Forest Ecology and Management 378 (2016) 57–67

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Patterns of conifer regeneration following high severity wildfire in ponderosa pine – dominated forests of the Colorado Front Range ☆

Marin E. Chambers [a,b,*], Paula J. Fornwalt [a], Sparkle L. Malone [a], Mike A. Battaglia [a]

[a] US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526, USA
[b] Graduate Degree Program in Ecology, Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO 80523, USA

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 30 June 2016
Accepted 1 July 2016
Available online 19 July 2016

Keywords:
Colorado Front Range
Fire severity
Pinus ponderosa Lawson & C. Lawson
Pseudotsuga menziesii (Mirb.) Franco
Tree regeneration
Forest resilience

ABSTRACT

Many recent wildfires in ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) – dominated forests of the western United States have burned more severely than historical ones, generating concern about forest resilience. This concern stems from uncertainty about the ability of ponderosa pine and other co-occurring conifers to regenerate in areas where no surviving trees remain. We collected post-fire conifer regeneration and other data within and surrounding five 11–18 year-old Colorado Front Range wildfires to examine whether high severity burn areas (i.e., areas without surviving trees) are regenerating, and how regeneration density is related to abiotic and biotic factors such as distance from surviving forest, elevation, and aspect. We found that some conifer regeneration has occurred in high severity burn areas (mean and median of 118 and 0 stems ha^{-1}, respectively), but at densities that were considerably lower than those in unburned and in low to moderate severity burn areas. Generalized estimating equation analyses revealed that distance from surviving forest was the most important predictor of conifer regeneration in high severity burn areas, with regeneration declining as distance from surviving forest increased; estimates of conifer regeneration were 211 stems ha^{-1} immediately adjacent to surviving forest but only 10 stems ha^{-1} 200 m from surviving forest. These analyses also revealed that conifer regeneration densities declined as elevation decreased. Regression tree analyses likewise showed that distance from surviving forest and elevation were important predictors of conifer regeneration in high severity burn areas; within 50 m of surviving forest mean (median) regeneration was 150 (0) stems ha^{-1} at elevations $\leqslant$2490 m and 1120 (1000) stems ha^{-1} at elevations >2490 m, but at distances $\geqslant$50 m from surviving forest mean (median) regeneration was only 49 (0) stems ha^{-1}, regardless of elevation. Applying regression tree results spatially to the 2002 Hayman Fire, Colorado's largest and most severe known wildfire, we found that 70% of the area without surviving forest exceeded this 50 m threshold. These patterns of conifer regeneration suggest that Colorado Front Range ponderosa pine – dominated forests may not be resilient to high severity wildfire, particularly where surviving forest is not in close proximity. We recommend that land managers consider planting conifers within the interiors of large high severity burn patches, as well as implementing treatments to reduce the risk of uncharacteristic high severity wildfire in unburned forests, where maintaining a forested condition is desired.

1. Introduction

Wildfire has long been an important and complex disturbance agent in ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) – dominated forests of the western United States. Studies conducted across the range of ponderosa pine have documented that historical fire regimes varied from frequent, low severity regimes, where high severity fire was but a minor component (Fisher et al., 1987; Baisan and Swetnam, 1990; Fulé et al., 1997; Everett et al., 2000; Scholl and Taylor, 2010; Brown et al., 2015), to mixed severity regimes, where high severity fire played a more substantial role (Brown et al., 1999, 2008; Veblen et al., 2000; Hessburg et al., 2007; Williams and Baker, 2012; Sherriff et al., 2014). However, many recent fires have burned with high severity across large, contiguous areas, resulting in vast expanses with no overstory tree survivorship, and the amount and extent of high severity burning in these fires commonly exceeds that of historical ones (Goforth and Minnich, 2008; Haire and McGarigal, 2010;

☆ This paper was written and prepared by US Government employees on official time, and therefore it is in the public domain and not subject to copyright.

* Corresponding author at: Colorado Forest Restoration Institute, Colorado State University, Fort Collins, CO 80523, USA.
E-mail address: mchamber@rams.colostate.edu (M.E. Chambers).

http://dx.doi.org/10.1016/j.foreco.2016.07.001
0378-1127/

O'Connor et al., 2014; Sherriff et al., 2014; Guiterman et al., 2015; Harris and Taylor, 2015; P.J. Fornwalt, unpublished data). This trend of more severe fire effects is thought to be the result of increased forest density and homogeneity due to fire suppression, livestock grazing, and logging activities since Euro-American settlement (Goforth and Minnich, 2008; O'Connor et al., 2014; Guiterman et al., 2015; Harris and Taylor, 2015), as well as of factors associated with changing climate (Westerling et al., 2006).

The life history traits of ponderosa pine and co-occurring conifers (e.g., Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)) present several challenges for the regeneration of ponderosa pine - dominated forests following uncharacteristically severe burning, making the resilience of these forests to recent fires unclear. Although ponderosa pine is well-adapted to survive low severity fire, it does not sprout, it has non-serotinous cones, and it has seeds that are short-lived in the soil seed bank (Oliver and Ryker, 1990; Bai et al., 2004), meaning that post-fire regeneration following high severity fire depends on seed production from surviving trees in adjacent areas. Furthermore, its relatively heavy seeds generally do not disperse more than two tree heights away from parent trees (Barrett, 1966; McDonald, 1980; Johansen and Latta, 2003), suggesting that they may not be able to readily disseminate into the interiors of high severity burn patches, particularly those that are large. Indeed, several studies conducted in severely burned ponderosa pine - dominated forests have found little or no tree regeneration, except sometimes near surviving trees (Fig. 1; Bonnet et al., 2005; Keyser et al., 2008; Roccaforte et al., 2012; Collins and Roller, 2013). Douglas-fir also relies on seed production from surviving trees to regenerate following high severity fire, although it may be able to more effectively regenerate in the interiors of high severity burn patches because its relatively light seeds can disperse further than those of ponderosa pine (Herman and Lavender, 1990).

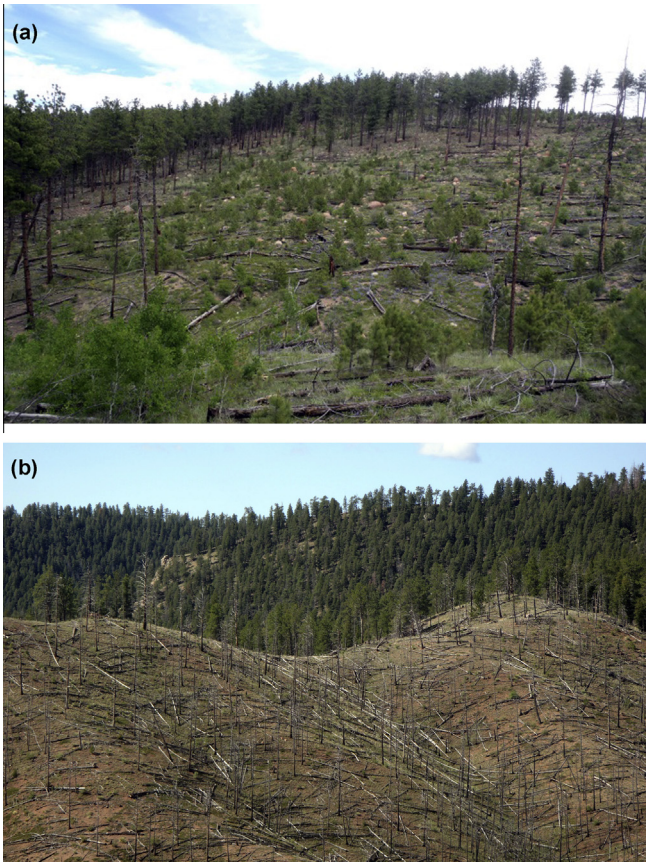

Fig. 1. Photos illustrating varying post-fire regeneration conditions in the 1996 Buffalo Creek Fire, Colorado, USA, 18 years after burning; (a) depicts high severity area in the central portion of the fire with ample conifer regeneration near surviving trees, and (b) depicts a high severity area in the eastern portion of the fire with no obvious conifer regeneration.

Other abiotic and biotic factors, such as aspect, elevation, and understory vegetation, may further limit the ability of ponderosa pine and co-occurring conifers to establish in high severity burn portions of recent fires. Ponderosa pine and Douglas-fir have been observed to have lower rates of post-fire regeneration on south-facing slopes compared to north-facing slopes (Rother, 2015). South-facing slopes receive more solar radiation than north-facing slopes during the hot afternoon hours, creating higher temperatures and higher evaporative demand. Similarly, lower elevations have also been shown to pose greater challenges for post-fire regeneration than higher elevations, owing to higher temperatures, lower precipitation, and higher evaporative demand (Dodson and Root, 2013; Rother, 2015). A warming or drying trend in future climate may further exacerbate conditions unfavorable for tree regeneration (IPCC, 2013; Lukas et al., 2014; Rother et al., 2015; Petrie et al., 2016). A dense layer of understory vegetation may also negatively impact post-fire regeneration due to competition (Bonnet et al., 2005; Collins and Roller, 2013; but see Kemp et al., 2016).

In ponderosa pine – dominated forests of the Colorado Front Range, historical fires often contained a high severity component (Brown et al., 1999; Veblen et al., 2000; Williams and Baker, 2012; Sherriff et al., 2014), yet many recent fires are thought to have more and larger high severity burn patches than historical ones (Sherriff et al., 2014; P.J. Fornwalt, unpublished data), paralleling trends observed across the west. Thus there is uncertainty about whether sufficient post-fire conifer regeneration in high severity burn patches will make these forests resilient to recent fires, or whether a lack of regeneration will cause them to convert to another vegetation type, such as grassland or shrubland. Our overall objective was to evaluate whether ponderosa pine and other conifers were regenerating in high severity burn patches of recent Colorado Front Range wildfires, and to relate regeneration density to potential abiotic and biotic drivers. Specifically, we aimed to: (1) quantify conifer regeneration in high severity burn areas and compare these values to those for unburned and low to moderate severity burn areas; (2) investigate the relationship between regeneration density in high severity burn areas and distance from surviving forest; (3) investigate how other biotic and abiotic factors relate to regeneration density in high severity burn areas; and given knowledge gained from addressing these three objectives, (4) develop a predictive map of regeneration density within high severity burn patches of the 2002 Hayman Fire, the largest and most severe wildfire known to have occurred in Colorado.

2. Methods

2.1. Study area

This study was conducted in a ~40 km wide by ~170 km long band of montane forest in the Colorado Front Range, USA (Fig. 2). At lower elevations (~1600–2200 m), forests are generally characterized by relatively open stands of ponderosa pine on south slopes and denser stands of ponderosa pine and Douglas-fir on north slopes; some Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) can also be found (Peet, 1981; Kaufmann et al., 2000). At higher elevations (~2200–2800 m), stands of ponderosa pine and Douglas-fir can also contain quaking aspen (*Populus tremuloides* Michx.), blue spruce (*Picea pungens* Engelm.), and lodgepole pine