Forest Ecology and Management 374 (2016) 154–165

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Long-term thinning alters ponderosa pine reproduction in northern Arizona

Kelsey N. Flathers [a], Thomas E. Kolb [a,*], John B. Bradford [b], Kristen M. Waring [a], W. Keith Moser [c]

[a] School of Forestry, Northern Arizona University, Flagstaff, AZ, United States
[b] US Geological Survey, Southwest Biological Science Center, Flagstaff, AZ 86001, United States
[c] U.S.D.A. Forest Service Rocky Mountain Research Station, Forest and Woodland Ecosystems Science, Flagstaff, AZ, United States

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 25 April 2016
Accepted 27 April 2016
Available online 14 May 2016

Keywords:
Pinus ponderosa
Regeneration
Seedling establishment
Silviculture
Soil water content

ABSTRACT

The future of ponderosa pine (*Pinus ponderosa* var. *scopulorum*) forests in the southwestern United States is uncertain because climate-change-induced stresses are expected to increase tree mortality and place greater constraints on regeneration. Silvicultural treatments, which include thinning, are increasingly being used to address forest health concerns by restoring ponderosa pine forests to more open conditions representative of historical forest structure. In light of the greater use of thinning and mounting concerns about the future of the species at the southern edge of its range, further investigations about impacts of thinning on ponderosa pine regeneration and underlying mechanisms are needed. We used a long-term (>50 years) experiment in northern Arizona to investigate impacts of repeated stand thinning that maintained different growing stock basal areas (0, 7, 14, 23, 34, 66 m^2 ha^{-1}) on early seedling survival, growth, and microenvironment. Seedling survival for the first two years after germination (2013–2015), which had above-average precipitation, was higher than reported in several earlier studies and ranged between 4 and 21% among all basal areas. Seedling density exhibited a negative quadratic relationship with basal area and was positively associated with litter cover. Growing stock levels that fostered the highest seedling survival and density were those with a low density of overstory trees, low canopy cover, high cone production, coverage of soil by a thin layer of litter, and high soil water content at a depth of 15–30 cm. Overstory basal area was positively associated with seedling height but negatively associated with seedling diameter. During this relatively wet period, all basal area treatments supported higher average seedling densities than those previously recommended to produce a multi-aged stand or presettlement structure in the southwestern United States. Our results show that long-term maintenance of low to intermediate basal areas (7–23 m^2 ha^{-1}) by thinning over the last 50 years led to a favorable microenvironment for early seedling establishment of ponderosa pine.

1. Introduction

Tree mortality has increased and expanded in western North American forests as a result of increasing drought, warmer temperatures, and associated disturbance by wildfire and insect attacks (Westerling et al., 2006; van Mantgem et al., 2009; Allen et al., 2010; Meddens et al., 2012; Williams et al., 2013; Cohen et al., 2015). Greater drought intensity in the 21st century is projected to contribute to increases in tree mortality and shift the distribution of dominant trees (Choat et al., 2012; McDowell and Allen, 2015) and vegetation communities (Jiang et al., 2013). Given these forecasts for higher forest turnover rates, better understanding of controls over tree regeneration is important to predict future tree species distribution and abundance. Seedlings are often more sensitive than adult trees to environmental stressors (e.g., drought) caused by climate change (Thuiller et al., 2005; Bell et al., 2014). Therefore, we may not be able to predict seedling responses on the basis of mature tree responses.

The future of ponderosa pine (*Pinus ponderosa* var. *scopulorum*) forests in the southwestern United States is unclear in the face of expected future increases in stresses caused by climate change. Models predict suitable climate space for ponderosa pine will be reduced by 50% in the next century, with 77% of the contemporary climate space lost at the rear (southern) edge of the species' distribution (Rehfeldt et al., 2014). Natural regeneration of ponderosa pine is already heavily constrained by climate (Heidmann et al., 1982; Heidmann, 2008; Petrie et al., 2016) and favorable opportunities

* Corresponding author.
E-mail address: tom.kolb@nau.edu (T.E. Kolb).

http://dx.doi.org/10.1016/j.foreco.2016.04.053
0378-1127/

for regeneration may become more limited in the future due to climate warming and deforestation caused by fire, insect outbreaks, and intense drought (Savage et al., 2013; Williams et al., 2013; Allen et al., 2015; Ouzts et al., 2015; Rother et al., 2015). Germination and establishment of ponderosa pine are influenced by precipitation and temperature (Schubert, 1974; Savage et al., 1996; Petrie et al., 2016), soil type (Heidmann and Thorud, 1976; Heidmann and King, 1992; Puhlick et al., 2012), and competing vegetation (Pearson, 1942, 1950; Heidmann et al., 1982; Heidmann, 2008). Within months of germination seedling roots of ponderosa pine can grow to depths of 50 cm in soil with abundant moisture (Larson, 1963), but only grow to half that depth or less when soil moisture is low (Larson and Schubert, 1969). Many southwestern ponderosa pine forests exhibit episodic recruitment linked to the combination of favorable climate conditions of above-average precipitation and high May temperatures (Pearson, 1933; Savage et al., 1996; League and Veblen, 2006), and well as heavy seed production, low occurrence of surface fire during the seedling stage (Brown and Wu, 2005), and openings in the canopy (Schubert, 1974).

Ponderosa pine forests are currently stressed by legacies of past exploitation and management. Prior to Euro-American settlement in the late 1800s southwestern ponderosa pine forests were described as open stands characterized by widely spaced older trees and sparse pockets of younger trees interspersed with openings of abundant herbaceous cover (Cooper, 1960). After logging removed most large trees by the early 1900s, a combination of factors led to an increase in tree density. The natural frequent-fire regime was disrupted through active fire suppression, and heavy domestic livestock grazing that denuded herbaceous cover created an environment relatively free of fire and herbaceous competition that promoted establishment of a large number of seedlings following years of amble seed production (Arnold, 1950; Cooper, 1960; Covington and Moore, 1994; Savage et al., 1996). As a result, many current stands contain thickets of slow-growing trees, heavy accumulations of litter and woody materials, and low understory vegetation cover (Harrington and Sackett, 1992; Covington and Moore, 1994). These conditions have led to forest health concerns about increased risks of deforestation caused by wildfires, insect outbreaks, and drought (Covington and Moore, 1994; Covington et al., 1997; Allen et al., 2010).

Silvicultural treatments are increasingly being used in the southwestern United States to restore ponderosa pine forests to more open conditions representative of historical forest structure (Arno et al., 1995; Covington et al., 1997), to reduce fuels and reduce wildfire severity (Agee and Skinner, 2005), to enhance growth and resilience of residual trees (Skov et al., 2004; Kerhoulas et al., 2013), and to increase water supply to trees and from forests to streams and aquifers (Grant et al., 2013; Robles et al., 2014). Few studies, however, have investigated impacts of treatments on ponderosa pine regeneration (Bailey and Covington, 2002) and investigations of regeneration under field conditions are notably rare (Petrie et al., 2016). Whereas several studies show that forest treatments can increase soil water availability to plants, most of these studies investigated soil water only for the first several years after treatment and focused only on mature trees (e.g., Stone et al., 1999; Simonin et al., 2007). Information about the relationship between ponderosa pine regeneration and both stand structure and abiotic conditions is needed to develop management strategies that promote successful ponderosa pine regeneration.

We used a long-term (>50 years) experiment at Taylor Woods in northern Arizona, USA, to investigate impacts of different overstory basal areas (cross-sectional area of all trees measured at 1.37 m height) on early seedling survival, growth, and microenvironment. Taylor Woods is one of several level-of-growing-stock (GSL) studies initiated in young, even-aged ponderosa pine stands throughout the western United States (Schubert, 1971; Ronco et al., 1985). Our study focused on a cohort of seedlings that established in 2013 following heavy cone and seed production and during an unusually wet summer. For this cohort we investigated impacts of six basal area levels (0, 7, 14, 23, 34 and 66 $m^2\ ha^{-1}$) on seedling density, survival, and growth; tree reproductive output; soil water content; light availability; and understory litter and vegetation. Our investigation of this suite of responses in a long-term thinning experiment is unique as far as we know. We hypothesized that the lower basal area levels (7 and 14 $m^2\ ha^{-1}$) would have the highest seedling density, survival, and growth, and that differences in seedling performance among basal areas would be associated with tree reproductive output, understory microenvironment, and soil water availability.

2. Materials and methods

2.1. Study area

Taylor Woods is a subdivision of the Fort Valley Experimental Forest located about 14.5 km northwest of Flagstaff, Arizona within the Coconino National Forest on the Colorado Plateau. Mean annual precipitation is 56.4 cm and is distributed in a bimodal pattern with approximately half of this precipitation falling as snow during winter (November–March) and the other half falling during the remaining months. About 29% of precipitation falls during the late-summer monsoon season (July–August). This region also experiences regular drought during May and June. Average daily temperatures range from −3.9 °C in January to 17.2 °C in July (Ronco et al., 1985). The stand has flat topography and is located at approximately 2266 m elevation. The soils at the study site are characterized as a montmorillontic complex of frigid Typic Argiborolls (USDA, 1975) derived from volcanic material, primarily basalt parent material (Ronco et al., 1985). The soil has a shallow A horizon (about 10 cm), but the soil profile extends from 114 to more than 152 cm in depth before a fractured basalt bedrock occurs (Ronco et al., 1985).

Seasonal precipitation during our study varied from long-term normals in each year. In 2013 when the seedlings we studied germinated and started to establish, precipitation in the study site region (Flagstaff Airport NOAA station) was 70% of average in winter, 20% of average in spring, but 200% of average in summer. In 2014, the first full year of seedling establishment, precipitation was 30% of average in winter, 60% of average in spring, but 160% of average in summer. In 2015, the second year of seedling growth, precipitation was 125% of average in winter, 220% of average in spring, and 85% of average in summer. Thus, the years included in our study had unusually high spring (2015) or summer (2013, 2014) precipitation.

Prior to the implementation of the GSL study in 1962 the stand consisted of overstory sawtimber-sized trees (>50 cm diameter at breast height [DBH]) and dense sapling and pole-sized trees primarily originating in 1919 (Schubert, 1971; Ronco et al., 1985). In 1962 all sawtimber was harvested in a removal cut to leave a dense, even-aged stand consisting of mostly 43-year-old small-diameter saplings and poles. Remaining trees were tagged and measured and thinning slash was lopped and scattered (Schubert, 1971). All plots in the GSL study are within a 36.4 ha stand on a gentle (4%) southwest-facing slope in the *P. ponderosa/Festuca arizonica* habitat type (Ronco et al., 1985). Site index is 22 based on height in meters at a base age of 100 (Minor, 1964; Ronco et al., 1985).

Taylor Woods includes six GSLs (34, 28, 23, 18, 14 and 7 $m^2\ ha^{-1}$) as well as unthinned control and clearcut treatments. Each treatment is replicated in three plots, which range in size