RESEARCH ARTICLE

Effects of Prescribed Fires on Young Valley Oak Trees at a Research Restoration Site in the Central Valley of California

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Abstract

Woodland restoration sites planted with *Quercus lobata* (valley oak) often have serious invasions of nonnative annual grasses and thistles. Although prescribed fire can effectively control these exotics, restoration managers may be reluctant to use fire if it causes substantial mortality of recently planted saplings. We studied the effects of prescribed fires on the survival and subsequent growth of 5- and 6-year-old valley oak saplings at a research field near Davis, California. One set of blocks was burned in summer 2003 at a time that would control yellow star thistle, a second set of blocks was burned in spring 2004 at a time that would control annual grasses, and a third set was left unburned. Very few oaks died as a result of either fire (3–4%). Although a large proportion was top-killed (66–72%), virtually all these were coppiced and most saplings over 300 cm tall escaped top-kill. Tree height, fire temperature, and understory biomass were all predictive of the severity of sapling response to fire. Although the mean sapling height was initially reduced by the fires, the growth rates of burned saplings significantly exceeded the growth rates of unburned control trees for 2 years following the fires. By 2–3 years after the fires, the mean height of spring- and summer-burned saplings was similar to that of the unburned control saplings. The presence of valley oak saplings does not appear to preclude the use of a single prescribed burn to control understory invasives, particularly if saplings are over 300 cm tall.

Key words: prescribed burn, fire temperature, *Quercus lobata*, valley oak, top-kill, basal sprout.

Introduction

Oak woodlands in California have been greatly reduced in the last 100 years, and the vast riparian woodlands dominated by *Quercus lobata* (valley oak) have been almost completely eliminated by conversion to cropland and development (Katibah 1984; Vaghti & Greco 2007). In addition, surviving oak populations of many species exhibit severe long-term recruitment failures that have created stands virtually devoid of saplings and young trees (Griffin 1976; Bolsinger 1988). In recent years, there has been considerable effort at restoring oak woodlands, and valley oaks are one of the most frequently planted trees at riparian restoration sites in the Central Valley (Young & Evans 2005).

Although natural oak stands often exhibit recruitment failure, the establishment of young valley oak saplings through active restoration has met with widespread success, but the establishment of native understories in these ecosystems has been severely hampered by invasive annual plants such as

Aegilops triuncialis (goatgrass), *Taeniatherum caput-medusae* (medusahead), and *Centaurea solstitialis* (yellow star-thistle) (Stromberg et al. 2007). One of the more successful tools for dealing with these invasives is fire (DiTomaso et al. 2006), which is increasingly being used in strategies to restore Central Valley grasslands (Lulow et al. 2007; Stromberg et al. 2007). However, in sites where oak saplings have been planted, there is concern about the effects of fire on these young trees (Swiecki & Bernhardt 1998; Mitch Sears, Chris Alford, Jeremiah Mann, personal communications).

There are reasons to believe that these communities, and oak trees in particular, have evolved in a naturally fire-prone ecosystem and survived anthropogenic fires for many centuries. Plant communities in California's Mediterranean climate have probably always endured fires (Greenlee & Langenheim 1990), and many of its plant species, including most oaks, exhibit adaptations to fire, such as basal sprouting and thick bark (Pavlik et al. 1991), similar to other woodland and savanna species worldwide (Gignoux et al. 1997; Bond & Midgley 2000; Hoffmann & Solbrig 2003). Native Americans are thought to have set frequent, low-intensity fires in Central Valley grasslands and oak woodlands up until the 1800s (Greenlee & Langenheim 1990; Wills 2006). With the 1848 gold rush and the concomitant increase in ranching, fire frequency initially increased, but fire suppression eventually

became the norm (Biswell 1989; McClaran & Bartolome 1989; Wills 2006), and now fires in California's oak woodlands are rare (Greenlee & Langenheim 1990). The effects of fire on oak recruitment and mortality are still not fully understood (Barbour & Minnich 2000; Holmes et al. 2008) and there is disagreement about the appropriate ways to reintroduce fire into oak woodlands (Biswell 1989, Bartolome et al. 2002). Similar restoration of woody species is common in fire-prone communities with Mediterranean climates worldwide (Cione et al. 2002; Benayas et al. 2004; Pausas et al. 2004; Midoko-Iponga et al. 2005; Sanchez-Gomez et al. 2006; Alvarado-Sosa et al. 2007)

There are several potential benefits to reintroducing fire into California's oak communities. Many of the exotic species invading California's oak woodlands and grasslands are not adapted to fire (especially spring and early summer fire), and controlled burns have proven effective in controlling common understory exotics such as *Cytisus scoparius* (Scotch broom), yellow star thistle, and various annual grasses (Bossard et al. 2000; DiTomaso et al. 2006). Wildfire can also increase the presence of fire-adapted native species in the understory of oak woodlands (Dagit 2002) and reduce levels of the parasitic oak mistletoe *Phoradendron villosum* (Haggerty 1994).

Fire may directly promote the establishment of oak seedlings, perhaps by reducing competitive pressure from understory vegetation, releasing soil nutrients, reducing litter-born pathogens, or improving contact with mineral soils. There is evidence that fire increases the recruitment of *Q. kelloggii* (black oak) (Kauffman & Martin 1987) and *Q. garryana* (Oregon white oak) (Regan & Agee 2004), although the same has not been found for *Q. douglasii* (blue oak) (Allen-Diaz & Bartolome 1992) or valley oak (Swiecki & Bernhardt 1998).

Unfortunately, reintroduction of fire is not without risk. Although mature individuals of many oak species usually survive fires, seedling and saplings are at greater risk. A survey of studies investigating the effects of fire on seven different species of California oak species found that mortality rates generally ranged between 1 and 11% for mature oaks, 2 and 10% for sapling oaks, and 17 and 52% for seedling oaks (Holmes et al. 2008). Although fire does not usually cause complete death of sapling oaks, it does result in top-kill 75–90% of the time (Holmes et al. 2008). Top-kill occurs when aboveground portions of saplings die, but subsequently recover via sprouting of new basal coppice shoots (Fry 2008). Even if these basal sprouting individuals survive fire, they are at risk of damage from deer browsing or subsequent fires until their coppice shoots grow up through susceptible height classes (Bartolome et al. 2002; Swiecki & Bernhardt 2002).

Several studies have investigated the effects of fire on non-sapling-sized valley oaks (Griffin 1980; Schwan et al. 1997; Fry 2008). However, no studies have comprehensively examined the effects of fire on sapling-aged valley oak individuals (Holmes et al. 2008), or of planted young oaks in a restoration setting. Newly planted valley oak stands often have understories dominated by invasive annuals that limit the restoration of functioning oak woodland communities. Although prescribed burning can effectively control exotic grasses and thistles, there is reluctance to burn restoration-stage oak plantings because of uncertainty over the effects of such burns on the young planted oaks (Swiecki & Bernhardt 1998; Chris Alford, Mitch Sears, personal communication).

The purpose of this study was to (1) investigate the response of sapling valley oaks to late spring and early summer prescribed fires; (2) identify predictors of sapling valley oak fire response and develop critical thresholds for mortality and top-kill; and (3) determine postfire growth rate and height recovery of valley oak saplings.

Methods

Study Site

Our study site was a 2 ha research field near Davis, California (38°31′26″N, 121°45′31″W). It experiences a Mediterranean climate, with rain restricted to the winter months. Mean annual rainfall is 18 inches (462 mm). Total winter rainfalls in 2003/2004 and 2004/2005 were 14.2 inches (360 mm) and 21.8 inches (554 mm), respectively. The original vegetation was likely valley oak woodland.

The site was planted with several hundred valley oak acorns and seedlings in the winter of 1999 as part of a separate restoration experiment (Hobbs & Young 2001; Young & Evans 2000, 2005). The original experiment was divided into 54 plots of nine oaks each, which received different combinations of planting stock (seed vs. container stock), and irrigation (none, 1 year, or 2 years). The experiment concluded in 2000 and 278 trees remained at the site by spring 2003. There had been no weed control or supplemental irrigation since 2000.

There was no overstory canopy layer at the site other than the planted oaks, and the understory layer was dominated by nonnative annual grasses (including *Bromus diandrus*, *Avena barbata*, *Lolium multiflorum*, and *Hordeum murinum*) and *Centaurea solstitialis* (yellow star thistle).

Burn Blocks and Tree Heights

There were still some residual differences in tree size due to the previous restoration experiment, which we mitigated in two ways. First, we combined pairs of adjacent plots (with different experimental histories) into 27 blocks of 72 m² each, with an average of 10 trees per block. Second, the burn treatments assigned to these blocks were stratified across previous experimental history and regularly interspersed. Nine blocks were assigned a summer burn treatment, nine were assigned a spring burn treatment, and nine were left unburned as a control. Of these 27 blocks, 1 (a control) had only 3 small trees (mean 2003 height, 49 cm), and was excluded from analysis. The net result was three sets of eight to nine fire treatment blocks that were similar in mean and variance of tree size (see Fig. 1).

The two burn treatments were carried out at two different times of a year, but were also each carried out once and in different years, so are not a direct test for the effects of burn timing (or year effects, or tree age). However, their consistent effects do add a greater confidence in the generality of our
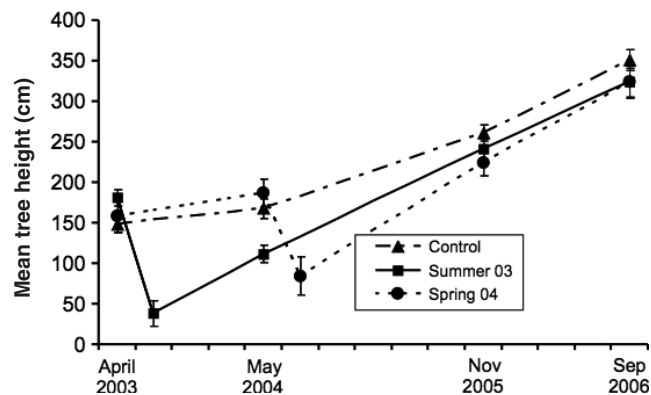
Figure 1. Mean height of *Quercus lobata* saplings over a 3.5 year period by burn treatment: unburned control, Summer03 prescribed burn, and Spring04 prescribed burn. Analysis is by burn treatment, treating the eight or nine fire blocks per treatment as replicates. Error bars denote one standard error.

conclusions. We called them Summer03 and Spring04 burns here to emphasize these multiple factors.

Summer 2003 Burn

In April 2003, the height was measured for all the trees in all the three treatments. For those trees included in the Summer03 burn treatment, the grass biomass under each tree was assigned a density level of 1 (low) through 5 (high). Ceramic tiles painted with five different temperature-sensitive welding paints (at regular intervals between 79 and 399°C) were hung at a height of 30 cm on each of the 88 Summer03-burn trees. Three weeks after the burn, the height of the top of the scorch level was measured for each tree. Three months after the burn, the survivorship of the main leader was assessed and the number of coppice sprouts and height of the tallest coppice were measured for each tree.

The Summer03 burn was conducted on 16 July 2003 from 12:00 pm until 4:00 p.m. During the burn, dry bulb temperatures averaged 34°C and average relative humidity was 37%. As recorded by the ceramic tiles, fire temperatures reached a high of 204°C with a mean of 95°C. Most of the litter and understory herb layer was consumed, although some patchiness was evident with small areas of litter only lightly charred. Fire carried into the crowns of many of the saplings and 26% percent of all individuals experienced 100% crown scorch, although leaves and small twigs were only rarely completely consumed by the fire.

Spring 2004 Burn

In May 2004, height measurements were taken again for all trees in all three treatments. Pre- and post-burn measurements similar to those described above for Summer03 burn trees were taken for all Spring04 burn trees. Aluminum tags painted with five different temperature-sensitive paints (at regular intervals between 79 and 232°C) were again used to measure fire temperature at each of the 94 Spring04-burn trees. In addition

to the aluminum tags, ceramic tags with the same paints were hung on 18 trees, to compare these two monitoring methods.

The Spring04 burn was conducted on 28 May 2004 from 11:00 am until 3:00 pm. During the burn, dry bulb temperatures averaged 23°C and the average relative humidity was 58%. As recorded by the aluminum tags, fire temperatures reached a high of at least 232°C with a mean of 197°C. For the 18 trees with both aluminum tags and ceramic tiles, mean aluminum tag temperature was 194°C and mean ceramic tile temperature was 141°C. As with the Summer03 burn, the litter and understory herb layer was mostly consumed, although patchiness was evident. High spring precipitation had created lush and uniform understory growth in 2004. Fuel ladders carried fire into the crowns of most of the saplings with 66% experiencing 100% crown scorch. As with the Summer03 burn, leaves and small twigs were usually not completely consumed by the fire.

Follow-up Measurements

In November 2005 and again in September 2006 the height was measured for all saplings in all three treatments, and main leader mortality and number of coppice sprouts were noted.

Statistical Analysis

Proportion of trees with different fire responses and mean heights for each year were calculated for each treatment block. Differences in sapling response to fire among the three treatments were compared with analysis of variance (ANOVA), treating the nine fire blocks per treatment as replicates (eight replicates for control).

Pre-burn tree height turned out to be a very strong correlate of tree fate (see Figs. 2 & 3) and averaging responses across trees within blocks would negate the most important covariate of fate for subsequent predictor analyses. We therefore used individual tree measurements in the multiple logistic regression analysis described below. Statistically, this means we treated all of the blocks within a given treatment as a single burn. Such pseudo-replication is not uncommon when performing difficult fire experiments (Van Mantgem et al. 2001), and we were at least partly protected from bias by the fact that the blocks we analyzed together had been previously stratified and interspersed in a manner that minimized potentially misleading block effects (see above).

We used multiple logistic regression to determine significant predictors of saplings' responses to fire. We used tree size, understory grass biomass class, and fire temperatures as predictors. In order to attain the minimum count and expected cell count frequencies necessary for statistical analyses, the two more severe response categories (death and top-kill) were combined. McFadden's ρ^2 values were used to determine the degree of correlation between predictive factors and tree response. Although McFadden's ρ^2 values are similar to the R^2 values of linear regression, they tend to be much lower and are considered highly satisfactory in the range of 0.2–0.4 (Tabachnick & Fidell 2001). Likelihood ratio tests were used
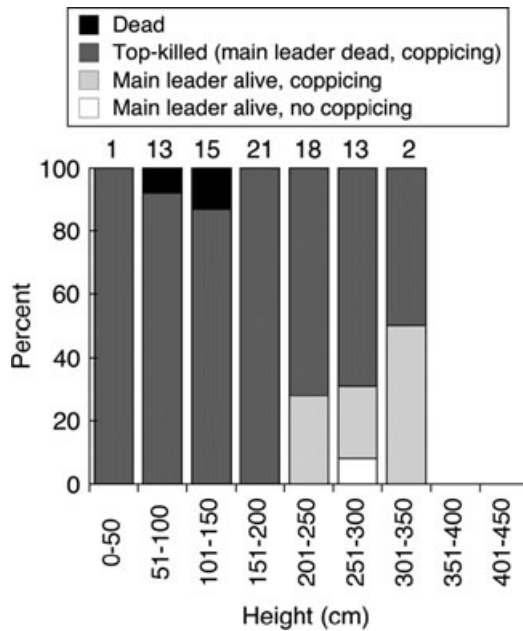
Figure 2. Proportions of *Quercus lobata* saplings of different heights that exhibited different fire responses in the Summer03 burn treatment. Sample sizes (shown above height classes) are the numbers of individual trees in each height class.
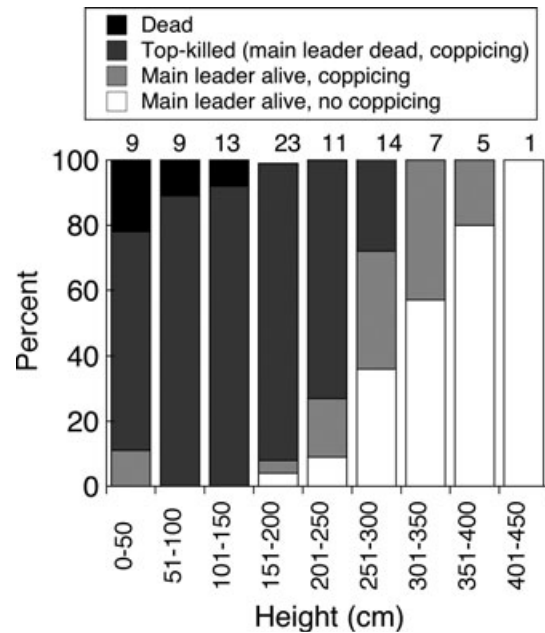

Figure 3. Proportions of *Quercus lobata* saplings of different heights that exhibited different fire responses in the Spring04 burn treatment. Sample sizes (shown above height classes) are the numbers of individual trees in each height class.

to determine which predictive factors were making significant contributions to the multiple logistic regression model.

Relative growth rates (RGR) of tree heights were used to compare the growth of burned trees versus control trees. The RGR during the first time interval following fire was calculated by (final height—post-burn height)/pre-burn height. The RGR of subsequent time intervals was calculated by (final height—initial height)/initial height. Mean RGR values for each block were calculated for each time interval. Growth rate comparisons (both RGR and absolute height) among fire treatments were made using ANOVA, treating the eight or nine fire blocks per treatment as replicates.

Results

Sapling Response to Fire

The burns resulted in three levels of sapling response with the most severe being entire tree death, followed by top-killed trees (dead main leader with sprouts from the tree base), and trees that still had live main leaders (Table 1). Very few of

the valley oak saplings died as a result of either fire (3–4%), although a majority of them were top-killed (66–72%). During the same time period, none of the control trees died or were top-killed. Basal sprouting was greatly increased by the burns, averaging 4.6 sprouts per tree, compared with less than 1 per tree in the control plots ($p < 0.001$). The latter was likely related to stem damage by small mammals.

Predictors of Sapling Response to Fire and Critical Thresholds

Multiple logistic regression indicated that a combination of pre-burn height, understory biomass, and fire temperature significantly predicted tree response to fire (Table 2). Each of these three factors also independently affected the severity of burn effects. For both Summer03 and Spring04 fires, smaller trees were more likely to exhibit a more severe burn response (either death or top-kill) than larger trees (Table 2). Fire temperature was also a good predictor of tree response to fire, with higher temperatures predictive of a more severe response

Table 1. Comparison of proportions of *Quercus lobata* saplings that exhibited different fire responses, and the mean number of basal sprouts per tree (±one s.e.), by burn treatment, treating the eight or nine fire blocks per treatment as replicates.

Treatment	Dead	Main Leader Dead, Basal Sprouting	Main Leader Alive	No. of Basal Sprouts	Total no. of Trees
Control	0.00 ± 0.00a	0.00 ± 0.00a	1.00 ± 0.00a	0.8 ± 0.1a	93
Summer03 burn	0.03 ± 0.02a	0.72 ± 0.09b	0.25 ± 0.09b	4.6 ± 0.5b	88
Spring04 burn	0.04 ± 0.02a	0.66 ± 0.06b	0.30 ± 0.07b	4.6 ± 0.3b	94

Responses significantly different (ANOVA, Tukey's HSD) within each fate class are denoted by different letters.

Table 2. Multiple logistic regression of pre-burn height, understory biomass and fire temperature as predictors of severity of *Quercus lobata* sapling response to prescribed fire (death or top-kill vs. leader alive), using individual tree measurements as replicates.

Predictive Factors	Burn Treatment	χ^2	p-Value	McFadden's ρ^2
Multivariate	Summer03	18.4	0.0004	0.36
combination of	Spring04	69.0	<0.0001	0.63
all three factors				
Tree height	Summer03	13.0	0.0003	
	Spring04	51.4	<0.0001	
Fire temperature	Summer03	4.3	0.04	
	Spring04	9.2	0.002	
Understory	Summer03	3.8	0.05	
biomass	Spring04	2.4	0.12	

(Table 2). Understory biomass class was only a weakly significant predictor, and only for the Summer03 burn, with trees growing in higher density understory biomass classes somewhat more likely to experience a severe response (Table 2).

The Summer03-burned trees did not have any height classes where all individuals avoided being top-killed by the fire (Fig. 2), while all Spring04-burned trees greater than 300 cm avoided being top-killed by the prescribed burn (Fig. 3). Of the seven trees that died in the fires, four were less than 1 m tall and all were less than 1.5 m tall.

Relative Growth Rates (RGRs) and Recovery of Height

Both Summer03- and Spring04-burned trees grew faster than the control trees for the first 2 years after their respective fires. The Summer03-burned trees' average RGR was significantly higher than controls during the first year (0.46 ± 0.05 vs. 0.27 ± 0.05; $F = 7.91$, $p = 0.013$) and second year (1.57 ± 0.11 vs. 0.74 ± 0.12; $F = 26.3$, $p<0.001$), but did not differ significantly during the third year (0.44 ± 0.06 vs. 0.39 ± 0.03; $F = 0.63$, $p = 0.44$). For Spring04 burned trees, average RGR was (nonsignificantly) higher during the first year (1.00 ± 0.13 vs. 0.74 ± 0.12; $F = 2.14$, $p = 0.16$) and significantly higher in the second year (0.54 ± 0.03 vs. 0.38 ± 0.03; $F = 16.60$, $p = 0.001$). By September 2006, both Summer03- and Spring04-burned trees had returned to heights similar to those of unburned control trees (Fig. 1, $F = 0.72$, $p = 0.50$).

Discussion

The valley oak saplings in this experiment experienced very low mortality rates but relatively high top-kill rates when exposed to a single low-to-moderate intensity prescribed fire, a pattern typical of saplings of other California oak species (Holmes et al. 2008). Saplings were more likely to survive prescribed fire when they were larger, were exposed to lower burn temperatures, or were surrounded by less-dense understory biomass.

Larger oaks trees in general are more likely to survive fires (Paysen & Narog 1993; Horney et al. 2002; Swiecki &

Bernhardt 2002; Regan & Agee 2004), as were the larger saplings in our study. Presumably, larger trees have thicker bark which insulates and reduces the amount of time living cells in the cambium layer are exposed to potentially lethal temperatures (Hare 1965; Plumb 1980). In addition, larger individuals may have less flammable twig and leaf material near the ground, because self-pruning produces bare lower trunks. Establishing critical size thresholds at which sapling oaks are known to escape death and top-kill is important for land managers who want to use prescribed fire as a restoration tool to control exotics without detrimentally impacting young trees (Swiecki & Bernhard 2002). Our study indicates that valley oak saplings over 300 cm tall are unlikely to be top-killed in a low-to-moderate prescribed fire. As very few of even the smaller saplings experienced complete mortality in either the Summer03 or the Spring04 burn, it does not appear that valley oak saplings need to attain a minimum threshold size to avoid death by prescribed fire.

Both ambient temperatures and fuel moisture levels, two factors relating directly to season of burn, can influence the degree of fire-induced damage to oak trees. Summer burns may be more severe because the higher ambient temperatures present during summer fires can result in internal tree temperatures increasing to lethal levels much more rapidly compared with the lower ambient temperatures present during early season fires (Hare 1965). Additionally, the low fuel moisture levels present during summer fires can create more intense fire conditions (Whelan 1995). Properties of trees' natural defenses may also interact with season to influence susceptibility. Trees may retain higher bark moisture during earlier seasons (DeBano et al. 1998). This may provide some resistance against fire (Plumb 1980; DeBano et al. 1998). However, in our study we did not find significant differences in overall survival or top-kill in the summer and spring burns.

Although we found understory biomass class to be only a weakly significant predictor of fire severity response, others have found that fuel loads do contribute to the level of fire damage sustained by oaks (Kauffman & Martin 1987; Tietje et al. 2001). Higher density understory biomass not only provides more fuel, thereby increasing fire temperatures, but also serves as a fuel ladder, carrying flames into tree crowns and increasing the potential severity of a fire's effects. One potential explanation for why understory biomass class was a better predictor for our Summer03 burn than our Spring04 burn is that there was very little variation in understory biomass in the Spring04 burn. High precipitation in spring 2004 created much more uniform and high-density biomass levels throughout the Spring04 burn blocks than was found in the Summer03 burn blocks.

Our study did not test the effects of multiple burns on valley oak sapling mortality and top-kill. Other oak species subjected to multiple prescribed fires within a relatively short period of time may experience higher levels of mortality (Peterson & Reich 2001; Regan & Agee 2004; Dey & Hartman 2005). Conversely, adult (but not sapling) trees in frequently burned areas may instead show lower mortality if frequent burning leads to lower fire intensity (Hutchinson et al.

2005). Although multiple burns are particularly effective in controlling annual grasses or star thistle, even a single burn followed up by spot herbicide treatments can substantially reduce cover by invasives, because many have very short-lived seed banks (DiTomaso et al. 2006), and future re-invasion can be greatly reduced by aggressive planting of native herbaceous species (Stromberg et al. 2007; John Anderson, personal communication). Further studies are needed to test whether multiple burns will have negative direct effects on valley oak saplings in restoration settings in the Central Valley.

The valley oak saplings in our study experienced rapid post-burn growth for 2 years following the fire, essentially recovering their height losses from the burns. Several other studies (McClaran & Bartolome 1989; Brose & Van Lear 1998; Bartolome et al. 2002; Swiecki & Bernhardt 2002) have also found that oaks experience accelerated postfire growth. Accelerated growth in other studies did not result in burned oaks returning within a few years to the full height they would have been had they not been burned, perhaps because of shading from overstory trees (Dey & Hartman 2005). Most restoration sites in the Central Valley are not light limited, including ours, which may partially explain the rapid height recovery exhibited by saplings in our study. It should also be noted that browsing deer or livestock populations (not present at our site) can significantly slow height recovery (McClaran & Bartolome 1989; Bartolome et al. 2002). In Africa, elephants are apparently attracted to recent controlled burns, killing savanna trees that survived the fire (Okello et al. 2008). Although there was significant rabbit and rodent herbivory at our research site, deer browsing was minimal. Oak saplings at sites with significant deer browse pressure might experience comparatively reduced rates of height recovery following prescribed burn.

In our study, most of the smaller burned trees changed from single-stemmed saplings to multi-stemmed with a more bushy architecture, and many of the larger saplings had considerable basal sprouting at their bases. It is not clear whether, or at what rate, these multiple coppices might self-prune and recover a single-stemmed architecture. In any case, the increase in fuel loads near the ground associated with these post-burn architectures may put these individuals at increased risk of more severe responses to future fires.

Burning to control or reverse forest encroachment into tropical and temperate savanna ecosystems (Brook & Bowman 2006; Nowacki & Abrams 2008) may encounter similar issues concerning the top-kill and survival of desirable woody species (Wolf 2006).

Implications for Practice

- Valley oak saplings appear to be able to survive and to recover in height from damage associated with one-time prescribed fires in the spring and early summer. This suggests that spring and early summer burning may be a viable management tool for controlling annual grass or star thistle understories in restored valley oak communities.
- Managers should consider the temporary setbacks associated with top-kill, including potential changes in architecture of saplings.
- Land managers may be able to mitigate some of these changes/setbacks by
  ○ not burning valley oak saplings that are under 300 cm in height,
  ○ conducting burns during the spring when ambient temperatures are lower and when relative humidity and fuel moisture is higher, and
  ○ reducing understory biomass around sapling oaks via weed control practices. The latter is currently in practice at several local sites, partly based on this study (Mitch Sears, Jeremiah Mann, personal communications).
- Repeated burning or intense ungulate herbivory in the first few years after burning are likely to impair recovery of top-killed oaks. Managers are encouraged to consider these factors in their restoration prescription and are encouraged to document their results to better understand impacts of browsing and repeat burns. Further research on these effects, including potentially interactive effects on trees and understory biomass, is needed to more fully evaluate fire management as a tool in newly restored valley oak woodlands.

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