely high- or low-severity (or frequency) oversimplifies variability inherent of many forest ecosystems (Perry et al., 2011).

By definition, mixed-severity fire regimes are inherently complex and vary at multiple scales (Agee, 1998; Lertzman et al., 1998; Falk et al., 2007; Perry et al., 2011). Across a landscape, different fires can burn at different severities (Halofsky et al., 2011). Within an individual fire, effects can be variable resulting in patches with low, moderate or high levels of tree mortality within the perimeter of a single fire (Lentile et al., 2006; Collins and Stephens, 2010; Turner, 2010). Over time, consecutive fires at a given location can burn at different severities leaving a range of compositional and structural legacies persisting for decades to centuries (Hessburg et al., 2007; Collins and Stephens, 2010; Heyerdahl et al., 2012). Moreover, this spatio-temporal variation in fire severity is influenced by topography, vegetation, climate and fire weather, past natural and anthropogenic disturbances, as well as their interactions and feedbacks (McKenzie and Kennedy, 2011; Moritz et al., 2011; Turner, 2010; Perry et al., 2011).

Wide variability in fire severity within and among regions has prompted re-evaluation of many fire histories, including understudied forest types. The re-evaluation of some ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests previously described as having a low-severity fire regime has yielded evidence of mixed-severity fire histories in the western US (e.g. Sherriff and Veblen, 2006; Sherriff et al., 2014; Odion et al., 2014) and British Columbia (e.g. Heyerdahl et al., 2012). Historical mixed-severity fires were also reconstructed at high latitudes in the foothills of the Rocky Mountains in west-central Alberta, Canada (Amoroso et al., 2011). In mountainous terrain, fire regimes vary along elevational gradients, with mixed-severity fire regimes commonly associated with montane forests growing in the ecotone between low-elevation woodlands and high-elevation subalpine forests (Schoennagel et al., 2004; Sherriff and Veblen, 2006; Sherriff et al., 2014). In the Canadian Cordillera, montane forests (elevations from 1200 to 1800 m.a.s.l) have received little attention and represent a significant knowledge gap in our understanding of the prevalence of mixed-severity fire regimes (Marcoux et al., 2013).

The use of multiple lines of evidence has helped bolster inferences of historical fire severity and regimes (Swetnam et al., 1999; Hessburg et al., 2007). While severity of modern fires can be measured directly by examining fire perimeters and variations in tree mortality using aerial photography (Andison, 2012), remote sensing (Lentile et al., 2006; Soverel et al., 2011; Arnett et al., 2015) or postfire field-work (Halofsky et al., 2011), inferring severity for historical fires that burned prior to the 20th century requires paleoecological methods because direct measurements are impossible. One dendrochronology approach reconstructs the occurrence and severity of past fires using fire scars on surviving trees in combination with tree age data to identify even-aged cohorts (Sherriff and Veblen, 2006; Amoroso et al., 2011; Heyerdahl et al., 2012). Fire scars and an abundance of veteran trees can provide evidence of low-or mixed-severity fire whereas the presence of even-aged cohorts often indicates mixed- or high-severity fire (Brown et al., 1999; Heyerdahl et al., 2012). A second approach uses variations in age structure to differentiate regeneration dynamics (after Veblen, 1992) associated with fires of different magnitudes (Sherriff and Veblen, 2006). Stands burned by high-severity fires regenerate forming even-aged cohorts as trees simultaneously colonize available growing space (Agee, 1993; Kipfmueller and Baker, 1998; Taylor and Skinner, 2003). Low-severity fires generate multiple regeneration opportunities through time yielding uneven-aged forests (Agee, 1993; Covington and Moore, 1994). Fires of intermediate severity (e.g., moderate-severity) or a mixture of low- and high-severity (e.g. mixed-severity) fires generate multi-aged stands including veteran trees and cohorts that establish on areas that burned at higher severity (Heyerdahl et al., 2012). Thus, a combination of fire scar, cohort, and age structure analyses could help strengthen severity inferences in forest types historically shaped by mixed-severity fire regimes.

Improving our knowledge of forests with mixed-severity fire regimes is a research and management imperative (Spies et al., 2006; Perry et al., 2011) and is essential to emulating natural disturbance regimes and the diverse patterns and habitats they help create (Landres et al., 1999; Cissel et al., 1999). For managers, knowledge of stand attributes produced by successive fires of a range of severities is quite limited. As a result, forest management can be influenced by a variety of untested assumptions. One assumption is that high-severity fires lead to simple age and size structures within individual stands, while mixed-severity fires result in age complexity and structural diversity (Agee, 1993; Taylor and Skinner, 2003). It has also been proposed that some forests frequently burned by low- and mixed-severity fires may harbor stand structural attributes similar to late successional stands that develop over long periods following stand-replacing disturbances (Spies et al., 2006; Perry et al., 2011). Comparisons of stand-level attributes generated by mixed- and high-severity fire regimes within the same landscape are rare; our research addresses this critical knowledge gap.

We reconstructed site-level fire histories using annually resolved fire scars and high-resolution forest age structures to address three questions: (1) *What is the prevalence of mixed-severity fire in two mid-elevation, mixed-conifer watersheds*? (2) *How do forest composition and structure differ between sites with mixed- and high-severity fire histories?* (3) *How do fire and topography influence forest composition, structure and dynamics?* To answer these questions, we sampled 20 sites for fire history, forest age, and size structure, including snag and veteran tree densities, and developed