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RESEARCH ARTICLE

Continued response of Oregon oak to release treatments 20 years after initiation in western Washington, United States

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Fire suppression has increased competitive tree encroachment of Oregon white oak (*Quercus garryanna* Douglas ex Hook) ecosystems, threatening maintenance of this important species. Restoration of oak ecosystems is ideal to address this threat but not always possible, giving rise to a need for novel treatments that will allow oak to persist on an altered landscape. We tested the effect of three release treatments centered around individual Oregon oak trees within four forested sites that had developed following encroachment and overtopping by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*). The release treatments entailed removal of competitive tree species (>10 cm dimaeter at breast heigh [DBH]) within zero (as control), half, or full distance of the associated Oregon oak trees' height. There was no effect of release treatment on height, but diameter was significantly increased in the full release treatment relative to both the control and half release treatments. The effect on diameter increased up to year 10 and then decreased to year 20. Growth response to canopy damage from an ice storm in year 12 of the study varied significantly with treatment; growth was negatively related to the percent crown damage in both release treatments but not the control treatment. Full release treatments around individual Oregon oak trees can have long-term positive effects on growth, providing managers with an option to maintain oak within altered ecosystems.

Key words: crown damage, Garry oak, ice damage, oak savanna, restoration, thinning

Implications for Practice

- Encroachment and overtopping by conifers in oak ecosystems are critical factors influencing their function; practices are needed that will allow Oregon oak to persist in altered landscapes when ecosystem restoration is not possible.
- Release treatments that remove competing trees within a distance equal to or greater than the height of the target oak tree are effective at increasing growth for at least 20 years.
- Stochastic disturbances, such as the ice storm evaluated in our study, can influence the trajectory of response and should be anticipated and planned for in developing a strategy for managing at-risk species.
- Release treatments do not restore oak ecosystems, but they can provide future options for land managers to ensure that oak persists in ever-changing landscapes.

Introduction

Globally, stressors such as climate change, altered disturbance regimes, and other human-induced changes to ecosystem functioning have created challenges for the maintenance of functional native ecosystems (Grimm et al. 2013; Johnstone et al. 2016). Restoration of these threatened ecosystems continues to be a challenge and focus of management efforts by natural resource managers. Although much effort has been expended to advance ecological restoration, there is still much uncertainty about the relative efficacy of these efforts at successfully restoring ecological functions (Suding 2011). Further, ecosystem restoration may not even be possible given the factor(s) leading to ecosystem degradation, limited resources for restoration treatments, or alignment with landowner management objectives. In such instances, it may be more feasible to maintain a subset of important ecosystem components, such as a certain tree species with high ecological value.

Oak savanna ecosystems are under threat regionally and globally due to land use conversion, invasive species encroachment, and altered disturbance patterns (Saving & Greenwood 2001; Dunwiddie et al. 2011; Wilson et al. 2015). In the Pacific Northwest (PNW) region of North America, oak savannas occur in inland areas extending along the western coast from

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southern California to the Puget Trough of Washington (Devine et al. 2013). Prior to European settlement, oak savannas were maintained under frequent low-severity fire regimes that kept the dominant competitor, Douglas-fir (*Pseudotsuga menziesii*), in check because of its susceptibility to fire in young growth stages (Engber & Varner 2012). With the onset of fire exclusion and land use conversion throughout the twenty-first century, large portions of oak savanna have been lost or significantly threatened, causing cascading impacts to wildlife habitat (Hagar & Stern 2001), native plant communities (Thysell & Carey 2001), and cultural values. Restoration of oak savanna may be possible, resulting in low densities of scattered oak with few other tree species in association with native grassland plant communities. However, continued fire exclusion and resource limitations are likely to hinder or prevent oak savanna restoration across much of its range (Dunwiddie & Bakker 2011; Hamman et al. 2011).

In instances where oak savanna restoration is not practically feasible, it should be possible to at least maintain a component of oak on the landscape with some level of active management. In areas where oak has been encroached by competing tree species, the localized removal of these competitors may allow remnant oak trees to increase growth and vitality (Brudvig et al. 2011). For example, Devine and Harrington (2013) found that removal (via harvesting) of nearby competing Douglas-fir increased growth and acorn production of Oregon white oak over a period of 10 years. Similarly, Kane et al. (2019) reported that girdling was effective at decreasing Douglas-fir competition in an Oregon white oak woodland in California, United States. Lariviere et al. (2021) observed an increase in crown width of oak (*Quercus robur* L.) following removal of competing trees within 2 m of the oak crown, while trees with no release had the largest amount of dead branches after 10 years. Although competitor tree removal treatments have generally been shown to be effective, it is not clear how much competition needs to be removed or how long treatment efficacy is maintained. This information is needed to develop management strategies that will allow oak to persist on altered landscapes and maintain the ecosystem services it provides (e.g., mast production).

External events, e.g. natural disturbances, may hamper restoration efforts by altering the trajectory of recovery. For example, disturbances that damage or stress previously released trees may reduce treatment effectiveness. Quantitatively assessing the effects of such events is challenging due to their random nature, highlighting the need to capitalize on these events when they coincide with existing studies.

Here, we report on the effectiveness of release treatments at increasing Oregon oak growth 20 years after treatment application at encroached sites in the Puget Trough province near Tacoma, Washington, United States (Devine & Harrington 2006). In an earlier assessment at these sites, Devine and Harrington (2013) showed that Oregon oak responded positively to treatments 10 years after initiation, with increases in diameter growth and acorn production associated with the amount of Douglas-fir removed adjacent to oak trees. Since that assessment, a large ice storm occurred in the region that damaged many of the study trees, but effects on the treatment response have not been quantified. Our objectives were to determine if (1) Oregon oak continue to have positive responses to release treatments 20 years after implementation and (2) determine if ice storm damage has influenced the growth response since the 10-year assessment. We also assessed competitor abundance to determine how that may have influenced the response. We hypothesized that diameter growth would continue to be higher with full release treatments due to reduced competition, but that the rate of diameter response would be lower than the initial 10 year response. In regard to ice storm damage effects, we hypothesized that crown damage would reduce growth, with no difference in the relationship among treatments.

Methods

The study was conducted at four sites within Joint Base Lewis-McChord located at the southern end of Puget Sound in western Washington, United States (Fig. 1). The climate of the region is Mediterranean with warm dry summers and wet winters with mean summer temperatures of 17.7°C and mean winter temperatures of 4.1°C. Total annual precipitation averages 1180 mm, with only 190 mm occurring from May 1 to September 30 (PRISM Climate Group 2023). The study sites are located within 15 km of each other and are characterized as forests that have developed over time as Douglas-fir (*Pseudotsuga menziessi*) has encroached into the savanna after fire exclusion. The overstory canopy is dominated by Douglas-fir with Oregon oak occupying the midstory canopy under variable levels of suppression (i.e. overtopped by Douglas-fir). Oak density at

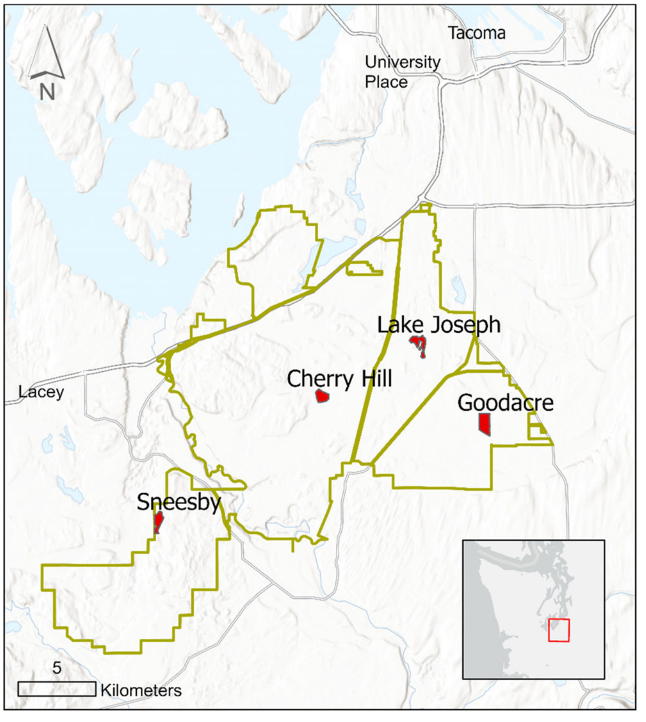

Figure 1. Study region (inset) and site locations relative to each other and local features.

the sites ranged from 57 to 192 trees/ha compared to other tree species that ranged from 176 to 257 trees/ha (predominantly Douglas-fir, Table 1) Soils at the sites were developed from glacial outwash and are generally coarse textured with high rock content, resulting in rapid drainage and low water holding capacity (Pringle 1990).

Study Design

At each site, 18 Oregon oak trees ($n = 72$ for the study) were selected to span a range of sizes and levels of suppression characteristic of the associated site following a light thinning as described in Devine & Harrington 2006 (Table 1). Study trees were also located to maintain spatial independence from each other. Mean distance from each study tree to the next nearest was 57 m (range 24–210 m). A plot was established around each target tree with a radius equal to the tree's height; mean height of target oak trees was 16 ± 3.2 m (Table 1). Each tree was randomly assigned to one of three release treatments: (1) none—no additional removal of Douglas-fir trees at time of study establishment (mean of 2 trees removed in the plot due to thinning), (2) half release—removal of all Douglas-fir greater than 10 cm DBH within the radius of one half the oak trees height (mean of six trees removed), and (3) full release—removal of all Douglas-fir greater than 10 cm within the radius of the oak trees height (mean of 15 trees removed). Given the design, the treatment/measurement plot were variable in size depending on tree height. Average height and diameter of competing Douglas-fir prior to removal was approximately 2.5–3.0 times greater than the center oak tree (Table 1). The release treatments were conducted in Spring 2001 with minimal residual damage to the target center oak trees. Since the 10-year (2011) measurement, three sites were commercially thinned (2012–2017) and a severe ice storm in January 2012 caused significant damage to many of the study trees (Table 2).

Measurements

Height and DBH were measured on each oak tree and all competitor trees (including other oaks and Douglas-fir) in each plot at years 1, 3, 5, 10, and 20 of the study. Height was measured with a laser hypsometer (Haglof Vertex Laser Geo, ± 0.5 m precision). Height to lowest live foliage was measured in years 5, 10, and 20 on the same trees. Competitor in growth greater than 10 cm DBH was quantified beginning in year 4 and again at years 10 and 20. Following the ice storm that occurred in 2012, a visual estimate of crown damage to each oak tree was made to the nearest 5%.

Analysis

We used mixed effects models to assess treatment effects on total height, height to lowest live foliage, and diameter of the center release trees, and competition indices calculated for each plot (see below; $n = 72$). Release treatment was modeled as a fixed effect and site as a random effect; most models (excluding the height to lowest live foliage model) incorporated repeated measures analysis and used a autoregressive (lag 1) covariance matrix to account for serial correlation among successive time periods (Copyright (c) 2016 by SAS Institute, Inc., Cary, NC, USA). In the repeated measures analyses, interaction between treatment and measurement period were modeled as fixed effects. Pre-treatment measures of height and diameter were included in these models as covariates when significant. We limited our assessment of treatment effects on competition to live study trees in plots that had no evidence of post-treatment thinning (Table 1; $n = 38$) and from measurement years 5, 10, and 20. Competition was assessed with Curtis's relative density (RD) of competitor trees (RD = basal area/[quadratic mean diameter$^{0.50}$]; Curtis 1982), competitor basal area (m^2/ha), and the sum line length index (m) which incorporates the sum of competitor distances from a target tree (Brodie & DeBell 2004). When

Table 1. Mean pre-treatment study plot and tree characteristics at sites used in this study. Error estimates are standard deviation of the mean.

	Site			
Parameter	*Cherry Hill*	*Goodacre*	*Lake Joseph*	*Sneesby*
Study plot characteristics				
Trees per ha (#)				
Oak	149	57	63	192
Douglas-fir	111	149	215	192
Other species	91	27	42	36
BA (m^2/ha)				
Oak	4.8	2.0	4.0	7.8
Douglas-fir	31.6	29.2	46.5	29.7
Other species	2.9	0.3	0.9	0.4
Oak center tree characteristics				
DBH (cm)	31.9 (8.7)	29.8 (9.7)	29.8 (7.7)	31.3 (8.3)
Height (m)	15.5 (3.4)	16.1 (3.3)	16.4 (3.4)	16.1 (2.5)
Tree age (year)	98	130	124	94
Douglas-fir characteristics				
DBH (cm)	83.4 (30.2)	81.8 (27.1)	88.5 (17.9)	80.4 (20.3)
Height (m)	39.4 (8.3)	40.0 (7.7)	44.0 (3.9)	39.0 (5.8)
Tree age (year)	80	75	75	65

Table 2. Characteristics of events that have occurred since treatments were initiated in 2000 by site location. Thinning treatments occurred after treatment that were not part of the original study design. Crown damage was associated with an ice storm that occurred in January 2012; values presented were calculated across all study trees within a site.

Site	*Initial study trees*	*Dead study trees*	*Post-treatment thinning year*	*Plots with thinning evidence (#)*	*Trees with less than 20% crown damage (#)*	*Mean crown damage (%)*
Cherry Hill	18	3	2013	16	2	8
Good Acre	18	1	2017	8	17	32
Lake Joseph	18	0	NA	0	7	21
Sneesby	18	3	2012	0	10	41

model results indicated significant treatment effects, multiple comparisons using a Tukey's adjustment were performed to determine differences among the treatments. To assess effects of crown damage caused by ice, mixed models were also developed to determine if there were significant differences among treatments in the relationship between crown damage and percent BA change from 2011 to 2021; percent change in BA was used to account for differences in diameter among the study trees ($n = 65$ after accounting for study tree mortality; Table 2). For these models, treatment, ice damage, and their interaction were modeled as fixed effects, and site was modeled as a random effect. Linear regression was used to estimate the parameters of these relationships for interpretation. Model assumptions of normality were visually assessed and data transformations were conducted if needed to stabilize variance. All error estimates presented are the standard error of the mean. All statistical analyses were performed in SAS version 9.4 for Windows (SAS Institute Inc.) and an alpha level of 0.05 was used for significance.

Results

Height and Diameter Growth

There was no effect of release treatment on height growth over the 20-year study period ($p = 0.952$). Height of oak trees at 20 years averaged 15.9 m (±0.9 m), 16.4 m (±0.8 m), and 16.5 m (±0.7 m) for the control, half release, and full release treatments, respectively. There was a main effect of treatment on diameter increment growth which manifested as increased growth in the full release treatment relative to the control and half release treatments ($p < 0.001$; Table S1). However, there was a significant interaction with measurement period in this effect ($p < 0.001$; Table S1)—growth responses were greatest in the first 10 years and have decreased since (Fig. 2). Mean diameter at 20 years was 33 cm (±2 cm), 34 cm (±1 cm), and 37 cm (±2 cm) for the control, half release, and full release treatments, respectively.

We also analyzed the height to lowest live crown to determine if oak tree crowns were lifting in response to treatment over the last 10 years. There was a significant difference among treatment in the change in height to live crown ($p = 0.024$; Table S1), where the control treatment had decreasing height to live crown height (−1.2 m ± 0.5) relative to the full release treatment which had an increase in height to live crown height (0.9 m ± 0.6). The half release treatment had decreased change in height to live crown (−0.6 ± 0.6) that was not different from zero or either the control or full release treatments.

Competition Effects

Across all measurement periods, the full release treatment had significantly lower RD (10.3 ± 5.3) than either the half release (29.6 ± 4.9) or control treatments (31.6 ± 5.6). There was also a significant interaction between treatment and measurement period on total basal area (Table S2). Multiple comparisons indicated that there were clear differences among treatments in general, that were most pronounced between the full release treatment and both the half release and control treatments (Fig. 3). Mean competitor total BA by treatment (averaged across measurement periods) was 4.2 m^2/ha (±0.5), 2.9 m^2/ha (±0.4), and 0.5 m^2/ha (±0.5) in the control, half release, and full release treatments, respectively. There were general trends of increasing total BA across time for all treatments, but differences across measurement periods were only significant in the full release treatment (Table S2; Fig. 3). There was no effect of treatment on the sum line length competition index (Table S2).

Effects of Ice Damage on Treatment Response

Mean ice damage to crown was 29% (±6%), 26% (±7), and 21% (±5%) for the control, half release, and full release

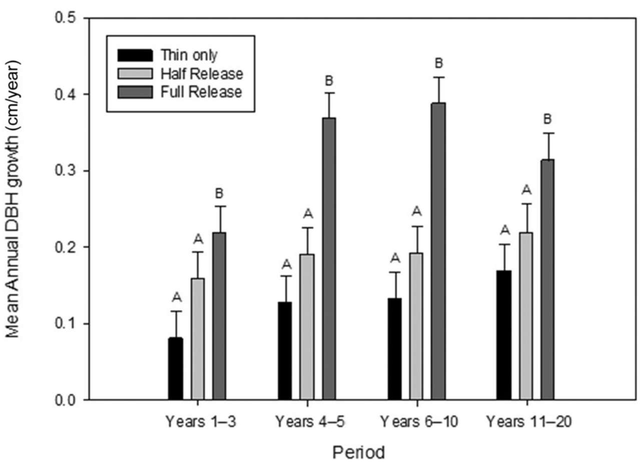

Figure 2. Mean diameter increment by treatment and measurement period. Treatments containing different uppercase letters within a measurement period are significantly different ($p < 0.05$); error bars are + SE.

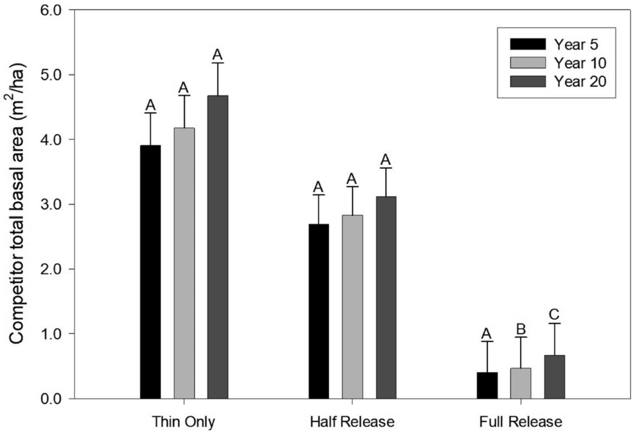

Figure 3. Non-transformed mean competitor total BA per plot by treatment and measurement period. Values within a treatment containing different letters are significantly different. Error bars are + SE.

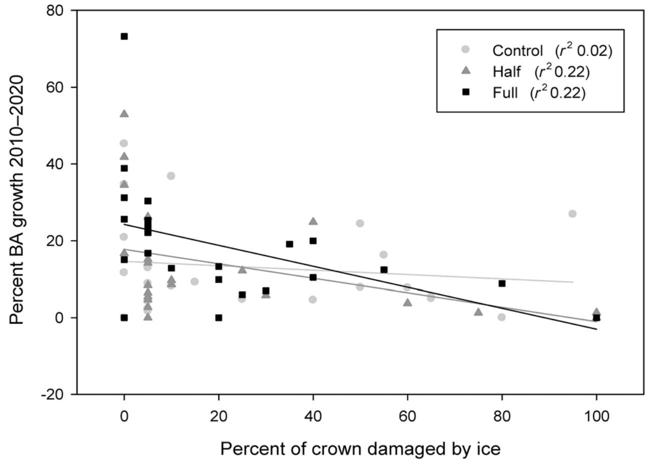

Figure 4. Relationship between percentage BA growth 2011–202 and the estimated percent crown damage from the 2013 ice storm by treatment. Regression models were run separately for each treatment. Regression models for release treatments were both significant but the model for the control treatment was not. Points are individual measurement trees associated with each treatment.

treatments, respectively. Mixed model analysis that included percent crown damage, treatment, and their interaction indicated a significant interaction on percent BA growth from 2011 to 2020. Based on this initial finding, we conducted regression analysis by treatment to assess differences in the significance of the relationship and differences in parameters among treatments (Fig. 4). Regression models for both release treatments were significant ($p = 0.0396$ for half release; $p = 0.022$ for full release) and parameter estimates for the slope coefficient similar between them (−0.19 and −0.27, respectively; Fig. 4), but the amount of variance explained by the models was relatively low (r^2 values of 0.22 for both the half and full removal treatment). In contrast, the overall model for the control treatment was not significant ($p = 0.685$).

Discussion

Oak ecosystems are globally imperiled, creating a need for restoration practices to maintain the species in ecosystems it currently inhabits. Here, we evaluated the long-term (20 years) response of Oregon white oak to two levels of release from overtopping Douglas-fir trees. Similar to previous assessments (Gould et al. 2011; Devine & Harrington 2013), our results indicate that the release treatments continue to have positive effects on oak diameter growth, but no effect on height growth. Further, crown damage associated with an ice storm at year 13 appears to have negatively affected the growth response in the half and full release treatments, highlighting the impact that stochastic disturbance events can have on overall restoration outcomes following treatment.

Effects of Release Treatments on Growth

Growing space is an essential control on plant performance, influencing the relative availability of limiting resources including nutrients, water, and light. For example, Gould et al. (2011) showed that the amount of competition (and its influence on growing space) in proximity to Oregon white oak is a key factor influencing growth across the western United States. Our full release treatment was effective at increasing growing space as indicated by the reduction in competitor RD (by 67% on average) and total BA (by 88% on average) within the treatment plots relative to the control plots. This decrease in competition was sufficient to increase diameter growth by 13% points relative to the control treatment (i.e. a 24% increase in diameter in the full removal treatment compared to a 11% increase in the control treatment) during the course of the 20 year study period. The growth response has slowed in years 10–20, which contrasts with findings from the first 10 years, where growth response increased with time (Devine & Harrington 2013). Results from silvicultural thinning (density reduction) studies align with these findings: growth of residual trees is generally low initially, then increases, and then decreases as available resources become limiting again (Valinger et al. 2000; Anning & McCarthy 2013). The lack of a significant response in diameter in the half release treatment can be attributed to the lower decrease in competition that occurred in that treatment (a reduction of only 6% in RD and 31% in total BA). Overall, the full release treatment appears to be effective at increasing encroached Oregon oak growth for at least 20 years. Increasing competition over time will likely require additional release activities for the treatment to remain effective over longer time periods.

The lack of any effect on height growth was observed at earlier times of the study (Devine & Harrington 2006; Devine & Harrington 2013). Maximum height of Oregon oak typically ranges from 15 to 27 m (Stein 1990), but Gould et al. (2011) estimated a mean of 16.7 m from a large (>2100 trees) dataset encompassing California, Oregon, and Washington. Our study trees averaged 16.2 m at the end of the study period, which is similar to the estimate from Gould et al. (2011). Thus, our study trees may have already been at their maximum height expected from this site type (i.e. site quality) at time of treatment, or the height growth response was inhibited by prolonged suppression. Earlier intervention, prior to full overtopping and suppression of the oak trees, may have allowed (presumably) healthier crowns to respond more favorably to the treatment. The differences in height to live crown among treatments may reflect differences in epicormic branching following crown damage from the ice storm (see below) rather than treatment effects on crown resource allocation, as there were no differences among treatments at year 10 prior to the storm.

Effects of Ice Damage on Treatment Response

The significant relationship between percent BA growth and estimated crown in the release treatments provides evidence that loss of crown biomass in those treatments reduced subsequent growth. Other studies in other ecosystems that have evaluated the response of *Quercus* spp. to ice crown damage have also documented reductions in growth that are related to the amount of crown damage (Turcotte et al. 2012; Sholes 2013). Crown position or canopy openness has been shown to influence damage, where trees in the upper crown positions or occurring under open canopies generally having greater crown damage than trees in lower crown positions or under closed canopy conditions (Rebertus et al. 1997; Kraemer & Nyland 2010; Turcotte et al. 2012). Here, ice crown damage was highest in the control (29%) and lowest in the full release treatment (21%). Thus, the general pattern of crown damage in our trees was opposite what would be expected from previous studies, possibly because of stronger branch development following release or more open canopy conditions that reduced ice buildup.

The lack of any effect of crown damage on subsequent growth in the control treatment may reflect other factors that are more constraining to growth than crown biomass; release treatments were already responding favorably to increased resource availability, which may have been counteracted by the negative effects of crown damage (i.e. the effect was detectable because of the increase in growth that was occurring). Regardless of the mechanism, the relationship between crown damage and biomass increment in the release treatments can be used to assess their continued viability over time, and the need for additional management actions such as follow-up release treatments for removal of Douglas-fir in growth.

Additional Considerations

Release treatments that remove only a portion of encroaching trees are not intended to restore functional oak savannas. Rather, they are a management action that can be taken to increase the vigor of individual oak trees and inhibit the process of encroachment that typically ends with oak mortality (Cocking et al. 2015). The release treatments we assessed are relevant to operational management; similar treatments are being tested in other ecosystems to promote the resilience and growth of at-risk or desirable species (e.g. Lariviere et al. 2021; Tomback et al. 2022). In most instances, these treatments align with management objectives (e.g. continued supply of Douglas-fir fiber) or in response to limited resources (e.g. insufficient funds to treat and maintain entire stands or landscapes).

The continuous positive response in diameter growth in the full release treatment indicates that this treatment is viable to increase the vigor of previously encroached and suppressed Oregon oak trees. Given the magnitude of diameter response, we conclude that this increase is biologically meaningful and likely to decrease the likelihood of tree mortality for a significant period of time (i.e. at least 20 years, but likely longer). In addition, Devine and Harrington (2013) also reported higher acorn production in the full release treatment during high mast years relative to the control treatment. We did not determine effects on acorn production in this recent assessment, but those previous findings indicate that release treatments may benefit wildlife dependent on this food source (e.g. acorn woodpeckers [Koenig & Haydock 2001, Altman and Stephens 2012] and the western gray squirrel [*Sciurus griseus*]; Ryan & Carey 1995).

Restoration treatments such as those evaluated here are often necessary to restore some semblance of ecosystem function following competitor encroachment. Mechanical removal of competing trees may be critical to maintaining Oregon oak savannas ecosystems given barriers to the use of prescribed fire (Wonkka et al. 2015; Schultz et al. 2019) and continued changes in climate. For example, recent work by Beckmann et al. (2021) had showed that encroaching Douglas-fir can reduce drought resistance of Oregon oak, making it more susceptible to drought events that are projected to become more frequent. Given this, release treatments may be a useful management tool to allow the species to persist in some semblance within the ecosystems it has historically inhabited.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. *F*-statistic probabilities for fixed effects of treatment, measurement period, and their interaction on diameter and height growth.

Table S2. *F*-statistic probabilities for fixed effects of treatment, measurement period, and their interaction on the competition metrics of relative density, total basal area, and sum line index.

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