Communications

Latent resilience in ponderosa pine forest: effects of resumed frequent fire

Andrew J. Larson,[1,6] R. Travis Belote,[2] C. Alina Cansler,[3] Sean A. Parks,[4] and Matthew S. Dietz[5]

[1]*Department of Forest Management, University of Montana, 32 Campus Drive, Missoula, Montana 59812 USA*
[2]*The Wilderness Society, Northern Rockies Regional Office, 503 West Mendenhall, Bozeman, Montana 59715 USA*
[3]*School of Environmental and Forest Sciences, University of Washington, Box 352100, Seattle, Washington 98195-2100 USA*
[4]*Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service, 790 East Beckwith Avenue, Missoula, Montana 59801 USA*
[5]*The Wilderness Society, 250 Montgomery Street, Suite 210, San Francisco, California 94104 USA*

Abstract. Ecological systems often exhibit resilient states that are maintained through negative feedbacks. In ponderosa pine forests, fire historically represented the negative feedback mechanism that maintained ecosystem resilience; fire exclusion reduced that resilience, predisposing the transition to an alternative ecosystem state upon reintroduction of fire. We evaluated the effects of reintroduced frequent wildfire in unlogged, fire-excluded, ponderosa pine forest in the Bob Marshall Wilderness, Montana, USA. Initial reintroduction of fire in 2003 reduced tree density and consumed surface fuels, but also stimulated establishment of a dense cohort of lodgepole pine, maintaining a trajectory toward an alternative state. Resumption of a frequent fire regime by a second fire in 2011 restored a low-density forest dominated by large-diameter ponderosa pine by eliminating many regenerating lodgepole pines and by continuing to remove surface fuels and small-diameter lodgepole pine and Douglas-fir that established during the fire suppression era. Our data demonstrate that some unlogged, fire-excluded, ponderosa pine forests possess latent resilience to reintroduced fire. A passive model of simply allowing lightning-ignited fires to burn appears to be a viable approach to restoration of such forests.

Key words: fire effects; fire exclusion; mixed-severity fire; surface fire; wilderness management.

INTRODUCTION

Ecological systems often express resilience (i.e., persistence of recognizable ecological states) that arises from negative feedbacks (Chapin et al. 2002, Beisner et al. 2003). In ponderosa pine (*Pinus ponderosa*) forests of western North America, fire historically represented the negative feedback mechanism that maintained ecosystem resilience and the characteristics of large, old, fire-resistant trees and an open understory (e.g., Covington and Moore 1994, Hessburg et al. 2005). Twentieth-century grazing (which removed fine fuels and altered competitive interactions between tree seedlings and understory plants), timber harvesting (which removed large trees), and fire exclusion (which removed the key feedback process), altered the character of millions of

hectares of ponderosa pine forests, which are now at elevated risk of crown fires that can cause a shift to alternative states (Savage and Mast 2005, Bowman et al. 2013).

The Crown of the Continent region of the northern Rocky Mountains in Montana, USA hosts ponderosa pine forests that occupy current climate refugia at the environmental and geographic boundary of the species' range (Ayres 1900, Arno et al. 2000, Keane et al. 2006). Like many ponderosa pine forests throughout western North America, these sites in the northern Rockies were historically maintained by a mixed-severity fire regime characterized by periodic low- and moderate-severity fires (Arno et al. 1995, 2000), although patches of crown fire did occasionally occur (Ayres 1900, Barrett et al. 1991, Arno et al. 1995). This historical fire regime functioned as a negative feedback (F1 in Fig. 1), maintaining a shifting patch mosaic of resilient low-density mixed-conifer forest (state S1 in Fig. 1)

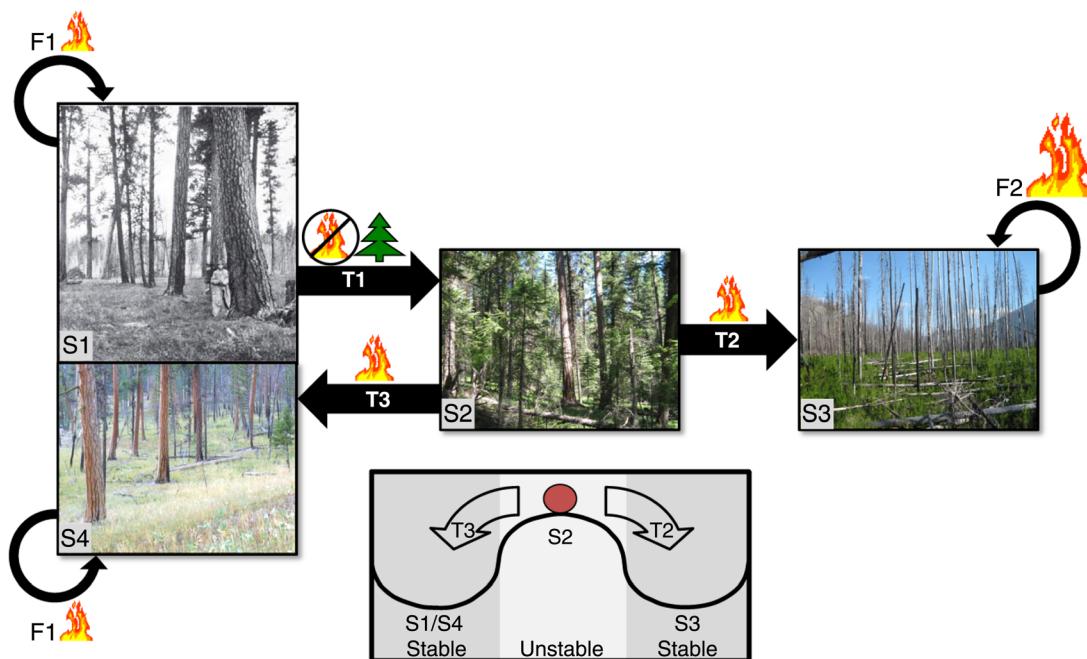[6] E-mail: a.larson@umontana.edu

FIG. 1. Conceptual model for the effects of active, excluded, and reintroduced fire in ponderosa pine forest, Bob Marshall Wilderness, USA. States are: S1, historical low-density mixed-conifer forest dominated by large-diameter ponderosa pine; S2, high-density, closed-canopy, mixed-conifer forest dominated by lodgepole pine and Douglas-fir with embedded residual large-diameter ponderosa pine; S3, closed-canopy lodgepole pine forest with minor amounts of Douglas-fir, western larch, and Engelmann spruce, with large-diameter ponderosa pine greatly reduced or eliminated; S4, contemporary low-density mixed-conifer forest dominated by large-diameter ponderosa pine. Transitions are: T1, Successional development resulting from fire exclusion; T2, hypothesis that reintroduction of fire causes transition to an alternative forest structure and loss of large-diameter ponderosa pine (S3); T3, hypothesis that reintroduction of fire causes a return to low-density stand structure with large-diameter ponderosa pine (S4). Feedbacks are: F1, stabilizing negative feedback of frequent low- and moderate-severity fire that maintains resilient low-density forest structure dominated by large-diameter ponderosa pine; F2, stabilizing negative feedback of high-severity fire that maintains resilient high-density forest structure dominated by lodgepole pine. See *Discussion* for an evaluation of the conceptual model against the empirical results. The photo depicting historical state S1 shows a site in the Swan Valley, Montana, USA, approximately 28 km west of our study site in the Bob Marshall Wilderness, and was reproduced from Ayres (1900).

dominated by large, old, ponderosa pine trees (Ayres 1900, Arno et al. 1995, 2000, Keane et al. 2006).

The familiar narrative of 20th-century fire exclusion and resultant successional changes to ponderosa pine forest structure and composition forests applies to sites in the Crown of the Continent. Fire suppression began early in the 20th century and, by the 1960s, the effects of fire exclusion (transition T1 to state S2 in Fig. 1) were apparent (Steele 1960), including increased tree densities, altered forest composition, and elevated surface fuel loads (Lunan and Habeck 1973, Arno et al. 1995). Strong effects of fire exclusion manifested even at sites with historical evidence of sporadic crown fire (e.g., sites Flathead 1 and 2 in Arno et al. [1995]). This fact illustrates how the ongoing debate about the historical prevalence of crown fire (Williams and Baker 2012) distracts from the need to understand and forecast how fire-excluded ponderosa pine forests will respond to the inevitable reintroduction of fire (Bowman et al. 2013).

The clear effects of fire exclusion on forest structure and composition led to calls for silvicultural intervention to restore forest conditions (e.g., Keane et al. 2006).

These calls for intervention were motivated by the perceived instability of sites that had transitioned from S1 to S2 (Fig. 1) due to fire exclusion, similar to the rationale for intervention in fire-excluded ponderosa pine forests in other regions (e.g., Covington and Moore 1994). The concern is that, upon reintroduction of fire, fire-excluded sites in state S2 will transition (T2 in Fig. 1) to an alternative resilient state that lacks large, old, ponderosa pines (S3 in Fig. 1) and is maintained by the feedback of high-severity fire (F2 in Fig. 1; c.f. Savage and Mast 2005). Recently, Naficy et al. (2010) showed for northern Rockies ponderosa pine forests that unlogged, fire-excluded sites were less departed from reference conditions than adjacent historically logged, fire-excluded sites, and proposed that unlogged, fire-excluded, ponderosa pine forests need not receive silvicultural treatment to restore forest conditions and reduce fuels prior to reintroduction of fire. This untested idea (Naficy et al. 2010) is represented as transition T3 in Fig. 1, in which reintroduction of fire causes return to the putative historical state, S4.

In July of 2003, fire returned to the ponderosa pine forests of the Bob Marshall Wilderness after at least 70 years of exclusion via the lightning-ignited Bartlett Mountain Fire (Keane et al. 2006). Then, in August of 2011, lightning ignited the Hammer Creek Fire in the Bob Marshall Wilderness. Within a few days, the Hammer Creek Fire burned into ponderosa pine forests previously burned by the Bartlett Mountain Fire in 2003. This historic event provided a rare opportunity to study the effects of resumed frequent fire in unlogged fire-excluded forest that had not experienced silvicultural intervention prior to the reintroduction of fire, and to test the alternative hypotheses that follow from our conceptual model (Fig. 1).

The objective of this study is to quantify effects of repeat lightning-ignited wildfires on forest structure and composition in unlogged, fire-excluded, ponderosa pine forest. We evaluate two alternative hypotheses: (1) reintroduction of fire causes transition to a forest structure and composition marked by loss of large ponderosa pine and dominance of lodgepole pine (*Pinus contorta*; T2 in Fig. 1) and (2) reintroduction of fire causes transition back to low-density mixed-conifer forest dominated by large ponderosa pine by preferentially killing small-diameter trees that established during the fire exclusion period (T3 in Fig. 1).

METHODS

The study site is located in the upper South Fork Flathead River Valley (1430 m elevation) in the Bob Marshall Wilderness, Montana, USA (47.5167° N, 113.2631° W), approximately 40 km by trail from the nearest road. Forest composition is dominated by ponderosa pine, lodgepole pine, and Douglas-fir (*Pseudotsuga menziesii*), with minor amounts of western larch (*Larix occidentalis*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). Attributes of the study area and the weather conditions under which the 2003 and 2011 fires burned are provided in the Appendix.

Sampling occurred where the 2011 Hammer Creek Fire reburned ponderosa pine communities that burned in the 2003 Bartlett Mountain Fire, the extent of which is estimated at 114 ha (Fig. A1). During August of 2012 we established 15 900-m² plots (30 × 30 m) along systematically arrayed transects emanating from a random starting point (plots spaced at 100-m intervals); sample plots were concentrated in the western half of the reburn area and were considered representative of the overall area based on a satellite derived assessment of 2011 burn severity and ground based reconnaissance of the entire reburn area in 2010 and 2012 (Appendix). All freestanding living and dead trees (≥1.37 m tall) in each plot were identified to species and tallied by 20 cm diameter classes. Status of each tree was recorded as healthy, minor injury, major injury, old dead (pre-2011), and new dead (post-2011); details of this classification are provided in Appendix: Table A1 and are based on

the methods of Leirfallom and Keane (2011). We sampled tree regeneration (≥1 year-old seedlings <1.37 m tall) by species in a 2.3 × 30.0 m belt transect centered within each forest structure plot. We used the macroplot variant of the photoload fuel loading estimation technique (Keane and Dickinson 2007) to quantify woody surface fuel loadings (four subplots per 900-m² plot).

RESULTS

The 2011 Hammer Creek Fire burned through the study area with highly variable effects and intensity. The variability was in large part influenced by the variable woody surface fuel loads created by the 2003 Bartlett Mountain Fire. In places where the 2003 fire caused high levels of lodgepole pine mortality, dense jackpots of coarse fuels were on the ground when the second fire burned the area in 2011, leading to locally intense fire effects (Appendix: Fig. A2). Much of the area, however, burned with low severity (Fig. A1) through a fuel bed of herbaceous materials and modest loadings of fine woody debris beneath an overstory of large, high-crowned, ponderosa pine that survived the 2003 fire (Fig. 2A and B). Many 100-hour and 1000-hour fuels burned with incomplete combustion in 2011, resulting in considerable black carbon or "char" production (Fig. 2C and Fig. A2). The deep duff mounds that had accumulated around the base of surviving large-diameter ponderosa pines during the fire-suppression era (Arno et al. 2000, Keane et al. 2006) were eliminated from most trees within the twice-burned area in 2012 (Fig. 2D).

New tree mortality caused by the 2011 fire was primarily limited to Douglas-fir and lodgepole pine trees that had survived the initial 2003 fire; only a negligible amount of new fire-related ponderosa pine mortality was observed (Fig. 3). Tree vigor and injury status (Fig. 3) depended strongly on species ($\chi^2 = 88.5$, df = 8, $P < 0.001$). Structural failure due to burning of old fire scars was a predominant cause of large-diameter ponderosa pine mortality following the second fire. Fire-caused injury and post-fire bark beetle attack were only rarely observed mortality factors for ponderosa pine in 2012, indicating a high level of resilience of the ponderosa pine population, including large-diameter individuals, to the direct and indirect effects of the second fire (Fig. 2A and B).

Woody surface fuel loadings averaged 45.7 ± 7.5 Mg/ha (mean ± SE) in 2012. Eighty-six percent of this total was 1000-hour fuels; 100-hour, 10-hour, and 1-hour fuels represented 7%, 2%, and 5%, respectively. The 1000-hour fuels were distributed throughout the study area at modest levels (e.g., Fig. 2A and B) with occasional heavily loaded patches of charred, partially consumed lodgepole pine logs that originated from trees killed in the 2003 fire (Fig. A2).

As of 2012, the study area has an average live tree density (trees ≥1.37 m tall) of 84 ± 16 trees/ha (range 0–200 trees/ha). Live ponderosa pine density averaged 14
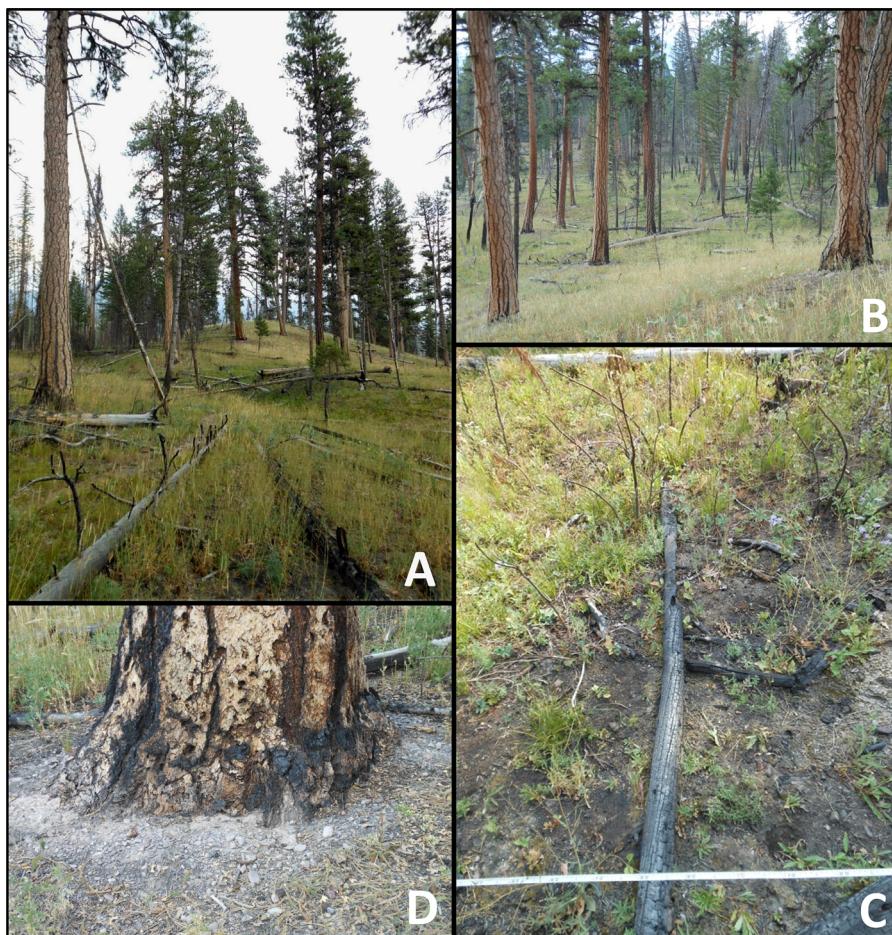
FIG. 2. Example conditions in twice-burned ponderosa pine forest (in 2003 and 2011) in the Bob Marshall Wilderness, USA (all photos taken during August 2012 by A. J. Larson). (A, B) The fires preferentially killed small-diameter Douglas-fir and lodgepole pine trees, leaving an overstory of large, high-crowned, ponderosa pines. (C) The second fire killed a large proportion of lodgepole pine seedlings that established following the initial fire, and the second fire partially consumed coarse woody surface fuels originating from trees killed in the initial fire. (D) After two fires in eight years, the duff mounds that accumulated at the base of large-diameter ponderosa pine trees during the fire exclusion era are now eliminated.

± 3 trees/ha (range 0–33 trees/ha). The smaller live-tree diameter classes (<60 cm dbh) were dominated by Douglas-fir, with lesser amounts of lodgepole pine also present, whereas the larger diameter classes (≥60 cm dbh) were composed primarily of ponderosa pine, with some Douglas-fir (Fig. 4A). Trace amounts of western larch, Engelmann spruce, and subalpine fir were also present in 2012, but their contribution to overall forest structure and composition was negligible. Snags were abundant in 2012, but primarily concentrated in the smallest diameter classes (Fig. 4B). Live and dead tree diameter distributions in 2012 differed significantly (Kolmogorov-Smirnov test, $P = 0.013$), indicating that the 2011 fire primarily caused mortality of small-diameter Douglas-fir and lodgepole pine trees that survived the 2003 fire (Fig. 3).

The 2011 Hammer Creek Fire strongly altered the successional trajectory of the study system by killing many of the lodgepole pine seedlings that established following the initial fire in 2003 (Table 1). A few dense patches of lodgepole pine regeneration remained scattered throughout the study area, but the overall effect of the 2011 fire on tree regeneration was to greatly reduce the total tree seedling density, especially of lodgepole pine. An example of a group of lodgepole pine seedlings killed in the 2011 fire is visible at the top of Fig. 2C. The second fire burned before the majority of regenerating lodgepole pines reached reproductive maturity.

DISCUSSION

Reintroduction of fire in the Bob Marshall Wilderness restored a low-density mixed-conifer forest dominated by large, old, ponderosa pines, suggesting that similar unlogged, fire-excluded forests (i.e., sites presently in state S2) may also possess latent resilience to future fires. Resumption of an active frequent fire regime through
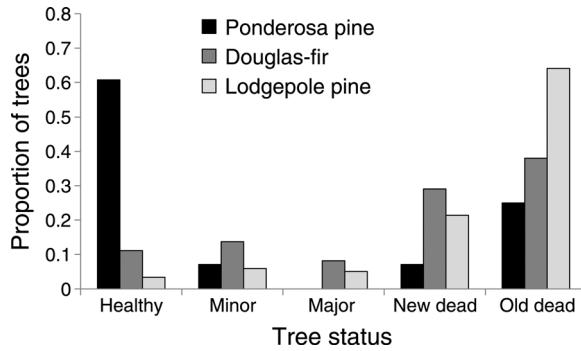
FIG. 3. Distribution of trees in 2012 among vigor status classes in twice-burned ponderosa pine forest, Bob Marshall Wilderness, USA. Vigor class definitions are provided in Appendix: Table A1.

the 2003 and 2011 fires returned forest structure and composition to the putative historical condition via transition T3 hypothesized in Fig. 1. The actual successional pathway and mechanisms of this transition, however, were more complicated than represented in Fig. 1.

The effect of the initial reintroduction of fire in 2003 was to continue the transition toward state S3 (Fig. 1) initiated by fire exclusion (Lunan and Habeck 1973). Six years of post-fire monitoring (Keane et al. 2006, Leirfallom and Keane 2011) revealed that about 19% of the ponderosa pines that burned in 2003 had died by 2009. A dense post-fire regenerating cohort of lodgepole pine (see Plate 1) was also established throughout much of the study area by 2009 (Leirfallom and Keane 2011). The initial 2003 fire did restore many attributes of these forests by consuming surface fuels, reducing or eliminating duff mounds around large, old ponderosa pines, and killing lodgepole pine and Douglas-fir trees that established during the fire-exclusion period. Despite these effects, however, the post-2003-fire successional trajectory was marked by attrition of large ponderosa pines and rapid transition to a high-density, closed-canopy forest dominated by lodgepole pine (see Plate 1): the initial fire was necessary, but not sufficient, to reverse the trajectory to state S3 initiated by fire exclusion.

The second fire in 2011 reversed the initial post-fire transition toward a state dominated by lodgepole pine (S3 in Fig. 1) and moved the system back into the domain of forest structure and composition represented by states S1 and S4 in Fig. 1. Injury and mortality of large-diameter ponderosa pine were minimal after the second fire (although delayed bark beetle attack and subsequent large pine mortality are possible); mortality was concentrated in small-diameter Douglas-fir and lodgepole pine that survived the 2003 fire. Importantly, the 2011 fire killed a large proportion of the regenerating lodgepole pine cohort (Table 1), halting the progression toward a closed-canopy lodgepole pine forest. Thus, we conclude that it was the resumption of an active frequent
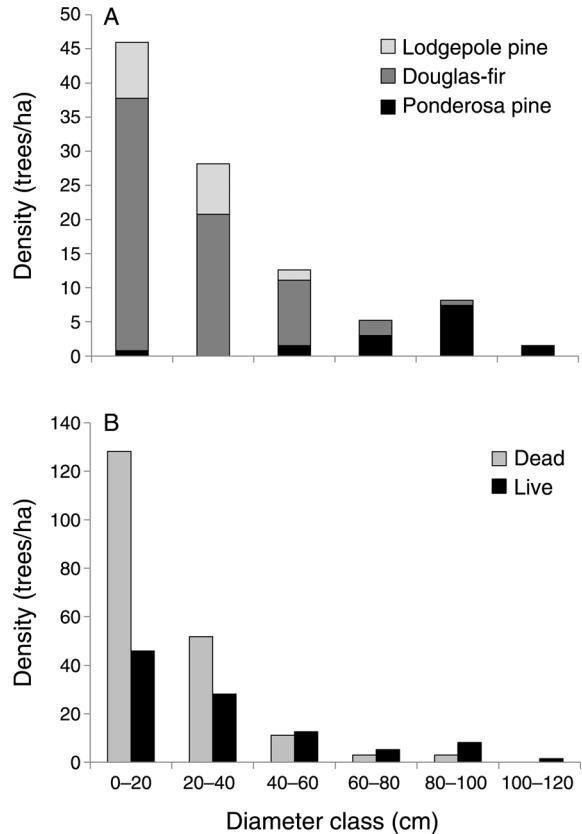

FIG. 4. Diameter (dbh) distribution in 2012 of living trees (A) by species and (B) for all live and dead trees in twice-burned ponderosa pine forest, Bob Marshall Wilderness, USA.

fire regime with an initial fire return interval less than the time needed for the regenerating cohort of lodgepole pine (see Plate 1) to reach reproductive maturity that effected the transition back to a low-density forest dominated by ponderosa pine (state S4 in Fig. 1). We report only first year post-fire effects: subsequent lodgepole pine and Douglas-fir seedling establishment, if not removed by future fires because of fire suppression, could reinitiate a trajectory back to S2.

The obvious next research problem that follows from our work is to investigate and quantify the parameters that determine the probability of a given fire-excluded site (i.e., a site in state S2 in Fig. 1) moving via T2 to an alternative state or via T3 to a restored putative

TABLE 1. Live and dead tree seedling (<1.37 m tall) density in twice-burned ponderosa pine forests in the Bob Marshall Wilderness in 2012.

Species	Density (seedlings/ha)	
	Live	Dead
Lodgepole pine	232	1372
Douglas-fir	48	68
Western larch	19	68
Engelmann spruce	10	0

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PLATE 1.   Dense lodgepole pine regeneration and coarse surface fuels within the study area seven years after the initial 2003 fire (cf. Fig. 2C). Photo credit: A. J. Larson, August 2010.

historical state upon the reintroduction of frequent fire. For example, the weather conditions under which the initial reintroduced fire burns, and therefore the severity of the initial fire, may exert strong control over the ultimate effects of resumed frequent fire (e.g., if the initial fire kills residual large-diameter ponderosa pine trees). Additions to our conceptual model (Fig. 1) would provide a general framework for further investigation of resumed frequent fire across a wider geographic area. For example, additional states, transitions, and feedbacks could be incorporated to represent the hypothesized transitions to grassland and shrubfield ecosystems upon reintroduction of fire in ponderosa pine and mixed-conifer forests of other regions (Savage and Mast 2005, Perry et al. 2011, Bowman et al. 2013).

Management implications

A passive restoration approach of allowing lightning-ignited fires to burn (Arno et al. 2000, Naficy et al. 2010) can restore unlogged, fire-excluded, ponderosa pine forests in the Crown of the Continent region. An important management implication of our results is that restoration of *frequent fire regimes* is required. A single

fire that is not followed by a second fire within approximately 5–20 years may move the system into an alternative state by facilitating dense lodgepole pine recruitment. Managed reignition of historically suppressed fires is a possible strategy to achieve restoration of frequent fire regimes (Arno et al. 2000). Our study system was never harvested and experienced minimal grazing—our inferences may be most applicable to forests with similar histories.

Some fire-excluded ponderosa pine and mixed-conifer forests thought to be at risk of crown fire and resulting ecosystem transition to alternative conditions (i.e., sites in state S2) may be more resilient than currently assumed. Studies of resumed frequent fire in the Sierra Nevada (Lydersen and North 2012), the southwest (Holden et al. 2007), and the southern Cascades (Taylor 2010) yielded results similar to those obtained here, indicating that many unlogged, fire-excluded forests possess latent resilience to reintroduced fire, and that a passive forest restoration approach of simply returning fire can be effective. The apparent generality of our results suggested by these studies from other regions is especially important because the available resources,

and social and political will, are insufficient to restore fire-excluded forests with thinning treatments and prescribed fire alone (North et al. 2012).

Our results underscore the need for managers and policy makers to clearly define when and where interventionist silvicultural treatments are used because passive reintroduction of fire is not socially acceptable, as opposed to when and where reintroduction of fire is not ecologically appropriate without preparatory silvicultural intervention. Failure to do so, and to instead espouse the position that most or all fire-excluded forests require intervention before reintroducing fire— a position contradicted by increasing scientific evidence—carries the risks of misspent resources, nontarget negative ecological effects, and erosion of public trust.

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SUPPLEMENTAL MATERIAL

Appendix

Description of the study area, sampling locations, fire weather conditions, burn severity, and tree vigor classification system (*Ecological Archives* A023-064-A1).