Six-Year Changes in Mortality and Crown Condition of Old-Growth Ponderosa Pines in Ecological Restoration Treatments at the G. A. Pearson Natural Area

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Abstract—Ecological restoration treatments using thinning and prescribed burning have been proposed to reverse the decline of old-growth ponderosa pines in the Southwest. However, long-term data on the effectiveness of such treatments are lacking. In 1993–1994, two ecological restoration treatments and a control were established at the G. A. Pearson Natural Area (GPNA) near Flagstaff, AZ. The thinned treatment removed many postsettlement-aged trees to create tree density and stand structure similar to pre-Euro-American forests. The thinned + burned treatment included prescribed burning of the forest floor in combination with this thinning. The control was a dense stand of pre- and postsettlement trees with no thinning or burning. Crown dieback of presettlement trees decreased by about 3 percent in both thinned treatments over 6 years since initiation of treatments, whereas dieback increased by about 4 percent in the control. Crown dieback was not related to tree age. Change in height of presettlement trees between 1994 and 2000 did not differ among treatments. Of 146 presettlement trees monitored for survival between 1994 and 2000, four died between 1997 and 2000, and all were in thinned treatments. Two of the four trees that died toppled or the stem broke in a severe windstorm in 1997. The other two dead trees died between 1997 and 2000 following the severe regionwide drought of 1996. These two dead trees had large amounts of canopy dieback prior to treatment initiation, suggesting that thinning did not contribute to their mortality. Our results indicate that heavy thinning of postsettlement trees improved the crown condition of presettlement trees at the GPNA over 6 years since treatment, but also may have increased windthrow and wind breakage.

Introduction

Ponderosa pine (*Pinus ponderosa*) forests in northern Arizona have changed dramatically in stand structure over the past century due to human alteration of the natural fire regime, overgrazing, and logging (Arnold 1950; Cooper 1960; White 1985; Covington and Moore 1994; Fulé and others 1997). In most areas of northern Arizona, fires have been suppressed for at least 87 years (Madany and West 1983; Savage and Swetnam 1990). Pre-Euro-American settlement forests were characterized by clusters of old pines separated by lush grassy areas. These open canopy conditions were maintained by low-intensity surface fires that occurred every 2–12 years (Weaver 1951; Cooper 1960; Dieterich 1980; Dieterich and Swetnam 1984; Swetnam and Baisan 1996). The present forests are currently dominated by dense thickets of sapling- and pole-sized trees and have heavy accumulations of litter and woody fuels, and poor understory grass, forb, and shrub growth (Cooper 1960; Harrington and Sackett 1992; Covington and Moore 1994; Dahms and Geils 1997).

There is currently much interest in improving the condition of Southwestern ponderosa pine forests by thinning to reduce competition among trees and by prescribed burning to reduce fuel loads. However, few studies have examined the effects of such thinning and burning treatments on presettlement ponderosa pines. Studies of historical tree growth rates of presettlement ponderosa pines in northern Arizona have suggested that the remaining presettlement trees are declining because of competition from postsettlement trees (Sutherland 1983; Biondi 1996). Two studies have reported negative effects of prescribed burning on the growth, water relations, and survival of presettlement trees (Sutherland and others 1991; Swezy and Agee 1991). In both studies, the burns were conducted in stands containing heavy fuel loads due to fire suppression, causing heat damage to the presettlement trees.

We initiated a study in 1993 designed to evaluate techniques for improving the condition of ponderosa pine forests in the Gus Pearson Natural Area (GPNA) in northern Arizona (Covington and others 1997). The GPNA is a unique, relict stand of presettlement ponderosa pines that has been protected from harvesting and heavy grazing. The treatments included thinning of postsettlement trees to create a more open stand condition, and a combination of thinning and prescribed burning. The influence of these treatments on the growth, water, carbon, and nutrient relations of presettlement trees have been reported by Stone and others (1999) for the first year following treatment, and by Feeney

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and others (1998) for the second and third years following treatment. These authors concluded that thinning increased uptake of water and nitrogen of presettlement trees, and these changes contributed to greater rates of photosynthesis and stem radial growth. Differences in growth and physiological characteristics between the thinned treatment and the thinned + burned treatment were small, except for tree resin flow, which was higher in the thinned + burned treatment than in the thinned treatment (Feeney and others 1998).

In this paper, we compare mortality and crown condition of presettlement trees 6 years after initiation of the restoration treatments at the GPNA. Measurements of these characteristics made in 1994 are compared to measurements made in 2000 to show temporal changes in each treatment area. Our general hypothesis is that the positive effects of the thinning and thinning + burning treatments on presettlement tree condition that were documented for the first 3 years after the initiation of treatments (Feeney and others 1998; Stone and others 1999) would continue through year 6. Specifically, we expected lower tree mortality and a greater improvement in crown condition in thinned and thinned + burned treatments compared with the unthinned and unburned control.

Methods

Study site

The study was conducted at the GPNA, within the Coconino National Forest approximately 10 km northwest of Flagstaff, Arizona. The study site occupies 3 ha of the 30-ha GPNA at an elevation of 2,195–2,255 m. Aspect is generally southwest, with gentle topography (slopes 0–5 percent). Soils, derived from basalt and volcanic cinders, are classified as a Brolliar stony clay loam, fine, smectitic, Typic Argiboroll. Mean annual precipitation in Flagstaff is 56.7 cm, with approximately one-half of the precipitation falling as snow from November to May and one-half falling as rain primarily during the late-summer monsoon season (July and August). Mean annual air temperature in Flagstaff is 7.5 °C. The climate is subhumid, with early summer droughts common. The average frost-free growing season is 94 days (Schubert 1974).

The vegetation community at the GPNA is a previously unharvested ponderosa pine stand that is uneven-aged with even-aged groups of pole-sized trees and uneven-aged groups of presettlement trees (Schubert 1974; White 1985). Pole-sized trees (10–37.4 cm d.b.h.) are the predominant size class. The predominant Euro-American influences at the GPNA have been livestock grazing, which occurred between 1876 and 1910, and fire suppression. The last natural fire was in 1876; prior to that time, the fire return interval averaged approximately 2 years (Dieterich 1980).

Experimental Design and Treatments

The GPNA study site was subdivided into three largely contiguous areas, each occupying approximately 1 ha (Covington and others 1997). Each area was subjected to one of three treatments: control, thinned, and thinned + burned. Each treatment area was further subdivided into five approximately 0.20-ha plots that served as experimental units. We grouped these plots into five blocks (one plot per treatment) that were used to implement all measurements.

Because our experimental design does not include true spatial replication across the landscape, we used precautions to strengthen our inferences regarding treatment effects. Specifically, an earlier analysis (Stone 1997) showed similar pretreatment levels of soil total nitrogen (P = 0.19), phosphorus (P = 0.25), organic matter (P = 0.19), predawn leaf water potential (P = 0.82 for May to June, P = 0.25 for July to August), basal area growth rate (P = 0.96), stem diameter (P = 0.32), and tree-to-tree competition index (P = 0.66) of presettlement trees among the areas to be treated. Thus, resource availability, tree growth, and tree physiological condition were similar among areas prior to treatment. Second, our interpretation of statistical results applies only to the specific locations in the GPNA where the treatments were applied.

The thinning was conducted to simulate the presettlement (circa 1876) stand structure, which was determined using dendrochronological techniques (Mast and others 1999). The average pretreatment basal area was 34.5 m^2 ha^{-1} (average of 3,100 trees ha^{-1}), which was retained in the control area. In November of 1993, two-thirds of the site was thinned to an average basal area of 13.0 m^2 ha^{-1} (average of 151 trees ha^{-1}), with all presettlement trees and all trees greater than 40 cm d.b.h. retained. Following the thinning treatment, the unthinned control area had an average d.b.h. of 16.6 cm in 1993, while both thinned areas had an average d.b.h. of 40.9 cm (Covington and others 1997). Thinning did not substantially change light availability to the presettlement trees used in the study because the crowns of the thinned postsettlement trees were lower than the crowns of the presettlement trees.

Half of the thinned area was also subjected to a low-intensity prescribed burn in 1994 (October) and 1998 (October). Prior to the first burn in 1994, the O_i (slightly decomposed organic matter), O_e (moderately decomposed organic matter), and O_a (highly decomposed organic matter) layers of the forest floor and woody debris were removed by hand raking to simulate presettlement forest floor conditions, which would have had little forest floor litter and debris because of frequent fire. The O_i layer (2–4 years of litterfall) was replaced prior to burning with dried native grass foliage from a nearby prairie (672 kg ha^{-1} dry biomass) to simulate presettlement forest floor conditions in which grasses were dominant. Fire characteristics for the 1994 burn were previously reported by Covington and others (1997); flame length averaged about 15 cm with maximum lengths of 60 cm. For the second burn in 1998, flame length averaged 11 cm with maximum lengths of 180–240 cm that occurred in fallen limbs and needles of windthrown trees.

Crown Dieback and Mortality

We measured crown dieback of 71 presettlement trees in July 1994 and March 2000. Of these trees, 27 were in control plots, 22 were in thinned plots, and 22 were in thinned + burned plots. These trees were selected for measurement in 1994 because all had good crown condition with little dieback

Table 1—Percentage classes for crown dieback.

Percentage class	Class range
0	0
5	1–5
10	6–15
20	16–25
30	26–35
40	36–45
50	46–55
60	56–65
70	66–75
80	76–85
90	86–95
100	96–100

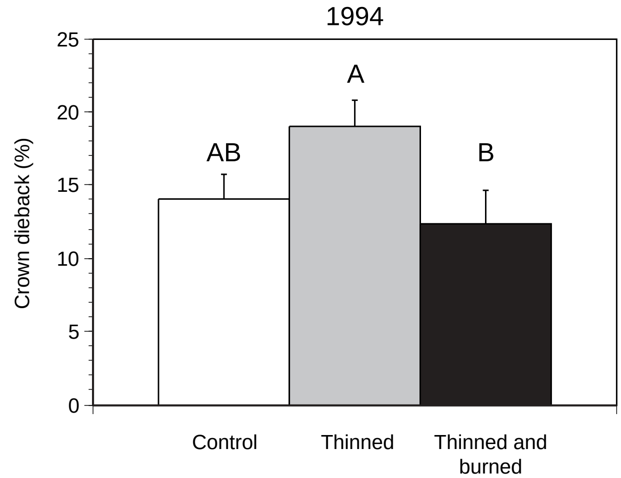

Figure 1—1994 average crown dieback of presettlement ponderosa pines at the GPNA in three treatments: control, thinned, and thinned + burned. The bars show one standard error of the mean. Means with the same letter do not differ significantly in Fisher's Protected LSD tests (P ≤ 0.01).

prior to initiation of the treatments and were located at least 10 m from treatment boundaries, which reduced potential influences from other treatments. Crown dieback of each tree was visually assessed by at least three trained observers using a system with 12 percentage classes (table 1) developed for forest health monitoring (Millers and others 1991; Kolb and McCormick 1993). The same leader (T. E. Kolb) trained assessment crews in both 1994 and 2000, and he checked the crown condition assessment of all trees in both years for accuracy. Crown dieback was defined as the percentage of total crown volume that contained dead branches with bark or with branch tips less than 2.5 cm diameter (Millers and others 1991). We also measured the height of all trees with a clinometer at the time of crown dieback assessment in both years. Tree mortality status (live or dead) was noted in 1994, 1996, and 2000 on a total of 146 presettlement trees that consisted of the same 71 trees measured for crown dieback and an additional 75 trees.

Data Analysis

We compared differences in crown dieback and height growth among the control, thinned, and thinned + burned areas of the GPNA using a fixed-effects analysis of variance (ANOVA) on plot means. Mean comparisons among treatments were performed with Fisher's protected LSD, and a threshold P value of 0.10 was used in all tests because of the inherent large variability of a population of old trees. All statistical analyses were conducted using the SAS JMP statistical package (SAS Institute Inc., Cary, NC, U.S.A.). Only trees that were living in both 1994 and 2000 were included in the analysis of crown dieback.

Results

Crown Dieback

Crown dieback of presettlement trees differed significantly (P = 0.073) among treatment areas in 1994 when treatments were initiated. Dieback was significantly greater in the thinned treatment (mean = 19.0 percent) compared with the thinned + burned treatment (mean = 12.4 percent) (fig. 1). Dieback did not differ significantly between the control (mean = 14.0 percent) and either thinned treatment in 1994 (fig. 1).

Crown dieback also differed significantly (P = 0.037) among treatments in 2000, 6 years after the initiation of treatments. In contrast to the results in 1994, dieback was greatest in the control (mean = 18.0 percent), intermediate in the thinned treatment (mean = 14.3 percent), and lowest in the thinned + burned treatment (mean = 10.4 percent) (fig. 2). The difference in dieback between 1994 and 2000 was

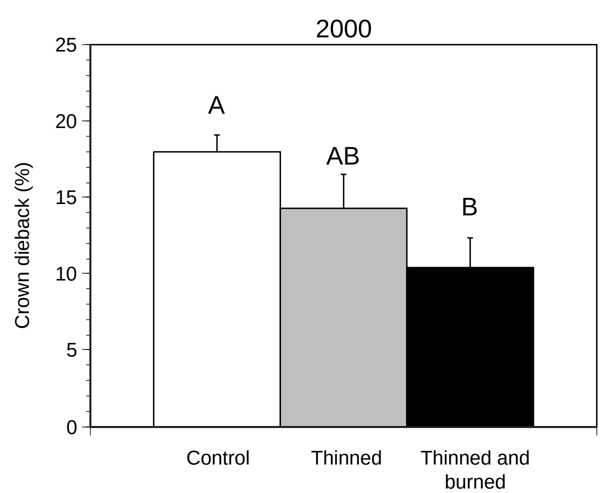

Figure 2—2000 average crown dieback of presettlement ponderosa pines at the GPNA in three treatments: control, thinned, and thinned + burned. The bars show one standard error of the mean. Means with the same letter do not differ significantly in Fisher's Protected LSD tests (P ≤ 0.01).

caused by a difference among treatments in temporal change in crown condition. In the control, crown dieback increased between 1994 and 2000 by an average of 3.5 percent, whereas crown dieback decreased during this period in the thinned (–3.9 percent) and thinned + burned (–2.5 percent) treatments (fig. 3). This difference in temporal change in dieback between the control and thinned treatments was significant (P = 0.037).

There was no relationship between tree age and 2000 crown dieback (R = 0.153, P = 0.284) or 1994–2000 change in dieback (R = 0.103, P = 0.473) for data pooled over all treatments (figs. 4 and 5). Correlations between these variables were also not significant for data analyzed by treatment group, except for 2000 crown dieback in the thinned + burned treatment which was positively associated with tree age (R = 0.466, P = 0.059) (fig. 4).

Change in Tree Height

Tree height growth, expressed as a percentage change between 1994 and 2000, was highest in the thinned + burned treatment (15.8 percent), intermediate in the thinned treatment (14.7 percent), and lowest in the control (12.8 percent), but these differences were not significant (P = 0.411) (fig. 6).

Tree Mortality

There was no mortality of the 146 trees between 1994 and 1996. However, four trees died between 1997 and 2000. Of these dead trees, all were located in thinned or thinned + burned plots. In thinned plots, 1 of 30 trees died. In thinned + burned plots, 3 of 49 trees died. In control plots, 0 of 67 trees

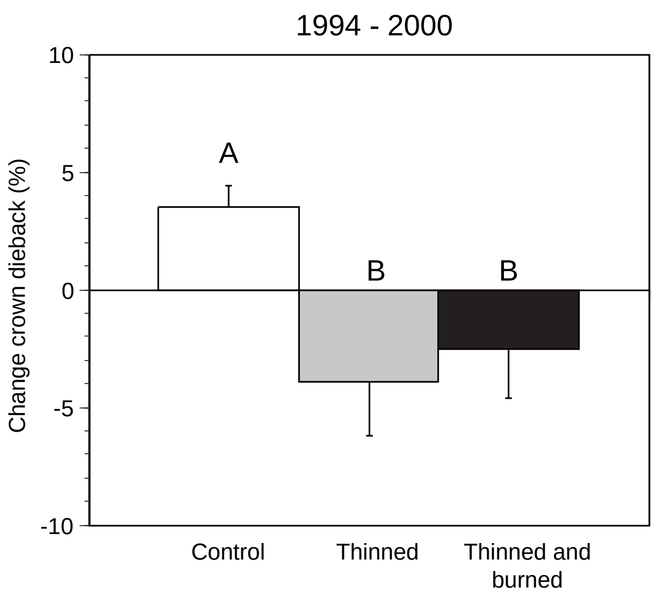

Figure 3—Average change in crown dieback between 1994 and 2000 of presettlement ponderosa pines at the GPNA in three treatments: control, thinned, and thinned + burned. The bars show one standard error of the mean. Means with the same letter do not differ significantly in Fisher's Protected LSD tests (P ≤ 0.01).

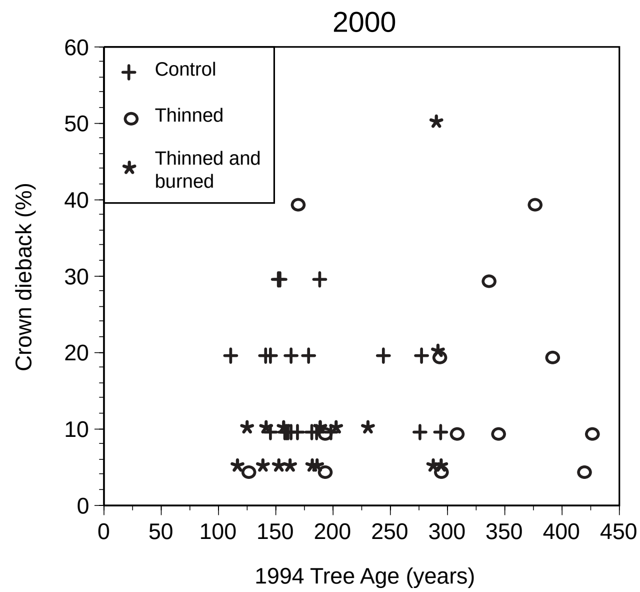

Figure 4—2000 crown dieback of presettlement ponderosa pines at the GPNA versus 1994 tree age in three treatments: control, thinned, and thinned + burned. Correlation coefficient for data pooled over all treatments is R = 0.153 (P = 0.284), control data R = 0.183 (P = 0.427), thinned data R = 0.062 (P = 0.841), and thinned + burned data R = 0.466 (P = 0.059).

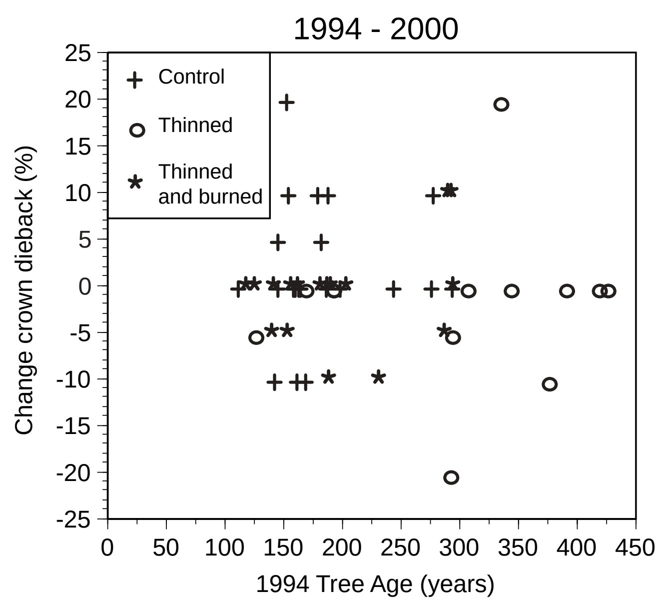

Figure 5—Change in crown dieback between 1994 and 2000 of presettlement ponderosa pines at the GPNA versus 1994 tree age in three treatments: control, thinned, and thinned + burned. Correlation coefficient for data pooled over all treatments is R = 0.103 (P = 0.473), control data R = 0.085 (P = 0.715), thinned data R = 0.091 (P = 0.769), and thinned + burned data R = 0.321 (P = 0.209).

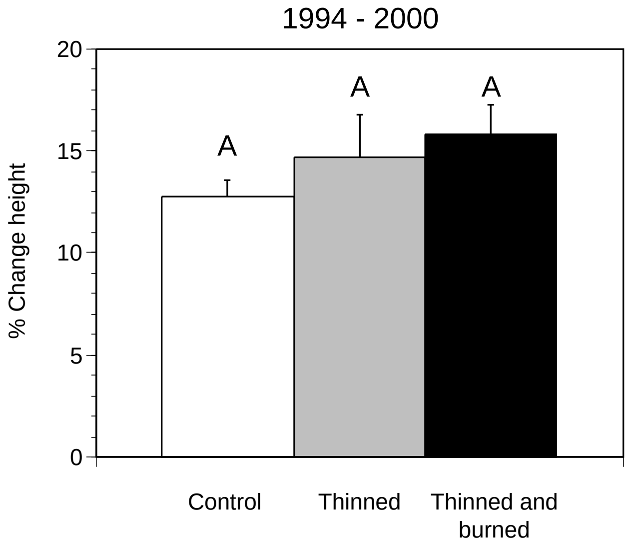

Figure 6—Average percent change in tree height between 1994 and 2000 of presettlement ponderosa pines at the GPNA in three treatments: control, thinned, and thinned + burned. The bars show one standard error of the mean. Means with the same letter do not differ significantly in Fisher's Protected LSD tests ($P \leq 0.01$).

died. Two of the trees that died in the thinned + burned treatment broke or toppled in a severe windstorm following a heavy, wet snow in 1997.

Discussion

Our results on changes in crown dieback of presettlement trees over 6 years since initiation of the restoration treatments are consistent with differences in tree radial growth rate and rates of resource uptake reported by Feeney and others (1998) and Stone and others (1999) for the first 3 years after treatment initiation. In these studies, thinning increased uptake of nitrogen and water, stimulated radial growth, and ameliorated effects of the 1996 drought on tree growth. Further, most growth and physiological characteristics were similar in the thinned and thinned + burned treatments in the first 3 years after the initiation of treatments (Feeney and others 1998). The increase in crown dieback that occurred between 1994 and 2000 in the control, coupled with the decrease in dieback in the thinned treatments, suggest that improved resource uptake in the thinned treatments has influenced carbon allocation to canopy growth and maintenance processes. We note, however, that these changes have been small in magnitude, which is not surprising considering the slow growth rate of old ponderosa pines. Moreover, the increase in canopy dieback in the control between 1994 and 2000 indicates a continued slow decline in the condition of presettlement trees when competition from postsettlement trees is severe.

Interestingly, both canopy dieback in 2000 and changes in canopy dieback between 1994 and 2000 were not related to tree age for ages between 100 and 450 years. This result suggests that mortality of presettlement-aged ponderosa pines at the GPNA is more strongly influenced by tree genotype or local variation in environment and disturbance rather than tree age alone. We lack a clear understanding of these factors, but we speculate that lightning strikes, other disturbances, genetic variation in response to stress, and perhaps local variation in rooting depth may be important factors that contribute to canopy dieback at the GPNA.

Our results on tree mortality should be viewed with caution because of the small number of trees assessed (146 over all treatments) and the small number of trees that died (four over all treatments). With this caveat, we believe that the occurrence of tree death by windthrow or wind breakage exclusively in the thinned treatments is not a coincidence. Our results suggest that windthrow and wind breakage are more common for presettlement trees growing in open stands that result from heavy thinning of postsettlement trees. Given that severe winter weather with high winds is common in ponderosa pines forests in northern Arizona, tree death because of wind breakage and windthrow may have been a common occurrence in open, savannalike forests dominated by old-growth trees prior to Euro-American settlement.

Wind damage was not an obvious causal factor in the death of two of the four presettlement trees that died in the thinned treatments between 1997 and 2000. One explanation is that thinning contributed to their death. However, we note that both of these trees had large amounts of dieback when the treatments were initiated. The tree that died in the thinned + burned plot was classified as "alive but declining" with a different crown classification system (Fulé and others 1997) in 1992, prior to initiation of the treatments. The tree that died in the thinned plot had 40 percent dieback in the 1994 assessment of crown condition. Instead, we speculate that these trees were already declining because of unknown factors at the time of treatment initiation, and were subsequently severely stressed by the regional 1996 drought in the Southwest. Further, bark beetle pitch tubes were evident in 2000 on both trees, suggesting a secondary role of herbivory in mortality. This interpretation is consistent with Manion's (1991) model of tree decline where tree death is often the result of predisposing and contributing factors that occurred many years before mortality and acted to reduce tree carbohydrate levels. Following this sequence of events, tree defense against biotic agents and capacity to recover from severe abiotic stress are diminished, and thus mortality is imminent.

Conclusions

In summary, our results indicate that heavy thinning of postsettlement trees improved the crown condition of presettlement trees at the GPNA over 6 years since treatment, but also may have increased windthrow and wind breakage. The effect of heavy thinning of postsettlement trees on wind damage to presettlement trees should be addressed in other ecological restoration experiments in ponderosa pine forests.

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