Forest Ecology and Management 354 (2015) 281–290

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Post-fire ponderosa pine regeneration with and without planting in Arizona and New Mexico

Jessi Ouzts [a,*], Thomas Kolb [a], David Huffman [b], Andrew Sánchez Meador [c]

[a] PO Box 15018, School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, United States
[b] PO Box 15017, Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011, United States
[c] PO Box 15018/15017, School of Forestry/Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011, United States

A R T I C L E I N F O

Article history:
Received 22 December 2014
Received in revised form 31 May 2015
Accepted 1 June 2015
Available online 10 June 2015

Keywords:
Reforestation
Wildfire
Pinus ponderosa
Seedling establishment

A B S T R A C T

Forest fires are increasing in size and severity globally, yet the roles of natural and artificial regeneration in promoting forest recovery are poorly understood. Post-fire regeneration of ponderosa pine (*Pinus ponderosa*, Lawson and C. Lawson) in the southwestern U.S. is slow, episodic, and difficult to predict. Planting of ponderosa pine after wildfire may accelerate reforestation, but little is known about survival of plantings and the amount of post-fire natural regeneration. We compared ponderosa pine regeneration between paired planted and unplanted plots at eight sites in Arizona and New Mexico that recently (2002–2005) burned severely. Two sites had no natural regeneration and no survival of planted seedlings. Seedling presence increased with number of years since burning across all plots, was positively associated with forb and litter cover on planted plots, and was positively associated with litter cover on unplanted plots. Survival of planted seedlings, measured five to eight years after planting, averaged 25% (SE = 8) and varied from 0% to 70% across sites resulting in seedling densities of 0–521 trees ha^{-1}. Based on a projected 44% survival of seedlings to mature trees and target density of mature trees determined by historical range of variability and ecological restoration principles, four of eight sites have a seedling density in planted plots (125–240 ha^{-1}) that will produce a density of mature trees (55–106 ha^{-1}) close to desired levels, whereas seedlings are currently deficient at three planted sites, and in surplus at one site, which had abundant natural regeneration. Natural regeneration in unplanted plots during the first decade after burning produced seedling densities inconsistent with desired numbers of mature trees. Natural regeneration in unplanted plots produced less than 33 seedlings ha^{-1} at seven of eight sites, but produced 1433 seedlings ha^{-1} at one high-elevation site that supported a more mesic vegetation community before burning than the other sites. Our results show that current practices for planting ponderosa pine after severe fires in Arizona and New Mexico produce desired numbers of seedlings in approximately half of all projects, whereas natural regeneration rarely does within the first decade after burning.

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1. Introduction

The occurrence of large forest fires has increased globally (Williams et al., 2013) and is projected to continue increasing due to climate warming (Liu et al., 2010; Flannigan et al., 2013; Xu et al., 2013). For example, fire size and perhaps severity have already increased over the last century in forests of western North America (Westerling et al., 2006; Littell et al., 2009; Miller et al., 2009; Westerling et al., 2011). Large intense wildfires have the potential to shift forest to other vegetation types when local tree seed sources are eliminated (Savage and Mast, 2005; Roccaforte et al., 2012). Deforestation caused by wildfire is especially pronounced in semi-arid forests of tree species lacking serotinous cones and resprouting capacity, and where tree establishment is limited by water stress (Pausas et al., 2008; Williams et al., 2010; Savage et al., 2013). Limitations to tree establishment by water and heat stresses likely will be amplified by increasing temperature over the next century (Castro et al., 2005; Herrero et al., 2013; IPCC, 2013). Whereas several studies have investigated natural regeneration of trees after wildfire (Bonnet et al., 2005; Donato et al., 2009; Haire and McGarigal, 2010; Crotteau et al., 2013), few also have considered the role of tree planting in accelerating forest recovery.

Post-fire tree planting is currently controversial. Long delays in tree natural regeneration after intense burning have prompted

* Corresponding author at: USDA Forest Service, 742 S. Clover Rd, Williams, AZ 86046, United States.

E-mail addresses: jessicarouzts@fs.fed.us (J. Ouzts), tom.kolb@nau.edu (T. Kolb), david.huffman@nau.edu (D. Huffman), andrew.sanchezmeador@nau.edu (A. Sánchez Meador).

http://dx.doi.org/10.1016/j.foreco.2015.06.001
0378-1127/Published by Elsevier B.V.

recommendations for planting native trees (Beschta et al., 2004; Sessions et al., 2004; Passovoy and Fulé, 2006; Zhang et al., 2006) in order to promote forest resilience and carbon sequestration (Millar et al., 2007). On the other hand, cautions against post-fire planting arise from abundant post-fire natural tree regeneration in some regions (Shatford et al., 2007), evidence that successful dense plantings increase future fire severity (Thompson et al., 2007), and preference for natural recovery processes (Haire and McGarigal, 2010).

Forests dominated by ponderosa pine (*Pinus ponderosa,* Lawson and C. Lawson) in the southwestern U.S. are a good example of a forest region where the need for post-fire tree planting is unresolved. Tree density in most ponderosa pine forests in the southwestern U.S. is currently greater than conditions documented prior to European settlement (*circa* 1880) due to early clear-cutting of old trees and over-grazing, followed by large region-wide pulses of tree regeneration and the suppression of low-intensity fires (Savage and Swetnam, 1990; Covington and Moore, 1994; Swetnam et al., 1999). Current forests are significantly more prone to large-scale severe burning than they were historically (Allen et al., 2002; Williams et al., 2010). Severely burned ponderosa pine forests of the southwestern U.S. are at risk of conversion to non-forested ecosystems due to slow, sparse pine regeneration (Savage and Mast, 2005; Dore et al., 2012; Roccaforte et al., 2012; Savage et al., 2013).

Natural regeneration of ponderosa pine following severe wildfire often takes many decades, especially in large openings distant from seed trees (Bonnet et al., 2005; Haire and McGarigal, 2010). For example, ponderosa pine regeneration was considered to be unsuccessful for the first decade after the high severity Cone Fire in northern California based on less than 72 established seedlings ha^{-1} (Ritchie and Knapp, 2014). In particular, plots with distance to seed trees greater than 60 m had less than 25 established seedlings ha^{-1} (Ritchie and Knapp, 2014). A recent study in the southwestern U.S. showed that ponderosa pine did not regenerate within the first decade in 57% of severely burned stands (Roccaforte et al., 2012). A longer term study of two severely burned sites in Arizona and New Mexico reported little natural regeneration of ponderosa pine for the first decade after burning, followed by a slow moving front of regeneration in the second decade that extended 200 m from seed source (Haire and McGarigal, 2010).

Slow regeneration after severe wildfire can be attributed to many factors that limit ponderosa pine seedling establishment. Basic regeneration requirements of ponderosa pine have been well established in the literature (Schubert, 1974; White, 1985) as a large supply of seed; a seedbed with loose soil, light litter cover, and mostly free of competing vegetation; light shade; consistent moisture for seed germination and early seedling growth; and low populations of seed- and seedling-eating mammals, birds, and insects. Slow regeneration of ponderosa pine after severe fire has been attributed to a lack of seed trees and its lack of fire-adapted serotinous cones and vegetative resprouting (Burns and Honkala, 1990; Haire and McGarigal, 2010; Puhlick et al., 2012). Post-fire factors that can make the seedbed unfavorable for ponderosa pine regeneration include high soil temperature (Kasischke and Johnstone, 2005), topsoil erosion (Moody and Martin, 2001), and heavy herbaceous competition (Pearson, 1942). These negative influences on natural seedling establishment may be ameliorated by "nurse logs" or lopped and scattered slash from logging activities that create favorable microsites (Salonius et al., 1996; Castro et al., 2011). Shrubs and herbaceous plants may facilitate seedling establishment initially (Keyes et al., 2007, 2009; Redmond and Barger, 2013), but later become resource competitors (Peppin et al., 2010; Huffman et al., 2012). Herbivory from ungulates and burrowing mammals can negatively influence seedling survival and growth (Heidmann, 2008; Waring and Goodrich, 2012). The occurrence of environmental conditions conducive to regeneration of ponderosa pine after high-severity fire is projected to decrease over the next century due to climate changes that reduce water availability to seedlings and increase risk of frost damage (Williams et al., 2013; Savage et al., 2013). Regeneration failures and possible range contraction have recently been reported for ponderosa pine in the western U.S. (Bell et al., 2014).

Planting ponderosa pine after severe wildfire may accelerate reforestation, yet little is known about survival of planted seedlings in recent reforestation projects, or whether planting is even needed. In the southwestern U.S, planting of ponderosa pine after wildfire is increasing after many decades of minimal planting (Sánchez Meador and Graves, 2011). Interest in planting ponderosa pine in the southwestern U.S. likely will increase in the future as high-severity fires, bark beetle outbreaks, and drought-induced tree dieoffs (e.g., Williams et al., 2010; 2013) leave sites without appropriate forest cover required by the National Forest Management Act for federal lands. Moreover, planting can be used to introduce heat- and drought-tolerant populations to deforested sites for the purpose of mitigating climate change impacts (Rehfeldt et al., 2014).

Constraints to establishment of planted seedlings are similar to those that influence natural regeneration, with the addition of agency-, manager-, and contractor-influenced variables. Planting practices important to regeneration success include decisions about seed source, seedling stock type, storage, site selection, timing and method of planting, and mitigation of browsing and competing vegetation (Schubert et al., 1970; Heidmann and Haase, 1989; Heidmann, 2008; Pinto et al., 2011). Survival of planted ponderosa pine seedlings in recent post-fire reforestation projects is not well known, but can vary widely. For example, survival of ponderosa pine seedlings planted following the Cone Fire in northern California ranged from 30% to 96% among plots ten years after planting (Ritchie and Knapp, 2014).

Most research on performance of planted ponderosa pine seedlings has focused on private forestlands in relatively mesic regions in its range (e.g., Pinto et al., 2011; Ritchie and Knapp, 2014). The need for post-fire planting of ponderosa pine in the southwestern U.S. is unknown and has not been widely considered aside from a recent recommendation for managers to facilitate natural post-fire recovery processes and to be patient because natural regeneration is slow after severe burning (Haire and McGarigal, 2010). Our study is the first (to our knowledge) to measure ponderosa pine seedling survival on multiple planted sites after severe wildfires and compare seedling density between planted and adjacent unplanted areas. We addressed the following questions using data collected at eight severely burned sites in Arizona and New Mexico: What is the survival of recent post-fire plantings of ponderosa pine? What tree densities result from planting? What tree densities result from natural post-fire regeneration? What biotic and abiotic factors are associated with post-fire seedling establishment, and do these factors differ between planted and naturally established seedlings? Is natural regeneration after severe burning adequate to produce desired future forest conditions? Our results provide guidelines for tree planting in post-fire reforestation of ponderosa pine forests in the southwestern U.S.

2. Methods

2.1. Study sites

In summer 2013, we sampled post-fire plantings of ponderosa pine at eight sites that burned between 2002 and 2005 distributed over four national forests in Arizona and New Mexico (Table 1). We