



Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests?

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ABSTRACT

We determine the time frame after initial fuel treatment when prescribed fire will be likely to produce high enough mortality rates in ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. ex Laws.) regeneration to be successful in maintaining treatment effectiveness in the Black Hills of South Dakota. We measured pine regeneration in disturbed stands and young pine growth rates to estimate the susceptibility of pine regeneration to prescribed fire with time since initial treatment. We also determined surface fuel accumulation rates for stands after prescribed fire to help estimate likely fire behavior in maintenance prescribed fire. Given our estimates of regeneration density and tree size, and likely fire behavior, we then used small pine tree mortality–fire effect relations to estimate the effects of prescribed fire on developing understory pine at specific times since initial treatments.

Fuel treatments in ponderosa pine forests will lose their effectiveness within 10–20 years if regeneration densities are not controlled. The ability to successfully use prescribed fire to maintain low regeneration densities is dependent on seedling/sapling size and the frequency of burns. Current prescribed fire prescriptions and fuel loads are adequate to maintain low densities of ponderosa pine seedlings (<1 m tall) if burns occur every 10 years. If burn intervals exceed 15 years, regeneration can attain sizes that reduce susceptibility to prescribed fire under typical operational weather conditions. After 20–25 years, ponderosa pine can reach sizes that will require flame lengths that exceed 2 m to obtain significant mortality. Achieving these flame lengths will require burning under drier weather conditions to allow coarse woody debris (CWD) consumption to contribute to the fire intensity. Alternatively, managers can augment sites with activity fuels to increase fine fuel loadings to achieve flame lengths that will increase sapling susceptibility to fire, while burning when CWD fuel moistures are high to limit the potential for extreme fire behavior. While the flames might kill sapling-sized trees, mature overstory trees could still maintain resiliency to fire.

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1. Introduction

Sustaining fuel treatment perpetually is an increasingly important management challenge as substantial investments are made in treating pine forests of the western United States to reduce fire hazard. Common fuel treatments in ponderosa pine forests include thinning of overstory trees to reduce continuity of canopy fuels and removal of understory trees to remove ladder fuel profiles. Thinnings are often coupled with prescribed fire or

mechanical treatments to reduce surface fuel accumulations. These treatments are applied with the goal of changing potential wildfire behavior from an active crown fire to a slow moving surface fire to aid suppression efforts (Agee and Skinner, 2005). Retention of a low-density mature overstory coupled with ground disturbance can create ideal conditions for prolific regeneration (Sackett, 1984; Oliver and Ryker, 1990; Sackett and Haase, 1998; Shepperd and Battaglia, 2002) and rapid growth of new or advanced pine regeneration (Fajardo et al., 2007). Ladder fuels and increased canopy density created over time by growth of these trees leads to increased potential for crown fire behavior (Fulé et al., 2004; Battaglia, 2007). Using prescribed fire to kill the emerging understory and reduce accumulation of surface fuel is a maintenance activity to sustain fuel treatment effectiveness (Sackett and Haase, 1998; Brose and Wade, 2002; Fulé et al., 2002; Raymond and Peterson, 2005; Hunter et al., 2007). In order

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for prescribed fire to be successful, there must be sufficient surface fuel to carry fire, and understory pine trees must be killed by fire behavior generated by surface fuels. Following initial fuel treatments, new regeneration would be small and very susceptible to fire (Battaglia et al., in press), but a lack of surface fuels would make prescribed burning difficult. Surface fuel accumulation and fire behavior associated with prescribed burning would increase with time following treatment, but the resistance of developing pine regeneration to fire would be also increasing. In this paper, we evaluate tree regeneration and fire susceptibility of developing pine understories relative to the kinds of fire behavior associated with prescribed fire for ponderosa pine forests of the Black Hills of South Dakota, USA to determine how prescribed fire can be used to extend the longevity of fuel treatment effectiveness.

In the Black Hills, favorable growing conditions and good seed crops often coincide and result in abundant natural ponderosa pine seedling establishment, often exceeding 1000 seedlings ha⁻¹ (Oliver and Ryker, 1990; Shepperd and Battaglia, 2002). Seedling establishment is often enhanced after mechanical treatments as a result of scarification or fire, both of which provide the mineral soil seedbed favored by ponderosa pine (Oliver and Ryker, 1990; Shepperd and Battaglia, 2002; Bonnet et al., 2005; Shepperd et al., 2006). Once established, the time it takes the regeneration to reach a height that connects the surface fuel complex to the overstory canopy is important in determining when a fuel treatment loses its ability to reduce crown fire initiation. Furthermore, the susceptibility of ponderosa pine to fire changes with tree size with seedlings requiring lower values of crown damage, cambial damage, and root damage than saplings (Harrington, 1987, 1993; van Mantgem and Schwarz, 2004; Battaglia et al., in press).

Managers need the ability to predict mortality based on potential fire behavior in order to tailor burn prescriptions to meet their regeneration reduction/maintenance target objectives (Johnson and Miyanishi, 1995). Fire managers frequently use BehavePlus, a fire behavior simulation program (Andrews et al., 2005), to predict flame lengths and fireline intensity under various fuels, weather, and topographic scenarios. While mortality models such as FOFEM (Reinhardt, 2003) and those included with BehavePlus do predict tree mortality based on flame length and fireline intensity (Van Wagner, 1977), the equations used in these models were developed for trees >10 cm diameter at breast height (dbh) and often over-predict mortality in seedlings and saplings (Battaglia, 2007; Hood et al., 2007). Direct measures of flame lengths during prescribed burns have been used to model mortality of ponderosa pine seedlings (<1.37 m tall) and saplings (0.25–10 cm dbh) in the Black Hills (Battaglia et al., in press). These models demonstrated that flame lengths sufficient to contribute to crown consumption were required to increase the probability of mortality in both seedlings and saplings (Battaglia et al., in press). Similar crown damage was needed to increase mortality in slash (*Pinus elliotti* Engelm.) and loblolly (*Pinus taeda* L.) pines of the Southeastern U.S. (Johansen and Wade, 1986; Waldrop and Lloyd, 1988; Wade, 1993) and ponderosa pine forests of the Southwestern U.S. (Harrington, 1993; Sackett and Haase, 1998).

The amount of fuel available to burn influences the potential flame lengths during a fire. Knowing fuel accumulation rates in fuel treatments maintained by fire can determine when an area has enough fuel to re-burn and produce a desired flame length. Data on fuel accumulation rates after fire for the Black Hills is limited to one recent study investigating the recovery after a mixed-severity wildfire (Keyser et al., 2008). In the low burn severity areas of that study, needle litter mass had recovered to 75% of the unburned areas within 5 years (Keyser et al., 2008). Fine (<7.62 cm diameter) and coarse (>7.62 cm diameter) woody debris had each recovered to approximately 40% of the unburned areas. Longer-term data is

needed to determine whether surface fuels continue to accumulate or if they reach an equilibrium state. Quantifying the temporal dynamics of fuel accumulation within a fuel treatment maintained by prescribed fire will help understand how potential fire behavior and seedling/sapling susceptibility to fire might change over time.

Fuel treatments in Black Hills ponderosa pine forests currently reduce overstory canopy density by thinning and reduce surface fuels by mechanical operations or prescribed fire (Hunter et al., 2007). By opening the canopy and creating suitable seedbeds, these practices create forest conditions that result in prolific ponderosa pine regeneration. Controlling the numbers and sizes of these young pine trees is essential to maintain fuel treatments over time. Therefore, we ask whether there is a time after initial fuel treatment when prescribed fire will be likely to produce high enough pine regeneration mortality to successfully maintain treatment effectiveness. We measured the numbers and growth rates of ponderosa pine and estimated the susceptibility of pine regeneration to prescribed fire over time since initial treatment. We also determined surface fuel accumulation rates after prescribed fire in ponderosa pine stands to help estimate likely fire behavior of subsequent prescribed maintenance fires. Given our estimates of regeneration density and tree size, and likely fire behavior, we then used relationships developed by Battaglia et al. (in press) to predict seedling and sapling mortality for a given flame length at specific times since initial treatment.

2. Methods

2.1. Study area

The Black Hills is an isolated forested geologic uplift located in southwest South Dakota and northeast Wyoming that extends 200 km from north to south and 100 km from east to west (Shepperd and Battaglia, 2002). Elevations in the Black Hills range from 1000 to 2207 m and are approximately 300–1200 m above the surrounding Great Plains. The increased elevation results in an orographically induced microclimate that increases precipitation. Annual average precipitation in the Black Hills ranges from 41 cm in the south to 74 cm in the north. Most of the precipitation occurs from April to August, with May and June receiving 33% of annual precipitation (Driscoll et al., 2000). Mean daily temperatures range from -3.3 °C in winter to 13.2 °C in summer. The frequent rain showers during the early growing season in combination with the warm temperatures are conducive to prolific natural ponderosa pine regeneration (Shepperd and Battaglia, 2002). Ponderosa pine dominates 85% of the forested land base (DeBlander, 2002) and is found at all elevations, soil types, and aspects.

2.2. Regeneration growth rates and resistance to prescribed fire

Three fuel treatment areas on the Mystic Ranger District of the Black Hills were sampled to determine seedling and sapling growth rates. Sampled sites had canopy coverage <40% and contained a broad range of ponderosa pine seedling and sapling sizes. Buffalo, a 182 ha unit, was located 21 km northeast of Hill City, South Dakota (approximately 44°07'N, 103°32'W). Lookout, a 223 ha unit, was located 24 km northwest of Hill City, South Dakota (approximately 44°02'N, 103°50'W). Medicine, a 728 ha unit, was located 10 km west southwest of Hill City, South Dakota east of Medicine Mountain (approximately 43°55'N, 103°42'W). All of these areas are representative of the geomorphological portion of the Black Hills known as the central crystalline core (Shepperd and Battaglia, 2002).

Ten sampling points within each unit were located based on randomly selected UTM coordinates that fell within the sampling

area. At each point, we recorded ponderosa pine regeneration by size classes based on height (0–0.15 m, 0.16–0.46 m, 0.47–0.76 m, 0.77–1.07 m, and 1.08–1.37 m) or diameter at breast height (dbh) if taller than 1.37 m (0.25–2.54 cm, 2.55–5.1 cm, 5.11–7.62 cm, 7.63–10.2 cm and 10.2–12.7 cm) as defined by the fire effects monitoring and inventory protocol (Lutes et al., 2006).

A total of 300 trees were sampled to determine an age–height relationship (10 trees for each size class \times 10 size classes \times 3 locations). At each point, the closest ponderosa pine tree to the center of the plot in each size class was harvested by cutting the tree as close to the root collar as possible and total tree height was measured. A cross-section of the stem was cut for age determination. Regression analysis was performed with general linear model procedure (SAS Institute, 2001) to determine a relationship between tree age and height. Tree age and height were natural log transformed to fulfill normality and constant variance assumptions. Bias due to logarithmic transformation was corrected with smearing estimate of 1.11 (Duan, 1983).

Flame lengths required to kill 95% of regeneration were estimated from tree heights of seedling (<1.37 m tall) and sapling (>1.37 m tall) using Eqs. (1)–(3) developed in an associated study (Battaglia et al., in press):

$$P(m) = \frac{1}{1 + \text{EXP}(-(-2.714 + (4.08 \times \text{flame length}) + (-3.63 \times \text{seedling height})))}, \quad (1)$$

where $P(m)$ is the predicted probability of mortality, flame length is in meters and seedling height is in meters.

$$P(m) = \frac{1}{1 + \text{EXP}(-(-0.7661 + (2.7981 \times \text{flame length}) + (-1.2487 \times \text{sapling height})))}, \quad (2)$$

where $P(m)$ is the predicted probability of mortality, flame length is in meters and sapling height is in meters.

$$P(m) = \frac{1}{1 + \text{EXP}(-(-2.5319 + (3.0796 \times \text{flame length}) + (-0.7563 \times \text{dbh})))}, \quad (3)$$

where $P(m)$ is the predicted probability of mortality, flame length is in meters and dbh is in cm.

2.3. Regeneration and surface fuels in developing stands

A chronosequence of eight sites (Table 1) that burned at various times were selected from GIS fire history maps of the Black Hills National Forest (BHNF). Sampling of recent (<15 years) fires ($n = 4$) were limited to prescribed fires. Prescribed burn locations were obtained from local Forest Service district staff. Because the prescribed burning program on the BHNF before 1990 was limited, we sampled wildfires >15 years old ($n = 4$) that burned with low to moderate severity. Low to moderate severity wildfire areas were determined by observing the amount of overstory mortality in the stands. Based on post-wildfire snag dynamics in ponderosa pine forests (Passovoy and Fulé, 2006; Keyser et al., 2008), stands with numerous broken or fallen snags were assumed to have burned with high severity and were not sampled.

The BHNF resource information system (RIS) database was used to identify potential open-canopied stands within each fire perimeter. This database contains information on stand structure, cover type, and canopy coverage. We randomly chose an open-canopied stand within each fire perimeter. If there was only one open-canopied stand represented within a fire, that stand was measured. Potential sites were ground-truthed and either accepted or rejected based on evidence of burning and harvesting activity. Evidence of burning was determined by the presence of char on trees and downed logs. Harvesting activity was assessed by the presence of recent stumps. Stands which burned as wildfires (>15 years) were assumed to be comparable to contemporary fuel treatment prescribed burn stands. We based this assumption on two factors: (1) tree basal area and density were similar to the contemporary fuel treatments (Table 1); and (2) the lack of standing/fallen snags in these older fire sites suggests they burned under similar severity as a prescribed fire in a contemporary fuel treatment. Elevations of the sites ranged from 1450 to 1750 m (Table 1) and were all dominated by ponderosa pine.

Fifteen sample points were located within each sampled stand by randomly drawing from UTM coordinates that fell within the stand. Four stands were measured in the summer of 2004, one stand was measured in the summer of 2005, and three stands were measured in the summer of 2006. Overstory live tree density was measured at all sites with a BAF 10 ft² (0.93 m²) prism from the center of each sample point. Pieces of dead and down woody debris were tallied along a 15.24 m sampling plane in the standard

Table 1

Fuel treatment stand characteristics of prescribed fires and wildfires measured for the time since fire (TSF) fuel accumulation across the Black Hills National Forest

Fire	TSF	Basal area (m ² ha ⁻¹)	Tree density (ha ⁻¹)	Elevation (m)	Location
Gordon	2	17.0 (1.5)	395 (73)	1500–1550	43°58'26"N, 103°30'36"W
Gordon	6	13.9 (1.9)	533 (118)	1600–1650	43°58'54"N, 103°32'00"W
Gordon	6	16.1 (2.0)	487 (98)	1700–1750	44°00'06"N, 103°33'39"W
Horse Creek	13	10.7 (2.0)	259 (64)	1600	44°00'48"N, 103°32'30"W
Ventling Draw	40	8.6 (1.5)	188 (34)	1600–1630	43°38'31"N, 103°40'54"W
Deadwood*	47	17.8 (1.9)	314 (44)	1450–1550	44°24'06"N, 103°43'31"W
McVey*	65	19.9 (1.6)	532 (98)	1600–1650	44°01'25"N, 103°33'02"W
Spring Creek*	80	15.6 (1.3)	309 (34)	1450	44°00'09"N, 103°23'56"W

Average (S.E.M.) basal area and density area values are for live trees >10 cm dbh. Wildfires are signified by asterisks.

moisture timelag size classes: 1 h (0–0.6 cm), 10 h (0.6–2.5 cm), and 100 h (2.5–7.62 cm.) (Brown et al., 1982). Pieces greater than 7.62 cm in diameter (1000 h) were recorded by diameter and decay class. Decay class was broken into two categories: sound and rotten (Brown, 1974; Brown et al., 1982). The 1 and 10 h fuels were tallied on the first 1.83 m of the sampling plane (i.e. measuring tape), the 100 h fuels along the first 5 m, and 1000 h along the entire sampling plane. Wood biomass was calculated using published equations (Brown, 1974; Brown et al., 1982).

Litter and duff depth were measured at 3 points along each sampling plane (at 4.5, 9, and 13.5 m). Litter was defined as the loose layer made up of twigs, dead grasses, and recently fallen needles that were still identifiable and not altered by decomposition. The duff layer was below the litter layer and above the mineral soil (Brown et al., 1982). Litter and duff depth was measured separately with a ruler to the nearest 0.5 cm. Litter mass and duff mass were calculated with Black Hills specific bulk densities of 60.71 kg m^{-3} for needle litter and 102.58 kg m^{-3} for duff (Battaglia, 2007).

We utilized regeneration density data from an associated study (Battaglia, 2007) for the first 40 years after disturbance for this study. In both the current study and the associated study, live regeneration densities were measured using a nested plot design consisting of a 2 m radius circular plot to sample seedlings (trees <1.37 m tall) located within a larger 5 m circular plot to sample saplings (trees 0.25–10 cm dbh).

Fuel data for 1 to 1000+ h timelag fuels, needle, and duff mass were placed into 10-year *time since fire* interval classes and summary statistics were calculated for each interval using PROC MEANS (SAS Institute, 2001). Since no fuel load data was collected for the 20–29-year interval, the values were calculated as the midpoint between the 10–19 and 40–49-year interval fuel loads. Significant differences among the sample means were not tested since stands were not replicated.

2.4. Fire behavior and regeneration mortality: time since fire

BehavePlus 3.0.2 (Andrews et al., 2005) was used to estimate surface fire behavior for the predicted fuel loadings over time. The Rothermel fire spread model used in BehavePlus utilizes fuels in size classes up to 7.62 cm diameter to calculate rate of spread and flame length, so only the 1 h, 10 h, and 100 h fuel loadings were used. Although 1000 h fuels (>7.62 cm) do contribute to fire intensity, their contribution to fire spread is very small, so they are not included in the model (Rothermel, 1972).

A custom fuel model, initialized with the parameters of the TL8 fire behavior model (Scott and Burgan, 2005), was built for each time interval using the measured fuel loading. Needle litter mass was added to the 1 h fuel load (*sensu* Agee and Lolley, 2006) because surface needles contribute to surface fire behavior and are considered fine fuels. BehavePlus was used to estimate potential flame lengths for each 10-year time since fire treatment interval class. Fire behavior was calculated with prescribed burning weather conditions commonly used in the Black Hills: 1 h fuel moisture = 7%, 10 h fuel moisture = 8%, 100 h fuel moisture = 11%, midflame windspeed = 5 km/h. Slope was set at 15%. We examined the predicted flame lengths that were associated with activity fuel loadings at each time interval class and predicted mortality of seedlings and saplings based on the predicted flame lengths (Battaglia et al., in press).

The fire and fuels extension (FFE) to the forest vegetation simulator (FVS) was used to calculate crown fuels and estimate crown fire potential for each time since fire treatment interval class. FFE–FVS calculates canopy bulk density (CBD) and canopy base height (CBH), parameters important for modeling crown fire

behavior. CBD of a stand is calculated as the maximum 4.5 m deep running mean of CBD for layers 0.3 m thick. This method is thought to be more realistic than assuming a uniform vertical distribution of canopy fuel (Scott and Reinhardt, 2001). CBH is calculated based on the lowest height above which a minimum of 0.011 kg m^{-3} of available canopy fuel is present (Scott and Reinhardt, 2001). Torching and crowning indices were predicted for each stand under 90th percentile weather conditions. The torching and crowning index is the 6.1 m windspeed required to initiate torching or sustain an active crown fire, respectively (Scott and Reinhardt, 2001).

FireFamily Plus, a statistical software program that imports weather data and allows analysis of fire-related variables (Bradshaw and Brittain, 1999), was used to determine the 90th percentile weather conditions. Weather data (1966–2004) was obtained from the Custer, SD weather station for July 1 through September 30, the historical fire season (Brown and Sieg, 1996, 1999; Brown, 2003). Potential crown fire behavior was calculated with 90th percentile burning weather conditions: 1 h fuel moisture = 6%, 10 h fuel moisture = 7%, 100 h fuel moisture = 10%, herbaceous fuel moisture = 62%, woody fuel moisture = 102%, and air temperature = 31 °C.

3. Results

3.1. Regeneration growth rates and resistance to prescribed fire

A relationship between age and height was observed for ponderosa pines in the Black Hills (Fig. 1). Table 2 lists the predicted average flame length required to kill a tree of a given age based on the predicted probability of mortality equations (Eqs. (1) and (2)). As ponderosa pine regeneration increases in size, it will require a taller flame length to be killed by fire (Table 2). For example, the predicted average height of a 5-year-old Black Hills ponderosa pine seedling is 0.20 m (Fig. 1). Flame lengths of 0.23 m would be required to kill 95% of seedlings of this size (Table 2). By 10 years, the predicted average seedling height would be 0.62 m (Fig. 1), which would require a flame length of 0.61 m for 95% mortality (Table 2). Our model predicts that on average, a ponderosa pine in the Black Hills can reach the threshold for dbh (1.37 m height) within 16 years (95% C.I. 8.9, 28.7) of establishment (Fig. 1), which would require an average flame length of 1.28 m to cause high mortality (Table 2). This trend of increasing flame lengths needed to achieve mortality continues

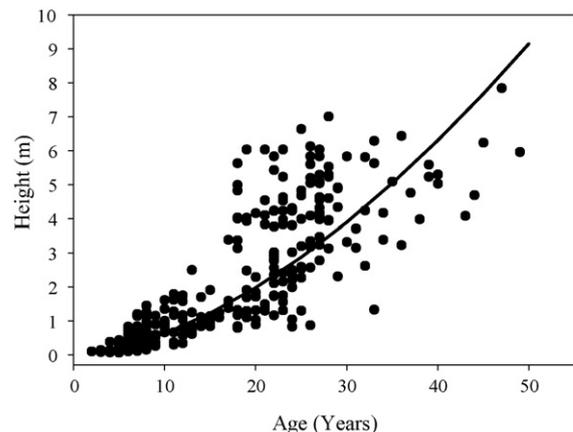


Fig. 1. Relationship between seedling/sapling height and age for Black Hills ponderosa pines less than 50 years old growing in open-canopied stands in the interior montane region. Regression: height (m) = $\exp(-4.2206 + 1.6727 (\ln \text{age}))$; $r^2 = 0.63$, S.E. = 1.24. Bias due to logarithmic transformation corrected with smearing estimate of 1.11 (Duan, 1983).

Table 2

Predicted average flame lengths under typical prescribed fire conditions required to kill 95% of ponderosa pine regeneration for different age classes in the Blacks Hills, SD

Age (years)	Average height (m)	Predicted average flame length (m)
5	0.20	0.23
10	0.62	0.61
16	1.37	1.28
20	1.98	2.21
25	2.87	2.61
30	3.90	3.06
35	5.04	3.57
40	6.30	4.14

Average height of regeneration was predicted using equation in Fig. 1. The predicted probability of mortality for regeneration <1.37 m tall was estimated by logistic regression ($P(m) = 1/(1 + \text{EXP}(-(-2.714 + (4.08 \times \text{flame length}) + (-3.63 \times \text{seedling height}))))$) developed with observed flame lengths and associated observed mortality on prescribed burns on the Black Hills National Forest (Battaglia et al., in press). The predicted probability of mortality for regeneration >1.37 m tall was estimated by logistic regression ($P(m) = 1/(1 + \text{EXP}(-(-0.7661 + (2.7981 \times \text{flame length}) + (-1.2487 \times \text{sapling height}))))$) developed with observed flame lengths and associated observed mortality on prescribed burns on the Black Hills National Forest (Battaglia et al., in press).

with tree age. By 40 years of age, predicted tree heights would be over 6 m and flame lengths required for 95% mortality would be over 4 m (Table 2).

Since most managers measure sapling-sized regeneration in terms of diameter at breast height (dbh) and the probability of mortality is diameter-dependent (Battaglia et al., in press), we attempted to predict dbh based on age, but the relationship was too variable and weak ($r^2 = 0.21$). Instead, we examined the age range for specific diameter size classes (Fig. 2b). Once regeneration reaches the sapling stage, competition influences the growth rate resulting in a wide range of diameters for a given age (Fig. 2b) and subsequently different flame lengths for high mortality. For instance, the diameter of a 25-year-old sapling can range between 0.25 and 12.7 cm. Based on the predicted probability of mortality equation using flame length and diameter (Eq. (3)) flame lengths ranging from 1.85 to 4.25 m would be required for 95% mortality for 25-year-old saplings. Saplings older than 30 years old would range between 5 and 12.7 cm dbh and would require average flame lengths of 3–5 m for 95% mortality.

3.2. Regeneration and surface fuels in developing stands

Our data indicate that ponderosa pine seedlings and saplings in the Black Hills reestablish and contribute to the ladder fuel complex within 10 to 20 years post-disturbance (Figs. 2a and b and 3). Once established, this ladder fuel complex persists in the absence of fire and shifts from seedling- to sapling-sized trees (Fig. 3). Seedling (<1.37 m tall) and sapling (0.25–10 cm dbh)

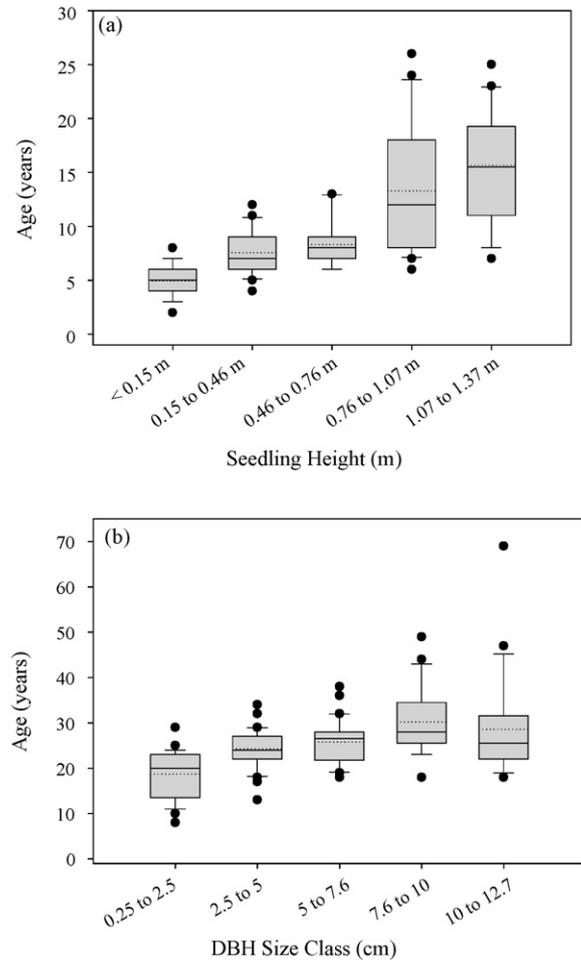


Fig. 2. Age distribution of ponderosa pine (a) seedlings and (b) saplings sampled in the interior montane region of the Black Hills National Forest. Each shaded box covers the 25th to 75th percentile of the distribution; dotted line is the mean and the solid line represents the median. Whiskers denote the 10th and 90th percentiles. Dots represent the 5th and 95th percentiles.

densities do vary with time since treatment, but in general, total densities still exceed several thousand stems ha^{-1} in untreated stands (Fig. 3).

The amount of fine fuels available for consumption influences flame lengths, rate of spread, and subsequent tree mortality during a prescribed burn. Our data show that the components making up the total fine fuels (litter, 1, 10, and 100 h) vary with time since fire in Black Hills ponderosa pine forests. Needle litter mass ranged between 10.3 and 12.9 Mg ha^{-1} across the 80-year chronose-

Table 3

Average (S.E.M.) surface fuel loadings in ponderosa pine forests of the Black Hills National Forest

Time since treatment (years)	n	Needle litter load (Mg ha^{-1})	1-h Load (Mg ha^{-1})	10-h Load (Mg ha^{-1})	100-h Load (Mg ha^{-1})	1000+ h Sound load (Mg ha^{-1})	1000+ h Rotten load (Mg ha^{-1})	Duff load (Mg ha^{-1})	Predicted flame length (m)
<10	3	12.9 (0.7)	0.33 (0.04)	1.20 (0.32)	2.06 (0.77)	4.44 (0.89)	0.52 (0.29)	7.0 (1.2)	0.9
10–19	1	12.9	0.35	1.84	6.59	2.99	5.37	3.7	0.6
20–29	^a	11.73	0.25	1.57	5.28	2.98	3.61	3.97	0.7
40–49	2	10.5 (1.1)	0.15 (0.06)	1.29 (0.13)	3.97 (1.68)	2.97 (1.52)	1.85 (0.06)	4.2 (3.1)	0.8
60–69	1	13.3	0.43	1.70	2.85	4.13	1.72	9.9	0.8
80–89	1	10.3	0.21	0.69	1.43	1.64	0.38	8.9	1.0

Fuel classification is based on the timelag diameter classes: 1-h (0–0.62 cm diameter), 10-h (0.63–2.54 cm diameter), 100-h (2.55–7.62 cm diameter), and 1000+ h (>7.62 cm diameter). Decay class for 1000+ h fuels were classified into two categories: sound and rotten (Brown, 1974; Brown et al., 1982). Surface fire flame lengths were estimated for typical prescribed fire weather conditions based on fine fuel loadings using BehavePlus simulations. Dead fuel moistures were 7% for 1-h, 8% for 10-h, and 11% for 100-h. Midflame windspeed was set at 5 km/h and slope was set at 15%.

^a Since no fuel load data was collected for the 20–29-year interval, the italic values were calculated as the midpoint between the 10–19 and 40–49-year interval fuel loads.

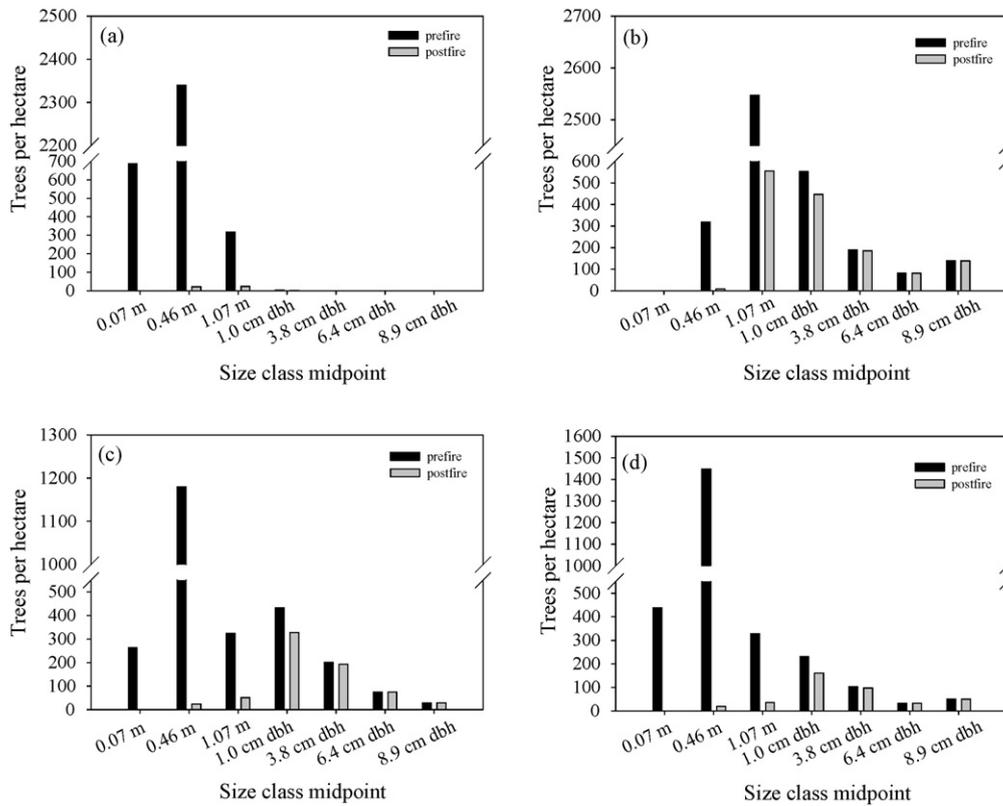


Fig. 3. Estimated ponderosa pine seedling and sapling density reduction during a prescribed fire in fuel treatments as predicted by the flame lengths associated with fine fuel loading accumulation and seedling/sapling susceptibility at (a) <10 years, (b) 10–19 years, (c) 20–29 years, and (d) 40–49 years post-disturbance. Densities for the fuel treatment stands <10 to 30 years are from stands that were harvested and not burned. Densities for the 40–49 years were measured in a stand that burned in a low-severity wildfire.

quence that we measured (Table 3). One-hour fuels ranged between 0.15 and 0.43 Mg ha⁻¹ and 10-h fuels ranged between 0.69 and 1.84 Mg ha⁻¹ (Table 3). Needle litter, 1-h, and 10-h fuels followed similar temporal patterns with higher values in stands burned less than 19 years ago and the highest loadings between 60 and 69 years post-fire (Table 3). One-hundred-hour fuel loadings peaked at 6.59 Mg ha⁻¹ in stands burned 10 to 19 years ago and declined with time (Table 3).

Temporal dynamics of sound coarse woody debris (CWD) was influenced by time since fire (Table 3). Sound CWD was highest within 10 years post-fire and 60–69 years post-fire at about 4–4.5 Mg ha⁻¹ (Table 3). Between 10 years and 49 years post-fire, sound CWD was about 3 Mg ha⁻¹ (Table 3). Rotten CWD was low <10 years post-fire (Table 3), but peaked at 10–19 years and decreased each decade post-fire thereafter (Table 3).

The amount of duff available to smolder during a fire can influence the amount of root and cambial damage to a tree if conditions are dry enough. Our data show duff loads in fires <10 years and >60 years old ranged between 7.0 and 9.9 Mg ha⁻¹ (Table 3). However, duff loads in fires 20–49 years old were lower, ranging from 3.7 to 4.2 Mg ha⁻¹ (Table 3).

3.3. Prescribed fire behavior and regeneration mortality

The success of using prescribed fire to control regeneration density in fuel treatments is strongly dependent upon the frequency of burning in these forests. BehavePlus simulations of surface fuel loadings measured at various times since fire indicate that potential surface fire behavior during prescribed burns varies over time. These changes in post-fire fine fuel loadings were due to the time that has elapsed since the stand was last subject to fire (Table 3).

As described earlier, within the first 10 years post-fire, when predicted flame lengths are 0.90 m (Table 3) most of the new regeneration would be <1 m tall (Figs. 1, 2a and 3a) and would be highly susceptible to mortality in a low intensity prescribed fire (Fig. 4a). The susceptibility of any advanced regeneration that survived the initial treatment entry would depend on the sapling size. For instance, mortality of saplings up to 1 cm dbh would be predicted to be 40%, but mortality of saplings >3.8 cm dbh would be predicted to be <10% (Fig. 4b). Based on our estimates of pre-fire seedling densities within 10 years post-disturbance (Fig. 3a) a large reduction in seedling densities would occur after a low intensity prescribed fire applied within this timeframe. Seedling densities would decrease from 3345 to 46 ha⁻¹ post-fire (Fig. 3a).

Ten to 19 years post-fire, fine fuel loads would produce flame lengths of 0.6 m (Table 3). Stands would have seedlings that range in size up to 1.36 m tall and some saplings (0.25–10 cm dbh) would be present (Figs. 1, 2a and b and 3b). Prescribed fire with these flame lengths would still be effective at reducing seedling densities with predicted mortality exceeding 95% for seedlings <0.46 m tall and 78% for the seedlings averaging 1.07 m tall (Fig. 4a). Regeneration that had reached dbh (1.37 m height) would not be highly susceptible to mortality by a prescribed fire with 0.6 m flame length (Fig. 4b). Predicted mortality of saplings 1 cm dbh would be only 20%, saplings 3.8 cm dbh would be 3%, and any sapling >6.4 cm dbh would have <1% mortality (Fig. 4). Based on our estimates of pre-fire seedling densities within 10–19 years post-disturbance, there would be a large reduction in seedling densities, but not sapling densities (Fig. 3b). Seedling densities would decrease from 2800 to 564 ha⁻¹ post-fire (Fig. 3b). However, sapling densities, which were approximately 963 ha⁻¹ pre-fire, would only be reduced to 852 ha⁻¹ (Fig. 3b).

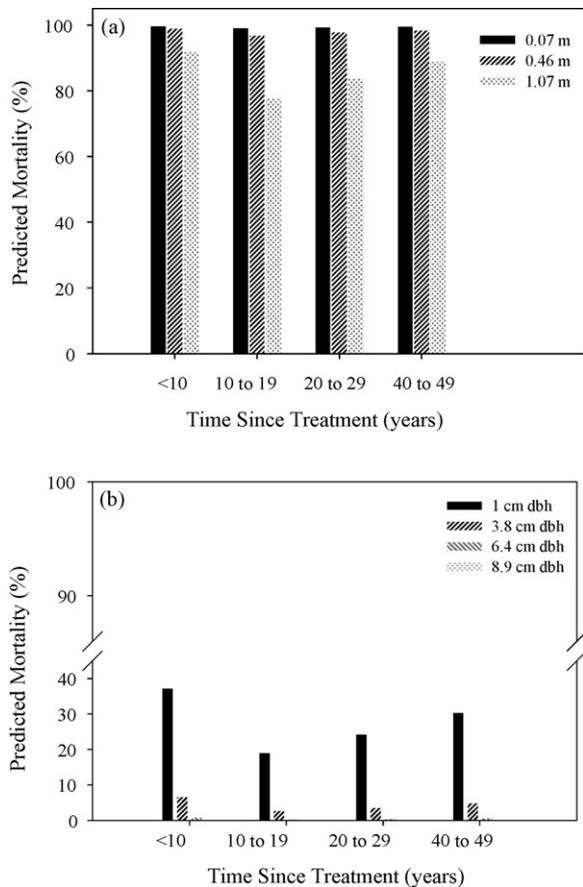


Fig. 4. Predicted % mortality of ponderosa pine (a) seedlings and (b) saplings in fuel treatments based on predicted flame lengths during a typical prescribed fire associated with fine fuel loading accumulation. Mortality was predicted for size class midpoints using logistic regressions developed with observed flame lengths and associated observed mortality on prescribed burns on the Black Hills National Forest (Battaglia et al., in press).

By the time 20–29 years had elapsed after fire, the size of ponderosa pine regeneration would range from seedlings <0.15 m tall to saplings that are 12.7 cm dbh (Figs. 2 and 3c), with a substantial increase in sapling densities (Fig. 3c). Fine fuel loads would produce predicted flame lengths of 0.7 m (Table 3). Prescribed fire with these flame lengths would still be effective at reducing seedling densities with predicted mortality exceeding 95% for seedlings <0.46 m tall and 84% for the seedlings in the 1.07 m tall height size class (Fig. 4a). Predicted mortality of saplings 1 cm dbh would only be 25% and saplings 3.8 cm dbh would be 4%, however, any sapling >6.4 cm dbh would have <1% mortality (Fig. 4b). Stands would still have substantial reductions in seedling densities if burned, but the reduction in sapling densities would be minimal (Fig. 3c). Seedling densities, which exceeded 1769 ha⁻¹, would have post-fire seedling densities of

75 ha⁻¹ (Fig. 3c). However, sapling densities, which were approximately 736 ha⁻¹, would only be reduced to 623 ha⁻¹ (Fig. 3c).

Predicted flame lengths in older treatments (>40 years) would increase to 0.8 m (Table 3), but so would sapling size (Fig. 3d). Seedlings would still be susceptible, but the predicted mortality of saplings >3.8 cm dbh would still be low (Fig. 4b). Seedling densities, which exceeded 2215 ha⁻¹, would have post-fire seedling densities of 57 ha⁻¹ (Fig. 3d). However, sapling densities, which were approximately 417 ha⁻¹, would only be reduced to 341 ha⁻¹ (Fig. 3d).

3.4. Crown fire potential in unmaintained stands

Crown fire simulations in FFE-FVS indicated that the presence of high-density sapling-sized regeneration which results in low canopy base heights, substantially increases the probability of crown fire behavior under 90th percentile weather conditions (Table 4). In stands treated within 10 years of regeneration establishment, torching and crowning indices exceed 85 km h⁻¹. However, in fuel treatments that allow regeneration to establish and grow into sapling-sized trees, torching indices range between 13 and 17 km h⁻¹ (Table 4). The probability of propagating an active crown fire is highest for stands in which maintenance treatment has elapsed for 10–30 years. These stands would require windspeed between 29 and 33 km h⁻¹ (Table 4) to sustain an active crown fire. After 40 years, the crowning index increased to 58 km h⁻¹ (Table 4).

4. Discussion

In ponderosa pine forests of the Black Hills, the potential to quickly develop ladder fuels after a fuel treatment is high if regeneration densities are not regulated. In the absence of mechanical or prescribed fire treatment, this ladder fuel complex remains and shifts from seedling- to sapling-sized trees over time. As ponderosa pine seedlings and saplings increase in height and diameter, their susceptibility to mortality during prescribed fire decreases (Battaglia et al., in press). The situation is complicated by changes in surface fuel availability and the low-intensity fire behavior typical of prescribed fires. These factors impact the ability to use prescribed fire to regulate ponderosa pine seedling and sapling density. Overall, current prescribed fire prescriptions can be successful in regulating ponderosa pine seedlings, but higher fine fuel loads or burning when fuel moistures are lower will be needed to produce the flame lengths needed to reduce high densities of saplings in Black Hills ponderosa pine forests.

The size distribution of ponderosa pine regeneration over time since a fuel treatment is influenced by several factors. Site productivity and stand density can influence the rate at which a seedling or sapling reaches a certain size (Shepperd et al., 2006). This age-size differentiation was reflected in our study by the variability in tree age with seedling height and diameter, especially as regeneration reaches 20–30 years old. Seedling and sapling size

Table 4

Predicted crown fire potential for 90th percentile fire weather conditions for fuel treatments without future maintenance activities in Black Hills ponderosa pine forests

Time since treatment (years)	Torching index (km h ⁻¹)	Crowning index (km h ⁻¹)	Canopy base height (m)
<10	85	90	8.0
10–19	15	29	1.2
20–29	13	33	1.2
40–49	17	58	1.5

Crown fire potential was predicted using the fire and fuels extension to the forest vegetation simulator. Torching index is the 6.1 m windspeed required to initiate a crown fire. Crowning index is the 6.1 m windspeed required to sustain an active crown fire.

distribution over time in a fuel treatment would also be influenced by the immediacy of regeneration establishment after treatment. Furthermore, the presence of any advance regeneration that was not mechanically thinned or killed in an initial prescribed fire would also provide for some size differentiation. These possible differences would be site specific and should be considered when future maintenance activities of fuel treatments are in the planning stage.

The temporal change in regeneration size distribution following fuel treatments will impact the potential for crown fire behavior and overstory mortality. Assuming regeneration establishes soon after a fuel treatment is implemented, the majority of regeneration within the first 10 years will be <1 m tall. Seedlings of this size would not likely transfer a surface fire to the overstory canopy during a wildfire, as indicated by the crown fire simulations. However, by the time that a fuel treatment is 20 years old, the probability of passive crown fire initiation was shown to increase for two reasons. First, the size distribution of seedling regeneration can now span from <0.15 m tall to 1.37 m tall. Second, within 20 years, the seedlings that established immediately post-treatment have now reached sapling-sized with diameters of 2.5 cm and are on average 2.2 m tall. The presence of a continuous fuel strata from <0.15 to 2.2 m would allow a surface fire to transfer into the crowns of the saplings and allow flames to heat the foliage of the overstory. Thirty years after regeneration establishment, the initial fuel treatment's ability to reduce crown fire risk is further diminished. The size distribution of ponderosa pine regeneration could range from seedlings <0.15 m tall to saplings that are 4 m tall. This continuous fuel stratum would allow surface fire to transfer into the overstory and result in passive crown fire behavior even under moderate weather conditions and an active crown fire behavior if windspeeds exceeded 33 km h⁻¹. As fuel treatments get older and are not maintained, regeneration will continuously establish until all growing space is occupied and trees eventually succumb to density-dependent mortality. Mechanical and/or prescribed fire treatments are therefore necessary to control ponderosa pine regeneration density in the Black Hills and reduce the future risk of crown fire.

The use of prescribed fire to control ponderosa pine regeneration will require enough fine (<7.62 cm diameter) fuel accumulation to carry a fire and produce intensities high enough to result in mortality. Although fine fuel loadings are often reduced by 50–70% immediately after a prescribed fire (Thomas and Agee, 1986; Sackett and Haase, 1998; Fulé et al., 2002), inputs from small tree mortality can aid in the recovery of these fuels. Thomas and Agee (1986) noted that within 5–10 years, fine fuels accumulated from the mortality of understory trees and recovered to 71% of the pre-burn levels in mixed conifer forests of Oregon. Parsons (1978) reported that fine fuels returned to pre-burn levels within 7 years in sequoia (*Sequoiadendron giganteum* [Lindl.] Buchh.)-mixed conifer forests, likely due to inputs from small tree mortality. In our study, we observed an increase in fine fuel loadings after 10 years post-fire with substantially higher fuel loads for several more decades. The temporal pattern in fine fuel load accumulation suggests that mortality and subsequent falling of the regeneration and small diameter trees is delayed for several years in open-canopied stands. In addition, the continued increase in fine fuel loadings in these stands is likely due to the initial death of lower branches from the fire and the gradual abscission of these branches over time. In later years, inputs from dead trees and branch breakage (Lundquist, 2007) in conjunction with low decomposition rates (Keane, 2008) leads to increased fuel loads.

In order to maintain a sustainable fuels treatment, regeneration densities should be kept at a level where some future overstory recruitment is allowed, but also at densities low enough to limit

the creation of dense ladder fuels. This can be achieved when regeneration densities do not exceed 500 stems ha⁻¹. Such low densities are feasible in other regions where ponderosa pine grows. For instance, ponderosa pine regeneration 10 years post-treatment in the Bitterroot Mountains of Montana ranged between 33 and 87 seedlings ha⁻¹ (Fajardo et al., 2007). In northern Arizona, ponderosa pine regeneration after prescribed fire or thinning ranged between 12 and 41 seedlings ha⁻¹ (Bailey and Covington, 2002), although the coincidence of a banner seed year and a very wet summer can produce several thousand ponderosa pine seedlings ha⁻¹ in northern Arizona (Sackett and Haase, 1998). In contrast, the average growing season climate in the Black Hills (Shepperd and Battaglia, 2002) commonly allows up to several thousand ponderosa pine seedlings ha⁻¹ to establish (Battaglia, 2007; Keyser et al., 2008). Even under droughty conditions, regeneration within the 2000 Jasper fire perimeter exceeded 1000 seedlings ha⁻¹ (Bonnet et al., 2005; Keyser et al., 2008). This situation is exacerbated with the continuous establishment of dense regeneration decades after fire in the Black Hills. Successful management of Black Hills ponderosa pine forests should emphasize the importance of planning silviculture and fuel treatment activities that restrict future ladder fuel densities to maintain fuel treatment efficacy.

Our data indicate that predicted flame lengths associated with the fine fuel loadings after fire in Black Hills ponderosa pine forests were large enough to cause appreciable mortality in seedling-sized, but not sapling-sized ponderosa pines, regardless of time since fire. These flame lengths would result in torching fire behavior within the seedling regeneration layer with high levels of crown consumption and subsequently higher mortality rates (Battaglia et al., in press). However, under typical prescribed fire conditions, the amount of fine fuel accumulated would not be enough to produce the intensities required to have any considerable crown consumption in the sapling-sized trees, damage that is required for high mortality levels in ponderosa pine saplings (Harrington, 1987; Harrington, 1993; Battaglia et al., in press). The lack of mortality in the sapling size classes would inevitably result in densities that exceed 500 ha⁻¹ and would therefore still contribute to ladder fuels and crown bulk densities conducive to crown fire. Our predicted reductions in seedling densities suggest that prescribe burning on a 10-year cycle would allow enough fine fuel accumulation to cause mortality in the seedling size classes that would be present.

It is important to note that the interacting factors that influence fire behavior are complex and difficult to model. Therefore, BehavePlus utilizes assumptions that simplify these factors to model fire behavior. For instance, the model assumes that the fuel complex, topography, and weather conditions are uniform and that the fire burns only on the surface. Each of these assumptions ignores the heterogeneity of fuel loads, fuel moisture, and topography, which can lead to erroneous outputs. BehavePlus also predicts the fire behavior at the flaming front and does not consider the convergence of numerous fire lines often lit during prescribed fire operations. Nor does it consider the shorter flame lengths associated with the fire flank. These limitations should be considered when using this model to predict the flame lengths required to meet regeneration density reduction objectives.

The flame lengths predicted from the BehavePlus simulations in the above examples also does not take into account the total amount of heat produced by smoldering of litter, duff, or coarse woody debris (CWD; >7.62 cm diameter). Smoldering of these fuels can damage tree roots and stem cambium independent of the flaming front (Hartford and Frandsen, 1992) and has been shown to increase tree mortality (Ryan and Frandsen, 1991; Swezy and

Agee, 1991; Stephens and Finney, 2002; Battaglia et al., in press). Because CWD is spatially variable in these forests, the effect of the combustion of these fuels would be localized. Furthermore, the total consumption of CWD fuels is unlikely due to the high fuel moisture (Knapp et al., 2005; Stephens and Moghaddas, 2005) required under typical early season prescribed fire conditions. However, if prescribed burns are implemented when fuel moisture of CWD is not high, the intensity produced by the combustion of these larger fuels could create localized mortality in sapling-sized trees.

The combustion of CWD during prescribed fires that were sampled by Battaglia et al. (in press) is likely what contributed to the mortality of sapling-sized ponderosa pine trees. Predicted flame lengths for the sampled plots ranged from 0.20 to 5.0 m and observed mortality increased with predicted flame length (Battaglia et al., in press). Minimal sapling mortality was observed at flame lengths <0.40 m, which is consistent with the findings of the current study. Observed mortality in saplings >2.5 cm dbh exceeded 50% when flame lengths were >1.5 m tall, but flame lengths of 2.0 m were needed for any significant mortality of >5.0 cm dbh saplings.

Achieving flame lengths that will cause mortality in saplings >2.5 cm dbh or >2 m tall may require prescribed burns to be carried out under drier conditions to allow some CWD consumption to contribute to fire intensity. Delayed death of pole-sized (10–25 cm dbh) trees from prescribed fire or other factors can serve as a source of future inputs of CWD for future prescribed fires. Evidently, the sound CWD converts to rotten CWD that can ignite easier if dry. In our study, this occurred between 10 and 29 years post-treatment, the time frame in which regeneration becomes less susceptible to prescribed fire conditions. Achieving reductions in sapling-sized regeneration with prescribed burning will need to consider the fire intensity contribution that CWD can provide. This would allow longer periods between prescribed fire intervals, but also increase the complexity of the operation.

An alternative to burning when fuel moistures are low enough to consume CWD is to increase the amount of fine surface fuels. For example, current practice in fuel reduction treatments is to whole-tree harvest, pile residual slash, and burn it at the landing. However, if the same area is to be prescribed burned in the future, whole-tree harvesting hinders the ability to effectively reduce ponderosa pine regeneration. Instead, lop and scattering the tops of trees would allow an increase in fine fuel loadings while keeping CWD fuel loadings at low levels. By leaving the tree tops as activity fuels, burning can still take place when CWD fuel moistures are high, but when the fine fuel moistures are low. Furthermore, having greater fine fuel loadings should increase the probability of mortality in the sapling-size classes. In addition, large portions of an ecosystem's nutrients are found in the branches, twigs, and foliage of a tree. Leaving activity fuels on site will allow these nutrients to return into the soil after a light broadcast burn (Monleon and Cromack, 1996; Garrison and Moore, 1998).

In areas where the use of prescribed fire is prohibitive, mechanical treatments such as thinning or chipping/mastication will be needed to keep regeneration densities low enough to prevent the loss of fuel treatment effectiveness. In the Black Hills, mechanical thinning is often cheaper (about \$134 ha⁻¹) and can be implemented on greater number of acres per year than prescribed fire (about \$172 ha⁻¹). Chipping and/or mastication, relatively new techniques being used in the Black Hills and other ponderosa pine forests, can vary in cost from \$100 to \$405 ha⁻¹ (USDA Forest Service, 2003; Hunter et al., 2007). Although these mechanical treatments can successfully reduce regeneration densities, the equipment is often restricted by steep topography and costs associated with constructing new roads.

Although prescribed fire can be more expensive, managers should consider the ecological benefits of fire to the ecosystem. Historically, fire was an important disturbance agent in ponderosa pine forests of the Black Hills (Brown and Sieg, 1996; Brown and Sieg, 1999; Brown, 2003) and other regions (Brown et al., 1999; Fulé et al., 2004). In addition to reducing tree densities, prescribed fires can be used to reduce surface fuel loads, improve nutrient cycling, increase forage plant production, and improve wildlife habitat (DeBano et al., 1998; Allen et al., 2002). While mechanical treatments can also produce some of these ecological benefits, the use of fire in ponderosa pine forests can help enhance ecosystem resiliency and sustainability, and aid in the restoration of ecosystem processes rather than just structure.

5. Conclusions

Based on the relationships that we established between seedling/sapling growth, fuel accumulation, and potential prescribed fire behavior, the use of prescribed fire to maintain low regeneration densities following fuel treatments in Black Hills ponderosa pine forests will require some careful planning. Results from this study suggest that current prescribed fire prescriptions and fuel loads are adequate to maintain low densities of ponderosa pine seedlings if burns occur every 10 years. If managers wait longer than 10 years between burns, pine regeneration can attain sizes (dbh and height) that reduce its susceptibility to prescribed fire under typical operational weather conditions. After 20 years, ponderosa pine will require flame lengths created only by burning under weather conditions that allow CWD to contribute to the fire intensity. However, burning under these conditions could increase the chance for escape and possibly some overstory tree mortality. Alternatively, managers can augment sites with activity fuels to increase fine fuel loadings to achieve flame lengths that will increase sapling susceptibility to fire, but burn when CWD fuel moisture are high to limit the potential for extreme fire behavior. While the flames might kill sapling-sized trees, mature overstory trees would still maintain some resiliency to fire. If prescribed fire cannot be used, some kind of mechanical treatment (thinning or mastication/chipping) will need to be implemented to keep regeneration densities low enough to prevent the loss of fuel treatment effectiveness.

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