

Early Responses to Crown Modification of California Black Oak Sprouts Initiated by High-Severity Wildfire

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Abstract

Hardwoods resprouting after wildfire or cutting develop as multistemmed clumps that gradually self-thin over time. There is increasing interest in thinning of sprouting species to accelerate the formation of tree characteristics important to indigenous cultural practices and wildlife such as large-diameter stems, large branches, broad crowns, and acorn production. We compared responses to three thinning treatments applied to black oak (*Quercus kelloggii*) resprouting after high-severity wildfire throughout northern California, USA. Basal area increment of the dominant stem was greatest after only one stem was retained, intermediate after three stems were retained, and lowest within unthinned oaks. Unwanted resprouting in response to the thinning was minimized by retaining three stems. Acorn production tended to increase as time elapsed since the fire (i.e., larger, older sprouts) but varied among sites and was noted as early as six years after fire at one site. More study is needed to test for the effects of thinning timing and intensity on the acceleration of acorn production as well as stem, branch, and crown size development over time.

Study Implications: California black oak is valued for mast production and wildlife habitat throughout its range in California and southern Oregon. After wildfire, sprouting oaks may assume a multistemmed shrub form that remains for decades. Treatment of sprouting California black oak after wildfire by thinning out sprouts can accelerate growth of the dominant stem and encourage apical dominance. This may offer an opportunity to recover hardwood forest cover in a burned landscape more rapidly than can be achieved without such treatments.

Keywords: forest thinning, *Quercus kelloggii*, forest restoration, silviculture, stump sprouts

Post-fire recovery of forests is a topic of concern in California, USA, where wildfires have become larger and more destructive (Riegel et al. 2018; Safford et al. 2022). The current fire regime in the region exhibits reduced pyrodiversity, increasingly shifting towards high-severity stand-replacing fire events (Hagmann et al. 2021). Native conifers are often killed by these high-severity events, and the impediments to successful post-fire conifer regeneration are well studied because conifers dominate throughout most California forests and many conifers produce merchantable timber (Crotteau et al. 2013; Williams et al. 2021). Conversely, native hardwoods are not generally managed for timber production as the market for hardwood commercial product has diminished in California. These species commonly suffer complete top kill and respond by resprouting at the base after high-severity wildfire (McDonald and Tappeiner 2002; Nemens et al. 2022). Consequently, there has been less concern about loss of hardwoods to fire, and less attention has been paid to post-fire hardwood regeneration.

Hardwoods are increasingly being recognized as providing important nontimber values, such as cultural resources, wildlife habitat, and other ecosystem services (Long et al.

2016, 2017). Oaks have long been a culturally important species for Native Americans, with acorns being a traditional indigenous staple food in many parts of the western United States (Anderson 2007). Among tribes across California, the California black oak is one of the most preferred species for food (Long et al. 2017). Hardwood sprouts of good form that are released from competition by removing adjacent stems in the sprout clump have the potential to quickly develop large branches, crowns, and stems with enhanced nontimber values (Long et al. 2016, 2017). Follow-up treatments such as release from inter- and intra-specific competition applied after basal sprouting may improve hardwood regeneration outcomes, but the benefits may not always outweigh the effort and cost of thinning (Barry et al. 1997).

California black oak (*Quercus kelloggii*) is a shade-intolerant hardwood that occurs naturally across foothills and lower mountains of California and western Oregon. Larger black oaks with thicker bark may benefit most from low-severity fire if they survive fire that removes competing trees and shrubs (McDonald 1969). Black oak sprouts vigorously after any top-killing disturbance (Regelbrugge and Conard 1993; Skinner et al. 2018; Stephens and Finney 2002). However,

these sprouting oaks may spend an extended period in a shrub-like form, with many stems and crowns extending to near the forest floor ([figure 1](#)). Sprouting black oaks will eventually self-thin to a point such that by age 50, most oaks will have one or two dominant stems ([McDonald 1969](#)). Forest managers are concerned with the difference between shrub-form and individuals expressing apical dominance of a single stem because single stem trees have the potential to develop a broad crown supported by a bole with cavities that provide important nesting habitat for some species of mammals and birds ([Purcell and Drynan 2008](#)).

There has long been interest in the possibility of accelerating the transition from a dense multistemmed sprout clump to a single stem or perhaps two dominant stems by thinning out sprouts at an early age ([Rodríguez-Calcerrada et al. 2011](#)). [McDonald \(1978\)](#) observed that sprout thinning before age 4 was not productive because dominance of individual stems was not yet in evidence and at a very early age, stems are tender and subject to being damaged by thinning surrounding stems. In addition, animal browsing can lead to mortality after thinning in very young clumps of black oak sprouts ([Longhurst 1956](#)). [McDonald \(1978\)](#), in a study of sprouting oaks thinned 4 years after disturbance, did not find any increase in height growth, but he did observe enhanced development of stem diameters after thinning to reduce the number of stems. His study was conducted on a single site (Challenge Experimental Forest), with high site quality, so extrapolation across the range of California black oak is unwarranted. Therefore, it is not known whether thinning out basal sprouts within individual black oaks promotes development of desirable characteristics of single-stemmed oaks. There may also

be unwanted consequences, such as resprouting in response to the thinning disturbance, as noted with other oak species ([Ducrey and Toth 1992](#); [Espelta et al. 2003](#); [López-Serrano et al. 2010](#); [Rodríguez-Calcerrada et al. 2011](#)).

The intent of this study was to observe the dynamics of black oaks that were regenerating in response to top kill due to wildfire, with and without manual removal of stems intended to release well-formed dominant stems within the regenerating oaks. Our objectives were to quantify effects of thinning of stems on diameter and height growth of the dominant stem as well as other attributes such as crown morphology and seed production. We hypothesized that time-since-fire (i.e., time elapsed after top kill and subsequent sprout regeneration until the time of thinning) would be influential, such that later thinning would result in a slower growth response but also less resprouting in response to the thinning treatment. We also hypothesized that clumps thinned to retain only one stem would exhibit a greater stem diameter growth response than those thinned to retain three stems, yet both treatments would have greater stem diameter response than untreated oaks. Similarly, we expected rapid crown expansion after thinning, especially thinning to one stem. We did not expect any height growth response but did hypothesize that thinning could affect acorn production following thinning when compared against black oaks left untreated.

Methods

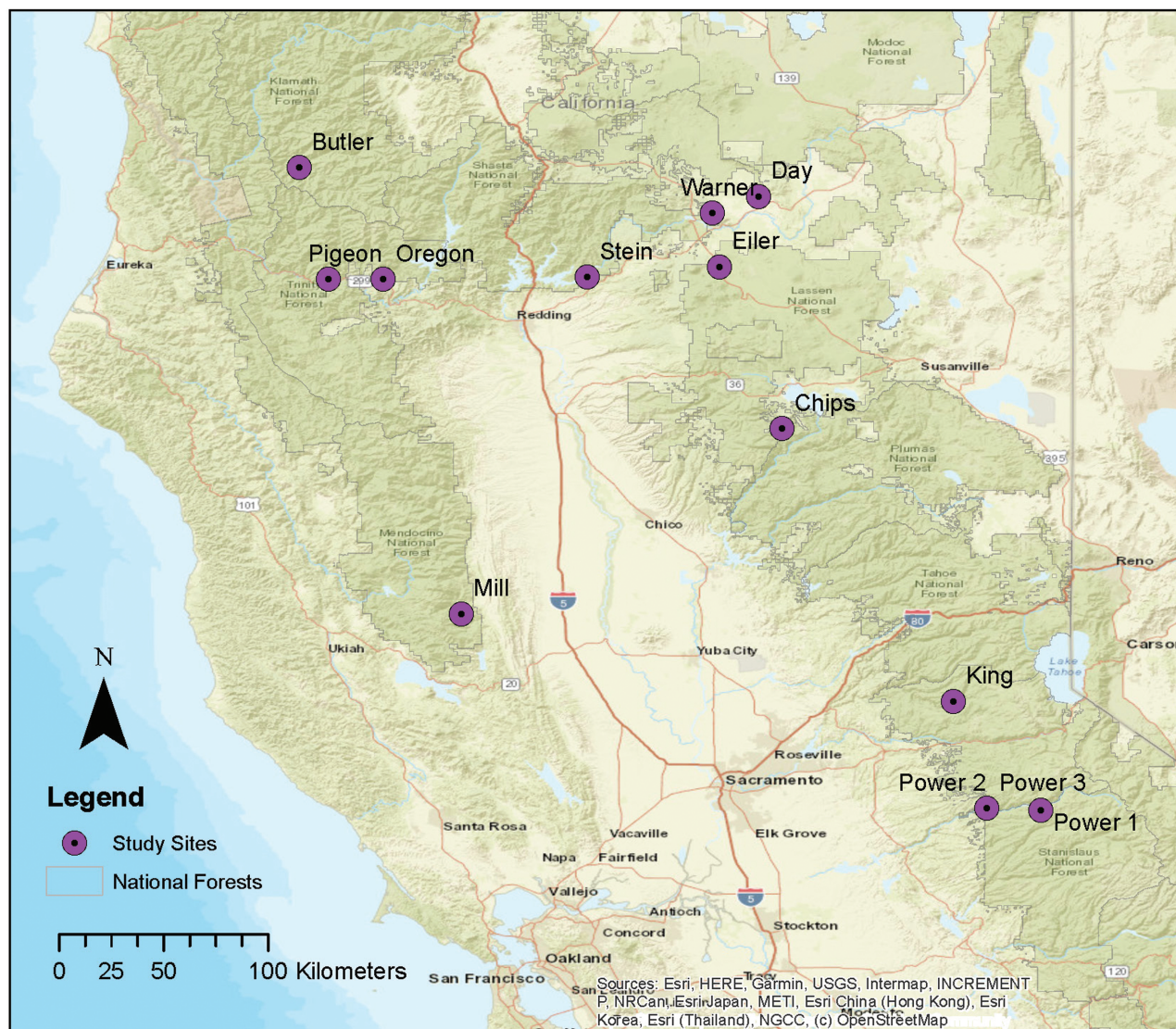
We considered sites for selection by examination of satellite imagery and consulting with land managers for sites where black oak was in abundance. Sites were selected for study



Figure 1 Untreated California black oak sprout. Photo credit: Ethan Hammett, USDA Forest Service.

from burned areas on national forests and private land spanning northern California and representing a range of times since fire (figure 2). Only sites readily accessible were chosen, no wilderness or roadless areas were considered. Within each site, a 300 m transect (perpendicular to the contour) was

established and qualifying oaks were selected that fell within 15 m of the transect. An oak was qualified for selection if it had an existing snag >10 cm breast height diameter (dbh) and at least four sprouting stems. Treatments were allocated alternatively with each selected sprouting oak for the King



Fire (Site) Name	Burned	Treated	Ownership	Latitude	Longitude
Oregon	2001	2017	Shasta Trinity NF	40.76269	-122.9674
Power 1	2004	2018	El Dorado NF	38.47473	-120.13475
Power 2	2004	2018	El Dorado NF	38.48303	-120.3681
Power 3	2004	2018	El Dorado NF	38.48437	-120.36669
Pigeon	2006	2017	Shasta Trinity NF	40.76305	-123.20311
Stein	2008	2017	Private	40.7724	-122.09028
Mill	2012	2017	Mendocino NF	39.3213	-122.63151
Chips	2012	2017	Lassen NF	40.12044	-121.24916
Butler	2013	2017	Klamath NF	41.24416	-123.3311
Warner	2013	2017	Lassen NF	41.04919	-121.55
Day	2014	2017	Lassen NF	41.12028	-121.35049
Eiler	2014	2017	Lassen NF	40.81666	-121.51912
King	2014	2017	Tahoe NF	38.94508	-120.50992

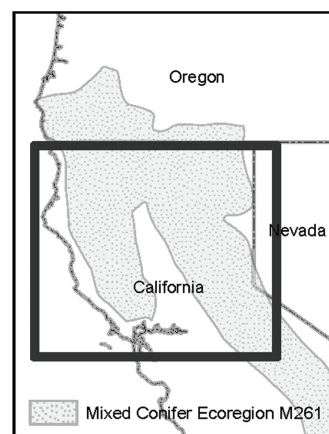


Figure 2 Study sites selected for observation of California black oak in northern California.

Fire and Mill Fire sites; all other sites treatment was assigned randomly. Individual oaks were selected that had been completely top-killed with at least four resprouting stems >140 cm in height. In addition, oaks with a neighboring oak within 5 m were not selected to ensure that only single individuals were being assessed and no belowground fusing would be influencing our aboveground observations.

If insufficient oaks were encountered in the 300 m transect then the recorder offset 30 m and returned 180 degrees until at least fifteen oaks were selected. All sites had five sprouting oaks for each treatment (fifteen oaks sampled in total), except for the King Fire, which had seven replicates (twenty-one oaks sampled in total).

The three treatments applied were (1) thin to one remaining dominant stem determined to be a single sprout having better-than-average size, form, and perceived stability (i.e., no excessive sweep, crook, forking, dead top or other major defects); (2) thin to three remaining dominant stems well-spaced about the snag; and (3) apply no treatment.

For treatments 1 and 2, the time to complete the removal of stems, including lopping, was timed to the nearest second; travel time to the tree was not included. Stems were removed with loppers for stems <7 cm basal diameter, and by handsaw or chainsaw when >7 cm. Cut material was dragged away a minimum of 2 m from the sprout clump, and lop and scattered to a fuel bed depth of <40 cm.

For each selected sprouting oak, height and height to crown base were measured vertically from a permanently marked ground point upwards to the highest living point or lowest live branch (to the nearest centimeter). Breast height diameter was recorded for the three largest stems (to the nearest millimeter). Crown width was observed with two perpendicular measurements (to the nearest centimeter) of horizontal limit of all branches in the sprouting oak. Crown volume was estimated using the three crown measurements and an assumed ellipsoidal form:

$$\text{Crown Volume} = \frac{4}{3}\pi \left(\frac{\text{crown length}}{2} \right) \times \text{crown radius long} \times \text{crown radius short}$$

Total number of sprouts, crown width, and height were recorded before and after treatment. One year following treatment, oaks were visited to assess immediate resprouting response to treatment. The sprouting oaks were observed again 3 years after treatment.

Because the focus of the treatment was to produce a single-stemmed individual in the long run, we considered growth of the largest sprouting stem. Basal area increment in square centimeters of the largest stem (BAI) was calculated for the 3-year period of observation as

$$\text{BAI} = \pi \left[\left(\frac{dbh_3}{2} \right)^2 - \left(\frac{dbh_0}{2} \right)^2 \right] \times 0.01$$

where dbh_0 is the diameter of the largest stem at study initiation and dbh_3 is breast height diameter of the same stem at the end of the 3-year period, measured in millimeters.

Two sites were eliminated due to damage sustained within 3 years after treatment. The Mill Fire site returned in a subsequent wildfire and the King Fire site was severely damaged by firewood cutters after treatments were installed. Neither of these sites were remeasured and are not included in the analysis of 3-year change in sprout dimensions, but

they are included in the consideration of time for treatment implementation.

To develop an index of acorn production, crews counted acorns from one side for 30 seconds. Acorns on the ground were not included in the count. If too many acorns were present to complete a full count in this time, acorn quantities were estimated to the nearest ten acorns. This was then repeated at 180 degrees from the first count and the sum was recorded.

Data were presented graphically and analyzed using mixed-effects modeling with R Statistical Software (v4.0.4; R Core Team 2021). For mixed-effects modeling the *nlme* package (version 3.1) was used. Treatments were included as fixed effects and a linear, site-specific, random effect was included for size. We could find no evidence of a nonlinear tree-size relationship because of the relatively limited range of sizes within any given site.

Results

Our immediate post-fire dataset comprised 158 sprouting California black oaks, including fifty-two untreated, fifty-three thinned to retain one dominant stem, and fifty-three thinned to retain three dominant stems. The original black oaks that had been top-killed by fire covered a wide range of sizes (2.2–71.1 cm dbh; Table 1). The observed stem sprout count range was four to thirty-one stems. On average, more sprouts were associated with larger snags; however, this relationship was quite variable ($R^2 = 0.20$). The pre-treatment crown area and total height also varied widely (Table 1).

The time for treatment implementation varied by pretreatment size of the sprout clump and was generally greater when only one stem was retained (mean of 13.8 minutes) than when three were retained (mean of 10.6 minutes) (figure 3).

Crown Volume Reduction from Thinning

Crown volume of each sprouting oak, derived from an assumed ellipsoid, was reduced by thinning (figure 4). The ratio between observed mean treated volume and the associated mean for untreated sprouting oaks indicated that, on average, thinning to retain one stem reduced crown volume by approximately 77% (i.e., 23% crown volume ratio) whereas thinning to retain three stems reduced crown volume by approximately 47% (i.e., 53% crown volume ratio) in relation to crown volume of unthinned oaks. Crown volume ratio was much smaller at the beginning of the study when compared with the same metric 3 years later, indicative of rapid crown volume recovery towards a ratio of one where thinned and unthinned oaks would have equal crown volume. Over 3 years, the ratio increased from 53% to 69% after thinning to retain three stems, and from 23% to 47% after thinning to retain one stem (figure 4). We observed no trend over time

Table 1. Black oak post-fire summary data, from initial pretreatment observations for thirteen sites throughout northern California.

Variable	Minimum	Mean	Maximum	Standard deviation
Snag dbh, cm	2.2	16.3	71.1	10.3
Stem count	4	11.2	31	5.6
Crown area, m ²	2.5	14.7	44.9	9.1
Height, m	1.7	4.2	8.5	1.7

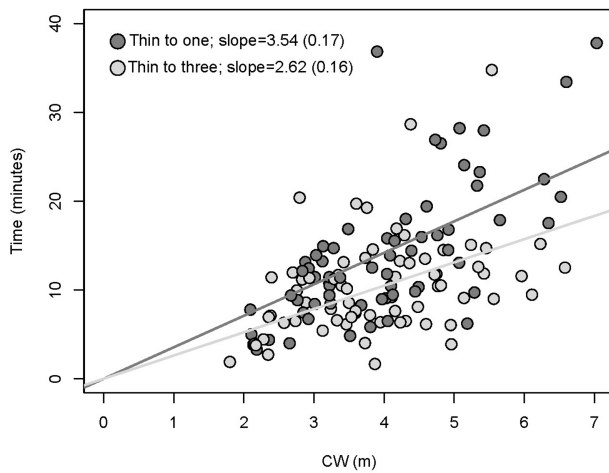


Figure 3 Relation between crown width (CW) of sprouting oaks at study initiation and time to complete thinning to retain one or three stems (ordinary least squares regression R^2 in parentheses).

since fire ($P > 0.20$). We attempted to model crown volume increment but found no treatment effect.

Diameter Growth Enhancement from Thinning

The mixed-effects regression analysis indicated that thinning of black oak stems within sprouting oaks enhanced BAI of the retained dominant stem. This enhancement was much larger when only one stem was retained versus when three stems were retained (Table 2). Additionally, we detected a stem-size effect where the BAI of dominant stems was higher when these stems were larger at the time of treatment. To derive estimates of increase in increment for any site, it is necessary to assume a given dbh and use the site-level random size effect. With this step, the model predicted, for example, when compared against leaving resprouting black oak untreated, that thinning down to three well-spaced 5 cm dbh stems gave a 25% increase in BAI of the retained dominant stem over the first 3 years; thinning to retain a single 5 cm dbh stem resulted in a 70% increase in BAI of that stem over the first 3 years. In contrast to BAI, we found no evidence of treatment influence on height increment (Table 2).

Resprouting in Response to Thinning

We did not observe mortality on any dominant stems during the course of this study. Three years after thinning within clumps to retain three stems per clump, some had one to four new sprouts, but few (13%) resprouted in response to the thinning treatment. This produced a mean of only 0.22 new sprouts (95% confidence interval [CI]: 0.03–0.42) assumed to have been initiated in response to the thinning treatment where three stems were retained. Thus, for these individuals, the mean count at the end of the period was 3.22. By contrast, 3 years after the heaviest thinning treatment where only one stem was retained, 68% of oaks resprouted with one to twenty-four new sprouts, and we observed a mean of 4.32 resprouts (95% CI: 2.77–5.87) (figure 5). In contrast, untreated oaks tended to lose sprouts over the 3-year period (mean of -1.37, s.e.=0.38).

Acorn Production

Acorn production within the first 20 years of black oak resprouting after fire-induced top kill was highly variable.

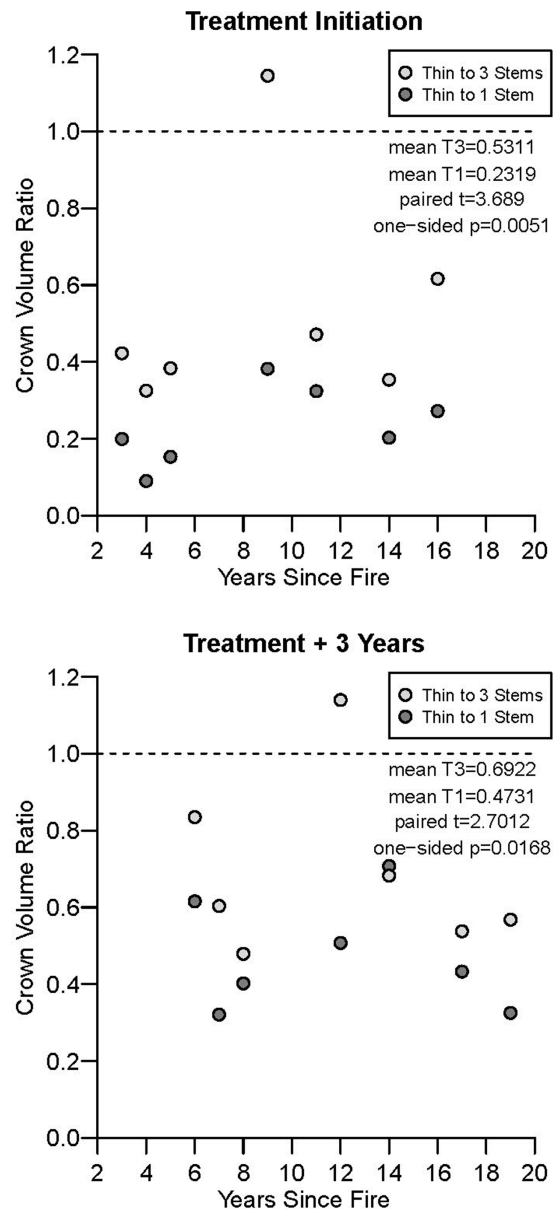


Figure 4 Crown volume ratio (mean crown volume treated/mean crown volume untreated) for two thinning treatments, immediately after treatment and 3 years later (P -value tests difference between thinning to one stem and thinning to three stems).

At the time of study initiation, only sites >10 years since fire were producing acorns. For trees with acorns the mean count index was 30 (s.d.=36, $n = 21$). However, three years later, all but one of the sites (Stein Fire) were producing acorns and the mean count was 119 (s.d.=167, $n = 157$). Numerous factors may influence acorn productivity (site productivity, time since burn, genetic variation, etc.) and these factors vary from site to site. Due to this high uncontrolled site-to-site variability, we did not have sufficient data to test for thinning effects. We can report averages across all treatments (including unthinned individuals) at two assessment times. At the time of study initiation, in the absence of thinning, acorns were absent on younger sites and visible on a varying percentage of oaks having time-since-fire of 11+ years. A higher percentage of these had acorns 3 years after treatment, including those with only 6 years of time

Table 2. Linear mixed effects analysis ($n = 158$) of 3-year dominant stem basal area increment (cm^2) and height increment (cm), as a function of thinning treatment type (fixed), and random-effect covariates: initial size in terms of dominant stem dbh or height respectively. Note that “-C” indicates the effect is adjusted by subtracting the control.

Basal area increment			
Treatment	Effect (cm^2)	S.E. (cm^2)	P
Control	5.190	1.587	.0013
Thin 1-C	11.73	1.670	.0000
Thin 3-C	4.220	1.671	.0126

Height increment			
Treatment	Effect (cm)	S.E. (cm)	P
Control	64.14	16.50	.0002
Thin 1-C	3.941	6.838	.5652
Thin 3-C	-1.349	7.012	.8477

elapsed since fire (Table 3). These percentages were based on acorn presence in thinned and untreated oaks combined. Unexplained extreme values included the absence of acorns at one site (time-since-fire: 9 and 12 years), the high percentage of oaks with acorns 3 years after thinning at one site with time-since-fire of only 8 years, and the low percentage of sprouting oaks with acorns within the southernmost Power Fire footprint. Unlike all other sites that were each located within a different wildfire footprint, all three sites that were thinned 14 years after fire were located within the Power Fire footprint.

Discussion

Our results indicate that thinning oak sprouts will increase stem BAI and reduce crown dimensions, although long-term studies will be needed to evaluate duration of these effects. There may be an optimal window for thinning black oak sprouts of between 4 and 6 years after a fire. Previous work suggested waiting at least 4 years after fire, which would allow time for expression of stem dominance (McDonald and Tappeiner 2002). However, at our earliest entry (age 3) in the King Fire, we did not encounter any problems. We found that delaying treatments for much longer periods will increase the time and effort required to remove stems (e.g., using a chainsaw rather than loppers). When the crown width was <3 m, individual stems were smaller and thinning of one sprouting oak could usually be completed in less than 10 minutes with loppers. Our data indicated that resprouting oaks can already have >3 m crown width after 3 years on high quality sites.

Crown Volume Response

Crown volume, not surprisingly, was reduced by the thinning treatment. However, the progression of crown volume ratio toward one over the study period (i.e., where thinned and unthinned oaks had equal crown volume) was indicative of rapid recovery. This suggests that in the longer term, there may be little effect on the total volume of the crowns except that thinning allowed each residual stem to develop a larger individual crown. This is consistent with our inability to find

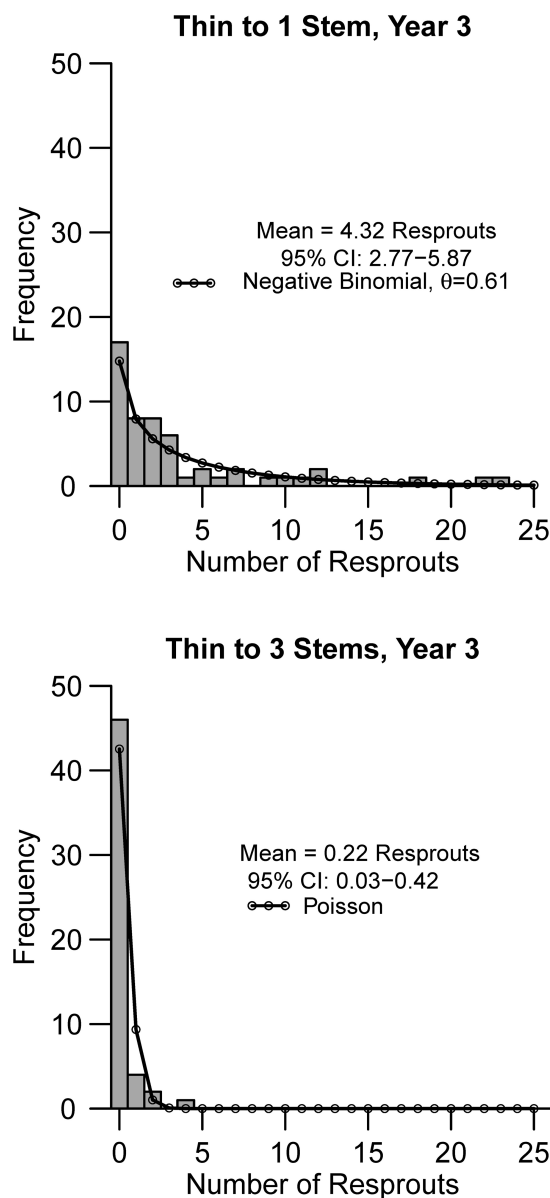


Figure 5 Frequency distribution of resprouts arising 3 years after thinning to retain one or three stems within sprouting black oaks.

any treatment effects on crown volume increment. Thinning to three stems appeared to reduce crown size less than thinning to one stem, but this difference also appeared to lessen over the 3-year observation period.

Diameter Growth and Resprouting Response

We did not identify one optimal thinning treatment. Thinning within sprouting black oaks induced a positive diameter growth response of the largest remaining stem and thinning to one stem produced greater increase in increment than thinning to three. Similarly, McDonald and Vaughn (2007) observed greater diameter growth of a single black oak sprout when compared against clumps of two to four sprouts; however, this was in a 60-year-old stand of hardwood sprouts.

Future benefits associated with the enhancement of stem BAI after thinning to retain only one stem within a black oak may have been offset by resprouting in response to this thinning disturbance. We assume that the large reduction

Table 3. Percentage of post-fire oak sprouts bearing acorns at the time of study implementation and 3 years later. Subscripted number denotes number of sites. Sample size at implementation ($n = 201$) includes some oaks that could only be assessed at the start but were lost due to damage.

Time of study implementation		3 years after treatment	
Years since fire	Percentage	Years since fire	Percentage
3 ₃	0	6 ₂	14
4 ₂	0	7 ₂	15
5 ₂	0	8 ₁	93
9 ₁	0	12 ₁	0
11 ₁	86	14 ₁	100
14 ₃	2	17 ₃	12
16 ₁	46	19 ₁	100

in leaf area signaled to the plant that more leaf area was required, inciting a resprouting response (Del Tredici 2001). Resprouting of stems soon after thinning to reduce stem density may negate any benefits of thinning. In contrast, thinning down to three stems was followed by very little resprouting. Our findings are consistent with responses to thinning of sprout clumps of two oak species in Spain, having similar dry summer climate, where thinning to retain three sprouts resulted in fewer instances of resprouting; yet unlike black oak, the three residual sprouts per clump exhibited more similar growth rates in response to thinning than the single sprout retained for comparison (Espelta et al. 2003). We found the growth responses of California black oak sprouts to be consistent with other studies of oaks adapted to Mediterranean climates, where heavier thinning within sprouting oaks generally led to enhanced growth of the residual stems (Ducrey and Toth 1992; Mayor and Roda 1993; Montes et al. 2004).

Repeat measurements giving longer-term response data are needed to show whether the effect on diameter growth is only short-lived or sustained into the future, and if there is an effect of time-since-fire (i.e., sprout age) when thinning is applied (Tappeiner and McDonald 1980) and stool age or size/age of the oak tree that was killed and resprouted (Espelta et al. 2003). We recommend future testing for an interaction between time-since-fire and thinning intensity, where delayed thinning may induce less resprouting (McDonald and Tappeiner 2002). Sprouts can be damaged by various disturbances, including when the fire-killed oak snag breaks and falls. As a risk mitigation strategy, oaks thinned to retain two or more stems would be more likely to have at least one surviving stem, whereas single-stem individuals sustaining future damage to that stem could lose any benefit of the thinning treatment. Future studies might also include extra treatments, in particular, a treatment of intermediate intensity where thinning to retain two dominant stems is tested. In the interim, McDonald and Tappeiner (2002) offer a conservative recommendation of retaining three to four sprouts per black oak, with these sprouts spaced evenly around the base of the snag. We also recommend expanding this study to include other hardwood species that resprout after fire and after other disturbances resulting in top kill. Consideration should also be given to the fate of surface fuels generated by these thinning treatments. For example, we moved cut stems away from clumps instead of leaving fuel accumulated adjacent to clumps where they may aggravate reburn fire damage

to thinned oaks. Piling and burning may be warranted, especially after delayed thinning in larger individuals where more biomass is removed.

Acorn Production

Among other oak species, acorn production has been observed to be variable both temporally and among individuals within the population (Greenberg and Parresol 2002). Acorn production in California black oak is likely tied to multiple factors and their interactions as well. For instance, there may be some genetic variation across the region as well as differences in soils and climate. More data are needed to study patterns of acorn production in response to treatment intensity (Espelta et al. 2003) and timing (Longhurst 1956), time since sprout initiation as it relates to sprout sizes and crown volume (Greenberg and Parresol 2002; Healy et al. 1999; Tappeiner and McDonald 1980), exposure to sunlight (Hammett et al. 2017; Johnson 1994), genetics, edaphic factors, climate, topography, geographic location, and periodicity of acorn production (Greenberg 2000; Healy et al. 1999). Nevertheless, our basic acorn summary data indicate that acorn production resumes sooner after fire than the 30-year threshold of McDonald (1978) but with some variation among sites.

We expected variability among sites because our large-scale study included sites in the Klamath Mountains, the central and northern Sierra Nevada Mountains, and the southern Cascades where black oak is found in several different forest cover types (Eyre 1980; McDonald 1990). Our data revealing early acorn production are consistent with other reports. Crotteau et al. (2015) noted presence of acorns on black oak that had resprouted 11–12 years earlier within the Storrie Fire footprint on the Lassen National Forest in the northern Sierra Nevada Mountains of California. Acorns were noted as early as age 5 on sprouts growing in full sun after clearcutting (McDonald and Tappeiner 2002).

There also appears to be potential for accelerated acorn production via thinning within black oak sprout clumps as suggested by the rapid increase in number of sites and percentage of oaks producing acorns within 3 years of thinning treatment implementation across our study sites. Rodríguez-Calcerrada et al. (2011) found greater production of acorns after thinning of sprouting oaks in Spain, suggesting promise for thinning as a tool to accelerate production of acorns after wildfires that eliminated much animal habitat and forage. However, drought lessened the positive response of acorn production to thinning (Rodríguez-Calcerrada et al. 2011). Due to the spatial and temporal variability present in black oak acorn production at our study sites across northern California, we were not able to reliably quantify acorn production response to thinning treatment. Our assessment of acorns 3 years after thinning may also have been too early to detect responses. Wiley et al. (2017) found that loss of leaf area prompted black oak to re-allocate carbon away from growth and new reproduction (2-year cycle) and into storage and reproduction initiated before thinning. Therefore, we recommend a second assessment of acorns and growth responses that may follow a posttreatment lag period. Nevertheless, we did observe that crown volume quickly rebounded after treatments over the 3-year observation period. Although longer-term observations are needed to confirm whether this trend will hold, it may bode well for future acorn production,

given that studies in other oak species have found that acorn production is closely related to crown dimensions (Sork et al. 1993). Previous studies in Oregon white oak (*Quercus garryana*) indicated that broad open-grown “mushroom-shaped” crowns resulted in the best acorn production compared with narrower “vase-shaped” crowns (Peter and Harrington 2002). However, relationships between stem development, crown dimensions, and acorn production are not necessarily clear because they may be confounded with site quality. McDonald (1969) reported that black oaks with multiple persistent sprouts were more common on poor quality sites, which he contrasted with “open grown” trees on better sites that are “prone to fork repeatedly, becoming multi-stemmed and broad crowned” (p. 12). Promoting a single main stem with a broad crown could also confer greater resistance to fire by raising canopy height (Espelta et al. 2012) or increasing relative bark thickness (Schwilk et al. 2013). Increasing resistance to fire could enhance long-term acorn production via greater survival of mature crowns.

In summary, land managers engaged in post-fire thinning of California black oak sprouts can expect enhancement in the diameter growth of resprouting oaks after stem thinning. Retention of more than one sprout, although causing a reduction in growth of the primary stem, may be warranted to avoid excessive resprouting while accelerating diameter and crown development of the residual sprouts and to have extra stems that provide for redundancy in case of damage or loss of stems. Because there is no clear economic benefit to these treatments, it may be difficult to justify large scale implementation. Thus, minimizing costs by treating early is advisable. More data are needed to affirm the expected longer-term benefits of thinning on branch and crown development and early acorn production from black oak stump sprouts regenerating after wildfire.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

Conflict of Interest

The authors have no conflicts of interest to declare.

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