Forest Ecology and Management 520 (2022) 120351

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Radial thinning ineffective at increasing large sugar pine survival

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ARTICLE INFO

Keywords:
Pinus lambertiana
Crop tree release
Free thinning
Daylighting
Northwest Forest Plan
Adaptive management

ABSTRACT

White pines (*Pinus*, subgenus *Strobus*) in North America are highly vulnerable to the native mountain pine beetle (*Dendroctonus ponderosae*), invasive white pine blister rust (*Cronartium ribicola*), and consequences of altered disturbance regimes, with sugar pine (*Pinus lambertiana*) being among the most in peril. Radial thinning treatments reflect an effort to balance the needs of late seral, high forest cover for some wildlife species with the desire to also promote habitat for species requiring higher light and lower competition, as well as to create heterogenous forest structure that can be more resilient to wildfire and drought. We examined 16-year effects of three radial thinning treatments that cleared approximately 0.017 ha to 0.05 ha around focal large sugar pines on reducing tree mortality and increasing sugar pine recruitment relative to untreated, control trees. Thinning treatments by order of increasing intensity included a compressed radius treatment which removed all trees and shrubs to 3 m from the crown edge, an extended radius with large tree retention treatment which removed trees <64 cm DBH and shrubs to 7.6 m from the crown edge, and an extended radius treatment which removed all trees and shrubs to 7.6 m outside of the crown edge. None of the three radial thinning treatments tested reduced mortality relative to the control, and mountain pine beetle caused the most mortality across the four treatments. However, mortality trended lower in the extended radius with retention treatment (19% compared to 30–37%) and was the only treatment where no mortality from wind or insects other than mountain pine beetle occurred. For trees that survived through the 16-year monitoring period, only trees in the extended radius treatment experienced increased growth above pre-treatment values and higher presence of sugar pine seedlings. Our results show no clear benefit was derived from the radial thinning treatments tested. While radial thinning may be a useful tool when used in conjunction with other silvicultural prescriptions that create heterogeneous stands and landscapes with a variety of forest structures, it seems unlikely that employing only radial thinning will meet restoration efforts that aim to decrease large tree mortality. This study highlights the value of long-term monitoring in the continual effort to develop new treatments that are effective at increasing forest resilience.

1. Introduction

Five-needle pines (*Pinus*, subgenus *Strobus*) in North America are in peril due to the invasive blister rust pathogen (*Cronartium ribicola* J. C. Fisch.), the native mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins), climate change, and altered fire regimes (Tomback and Achuff, 2010, Dudney et al., 2020). In many forests, five-needle pines function as foundational species providing important ecological, economical, and social services (Schwandt et al., 2010, Long et al., 2021), making restoration and management strategies to conserve white pine species in the face of these multiple threats urgently needed (Keane and Schoettle, 2011, Schoettle et al., 2019). Numerous restoration treatments are used in an attempt to conserve genetic diversity by increasing both mature white pines and regeneration through increased resistance to insects and disease (Zeglen et al., 2010, Keane and Schoettle, 2011). Past efforts largely focused on control of white pine blister rust (Geils et al., 2010), but contemporary treatments have shifted to promoting genetic resistance through maintaining cone-bearing, resistant trees on the landscape and improving conditions for natural and planted regeneration (Zeglen et al., 2010, Keane and Schoettle, 2011).

Restoration treatment options are often constrained by numerous, sometimes conflicting management objectives (Collins et al., 2010). In the Pacific Northwest region of the U.S., the 1994 Northwest Forest Plan

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https://doi.org/10.1016/j.foreco.2022.120351
Received 2 March 2022; Received in revised form 3 June 2022; Accepted 5 June 2022
Available online 14 June 2022
0378-1127/Published by Elsevier B.V.

(NWFP) requires federal land management agencies to protect and enhance old-growth forests to promote biodiversity, with a large focus on species that require late-seral, multi-layered forests, such as the northern spotted owl (*Strix occidentalis caurina* Merriam), the marbled murrelet (*Brachyrampus marmoratus* Gmelin), and anadromous fish species (Thomas et al., 2006). In the 25+ years since the NWFP was enacted, thinking has shifted from a focus on single species conservation to broader ecosystem services and landscape management under climate change and its associated changes to disturbance regimes (Spies et al., 2018, Spies et al., 2019). These shifts create challenges for managing forests as required under the NWFP, but that still foster increased resilience of white pine species in the face of insects, disease, fire, and climate change.

The NWFP provided allowances for testing and development of new silvicultural methods to promote adaptive management of forests through the creation of Adaptive Management Areas (Stankey et al., 2003, Spies et al., 2019). Radial thinning is a treatment developed with the goal to improve resilience of individual trees within the constraints of the NWFP. Radial thinning, also called free thinning, crop tree release, and daylighting, removes competing vegetation around focal trees of interest with limited effect on overall stand density (Zeglen et al., 2010). The idea behind radial thinning treatments is to improve long-term survival and growth of culturally and ecologically important trees (Long et al., 2021), while maintaining high forest cover to meet regulatory and social constraints that limit stand-level thinning (Hood et al., 2018).

There is limited research on the efficacy of radial thinning. Studies have examined different radii of treated area around focal trees, some of which are fixed distances and some of which are proportional to the size of the focal tree. Clearing to a radius of 9.1 m around old, large ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and Jeffrey pines (*Pinus jeffreyi* Balf.) did not increase growth rates, but did stabilize growth over a 15-year treatment period (Hood et al., 2018). Using dendrometers to examine daily growth patterns in large sugar pine (*Pinus lambertiana* Douglas) and ponderosa pine, Hirsch (2021) reported longer growth periods only for radial thinning treatments based on 1.25 times the focal tree stem diameter (where the radius was 1.25 times the product of 0.305 m per 2.54 cm of diameter) compared to untreated trees and trees treated with a fixed radial thinning diameter of 9.1 m. Thinning 5.5 m around whitebark pine (*Pinus albicaulis* Engelm.) reduced MPB attacks, but tree mortality relative to untreated trees was only reduced in radial thinning treatments that also included pruning lower limbs (Sturdevant et al., 2015).

The current study to examine the effects of radial thinning on sugar pine was implemented in 2000 in southwest Oregon, U.S., located within a NWFP Adaptive Management Area. As a five-needle pine species, sugar pine is susceptible to MPB and white pine blister rust. Sugar pine's range extends from Oregon south to Baja California. It is the largest and tallest pine species and is highly valued culturally, ecologically, and economically (Kinloch and Scheuner, 1990, van Mantgem et al., 2004). As elsewhere in southwest Oregon, mortality of sugar pine in the study area had increased in recent decades, with MPB as the primary mortality agent of mature sugar pines (Goheen and Goheen, 2014). Drought, top and branch killing by white pine blister rust, and high tree competition were considered major predisposing factors. Based on historical estimates of fire frequency, increases in tree density can be attributed to a sharp reduction in fires at the time of European colonization that reduced Indigenous burning (Carloni, 2006, Long et al., 2021) and continued with organized suppression efforts (Hagmann et al., 2021). Concerns about the long-term outlook of sugar pine and appropriate management options precipitated the study. Study objectives were: (1) determine if radial thinning improved health of old sugar pine, with health quantified as increased survival and growth rates and reduced infection by white pine blister rust, and (2) determine if radial thinning increased sugar pine regeneration. We examined the effects of three levels of radial thinning and an untreated, control on tree mortality and growth rates, as well as sugar pine regeneration patterns, for 16 years after treatment implementation.

2. Material and methods

2.1. Site and treatment descriptions

The study site is located in the Little River Adaptive Management Area on the Roseburg District, Bureau of Land Management and Umpqua National Forest lands in southwest Oregon, U.S. (10T 507266E 4788284N). The area is within the Western Cascades physiographic province, characterized by dissected topography with Alfisols being the dominant soil order (Peterman, 2012). Climate is Mediterranean with cool, wet winters and hot, dry summers; average precipitation is 90–200 cm, most of which occurs between November and March as rain (Van Norman, 1998, Carloni, 2006). Treatment stands consisted of mixed conifer/hardwood, dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), incense cedar (*Calocedrus decurrens* (Torr.) Florin, western red cedar (*Thuja plicata* Donn ex D. Don), and sugar pine, with very few ponderosa pine. The hardwoods Pacific dogwood (*Cornus nuttallii* Audubon ex Torr. & A. Gray), bigleaf maple (*Acer macrophyllum* Pursh), Pacific madrone (*Arbutus menziesii* Pursh), canyon live oak (*Quercus chrysolepis* Liebm.), and golden chinquapin (*Chrysolepis chrysophylla* (Douglas ex Hook.) Hjelmqvist) also occur in the stands. The area surrounding the treatment stands is mixed ownership, with much of the non-federal forested land managed as single-age Douglas-fir plantations interspersed with federal lands, many of which are old clearcuts also dominated by Douglas-fir. Additional detail on the history and forest ecology of the Little River Adaptive Management Area is provided in Van Norman (1998) and Carloni (2006).

A total of 592 living sugar pines > 38 cm DBH (diameter at breast height, 1.37 m above ground) were identified, numbered, and mapped in 1997, comprising a complete ground survey of 10 selected stands. Stands were 4 to 27 ha (mean = 10 ha) and were located across an area roughly 10 by 5 km in size with the Little River roughly bisecting the north and south halves, ranging from 435 to 661 m elevation. The generated maps were then used to select and tag sugar pines, assign treatments, and mark surrounding trees for harvest in the radial clearing treatments. Study layout and tree marking in the stands were completed in 1997. This resulted in a total 234 individual focal trees, representing about 40% of the existing large sugar pine in the selected stands. Sugar pine with signs of MPB attack were avoided. The number of selected sugar pine varied by stand from 6 to 38 trees.

In each stand, one of four treatments was randomly assigned to the first tree and then treatments were assigned to following trees in sequence (Fig. 1). Treatments included: (1) control: no clearing around the focal sugar pine, (2) compressed radius: complete removal of trees and shrubs from the base of the focal sugar pine to 3 m outside of the average crown radius, (3) extended radius with large tree retention: complete removal of trees <64 cm DBH and shrubs from the base of the focal sugar pine to 7.6 m outside of the average crown radius, and 4) extended radius: complete removal of trees and shrubs from the base of the focal sugar pine to 7.6 m outside of the average crown radius.

Treatments were implemented from 2000 to 2001. Merchantable trees were logged by ground or helicopter in 2000. Brush and small trees were cut by hand and material was piled away from each focal sugar pine. In 2001 the piles were burned. Pile burning did not cause crown scorch or bark charring on any of the sampled trees.

At the time of study initiation, MPB was active in the area, causing persistent, but low mortality of sugar pine. An estimated 20% of sampled sugar pine were within 30.5 m of at least one sugar pine killed by MPB within the last 10 years. Nine focal sugar pine were deleted from the study because they were attacked and killed after study initiation, yet before treatments were completed in 2001, reducing the total number of

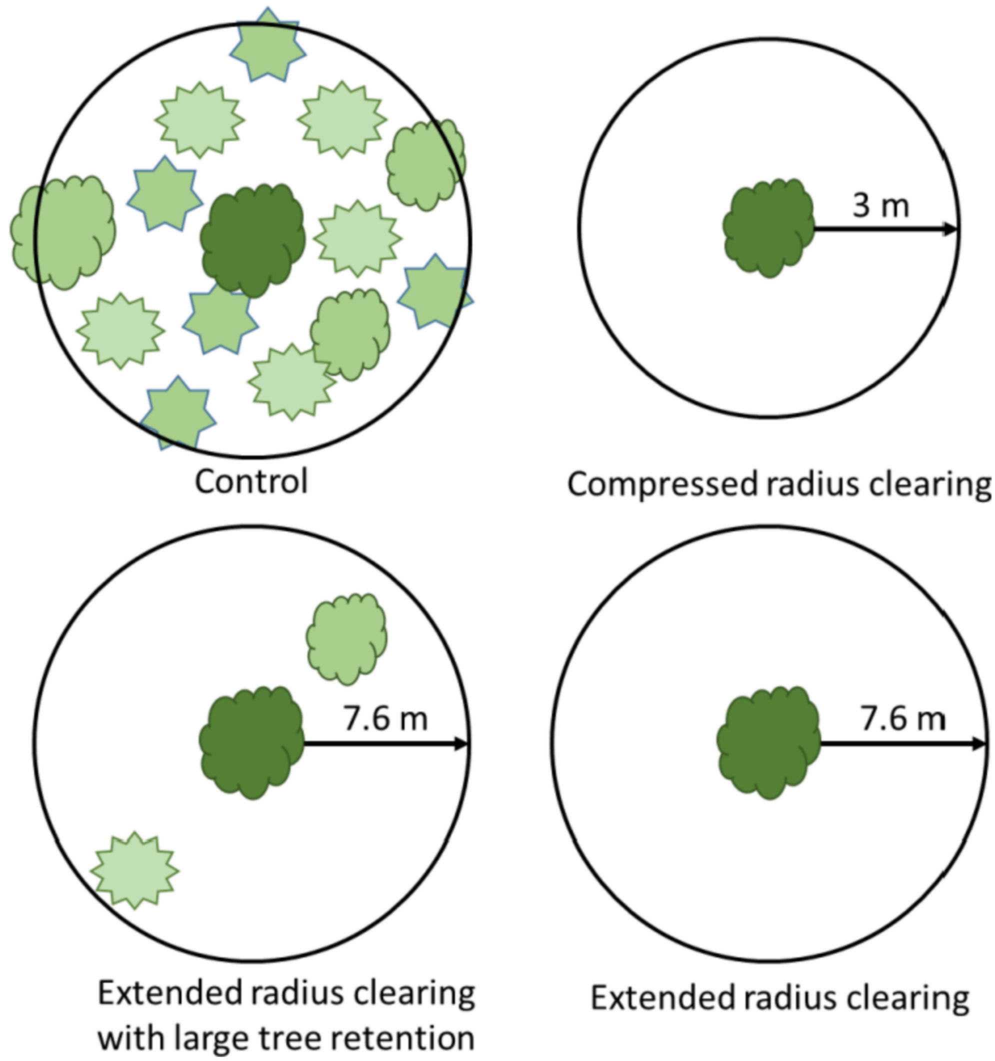

Fig. 1. Radial thinning treatments around focal sugar pines (center dark green tree). Radii prescriptions are from the crown edge. Median radii from tree stem: compressed radius = 7.3 m, extended radius with retention = 12.2 m, extended radius = 12.5 m. See text for full treatment descriptions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sampled trees to 225.

2.2. Data collection

In 1997 and 1998, prior to treatment initiation, the tagged focal trees were again visited to collect vigor and growth measurements. Tree DBH, crown radius in each cardinal direction, and live crown ratio were measured. To quantify local competition, basal area around each tree was measured using a relascope 1.5 m north of and excluding the focal sugar pine prior to treatment and again in 2001 for immediate post-treatment basal area. In addition, the number of small trees (>15.2 cm tall and <12.7 cm DBH) were tallied before and after treatment on a 0.008 ha plot 5 m northwest of each focal tree. A shallow tree core was collected using an increment borer and radial growth for the previous 10 years in 5-year increments was estimated in the field by counting rings and measuring the radial growth using a ruler. Average crown radius was calculated using the four measurements of crown radii for determining the extent of clearing around each focal tree based on the assigned treatment. This resulted in median treatment radii from the tree stem (rather than from the crown edge) of 7.3 m for the compressed radius, 12.2 m for the extended radius with retention, and 12.5 m for the extended radius treatments.

Trees were assessed for mortality in 2001, 2006, 2010, and 2017/spring 2018 at 0-, 5-, 9-, and 16-years post-treatment. Trees were considered dead when no green needles remained. The year of death was estimated based on crown color, amount of faded needles retained, and condition of bark. Mortality agent was recorded as mountain pine beetle, wind, *Armillaria*, or other insects (woodboring beetles in the Buprestidae and Cerambycidae and red turpentine beetle (*Dendroctonus valens* LeConte). Local basal area was remeasured in 2001, 2010, and 2017/2018 to quantify changes in tree competition. White pine blister rust infection was recorded at each measurement by noting if the tree had a dead top and if fading needles on branches was observed. At the end of the study a shallow tree core was collected on living trees using an increment borer and radial growth for the 15 years prior to treatment and the 15 years post-treatment were estimated by counting rings in the field.

Regeneration of sugar pine was assessed 16-years post-treatment using a 0.004 ha plot located 3.5 m northwest from the stem of each surviving focal tree. Seedlings (<1.37 m tall) and saplings (≥1.37 m tall and <12.7 cm DBH) were tallied. White pine blister rust infection on each seedling and sapling was recorded by noting if the rust symptoms were on a branch ≥15 cm from stem, on a branch <15 cm from stem, and on the stem (i.e., lethal).

Seasonal drought varied throughout the study period based on the Palmer Drought Severity Index (Palmer, 1965; Supplemental Fig. 1). In the 15 years prior to treatment implementation, there were three years of moderate drought, but the four years immediately pre-treatment were all were unusually wet (PDSI > 2), with 1997 being extremely wet (PSDI = 3.9). This pattern reversed after the treatments were initiated in 2000, and the next three years from 2001 to 2003 were under moderate drought (<−2). Drought conditions fluctuated for the rest of the study period but remained near normal (−1.9 to 1.9) except for 2011 and 2017, which were both unusually moist periods.

2.3. Data analysis

We created two white pine blister rust variables to test the effects of infection by treatment and mortality: presence/absence and severity. If blister rust was noted on a branch or the tree had a dead top, blister rust presence was 1; presence was 0 for trees with no sign of rust. We calculated a blister rust severity level as follows: no sign = 0, branches infected = 1, dead top = 2, and branches infected and dead top = 3. Growth ratio was calculated by dividing the 15 years post-treatment radial growth by the 15 years of pre-treatment radial growth.

We used general linear mixed models (GLMM) with a randomized block design for all analyses of treatment effects on tree mortality, growth, white pine blister rust, and regeneration in SAS 9.4 (SAS Institute Inc. Cary, NC, USA). Individual sugar pines were the experimental units within each stand (i.e., block) and block and block × treatment were random effects. For tree mortality, rust, and regeneration presence/absence data GLMMs, we used events/trials syntax (e.g., number of trees killed/total number of trees, number of tree plots with seedlings/total number of plots) with a binomial distribution. For the dependent variable of growth ratio, we used a normal distribution with a lognormal link to stabilize residuals. We modeled the count data for sugar pine seedling response using a negative binomial distribution. Binomial and log-normal model estimates were back-transformed for the purpose of reporting mean and standard error. Pairwise differences in categorical variables were tested using Tukey's post hoc test ($\alpha = 0.05$).

3. Results

3.1. Tree responses

A total of 225 sugar pines were followed for 16 years following treatment. Tree characteristics did not differ before treatment (Table 1). DBH ranged from 38.6 to 171.7 cm ($F_{3,211.6} = 1.89$, $P = 0.1319$). Live crown ratio ranged from 20% to 65% ($F_{3,212.4} = 0.28$, $P = 0.8434$) and crown radius ranged from 2.1 m to 8.2 m ($F_{3,23.2} = 1.28$, $P = 0.3035$). Pre-treatment radial growth did not differ for either the past 0 to 5 or 0 to 10 years (0–5: $F_{3,26.87} = 1.04$, $P = 0.3918$; 0–10: $F_{3,25.84} = 0.7$, $P = 0.5589$). Local basal area also did not differ prior to treatment ($F_{3,18.34} = 2.93$, $P = 0.0611$). Thinning reduced local basal area relative to the control (Table 1; $F_{3,215.4} = 98.43$, $P < 0.0001$). After treatment, local basal area was lowest in the extended radius (9.5 m^2 ha^{-1}). Local basal area was similar between the compressed radius (18.5 m^2 ha^{-1}) and extended radius with retention (23.7 m^2 ha^{-1}) and highest in the control (52.4 m^2 ha^{-1}). Forty-two percent of the trees showed signs of infection by white pine blister, but infection did not differ among treatments ($F_{3,36} = 0.98$, $P = 0.4115$).

Over the 16-year post-treatment period, 65 of the 225 trees died (29%). Mortality rates ranged from a low of 19% in the extended radius with retention treatment to a high of 37% in the compressed radius treatment, but no treatment effect was detected (Table 2; $F_{3,36} = 1.5$, $P = 0.2317$). Annual mortality was low, but consistent throughout the study, with 1% to 3% of trees dying every year except in 2005 when no mortality occurred. Mortality over the 16 years occurred in 9 of the 10 stands, resulting in cumulative mortality levels of study trees within a stand ranging from 19% to 45%. Stand 10 had 26% of all dead trees in the study. MPB was the main cause of death, accounting for 79% of dead trees (74% of trees had MPB as the primary cause of death and 5% of trees had MPB plus *Armillaria* or wind as the cause of death). Mortality did not differ between white pine blister rust uninfected and infected trees ($F_{1,18} = 3.72$, $P = 0.0698$), with 32% of dead trees and 46% of living trees having rust. We found no differences between dead versus surviving trees for pre-treatment DBH, live crown ratio, crown radius, radial growth, or basal area (Table 3).

Although there was no statistical treatment effect on mortality over the 16 years of monitoring, mortality patterns tended to differ between the first half and second half of the study (Fig. 2). After 9 years, mortality was highest in the control treatment, where 23% of the trees died. Mortality trended lower for treated trees, with 18% mortality in the compressed radius treatment, 11% in the extended radius, and 7% in the extended radius with retention (Fig. 2a). In the second half of the study, mortality increased for the treated trees, with 23% of the remaining trees dying in this period in the compressed radius treatment, 21% in the extended radius treatment, and 13% in the extended radius with retention treatment, while mortality in the control treatment declined to 9% (Fig. 2b). This decline was not due to a depletion of control trees, as there were still 39 living control trees (70%) by the end of the study, which was similar to the other treatments (Table 2; Fig. 2c). MPB accounted for 64% of the mortality in the first half of the study and 94% in the second half. Whereas wind caused the death of 30% of the trees in the first half of the study, it killed only one tree (3%) in the second half.

Treatment influenced growth for the 160 trees that survived through the 16-year sampling period (Fig. 3; $F_{3,32.79} = 4.61$, $P = 0.0085$). Growth declined in control trees, with a mean growth ratio of 0.91. The compressed radius and extended radius with retention exhibited stable growth (i.e., growth ratios approximately equal to 1.0). The extended radius treatment, with a growth ratio of 1.5, was the only radial thinning treatment that improved growth above the control trees.

3.2. Regeneration responses

The percentage of plots with sugar pine seedlings increased with treatment intensity (Fig. 4A; $F_{3,35} = 3.7$, $P = 0.0207$). After 16 years and for the surviving focal trees, only 18% of control trees had sugar pine seedlings nearby, while 36% of the compressed radius, 49% of the extended radius with retention, and 61% of the extended radius trees had sugar pine seedlings in the regeneration survey plots. However, seedling density did not differ among treatments (Fig. 4B; $F_{3,26} = 1.95$, $P = 0.1462$). Stocking levels averaged 0.4, 0.8, 1.1, and 1.0 per 0.004 ha for the control, compressed radius, extended radius, and extended radius with retention, respectively. Fewer than 10% of seedlings had white

Table 1
Mean (±SE) pre-treatment values of sugar pine characteristics and pre-treatment and one-year post-treatment local basal area (1.5 m north of and excluding focal tree) values. Within each variable, different letters denote significant treatment differences (α = 0.05).

Variable	Control	Compressed radius	Extended radius with retention	Extended radius
n	56	57	58	54
DBH (cm)	78.8 (6.1)[a]	85.5 (6.1)[a]	80.4 (6.1)[a]	88.0 (6.1)[a]
Live crown ratio (%)	39 (2)[a]	41 (2)[a]	40 (2)[a]	40 (2)[a]
Crown radius (m)	4.4 (0.2)[a]	4.6 (0.2)[a]	4.6 (0.2)[a]	4.9 (0.2)[a]
Previous 5 years growth (cm)	3.46 (0.27)[a]	3.18 (0.27)[a]	3.06 (0.27)[a]	2.96 (0.27)[a]
Previous 10 years growth (cm)	7.34 (0.58)[a]	7.00 (0.58)[a]	6.79 (0.58)[a]	6.54 (0.59)[a]
Pre-treatment basal area (m^2 ha^{-1})	52.9 (3.1)[a]	49.2 (3.1)[a]	58.0 (3.1)[a]	60.8 (3.2)[a]
Post-treatment basal area (m^2 ha^{-1})	52.4 (2.2)[a]	18.5 (2.2)[b]	23.7 (2.2)[b]	9.5 (2.2)[c]

Table 2
Sugar pine mortality and cause of death by treatment. MPB = mountain pine beetle.

Treatment	Alive (n)	Dead (n)	% Dead	Cause of Death (%)				
				MPB	Wind	MPB + *Armillaria*	MPB + Wind	Other insects
Control	39	17	30	82	18	0	0	0
Compressed radius	36	21	37	62	19	5	5	10
Extended radius with retention	47	11	19	91	0	9	0	0
Extended radius	38	16	30	69	25	0	0	6
Total	160	65	29	74	17	3	2	5

Table 3
Mean (±SE) values of sugar pine characteristics and local basal area (1.5 m north and excluding focal tree) before and one-year after treatment, segregated by final tree status at 16 years post-treatment. Within each variable, different letters denote significant treatment and tree status differences (α = 0.05).

Variable	Tree Status	Control	Compressed radius	Extended radius with retention	Extended radius
Pre-treatment DBH (cm)	Live	79.1 (6.5) [a]	82.1 (6.6) [a]	80.6 (6.3) [a]	90.0 (6.5) [a]
	Dead	77.7 (7.9) [a]	91.1 (7.4) [a]	78.9 (9.0) [a]	82.8 (8.1 [a])
Pre-treatment live crown ratio (%)	Live	35 (2) [a]	40 (2) [a]	41 (2) [a]	39 (2) [a]
	Dead	41 (3) [a]	43 (3) [a]	38 (4) [a]	42 (3) [a]
Pre-treatment crown radius (m)	Live	4.3 (0.3) [a]	4.6 (0.3) [a]	4.6 (0.2) [a]	4.8 (0.3) [a]
	Dead	4.6 (0.3) [a]	4.8 (0.3) [a]	4.6 (0.4) [a]	4.9 (0.3) [a]
Pre-treatment 5-year growth (cm)	Live	3.30 (0.29) [a]	3.17 (0.30) [a]	3.09 (0.27) [a]	2.69 (0.29) [a]
	Dead	3.85 (0.39) [a]	3.24 (0.36) [a]	3.00 (0.47) [a]	3.65 (0.41) [a]
Pre-treatment 10-year growth (cm)	Live	6.92 (0.63) [a]	7.00 (0.64) [a]	6.87 (0.59) [a]	5.94 (0.63) [a]
	Dead	8.36 (0.82) [a]	7.12 (0.76) [a]	6.56 (0.97) [a]	8.05 (0.85) [a]
Pre-treatment basal area (m^2 ha^{-1})	Live	56.1 (3.6) [ab]	48.8 (3.7) [b]	57.3 (3.3) [ab]	56.4 (3.6) [ab]
	Dead	46.0 (5.4) [b]	50.3 (4.9) [ab]	61.7 (6.6) [ab]	72.1 (5.6) [a]
Post-treatment basal area (m^2 ha^{-1})	Live	54.5 (2.5) [a]	17.8 (2.6) [bc]	24.6 (2.3) [b]	9.7 (2.5) [c]
	Dead	47.5 (3.6) [a]	19.8 (3.3) [bc]	19.5 (4.4) [bc]	8.8 (3.7) [c]

pine blister rust within each treatment. Infected seedlings all showed rust symptoms on the stem.

Sugar pine sapling presence was low (8% of the 159 trees) and did not differ among treatments ($F_{3,34} = 0.27$, $P = 0.8477$). Presence ranged from a low of 5% of plots for the compressed radius to a high of 11% of plots for the control treatments. The higher number of plots with saplings in the control, though non-statistically different, was expected because the cutting treatments removed all stems, including sugar pine, and 16 years is likely not enough time for seedlings to grow into the sapling stage. The pattern of blister rust infection in saplings due to treatment is difficult to discern as there were only 24 saplings across the study. Consistent with the seedling response, most saplings showed no sign of rust, but four of the six infected saplings showed rust symptoms on the stem.

4. Discussion

Forest management for disparate, multi-disciplinary objectives is challenging. In the U.S. Pacific Northwest, as elsewhere, forests provide essential ecosystem, social, and economic services, such as carbon sequestration, habitat diversity, water quality, recreation, and forest products. The NWFP additionally placed an emphasis on forest management to promote sensitive wildlife species that depend on multi-layered, dense forests. Ongoing climate change and associated climate-induced increases in wildfire activity (Abatzoglou and Williams, 2016), can make managing forests for resilience to disturbances and climate stress exceedingly difficult with restricted treatment options for restoration. Radial thinning treatments reflect an effort to balance the needs of late seral, high forest cover for some wildlife species with the desire to also promote habitat for species requiring higher light and lower competition (Hood et al., 2018), as well as create heterogenous forests consisting of a matrix of openings, single and small groups of trees, and larger tree patches that can be more resilient to wildfire and drought (Churchill et al., 2013, Bennett et al., 2015, Hessburg et al., 2016, Sohn et al., 2016).

We found little evidence that the radial thinning treatments tested were effective at increasing sugar pine survival, a result consistent with

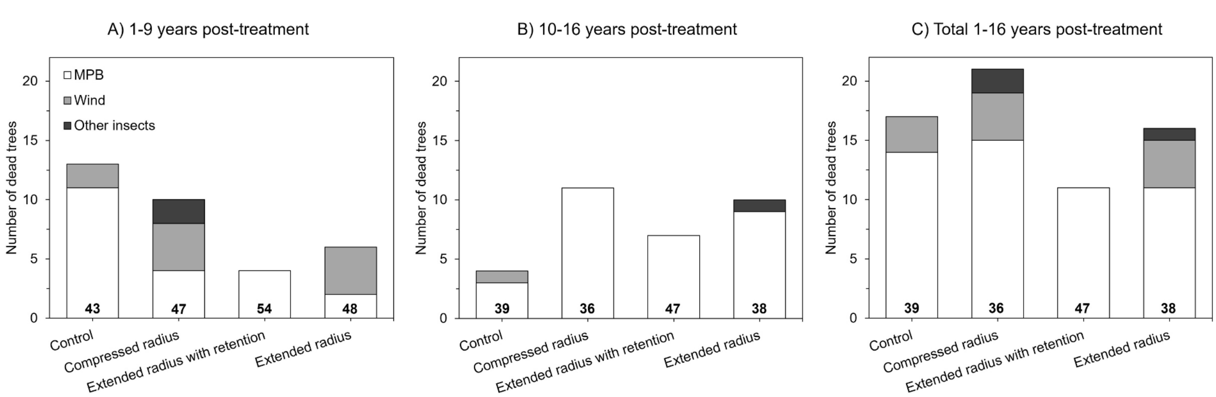

Fig. 2. Number of dead sugar pines by cause of death and treatment for (A) first half, (B) second half, and (C) total study period. Trees killed by a combination of MPB and either *Armillaria* or wind are attributed to MPB. Number of trees living at the end of each period is shown at base of each column. Treatments were implemented by 2001 and trees were assessed for mortality in 2006, 2010, and 2017. MPB = mountain pine beetle.

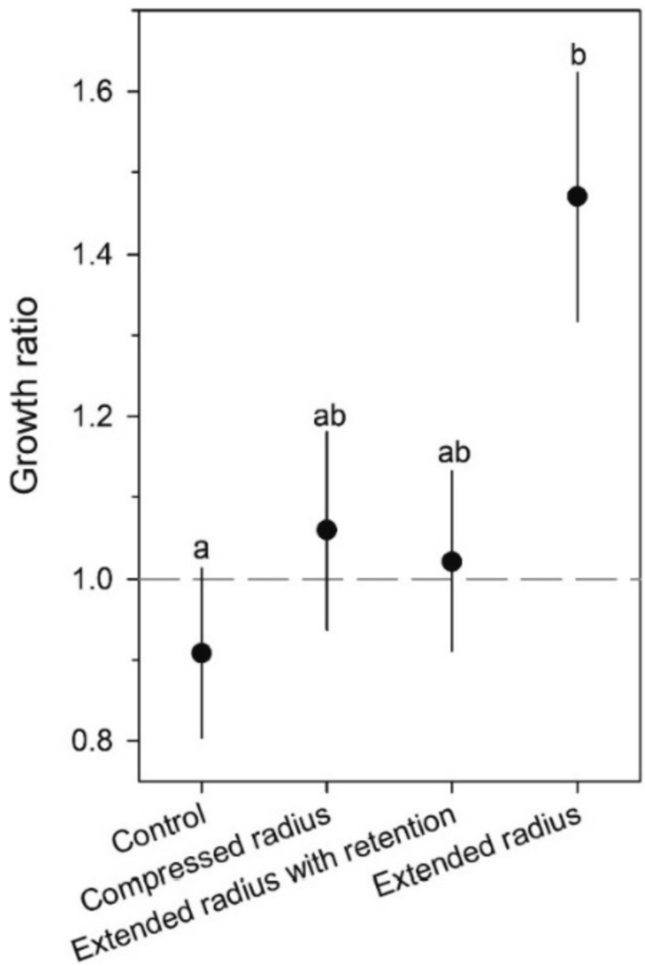

Fig. 3. Mean (±SE) growth ratio by treatment for surviving trees. Growth ratio greater than 1 indicates higher 15-year mean annual growth post-treatment compared to the 15 years pre-treatment, less than 1 indicates lower growth, and 1 (dashed line) indicates no change. Different letters denote significantly different treatment means (α = 0.05).

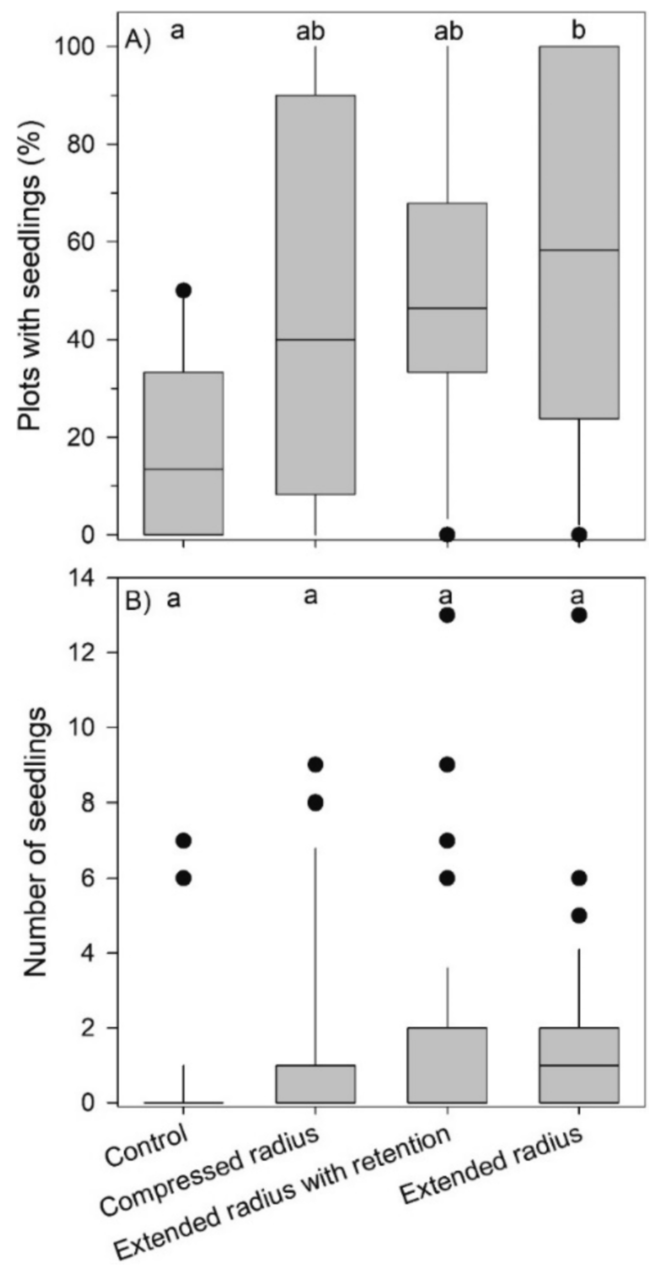

Fig. 4. Sugar pine seedling A) presence and B) density in 0.004 ha plots 3.5 m northwest from each focal sugar pine by treatment 16 years post-treatment. Density values are shown by plot size as these numbers may not reflect stand-level means due to the radial treatments only affecting the area around focal trees. Different letters denote significant differences ($P < 0.05$).

Hood et al. (2018). This study differed from Hood et al. (2018) in that they observed little mortality in ponderosa and Jeffrey pine over a 15-year post treatment period regardless of treatment, whereas cumulative mortality in our study was relatively high across all treatments, including the control, mostly from MPB. Annual mortality was low and occurred in all but one of the ten stands, regardless of whether no treatment or any of the radial thinning treatments were applied. But by the end of the 16-year monitoring period, cumulative mortality was higher than or equal to the untreated control trees for all but the extended radius with retention treatment (19% compared to 30%; Table 2); however, this difference was not statistically lower than the control, likely due to large variation within stands. We found no differences in trees that died versus survived in any of the variables measured (i.e., DBH, crown ratio, pre-treatment radial tree growth, pre-treatment or post-treatment basal area; Table 3). Other studies have reported that sugar pine mortality was preceded by declining radial growth and total resin duct area compared to surviving trees that exhibited both increasing growth and resin duct area (Slack et al., 2021). We did not collect annual growth data nor resin duct data so cannot determine if these patterns would have explained differences in trees that died versus survived. The only other report of radial thinning effects on mortality also found no difference in mortality between untreated whitebark pine trees and trees cleared to a radius of 5.5 m; however, survival was higher in trees receiving the radial thinning treatment followed by pruning relative to untreated trees (Sturdevant et al., 2015). Sugar pine and whitebark pine have very different growth patterns and growth environments, and it seems unlikely that pruning of the large trees in our study would have altered the outcome as they had little-to-no lower branches. MPB was the biggest mortality agent in both our study (Table 2; Fig. 2) and Sturdevant et al. (2015).

Our study highlights the importance of long-term monitoring when evaluating treatment success. The first nine years of the study seemed to show positive effects of radial thinning in reducing tree mortality from MBP relative to the control, especially in the extended radius with retention and extended radius treatments (Fig. 2A). Yet in the second half of the study, the pattern reversed and mortality was lowest in the control treatment (Fig. 2B). We were not able to discern any possible mechanism to explain this pattern, but speculate that the tendency for

MPB to attack and kill neighboring trees and create clustered mortality over time (Preisler 1993, Fettig et al., 2014) played a role. The shift in pattern was not due to a lack of available host trees in the control trees in the second half of the study forcing MPB towards trees that had been radially thinned, as the number of living control trees was similar to the number of living trees in each of the radially thinned treatments (Fig. 2b-c). Although the first several years of the study occurred under moderate drought conditions, PDSI did not seem to explain any patterns related to mortality (Supplemental Fig. 1). Wind had a larger effect in the first half of the study, uprooting 10 trees, compared to only one in the study's second half (Fig. 2). The extended radius with retention treatment was the only treatment with no windthrown trees, but it is difficult to determine if this was a treatment effect or simply due to micro-topography effects of strong winds, as mortality from wind also occurred in the control in both the first and second halves of the study. Another possibility of the change in mortality patterns over the study period is that by the second half of the study, resprouting shrubs and residual trees likely increased, potentially diminishing any positive effect of the radial thinning treatments. Research is needed on how treatment efficacy wanes over time to determine if maintenance treatments could be used to mitigate mortality.

Throughout the study timeline, MPB caused low-level, but persistent mortality that was restricted to sugar pine, the only host tree species in the area besides some scattered ponderosa pine. The study site is located near the northern range of sugar pine on relatively wet sites compared to the rest of its distribution based on plant associations. Additional research is needed to determine how well our results apply to other forests with sugar pine. Our results are partially consistent with Struble (1965), who also reported no differences between MPB-attacked and unattacked for younger sugar pine in California, but did report that MPB preferred older trees with small, thin crowns compared to older trees with full crowns of healthy-appearing foliage. A consistent death rate of 2–3% per year by MPB, with only one year at 0% mortality, implies an endemic MPB population in the Little River Valley that is stable at a size sufficient to overwhelm and kill a few mature sugar pines annually. MPB outbreaks in other host tree species can cause widespread, high levels of tree mortality over only a few years (Raffa et al., 2008, Berner et al., 2017). It remains to be seen if an abrupt increase in the MPB population will occur in sugar pine in this area. Regardless, based on the pattern observed over 16 years, we expect sugar pine to continue to decrease, especially given anticipated increases in drought stress due to climate change (Kolb et al., 2016).

Radial thinning tended to stabilize tree growth in the compressed radius and extended radius with retention treatments and increased growth in the extended radius treatment relative to the control over the 16-year monitoring period. A major caveat to these results is that we did not measure post-treatment growth for trees that died. Also, growth measurements were measured from unsanded cores in the field (i.e., cores were not crossdated for annual growth and assignment of calendar years). Therefore, it is possible that the growth periods recorded contained extra years if there were false rings or fewer years if there were missing rings. That said, at the time of treatment implementation, there were no differences in recent growth increment among treatments (Table 1), nor were there differences in pre-treatment growth between trees that lived versus died for any treatment (Table 3). The four years prior to treatment were unusually wet, while the three years immediately after treatment were moderately dry based on PDSI (Supplemental Fig. 1). In the remaining 10 years, the area experienced mostly normal levels of precipitation with two above average moisture years and no severe drought conditions. Therefore, the growth ratios we report are unlikely to be biased based on long-term climatic trends relative to the treatment timing. If anything, the treatments likely mitigated the negative effect of the moderate drought that occurred for three consecutive years post-treatment. Consistent with other studies that showed increased growth is positively related to thinning intensity (Latham and Tappeiner 2002, Gray et al., 2012, York et al., 2015, Hood et al., 2018, Zald et al., 2022), growth ratio was only higher than the control for the extended radius treatment. Neighborhood competition from trees ≥ 25 cm DBH has been associated with decreased growth of large sugar pine (Steel et al., 2021). Post-treatment local basal area values in the compressed radius and extended radius with retention were similar to the local basal area for the radial thinning treatment in Hood et al. (2018), and our results on the impact of local basal area competition are also similar, where less intense radial thinning somewhat stabilized growth ratio but did not increase it. Post-treatment local basal area in the extended radius treatment was much lower than the radial thinning treatment tested in Hood et al. (2018) at 9.5 m^2 ha^{-1} compared to 20.9 m^2 ha^{-1}. Taken together, these results suggest that for radial thinning to increase growth, local competition must be greatly reduced by treating a larger area around focal trees to at least 12 m from the stem such that basal area is lower than 18.5 m^2 ha-1 and likely lower than 10 m^2 ha^{-1} based on our post-treatment basal area reported in Table 1. We note again, the important point that while this level of radial thinning could increase growth, the small-scale nature of radial thinning likely would not affect tree mortality if MPB was active in the area based on our results that mortality levels did not differ among the control or any of the radial thinning treatments. While larger scale stand-level thinning can increase resistance to MPB (Fettig et al., 2014, Steel et al., 2021), our results suggest that radial thinning is too localized to affect resistance to MPB.

While we did not measure any physiological variables, other studies can provide insight into potential treatment effects on microclimate around focal trees that in turn, may affect growth and stress responses. Growth of large sugar pines comparable to those in our study was negatively correlated with maximum monthly temperatures, and this relationship was stronger during summer through fall months in larger trees relative to smaller trees (Hirsch 2021). Large sugar pine growth was also affected by the previous summer's maximum temperature, with higher temperatures associated with decreased growth the following year (Hirsch 2021). Other studies of large sugar pine found a positive relationship with growth and minimum winter temperatures (Bigelow et al., 2014, Slack et al., 2017) and lower intraspecific competition (Slack et al., 2017). Growth in large sugar pines that received a radial thinning treatment that was proportional to 1.25 times the stem diameter (i.e., 14–18 m thinned around focal trees) was positively correlated with mean solar summer radiation and less impacted by increasing temperatures compared to control trees and trees radially thinned to 9.1 m (Hirsch 2021). This may explain why the trees in our extended radius treatment (average radius of 12.5 m) had the highest growth responses in our study. Faster growing sugar pines were more likely to survive an extreme drought in California compared to slower growing trees (Steel et al., 2021). While our study period did not coincide with prolonged drought periods, our results suggest that the faster growth rates of surviving trees in the extended radius treatment compared to surviving control trees did not confer increased resistance to MPB nor affect mortality at the treatment level. Yet our results also suggest that the thinning treatments did not negatively affect the trees — if the pile burning or thinning altered microclimates in such a way to increase susceptibility to MPB or increase physiological stress, we would have expected that to translate to lower growth rates and higher mortality levels in the treated trees relative to the control.

Sugar pine seedling presence increased with radial thinning intensity, with the extended radius treatment having more plots with at least one sugar pine seedling compared to the control (Fig. 4a). However, seedling frequency was low across all treatments (Fig. 4b). We note that, as with growth ratio, regeneration was only measured near surviving trees. Other studies have reported stable to slightly declining sugar pine populations in California, U.S., with a paucity of seedlings that recruited into larger size classes over time due to mortality from white pine blister rust and stress (van Mantgem et al., 2004, Maloney et al., 2011, Levine et al., 2016). Blister rust infection on seedlings was less than 10% in our study, but all infected seedlings had symptoms on the main stem, suggesting these seedlings will likely die. Maloney et al. (2011) found sugar pine establishment was highly variable, so it may be that there simply has not been enough time for sugar pine to establish. Our general findings of higher sugar pine presence around thinned versus control trees is likely due to its shade intolerance and increased establishment success on mineral soils (North et al., 2005). The thinning certainly would have increased sunlight to the forest understory, and it is possible that the regeneration tally plots were located in areas impacted by pile burning that increased the amount of mineral soil; however, we did not record this level of detail to test this hypothesis.

Radial thinning treatments are designed to add heterogeneity to dense forests, typically with a focus on retaining large, old trees, where treatment options are constrained. Although our study found no effect of radial thinning in increasing survival of large sugar pines, it is important to report these negative results. Adaptive land management is only possible through monitoring of treatment effects, where results are evaluated and incorporated into future management decisions (Allen et al., 2011). Our findings showing that the radial thinning treatments tested were largely ineffective or statistically non-significant in reducing mortality are an important step towards increasing knowledge of this relatively new silvicultural treatment. It was only through the foresight of managers and researchers that originally designed the study and continued with the often undervalued work of ecological monitoring that we were able to test treatment effects over a 16-year period – a feat few have completed (Westgate et al., 2013). After the first nine years of monitoring, when radial thinning looked very promising at reducing tree mortality, there were several manager workshops and field trips to learn from the study (W. Schaupp, personal communication). Additional technology transfer is now needed to disseminate the longer-term study results. Other studies of radial thinning have also shown little positive benefits of radial thinning in pines (Sturdevant et al., 2015, Hood et al., 2018, Hirsch, 2021), but radial thinning did increase growth for eucalypts (Brown et al., 2019). It is only through transparent reporting of both successes and failures of management treatments that we are able to learn and improve future outcomes.

Acknowledging both the impact of altered disturbance regimes and even-aged, single-species management is essential context for the justification of radial thinning treatments in the U.S. Pacific Northwest (Stephens et al., 2019). Prior to European colonization, mixed-conifer forests in western Oregon had a relatively frequent, mixed-severity fire regime. On a site also on the Umpqua National Forest, Olson and Agee (2005) estimated historical median fire frequency in Douglas-fir forests in the western hemlock series ranged from 35 to 39 years in riparian areas and 27–36 years for upslope forests. Within the Little River Watershed of our study site, Van Norman (1998) reported a much longer historical median fire return interval of 44–123 years, but on the subset of sites where Weibull median probability fire return intervals were able to be estimated, which matches the methods of Olson and Agee (2005), fire return intervals were shorter – 45–72 years. One reason for the difference in fire return intervals may be because Olson and Agee (2005) did not include years after 1900, while Van Norman's analysis included years through 1996. Both studies found strong evidence that fires typically burned over small areas as mixed-severity and patchy. Cultural burning by Native Americans, including the Kalapuya, Upper Umpqua, Cow Creek, and Molalla tribes, was common prior to around 1850 and increased fire frequency and fostered a matrix of open patches and uneven-aged forests (Carloni, 2006, Long et al., 2018, Long et al., 2021). Fire activity sharply decreased in the later 1930s in the area with improved fire suppression tactics and this continued as widespread logging converted many naturally-established mixed-conifer forests to Douglas-fir plantations (Carloni, 2006). Habitat decline of late seral, multi-layered forests subsequently led to the decline of several species such as the spotted owl and marbled murrelet, eventually precipitating the creation of the NWFP. Since the NWFP was established in 1994, stressors on forests and wildlife have only increased with climate change, higher incidence of large, high-severity fires, non-native species, and other stressors (Spies et al., 2018). Concomitantly, there has been a vast improvement in understanding of the large role that mixed-severity fire historically exerted in shaping forest composition and structure in Pacific Northwest forests (Churchill et al., 2013, Hessburg et al., 2015, Hessburg et al., 2016). Restoration treatments that attempt to improve forest resilience are likely to be most successful when treatments mimic disturbance processes and place ecosystems within a landscape perspective. Additional research is needed to determine how radial thinning may affect fire behavior and resulting severity. Radial thinning may be a useful tool when used in conjunction with other silvicultural prescriptions that create heterogeneous stands and landscapes with a variety of forest structures (e.g., opening, single trees, small groupings of trees, and unthinned groups), but it seems unlikely that employing only radial thinning will meet restoration efforts that aim to decrease large tree mortality.

5. Conclusions

The native MPB, invasive blister rust, and consequences of altered disturbance regimes are causing heavy losses of white pines (Schwandt et al., 2010), with sugar pine being among the most vulnerable (Spies et al., 2018, Dudney et al., 2020). In this study we examined 16-year effects of radial thinning treatments that cleared approximately 0.017 ha to 0.05 ha (7.3–12.5 m radii) around focal large sugar pines on reducing mortality and increasing sugar pine growth and recruitment. None of the three radial thinning treatments tested reduced mortality relative to the control, with MPB causing most mortality across the four treatments. However, mortality did trend lower in the extended radius with retention treatment (19% compared to 30–37%) and was the only treatment where no mortality from wind or insects other than MPB occurred. For trees that survived through the 16-year monitoring period, only trees in the extended radius treatment experienced increased growth from pre-treatment values and higher presence of sugar pine seedlings. Our results show no clear benefit to sugar pine survival was derived from the radial thinning treatments tested. The treatments were implemented in mesic mixed-conifer forests where sugar pine is at the northern limits of its distribution and results may be different on other sites. While radial thinning may be a useful tool when used in conjunction with other silvicultural prescriptions that create heterogeneous stands and landscapes with a variety of forest structures, radial thinning alone will likely not meet restoration efforts that aim to decrease large tree mortality. This study highlights the value of long-term monitoring in the continual effort to develop new treatments that are effective at increasing forest resilience.

CRediT authorship contribution statement

Sharon M. Hood: Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Willis C. Schaupp:** Investigation, Methodology, Data curation, Resources, Writing – review & editing. **Donald J. Goheen:** Conceptualization, Funding acquisition, Investigation, Methodology, Data curation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the USDA, Forest Service and USDI, Bureau of Land Management. We gratefully acknowledge Bob Schroeter, Ellen Goheen, Katy (Marshall) Mallams, Alan Baumann, Barb Fontane, Rick Abbott, Don Morrison, Leslie Elliot, Richard Helliwell, Joe Linn, Jeanette Griese, Craig Kintop, Trixie Moser, Dayne Barron, and many others for their assistance. All sugar pines in the study stands were originally located and mapped by students and personnel from the Wolf Creek Job Corps Civilian Conservation Center. We thank Laura Lowrey and two anonymous reviewers for their comments.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120351.

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