Growth Response of *Pinus ponderosa* following a Mixed-Severity Wildfire in the Black Hills, South Dakota

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ABSTRACT

In late summer 2000 the Jasper Fire burned ~34,000 ha of ponderosa pine forest in the Black Hills of South Dakota. Although regarded as a catastrophic event, the Jasper Fire left a mosaic of fire severity across the landscape, with live trees present in areas burned under low and moderate fire severity. In October 2005, we cored 96 trees from unburned, low-severity, and moderate-severity stands and assessed whether tree growth differed among fire severity classes during the 5 years postfire. We observed no differences in basal area increment (BAI) 10 years prefire among fire severities with BAI averaging 9.6 cm^2 per year. Despite severe drought conditions, BAI in moderate severity sites 2 years postfire was 58% greater than in unburned and low-severity stands. Although significant, this growth increase was short-lived. Three, 4, and 5 years postfire, no differences in growth among unburned, low-severity, and moderate-severity sites were detected, as BAI averaged 8.3, 7.5, and 7.0 cm^2, respectively. The lack of a consistent and prolonged growth response suggests that the Jasper Fire did not result in any short-term changes in growth patterns. Data extending beyond 5 years postfire are required to infer potential long-term changes in tree growth and productivity.

Keywords: Ponderosa pine, basal area increment, postfire tree growth, South Dakota, fire effects, general

In late summer 2000, the Jasper Fire burned ~34,000 ha of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests in the central Black Hills of South Dakota under extreme weather conditions, leaving behind a mosaic of fire-severity evidence across the landscape (US Forest Service 2000). Approximately 73% of the fire-affected landscape burned under low or moderate fire severity (Lentile et al. 2005) and, as a result, contained a substantial number of surviving trees (Keyser et al. 2008). The future growth and development of the surviving overstory may vary across areas of different fire severity. Variation in tree growth following wildfire has the potential to affect postfire forest productivity (Peterson and Ryan 1986), postfire tree mortality (van Mantgem et al. 2003), and susceptibility of individual trees to mountain pine beetle (*Dendroctonus ponderosae* Hopkins) attack (Mohoney 1978), and it has also been used as supporting evidence in constructing disturbance histories (Bergeron and Brisson 1990, Morrison and Swanson 1990, Swetnam et al. 1995, Mutch and Swetnam 1995). Despite the significance of such data, little information has been made available regarding tree growth following wildfire. This study fills a void in the literature by examining variations in the growth of ponderosa pine following the Jasper Fire as a function of low- and moderate-severity fire.

Despite the frequent occurrence of large-scale wildfires across the western United States, relatively few studies have quantified the short- and long-term effects of wildfire on individual tree growth of western tree species. The few published studies regarding tree growth following wildfire have shown that growth varies considerably with species as well as with levels of crown damage. For example, following a small (~325-ha) wildfire in northern Arizona, Pearson et al. (1972) reported radial growth increased from 1.2 mm prefire to 4.3 mm in ponderosa pine trees sustaining <60% crown damage 2 years postfire, but growth decreased to 0.6 mm when trees experienced >85% damage. Similarly, Peterson et al. (1991) observed 4 years of decreased growth of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), especially in trees that had sustained >50% crown damage following a wildfire in the northern Rocky Mountains. Peterson et al. (1991) also documented a significant decrease in growth of lodgepole pine (*Pinus contorta* Doug. Ex. Loud.) following wildfire, and reductions were most prominent in trees that experienced >30% crown damage.

Although there is a lack of information on tree growth following wildfire, much information is available regarding the effects of prescribed fire on the growth of tree species including ponderosa pine, Douglas-fir, western larch (*Larix occidentalis* Nutt.), and giant sequoia (*Sequoiadendron giganteum* [Lindl.] Buchholz). However similar to growth following wildfire, the results are conflicting and vary, both by species (Reinhardt and Ryan 1988) and fire severity (Mutch and Swetnam 1995). For ponderosa pine, in particular,

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This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; square centimeters (cm^2): 1 cm^2 = 0.155 $in.^2$; meters (m): 1 m = 3.3 ft; hectares (ha): 1 ha = 2.47 ac.

Table 1. Initial fire effects (trees ≥15 cm dbh) and fire-related tree mortality (trees ≥5 cm dbh) in low- and moderate-severity sites. Values represent the mean (minimum to maximum) damage observed during initial measurements in June 2001. Basal char represents the proportion of the bole circumference of each sample tree charred below 30 cm. Ground char represents the proportion of the ground within a 1-m radius of each sample tree displaying unburned ground, light, moderate, and heavy ground char. Ground char ratings are based on Ryan and Noste's (1985) classification system.

Fire severity class	Initial tree mortality	Crown damage	Basal char	Unburned ground	Light ground char	Moderate ground char	Heavy ground char
	(%)						
Low	<1 (0–3)	30 (8–52)	9 (1–32)	8 (0–28)	46 (11–70)	37 (11–83)	9 (0–21)
Moderate	22 (0–54)	84 (61–98)	19 (1–49)	<1 (0–1)	30 (<1–66)	47 (26–80)	23 (8–61)

numerous studies have documented a temporary decrease in growth following prescribed burning (e.g., Landsberg et al. 1984, Grier 1989, Sutherland et al. 1991, Peterson et al. 1994, Busse et al. 2000), whereas other studies have reported a positive growth response in ponderosa pine (Wyant et al. 1983, Skov et al. 2005), giant sequoia (Mutch and Swetnam 1995), and Douglas-fir (Reinhardt and Ryan 1988). For giant sequoia, increased growth was most notably evident following moderate-severity (<50% of subcanopy trees killed) and high-severity (>50% of subcanopy trees killed but <50% of canopy trees killed; Mutch and Swetnam 1995) prescribed burns.

The variability in growth following fire is likely due to the heterogeneity in fire behavior, fire severity, and initial tree-related fire effects associated with both wild- and prescribed fire. Tree-specific, fire-related tissue damage including severe cambial, root, and crown damage may negatively affect water and nutrient uptake as well as photosynthetic potential, resulting in growth decreases. In contrast, residual trees with less severe fire damage may benefit from increased plant-available nitrogen (Keyser et al. 2008), as well as reduced competition for water (Skov et al. 2004) and nutrients (Reigel et al. 1992), and may even experience an increase in postfire tree growth and resistance to insect or disease attack.

Differences in factors such as fire behavior, fire intensity and severity, degree of fire-related damage, season of burn (dormant versus growing season), and weather conditions that occur during prescribed versus wildfire, as well as differences in geographic region and inconsistent results, make it hard to extrapolate results pertaining to the growth of ponderosa pine following prescribed burning to that expected following a wildfire. Given that wildfires are increasing in size and severity, it would be useful that resource managers understand how forest growth patterns may change as a result (i.e., substantial fire-related mortality combined with reductions in tree growth can result in significant and long-term reductions in stand-level production). We evaluated the effects of a large, mixed-severity wildfire on postfire tree growth and assessed whether growth of surviving ponderosa pine trees differed among trees in unburned stands and those affected by low- and moderate-severity wildfire.

Methods

Study Area

The study area is located within the Jasper Fire perimeter in the Black Hills National Forest, South Dakota (latitudes between 43°42′ and 43°57′ and longitudes between 103°46′ and 104°1′). The Black Hills are an isolated, forested uplift that rises ~900 to 1,200 m above the surrounding Great Plains in southwestern South Dakota and northeastern Wyoming (Hoffman and Alexander 1987, Froiland 1990). The climate is continental with cold winters and mild, moist summers (Johnson 1949). Mean daily temperatures range from −3.3°C in winter to 13.2°C in summer, and yearly precipitation averages ~47 cm, with up to 75% occurring between April and October (Hoffman and Alexander 1987, Froiland 1990, Shepperd and Battaglia 2002).

On Aug. 24, 2000, the Jasper Fire was ignited near the town of Custer, SD, during a period of record low fuel moisture and extremely unstable atmospheric conditions that resulted in strong wind gusts and a maximum rate of spread of 16 ha/minute (Lentile et al. 2006). The fire was contained on Sept. 8, 2000, after burning ~34,000 ha of predominantly second-growth ponderosa pine forest (US Forest Service 2000). The postfire assessment revealed that the Jasper Fire was a mixed-severity fire that produced a combination of low-, moderate-, and high-severity fire effects across the landscape (Lentile et al. 2005).

Data Collection

Following the fire and in collaboration with Black Hills National Forest staff, we identified three 800-ha forest units in which no postfire silvicultural activities (e.g., salvage harvesting and planting) were to occur. In June 2001, we established 36 permanent study sites of 0.3 ha each in burned and unburned ponderosa pine stands within and immediately outside the Jasper Fire perimeter throughout the three 800-ha forest units. Sites were randomly established within unburned and low-, moderate-, and high-fire severity classes, which we assigned on the basis of estimates of crown and forest floor damage from aerial photographs. A total of 27 of the 36 total study sites were located in burned stands. Within the burned stands, nine sites were located in areas where overstory trees were estimated to have <25% crown scorch with no crown consumption, only partial litter and duff consumption, and little to no exposure of bare mineral soil (treatment = low severity); nine sites were located in stands containing overstory trees that had >25% but <100% crown scorch with only partial crown consumption and also had the majority of litter and duff consumed (treatment = moderate severity); and nine sites were located in stands where all trees had experienced ~100% crown consumption and contained extensive areas of bare mineral soil (treatment = high severity; Keyser et al. 2008). Nine adjacent, unburned stands that had most likely not experienced fire activity during the last 100 years (Peter Brown, personal communication) served as controls. Each of the three 800-ha forest units contained three replicates of each fire severity class. Average crown and forest floor damage along with initial levels of tree mortality associated with fire severity classes are presented in Table 1.

Each study site consisted of three 0.03-ha overstory plots. We tagged every tree ≥1.4 m tall and assessed direct fire effects and initial tree mortality within each overstory plot. On each tagged tree, we recorded diameter at 1.4 m above the soil surface (dbh), total height, and crown base height, measured at the point of branch-bole attachment of the lowest prefire live whorl both 1 and 5 years postfire. In burned sites, we identified prefire crown base height from the

Table 2. Annual changes in stand structure (live trees ≥5 cm dbh) as reported in Keyser et al. (2008) in unburned, low-severity, and moderate-severity sites. Stand density is reported as live trees ha^{-1} (TPH) and basal area (BA) is reported as $m^2\ ha^{-1}$. Values represent mean ± 1 SE.

	Prefire	2001	2002	2003	2004	2005
Unburned						
TPH	727 ± 109	727 ± 109	727 ± 109	725 ± 107	717 ± 108	714 ± 104
BA	24.8 ± 1.1	24.8 ± 1.1	25.2 ± 1.0	25.5 ± 1.0	25.6 ± 0.9	26.3 ± 1.0
Low						
TPH	667 ± 137	659 ± 132	553 ± 62	493 ± 49	479 ± 45	474 ± 43
BA	23.2 ± 2.5	23.2 ± 2.5	22.5 ± 2.3	20.9 ± 2.1	20.8 ± 2.1	21.3 ± 2.1
Moderate						
TPH	521 ± 59	414 ± 60	335 ± 52	230 ± 44	200 ± 42	190 ± 41
BA	24.1 ± 1.5	20.0 ± 2.2	17.4 ± 2.1	12.6 ± 2.1	11.1 ± 2.0	10.8 ± 2.0

position of scorched needles in cases where no foliage consumption occurred and fine-branch structure in the case where consumption of needles occurred. We revisited study sites and assessed tree mortality annually through year 5. In late October 2005, we randomly chose and cored live trees ≥25 cm dbh from unburned ($n_t = 39$) low-severity ($n_t = 34$), and moderate-severity ($n_t = 23$) sites (total = 96 trees). All trees in high-severity sites were immediately killed by the fire; therefore, no growth samples were obtained from them. A diameter limit of 25 cm was chosen because the majority of trees <25 cm dbh had died as a result of fire on moderate-severity sites (Keyser et al. 2008). On each tree, we took two increment cores at breast height 90° from each other. Trees were cored deep enough to obtain data on postfire radial growth as well as radial growth data from the 10 years prior to the Jasper Fire. Cores were stored in paper straws until processed in the laboratory.

Prior to measurement, all cores were dried, mounted in wooden holders, and then sanded with progressively finer sandpaper (120, 200, 320, and 400 grit) until the rings were clearly defined. Radial growth was measured to the nearest 0.001 mm using a linearly controlled stage and microscope attached to a digital encoder (Velmex, Inc.). Using the 5-year postfire dbh, average ring widths were used to calculate basal area increment (BAI; cm^2) for each tree. BAI was calculated annually for the 10 years prior to the Jasper Fire and the 5 years postfire.

Statistical Analysis

Using a randomized complete block design, we used an analysis of variance (ANOVA) with repeated measures to determine differences in BAI during the 10 prefire years. Using the same design and analysis, we determined the effects of fire severity (unburned, low, and moderate) and time, 1 (2001), 2 (2002), 3 (2003), 4 (2004), and 5 (2005) years on both postfire BAI and relative BAI for trees ≥25 cm dbh. Relative BAI is unitless and is defined as BAI in any given year postfire divided by the 10-year prefire average BAI. By using relativized growth data, each tree serves as its own control (Salonius et al. 1982, Reinhardt and Ryan 1988) and represents a proportional change in BAI based on prefire growth patterns (Skov et al. 2005). Relative growth rates <1.0 signify a slow-down in growth relative to prefire rates, whereas relative growth rates >1.0 indicate an increase in growth. Relative growth rates equal to 1.0 signify no change in postfire growth relative to the prefire growth rate.

The covariance structure used for the repeated measures analysis was a first-order autoregressive model. Following a significant severity by year interaction in the repeated measures analysis ($\alpha = 0.05$), separate ANOVAs were performed to test the effect of fire severity on growth during individual years. Individual year ANOVAs were significant at the Bonferroni-adjusted $\alpha = 0.01$ (0.05/5) to maintain an experiment-wise error rate of 0.05. Differences in BAI and relative BAI among fire severity classes within individual years were compared using Tukey's multiple comparisons procedure ($\alpha = 0.05$). Growth data were square root transformed to achieve normality and homoscedasticity (Steel et al. 1997). The means and standard errors we report are from the untransformed data. All analyses were performed using the Proc Mixed procedure in SAS v. 9.1 (SAS Institute, 2005).

Results

Prior to the Jasper Fire, study sites were well stocked, second-growth ponderosa pine stands. Because of similarities in site productivity and land-use management histories, stand structure among fire severity classes was similar prior to the fire. Prefire stand density and basal area (BA) of live trees ≥5 cm dbh averaged 683 trees/ha and 24.0 m^2/ha, respectively. Stands contained moderately sized trees with the quadratic mean diameter averaging ~23 cm dbh. Fire effects in study sites were generally within the parameters used to categorize low- and moderate-severity fire, but some low-severity sites had higher crown damage than in their classification based on aerial photography estimates, resulting in average crown damage values of 30% and 84% in low- and moderate-severity sites, respectively. Low levels of crown damaged resulted in a negligible reduction of crown ratio on low-severity sites (57% prefire to 53% postfire), whereas the more extensive crown damage observed in moderate-severity sites reduced crown ratio on sample trees from 59% prefire to only 40% postfire. During the 5 years postfire, stand structure was significantly altered. After 5 years, fire-related tree mortality reduced stand density to 474 trees/ha in low severity and 190 trees/ha in moderate severity sites (Table 2; Keyser et al. 2008). Although total stand density was reduced, mortality of mostly small-diameter trees in low-severity sites maintained BA levels similar to those in unburned stands, whereas mortality throughout the size classes in moderate-severity sites lowered BA 55% below prefire levels (Keyser et al. 2008).

Although annual variation in BAI was significant ($P < 0.05$), no differences in BAI among the fire severity classes existed during any of the 10 years prior to the Jasper Fire (Figure 1). During the 10 years prior to the fire, sample trees averaged 9.6 cm^2 of growth per year. One year postfire, we observed no differences in either BAI or relative BAI among fire severity classes ($P > 0.01$; Figure 2a, 2b). Over 70% of sample trees in unburned and low-severity sites were growing substantially slower than prior to the fire (relative BAI <1.0), compared with only 52% of sample trees in moderate-severity sites (Table 3). Two years postfire, relative BAI was significantly greater in moderate-severity sites than in unburned and low- severity

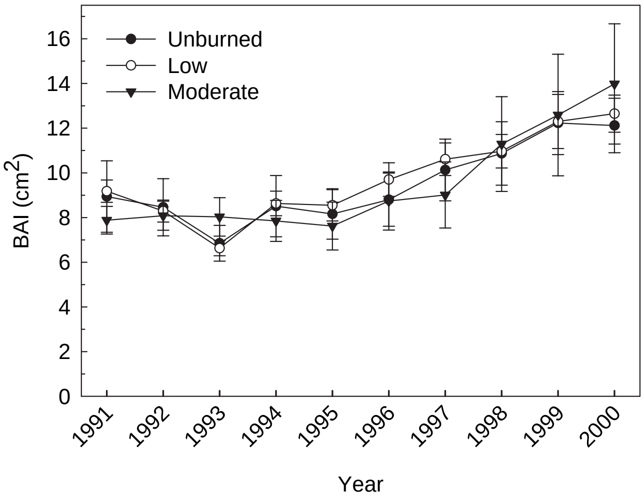

Figure 1. Basal area increment (BAI) (cm²) during each of the 10 years prior to the Jasper Fire (1991–2000) in unburned, low severity, and moderate severity sites. Error bars represent ±1 SE.

sites (Figure 2b), despite the fact that the Black Hills was experiencing extreme drought conditions (Palmer drought severity index [PDSI] July value < -4.0; Figure 2c) and 61% of the sample trees in moderate-severity sites were growing slower than the average prefire BAI (Table 3). The increase in relative BAI in moderate-severity sites during this time period corresponded to a 58% increase in absolute BAI over that in unburned and low-severity sites ($P < 0.01$; Figure 2a). Although significant, the growth increase in moderate severity sites was short-lived. By the third, forth, and fifth years following the Jasper Fire, we detected no significant differences in relative or absolute BAI among unburned, low-severity, and moderate-severity sites ($P > 0.01$). The average BAI among fire severity classes 3, 4, and 5 years postfire was 7.8, 6.8, and 8.2 cm^2, respectively; with the vast majority of sample trees possessing growth rates less than the prefire 10-year average growth rate (Table 3). Because of the lack of any significant and sustained changes in BAI during the 5 years postfire, the 5-year average relative and absolute BAI did not differ among fire severity classes (Figure 2a, 2b).

Discussion

Although the average 5-year postfire relative BAI did not differ among trees affected by unburned, low-severity fire, and moderate-severity fire, postfire BAI (both relative and absolute) did vary between individual years (Figure 2a, 2b). Compared with unburned stands, the only increase in BAI observed over the 5-year period occurred 2 years postfire and was limited to trees found on moderate-severity sites. Heavy thinning, similar to what occurred in moderate-severity sites, of second-growth ponderosa pine stands has been shown to decrease competition for water and nutrients (Feeney et al. 1998, Skov et al. 2004) and increase tree growth (Smith et al. 1997, Feeney et al. 1998, Sala et al. 2005, Skov et al. 2005). Two years postfire, immediate and delayed tree mortality reduced stand density in moderate-severity sites by ~55% relative to unburned controls (Keyser et al. 2008). This period of increased growth coincides with an episode of extreme drought (July PDSI values < -4.0) in the Black Hills, which is likely why unburned and low-severity stands showed strong relative decreases in BAI (Figure 2a, 2b). Skov et al. (2004) reported that despite extreme drought conditions following restoration treatments in ponderosa pine forests of the

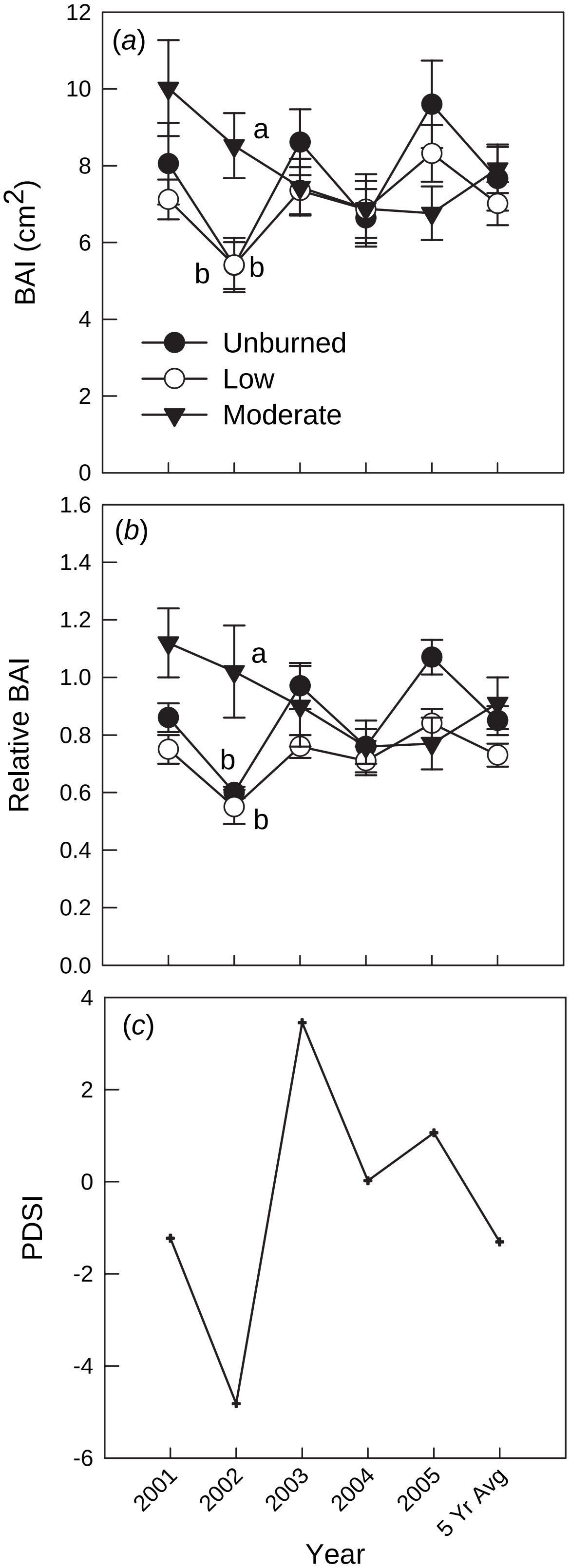

Figure 2. Mean basal area increment (BAI) (cm²) (*a*) and relative BAI (*b*) during each of the 5 years following the Jasper Fire and corresponding July Palmer drought severity index (PDSI) values (*c*). Individual year analyses were performed following a significant severity × year interaction in the repeated measures analysis ($P < 0.0001$) and were significant at Bonferroni-adjusted $\alpha = 0.01$ (0.05/5). Means followed by the same letter within a given year are not significantly different using Tukey's multiple comparisons procedure at $\alpha = 0.05$. Error bars represent ±1 SE.

Table 3. Number of sample trees within unburned, low-severity, and moderate-severity sites possessing a relative basal area increment (BAI) <1.0 and ≥1.0 1 (2001), 2 (2002), 3 (2003), 4 (2004), and 5 (2005) years postfire.

Fire	Relative BAI	Relative BAI
Severity	<1.0	≥1.0
Unburned		
(2001)	30	9
(2002)	39	0
(2003)	23	16
(2004)	32	7
(2005)	18	21
Low		
(2001)	25	9
(2002)	32	2
(2003)	26	8
(2004)	29	5
(2005)	28	6
Moderate		
(2001)	11	12
(2002)	14	9
(2003)	15	8
(2004)	17	6
(2005)	15	8

Southwest, post-treatment growth of trees <30 cm dbh was equivalent to pretreatment growth. The authors suggest that restoration treatments designed to reduce stand density may compensate for the negative effects drought has on tree growth. It is possible the removal of inefficient portions of the canopy (Assman 1970, Wyant et al. 1983, Ryan 1998) in trees affected by moderate fire severity, coupled with increased available nitrogen (Keyser et al. 2008) and decreased competition for resources due to fire-related tree mortality, compensate for lack of adequate moisture, resulting in a short-term increase in growth compared with trees in unburned and low-severity sites in this study.

Despite ongoing tree mortality and further reductions in density and BA, absolute and relative BAI in stands burned under low- and moderate-severity fire did not differ from what was found in unburned controls 3, 4, or 5 years postfire (Figure 2a, 2b). The persistent lack of growth response on low-severity sites in this time frame was expected, given that the relatively minor reduction in stand density was a consequence of small-tree rather than large-tree mortality (Keyser et al. 2008). The type of light, low thinning that occurred as a result of the fire in low-severity sites does not typically improve residual tree growth (Smith et al. 1997). The lack of a consistent and prolonged increase of BAI on moderate-severity sites during the third, fourth, and fifth years postfire, however, was unexpected. Heavy thinning of ponderosa pine has been shown to have a prolonged and positive effect on diameter growth increment (Schubert 1971, Cochran and Barrett 1995, 1998). However, similar to the results presented here, Sutherland et al. (1991) found no significant relationship between postfire growth rate of ponderosa pine and fire-caused thinning following prescribed fire in northern Arizona, perhaps because fire damage included substantial fine root mortality and cambial heating. Fine-root mass in ponderosa pine forests is concentrated in the upper 10 cm of the forest floor (Swezy and Agee 1991). The Jasper Fire consumed a significant proportion of the litter and duff layers on moderate-severity sites (Keyser et al. 2008), which, coupled with moderate levels of cambial and crown damage (Table 1), contributed to a significant amount of delayed, fire-related tree mortality (Keyser et al. 2006). The long-term stress created by the fire, along with prolonged drought, likely offset any positive effects of thinning that occurred via fire-related mortality during the 5 years postfire. It is possible the increase in residual tree growth we expected to occur as a result of substantial reductions in basal area in moderate-severity sites had not manifested itself after 5 years and with time, residual tree growth in these sites could increase relative to the "unthinned" unburned and low-severity sites (Latham and Tappeiner 2002).

Unlike past studies, we did not detect consistent reductions (Peterson et al. 1991), nor did we observe prolonged increases (Reinhardt and Ryan 1988) in postfire tree growth. Although there was an increase in BAI for a brief time on moderate-severity sites, we observed no difference in the 5-year average growth, suggesting that the Jasper Fire did not result in any short-term changes in tree growth patterns. Data extending beyond the immediate 5 years postfire, however, are required to infer potential long-term changes in tree growth and stand-level productivity as it relates to fire severity following wildfire, as the expected "thinning" effect of the fire was not be evident during the early postfire years.

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