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# Effectiveness and impacts of girdling treatments in a conifer-encroached Oregon white oak woodland

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ABSTRACT

The prolonged absence of fire in Oregon white oak (*Quercus garryana*) woodlands and savannas of the Pacific Northwest has resulted in substantial conifer encroachment over the past century. Use of low intensity prescribed burns often lacks sufficient intensity to kill larger encroached trees, requiring alternative approaches. In the Bald Hills region of Redwood National Park, managers have implemented girdling treatments to kill Douglas-fir (*Pseudotsuga menziesii*) over the past two decades with the objective of recovering remnant oaks and restoring historical woodland area. We surveyed 258 girdled Douglas-fir to examine the effectiveness of girdling treatments to create snags and the impacts of girdling on tree regeneration and fuel recruitment over a 17 year time since girdling chronosequence. Girdling was successful in killing 91% of the treated Douglas-fir independent of the method used (axe or chainsaw). Larger trees with a low girdle width-to-tree diameter ratio tended to survive girdling. Trees with a girdle width-to-tree diameter ratio ≥ 1 were most effective at killing trees. Snags generated through girdling decayed over time but did not significantly reduce in height over the time period examined. Bird activity was observed on 19% of snags across the chronosequence but 88% of 10 y old snags had signs of bird foraging. Fine woody fuel loading and fuelbed depths were potentially elevated 7 years after treatment but did not persist through the time period examined. Regeneration of Douglas-fir and oaks were highly variable and did not seem to be clearly linked to girdling activity. Our results indicate that girdling is a highly effective treatment to kill Douglas-fir and aid restoration of Oregon oak woodlands with limited negative impacts on surface fuel hazards or regeneration.

## 1. Introduction

Fire is an essential ecological process that creates and sustains many woodland, savanna, and prairie ecosystems worldwide (Bond and Keeley, 2005; Dantas et al., 2016). Repeated fires in these ecosystems serve as a negative feedback process that promotes an alternative stable state (Beckage et al., 2009), with many species having traits capable of withstanding and promoting a frequent fire regime. The absence of fire allows for the rapid encroachment of woody plants (Staver et al., 2011), many of which are more shade-tolerant and less fire-tolerant. These encroaching species can often alter the microclimate and fuel structure that promotes a positive feedback process that impedes the spread of fire and shifts the community toward less fire tolerant species (e.g., Nowacki and Abrams, 2008). The process of encroachment can result in numerous ecological consequences, such as decreased landscape heterogeneity (Brudvig and Asbjornsen, 2009), reduced biodiversity (Livingston et al., 2016), and altered animal community structure (Alford et al., 2012). Restoration of these ecosystems can prove difficult using prescribed fire alone. Shading from dense stand conditions can elevate surface fuel moisture and shift the fuel structure from more vertically-oriented herbaceous fuels to horizontally-oriented woody fuels (e.g., Stam et al., 2008; Engber et al., 2011). These conditions are often insufficient to generate fire intensities that can kill encroaching species, prompting a need for alternative treatments in many areas to restore the structure and composition.

The Pacific Northwest contains a unique assemblage of prairie and Oregon white oak (*Quercus garryana*) woodland ecosystems among a predominantly forested landscape. Once maintained by frequent surface fires, these ecosystems have been fire excluded for many decades, allowing encroachment by surrounding conifers, primarily Douglas-fir (*Pseudotsuga menziesii*), that were previously limited by fire (Thysell and Carey, 2001). Seedlings and small trees now reach a size with thick enough bark that can withstand fire (Engber and Varner, 2012). Over time Douglas-fir are capable of growing up through the oak crowns (i.e.

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**Fig. 1.** An example of a girdled Douglas-fir over-topping Oregon white oak with an intertwined stem (Photo by J. McClelland, Redwood National Park).

through-growth; Hunter and Barbour, 2001), eventually over-topping the shade-intolerant oaks (Fig. 1), reducing their growth and survival (Devine and Harrington, 2006). Encroached areas also accumulate more compact litter that has higher moisture content, and suppresses grass productivity, substantially lowering the flammability of these ecosystems relative to prairie and oak woodlands during prescribed fire seasons (Engber et al., 2011). The prolonged exclusion of fire has contributed to an estimated 30% loss of prairie and oak woodland habitats due to conifer encroachment (Fritschle, 2008). Encroachment from Douglas-fir also poses an increased risk of crown fire initiation and spread during wildfire season due to the increased vertical continuity of fuels and canopy bulk density (Agee and Skinner, 2005).

The reintroduction of fire through prescribed burning has been an effective management tool to maintain relatively intact prairies and oak woodlands (Hamman et al., 2011; Tveten and Fonda, 1999) but it is often less successful at treating encroached stands, requiring alternative treatments to kill encroached trees (e.g., Devine et al., 2007). Felling treatments are often advantageous because removal of these competing trees can quickly aid in releasing oaks, increasing acorn productivity, and increasing the probability of oak survival (Devine and Harrington, 2006). While felling treatments can be effective, there are some potential drawbacks. For instance, following a prolonged absence of fire, some encroached trees are large enough to require advanced falling skills that might not be locally available or add substantial cost and risk to the faller. Often encroached trees are intertwined with remnant oaks (Fig. 1) that can further complicate falling, especially if the cut stem becomes hung up within the oak crown. If these trees are successfully felled, they can cause damage to residual oaks and limit their ability to recover. The felled trees can also contribute to an abrupt build-up of surface fuel, requiring subsequent treatment to reduce potential fire hazard (e.g., pile and burn, broadcast burn) at additional expense.

Another option available to managers is to girdle, or more specifically "peel-girdle" (Noel, 1970) encroached trees. This method involves the removal of bark and phloem from the circumference of the tree. Girdling can kill trees due to root carbohydrate starvation through the disruption of phloem transport (Fujimori, 2001) and increase water stress by reducing water conductivity due to exposing the secondary xylem (Ueda et al., 2014). In many species this method can be an effective form of killing trees for a variety of purposes (Fujimori, 2001); however, the effectiveness can vary widely depending on the species, size of trees, and characteristics of girdling (Noel, 1970).

The girdling methods employed by managers range considerably and information that compares the effectiveness among commonly used methods is needed. Two methods typically used to girdle thick-barked species are chainsaws and axes. Chainsaws are often preferred to treat larger trees but may unintentionally "notch-girdle" stems by cutting into the secondary xylem. While this could hasten tree death, it may also promote more rapid stem failure due to accelerated decomposition or increased susceptibility to windthrow. Using an axe for girdling has other advantages, as it tends to be faster, cheaper, and less fatiguing than the use of a chainsaw (J. McClelland, pers. obs.). Another aspect of girdling that managers must consider is how much bark and tissue to remove (i.e. girdle width). Some evidence suggests that wider girdles are more effective at limiting survival (Lea, 1957), with vary narrow girdles (i.e. one cut around the circumference of a tree) being less successful in killing trees. However, the relationship between girdle width and tree size (e.g., diameter) is not well understood and information that helps provide guidance on the optimal girdle width to maximize tree mortality in unavailable. One possibility is that scaling the width relative to the size of the tree (e.g., girdle width-to-diameter ratio) may serve as a potential guideline for managers, yet this consideration has not been tested.

Successful girdling may also result in possible drawbacks depending on the desired objectives. One potential drawback of girdling is that many species, including Douglas-fir, have a hormonally-induced masting response that triggers a tree to produce more cones than usual (e.g., Ebell, 1971; Woods, 1989). Increased seed production could lead to the undesired establishment of Douglas-fir that would require subsequent treatment to remove these newly encroached trees. Conversely, girdling may have an indirect, positive effect on oak regeneration through increased acorn production (Devine and Harrington, 2006) or increased light availability. Another potential positive benefit of girdling is the generation of snags that provide habitat for numerous insect and wildlife species, especially for cavity nesting birds (Brandeis et al., 2002; Lewis, 1998). The persistence of girdle-generated snags over time is not well understood, but evidence suggests that girdled trees may be quite resistant to falling relative to snags generated by other means (Bull and Partridge, 1986). Still, some speculate that girdling could increase the rate of decay and stem breakage at the girdled location. As snags decay, they can also contribute to surface fuels (e.g., Dunn and Bailey, 2015) that may have the unintended consequence of increasing surface fire behavior that could compromise subsequent prescribed fire treatments or increase fire-damage to remnant oaks. Problematic fuel characteristics would likely resemble slash-based fuel models with fine fuel loading around 20–30 Mg $ha^{-1}$ and fuelbed depths of 0.3–1.0 m (Scott and Burgan, 2005). Conversely, the slow accrual of fuels over time from decaying snags may not contribute to a substantial build-up of fuels.

Over the past three decades, Redwood National Park in northwestern California has been employing girdling treatments within the Bald Hills region to aid in the restoration of Oregon white oak woodlands and prairies. Using these prior girdling treatments, we examined the efficacy and impacts of girdling over a 4–17 y chronosequence. Specifically, the objectives of this study were to: (1) determine the effectiveness of girdling to kill encroached Douglas-fir based on girdle characteristics, tree size, and time since treatment, (2) examine the effect of time since treatment on snag decay, (3) assess the patterns of surface fuel changes as snags decay with time since girdling, and (4) quantify Douglas-fir and oak regeneration response over time in girdled stands. Results from the study will provide managers with a better assessment of the effectiveness of girdling treatments and the potential benefits and drawbacks of this treatment in Oregon white oak woodlands, with possible implications for other ecosystems that are encroached by conifers.

## 2. Methods

### 2.1. Study site

The Bald Hills region of Redwood National Park (41.2°, −123.9°) is characterized by a 1700 ha matrix of oak woodlands and grasslands along the upper portions of south- and west-facing slopes with the lower slopes occupied by Douglas-fir/tanoak (*Nothofagus densiflorus*) forests (Redwood National Park, 1992). Elevation in the region ranges from 76 m to 945 m. The predominant oak species include Oregon white oak and California black oak (*Quercus kelloggii*). Other associated tree species included Pacific madrone (*Arbutus menziesii*), tanoak, California bay (*Umbellularia californica*), bigleaf maple (*Acer macrophyllum*) and grand fir (*Abies grandis*). Soils in the area are either poorly drained Xeralf that tend to resist encroachment and Umbrept soils that tend to favor encroachment by Douglas-fir (Gordon, 1980). Climate for the region from 2001 to 2017 had an annual rainfall of around 1400 mm, with 95% falling between October and May based on observations from the Schoolhouse Peak Remote Automated Weather Station that is located within the study site. Average annual temperature ranges from a minimum of 5.8 °C to a maximum of 20.1 °C. Most summer evenings are characterized by fog that usually clears by late morning.

The Chulula and Yurok Native American tribes utilized the Bald Hills region for many centuries prior to Euro-American settlement. A common practice of the tribes was to conduct widespread burning for many purposes (Underwood et al., 2003). In the 1860s, Native American tribes were largely extirpated from the region and the area was permanently settled by Euro-American ranchers, some of whom continued the use of burning to prevent conifer encroachment and improve forage quality. By the 1930s, burning was largely halted, after which restrictions were imposed and burn permits were required by the State (Stanton and Van Kirk, 1992). In 1978, much of the area became part of Redwood National Park and later was expanded in 1991 to include the remainder of the Bald Hills (Redwood National Park, 1992). Following the development of a vegetation management plan, prescribed burning began in earnest in 1993. Since this time, Redwood National Park has maintained an active prescribed burn program in the Bald Hills region with the objective of burning most prairie and oak woodland units on a 3–5 year return interval, as has been recommended by others for maintaining oak woodlands (Tveten and Fonda, 1999; Peterson and Reich, 2001). Conifer removal and girdling treatments began in the late 1980s and continue today.

### 2.2. Treatment description

Girdling of trees at our research sites occurred between 2001 and 2014 using either a chainsaw (65% of trees) or an axe (35% of trees) in the late spring to early summer (May-July), when the bark is much easier to remove from the cambium. Girdling was primarily focused on Douglas-fir, but grand fir was also girdled when present. Girdling involved making two cuts about 10–40 cm apart, depending on the size of a tree, along the circumference of the tree around 1–1.5 m above the ground. All bark and phloem were removed between the two cuts to expose the cambium. The proportion of Douglas-fir treated within a plot (0.04 ha circular plots, more details provided below) ranged from 13 to 100% (mean = 66.2%). Girdling intensity at the plot level was not related to year of girdling ($p > 0.28$), indicating that the proportion of girdled trees within an area did not vary significantly over time. Girdled trees ranged from 25.7 cm to 66.6 cm in DBH and from 1.4 m to 39.7 m in height. Trees smaller than 25.4 cm in the Bald Hills were typically removed through cutting during the same time period as the girdling treatment.

### 2.3. Data collection

Throughout the Bald Hills region, we surveyed nine sites girdled between 2001 and 2014 (Fig. 2). Each site had one to three subunits ranging in size from 0.2 to 2.6 ha that differed in the time since girdling (Table 1). Within each subunit, we established one to two 0.04 ha circular plots depending on the size of the treated area. Plots were strategically located so that they were visually representative of the area treated (i.e. tree density, composition, and proportion of trees girdled

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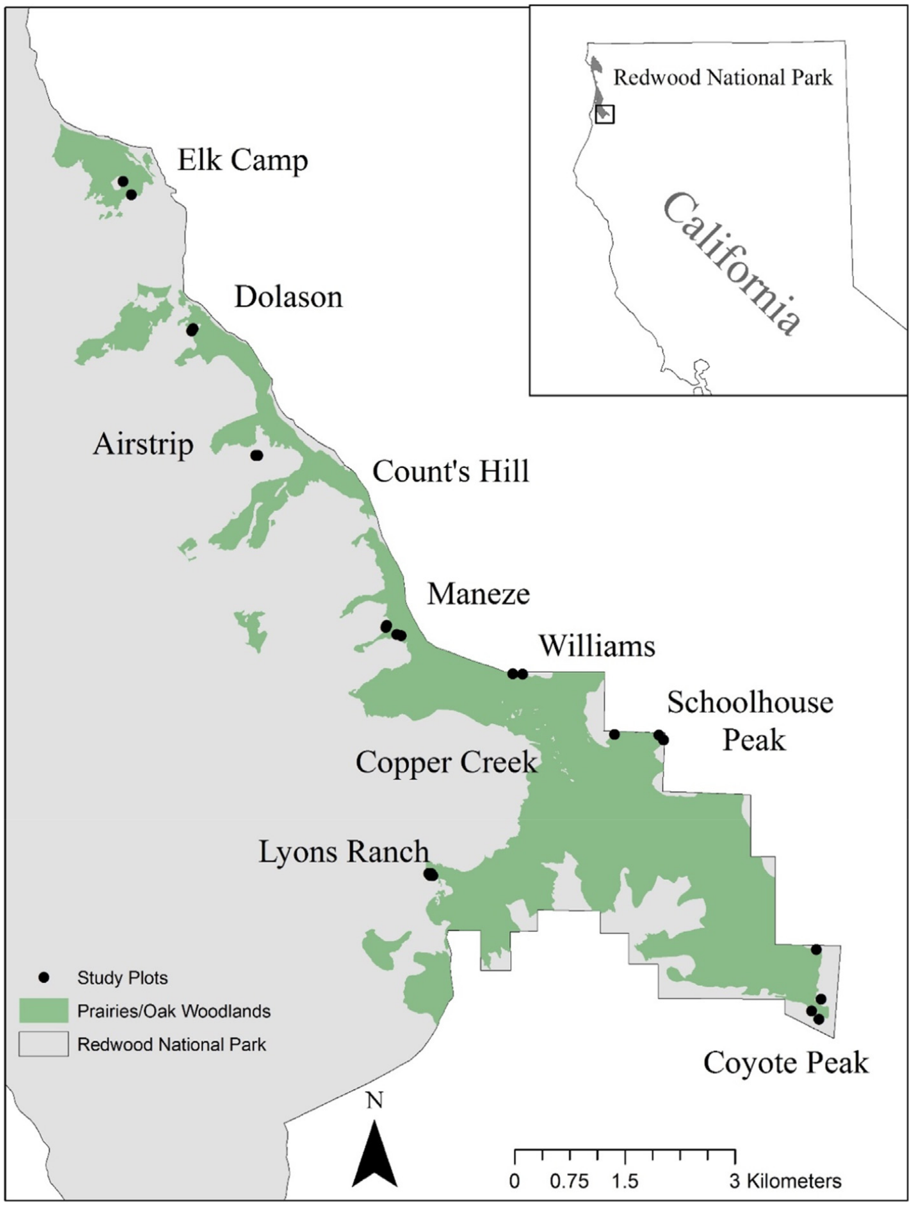


**Fig. 2.** Location of study plots within the oak woodlands and prairies of the Bald Hills region in Redwood National Park.

**Table 1**
Site characteristics by time since girdling. Mean basal area represents the basal area of all live and girdled trees within plots and mean girdle intensity represents the basal area of girdled trees within plots.

| Time since girdle (y) | Site name | No. subunits | No. plots | No. girdled trees | Mean basal area ($m^2$ $ha^{-1}$) | Mean girdle intensity ($m^2$ $ha^{-1}$) |
|---|---|---|---|---|---|---|
| 4 | Coyote Peak | 2 | 2 | 40 | 91.9 | 36.8 |
| 5 | Lyons | 2 | 4 | 78 | 77.7 | 24 |
| 5 | Maneze | 2 | 4 | 49 | 75.3 | 47.9 |
| 6 | Schoolhouse | 2 | 2 | 22 | 102.1 | 40.5 |
| 7 | Lower Dolason | 1 | 2 | 20 | 78.6 | 27.5 |
| 9 | Elk Camp | 1 | 1 | 10 | 121.5 | 15 |
| 9 | Lower Airstrip | 2 | 2 | 9 | 47.2 | 17.1 |
| 9 | Coyote Peak | 2 | 2 | 7 | 58.7 | 29.3 |
| 10 | Elk Camp | 1 | 1 | 8 | 36.6 | 23.7 |
| 15 | Schoolhouse | 1 | 1 | 9 | 76.1 | 15.2 |
| 17 | Williams | 1 | 2 | 9 | 80.5 | 47.4 |

were relatively similar), were not located along the edge of the treated area, and did not receive a prescribed fire based on either management records or signs of char on tree boles. If more than one plot was included within a subunit, they were located at least 50 m apart. Each plot was georeferenced and the tree closest to the center was tagged and given a unique identification number. The majority of the plots occurred along a southwestern aspect with all slopes less than 30°. Within each plot we recorded the diameter at breast height (DBH) and status (live or dead) for all trees ≥25.4 cm DBH. For all girdled Douglas-fir trees within each plot, we recorded the type of girdle that was implemented (chainsaw or axe) and the minimum distance between girdle cuts (hereafter girdle width). We examined each girdled tree for healing and estimated the percent of the girdled area that was grown over. Each girdled tree was assigned a nine-stage decay class with live trees classified as healthy (class 1) or declining (class 2), and dead trees (i.e. snags) assigned a range from recently dead trees with fine branches still intact (class 3) to a decayed stump (class 9) (Maser et al., 1979). We also recorded the height of each girdled snag. The presence of insect and wildlife activity (e.g., boring holes, cavities, excavations) was recorded for each dead tree. We also established a nested 0.008 ha circular plot centered on the larger 0.04 ha tree plot and counted all Douglas-fir and oak regeneration (by species) within two categories, seedlings (< 1.37 m in height) and saplings (> 1.37 m and < 25.4 cm DBH).

We characterized surface fuels along two 9.1 m planar intercept transects that radiated from the center of each tree plot (Brown, 1974). The first transect was established along a random azimuth and the second transect was positioned 120° clockwise from the first transect. In the two subunits that also contained piles due to removal of small Douglas-fir through cutting, a new random azimuth was taken to avoid piles because they were not associated with the post-gridling fuel recruitment of interest. Along the first 1.8 m of the transect, we counted all 1 hr (< 0.64 cm) and 10 hr (0.64–2.54 cm) fuels. Along the first 3.7 m of the transect, we counted all 100 hr (2.54–7.62 cm) fuels. Along the complete transect length, we recorded the species and diameter of all 1000 hr (> 7.62 cm) fuels that intersected the transect and classified whether the particle was sound or rotten. We also recorded litter and duff depths at the 1.8, 3.7, and 5.5 m marks along each transect. At these locations, maximum depth of the dead surface fuels was record within a 30 cm section.

We calculated fine fuel loading (Mg $ha^{-1}$) for 1–100 hr fuels and coarse fuel loading for 1000 hr fuels (Equation 2) using values for particle diameter, particle angle, and specific gravity of conifers provided by Brown (1974). For 1000 hr fuels, the sum of the squared diameters for all particles that intercepted the transect was used instead of the count of particles. Given that $n$ signifies the number of particles intercepted, $d$ is the mid-point of particle diameter size class, $s$ is the particle specific gravity, $a$ is the particle angle correction factor, and $Nl$ is the transect length.

$$Woody\ \ Fuel\ \ Loading = \frac{\left(1.234 * n * d^2 * s * a * \left(\sqrt{1 + \left(\frac{\%\,slope}{100}\right)^2}\right)\right)}{Nl} \tag{1}$$

### 2.4. Data analysis

We assessed the effect of girdling treatments on mortality at the individual tree level with a generalized linear mixed effect model with an assumed binomial distribution using the package *lme4* (Bates et al., 2014) in R (R Development Team, 2018). We accounted for variance at the site, subunit, and plot level as nested random effects in our model. The fixed effects considered included DBH, time since girdling, girdle width, and a girdle width-to-DBH ratio. Including the girdle width-to-DBH ratio allowed us to relativize the girdling extent to the size of the tree, with the thought that larger trees may require a larger girdle width to achieve mortality. We also estimated the area under the receiver operating characteristic curve (AUC) using the R package *pROC* (Robin et al., 2011) to evaluate the performance of the mortality models. AUC values range from 0.5 to 1, where 0.5 indicates no discrimination. Hosmer and Lemeshow (2000) recommend that AUC values < 0.7 indicate poor discrimination; values between 0.7 and 0.8 are acceptable discrimination; values between 0.8 and 0.9 are excellent discrimination; and values > 0.9 are outstanding discrimination. Significance was determined for these and all subsequent models at an $\alpha$ of 0.05.

To assess the effects of girdling on snag characteristics including decay class and snag height at the plot level, we used a linear mixed effects model with the package *lme4* in R. Random effects included subunit and plot nested within site and fixed effects included time since girdling and the DBH of the girdled snag. We also examined the relationship of snag height and proportion of snags with evidence of bird activity along the time since girdling gradient, using the same approach as snag decay.

We examined patterns of fuel loading with time since girdling separately for fine woody fuels, coarse fuels, and fuelbed depth using a linear mixed effects model. Random effects considered included plot, subunit, and site. Since changes in fuel loading over time are often nonlinear, we also visualized patterns using a locally estimated scatterplot smoothing (Loess) fit to examine potential pulses in mean fine woody fuel loading and fuelbed depth at the transect level along the time since girdling gradient.

Douglas-fir and oak regeneration were analyzed using a linear mixed effect model. Variables considered in our models of Douglas-fir regeneration included time since girdling, girdle intensity, live Douglas-fir basal area, and slope. We examined oak separately for Oregon white oak and California black oak and considered the same variables used in the Douglas-fir regeneration models, but also included basal area of mature oaks as a candidate model. Random effects considered included subunit nested within site. We also considered other environmental variables including slope and elevation for both Douglas-fir and oak regeneration.

## 3. Results

Girdling was a highly effective treatment killing 91.2% (235 of 258 trees) of Douglas-fir ranging between 25.7 cm and 66.6 cm DBH that were treated between 4 and 17 years ago. Trees that survived were on average 59% larger in DBH than trees that died from girdling, in spite of having a slightly wider girdle applied (+6.4 cm). Time since girdling did not have an effect on tree mortality at the individual tree level ($p = 0.29$). Trees that survived had been girdled 4–9 years ago. The top three mortality models included girdle width-to-DBH ratio and girdle method. The most informative factor indicating the effectiveness of girdling was the girdle width-to-DBH ratio ($p = 0.017$; Fig. 3) and the model had outstanding discrimination (AUC = 0.94). Trees with an average ratio around 1.0 had a higher probability of mortality, while trees that survived had an average ratio of 0.7 with 22% of the girdled area healed compared to < 1% in girdled trees that died.

Time since girdling had a strong positive relationship with the decay class of snags ($p < 0.0001$; Fig. 4). Snags girdled ten or more years ago typically had a decay class of either 4 (loose bark) or 5 (clean snag). However, decay class was not strongly associated with snag height ($p = 0.117$) or DBH ($p = 0.117$) over time. Standing snags 17 years after girdling were still on average more than 10 m tall. Snags also had evidence of animal activity. The proportion of snags that contained insect signs was 93% and 19% had evidence of bird boring holes or excavations. There was a positive relationship between time since girdling and the proportion of snags containing bird activity over the first ten years after girdling ($p = 0.01$), with 88% of ten year old snags containing bird activity.

Mean fine woody fuel (1–100 hr) loading was highly variable across all subunits, ranging between 0.29 Mg $ha^{-1}$ and 2.63 Mg $ha^{-1}$. This variation was unrelated to time since girdling ($p = 0.965$), basal area of girdled trees ($p = 0.971$), or live tree basal area ($p = 0.295$). However, there was a pulse of fine woody fuels and fuelbed depth at sites, seven years after girdling (Fig. 5). Litter loading was negatively related to the basal area of dead girdled trees ($r^2 = 0.21$, $p = 0.03$). Time since girdling was not related to 1000 hr sound fuel loading.

Douglas-fir regeneration density was highly variable ranging from 0 to 2841 individuals $ha^{-1}$ (mean = 632 individuals $ha^{-1}$). We did not detect any evidence that girdling-induced regeneration of Douglas-fir based on time since girdling ($p = 0.20$) or girdle intensity ($p = 0.08$). As expected, older girdled sites had a higher density of Douglas-fir saplings with the transition from seedling to sapling occurring around 10 y after girdling. Basal area of mature, live Douglas-fir was not associated with seedling regeneration ($p = 0.53$) but slope had a negative relationship with Douglas-fir seedling regeneration ($p = 0.006$). Oregon white oak and California black oak seedlings were also highly variable ranging from 0 to 3,186 seedlings $ha^{-1}$. We did not find any effect of time since girdling ($p > 0.21$) or girdling intensity ($p > 0.24$). Oak seedling regeneration was strongly associated with

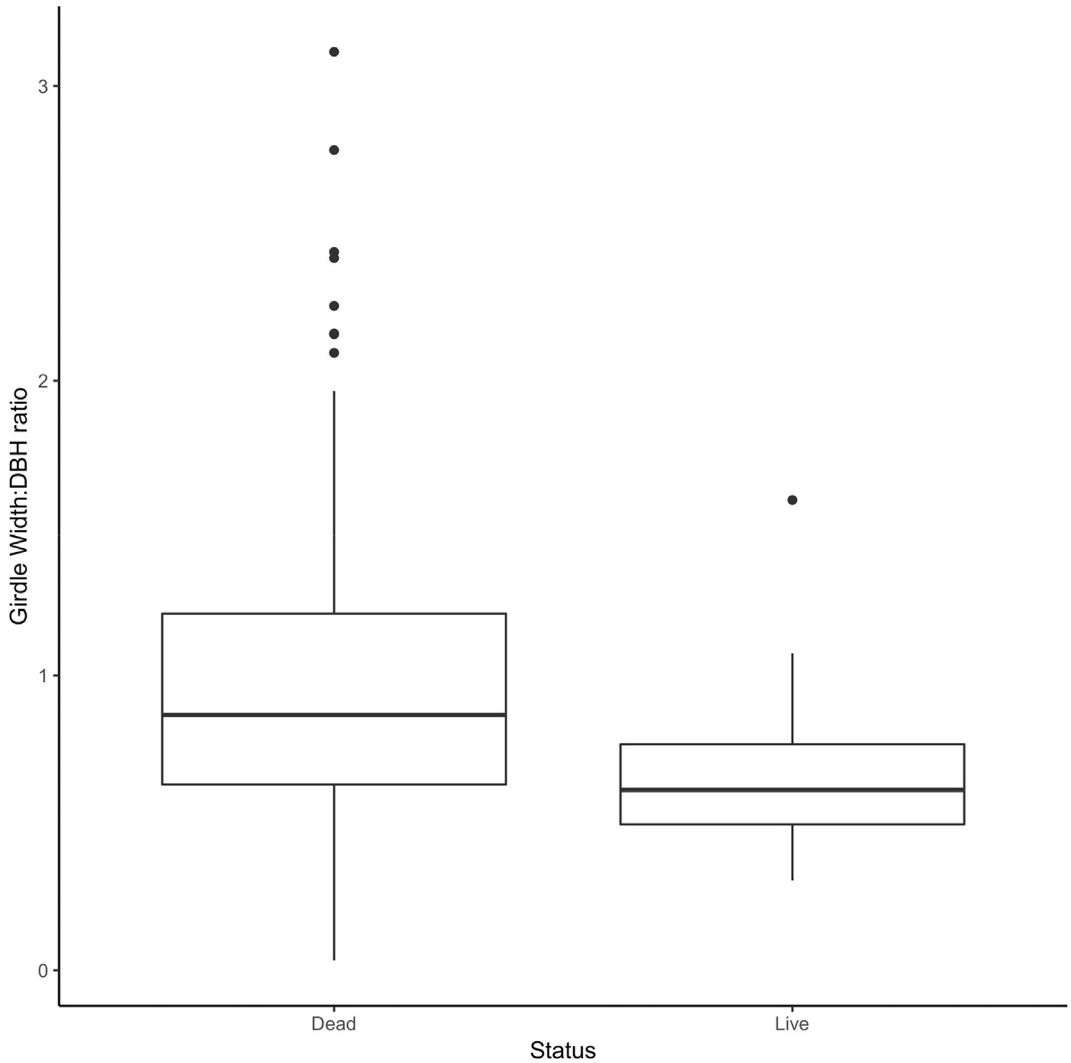


**Fig. 3.** Comparison of girdle width-to-DBH ratio between live and dead girdled Douglas-fir in the Bald Hills region of Redwood National Park. DBH = diameter at breast height.

mature oak basal area ($r^2 = 0.7$, $P < 0.001$). Saplings of Oregon white oak or California black oak were not observed in any of the surveyed plots.

## 4. Discussion

### *4.1. Girdling effectiveness*

Girdling was an effective treatment to kill Douglas-fir in oak woodlands of northwestern California. While this outcome was expected considering that this technique has been demonstrated to work on numerous species (Fujimori, 2001), variability in the effectiveness across some species has been documented and limited research was available on Douglas-fir. Hastings et al. (1997) reported girdling activity in Annadel State Park in northern California to manage encroaching Douglas-fir ≥ 15.2 cm DBH by applying a single chainsaw cut through the cambium (i.e. "ringing"). Results were mixed, with some trees showing signs of decline one year after treatment, but some larger trees (≥30.5 cm DBH) survived. Beyond assessing the effectiveness of girdling, our work provides a simple guideline for managers: the ratio of girdle width-to-DBH should be at least 1:1, especially for larger trees. It is possible that this ratio provided greater exposure of secondary xylem that can more effectively decrease hydraulic conductivity (Ueda et al., 2014) or because the greater separation of phloem decreases the chances of a tree healing over (Noel, 1970). We cannot be certain about the direct mechanism that supports the increased success without further study, but we did observe that girdled trees that survived had more healing. Thus, we speculate that a single chainsaw cut is likely to be markedly less effective due to the greater potential for healing. We would expect that this 1:1 criterion should broadly apply to treating Douglas-fir in Oregon white oak woodlands throughout the Pacific Northwest with similar climate to the Bald Hills; however, lower ratios in drier inland or drought-stressed sites could potentially be utilized. Different girdling methods, chainsaw or axe, did not have a strong effect on mortality but may affect time/cost of treatment. As long as treatments occur during the growing season when sap is flowing, either method will facilitate efficient bark removal.

### *4.2. Snag longevity and fuel hazard*

Snags provide an important resource for many bird species and creation of snags through girdling is an effective way to promote foraging and nesting habitat. Snag longevity is an important consideration for land managers and we observed standing clean snags 17 years post-treatment, suggesting girdled trees that become snags have a similar or longer duration (i.e., decades) to snags generated from other disturbances or methods. For example, Everett et al. (1999) observed 50% of 23–41 cm DBH Douglas-fir standing 15 years post-

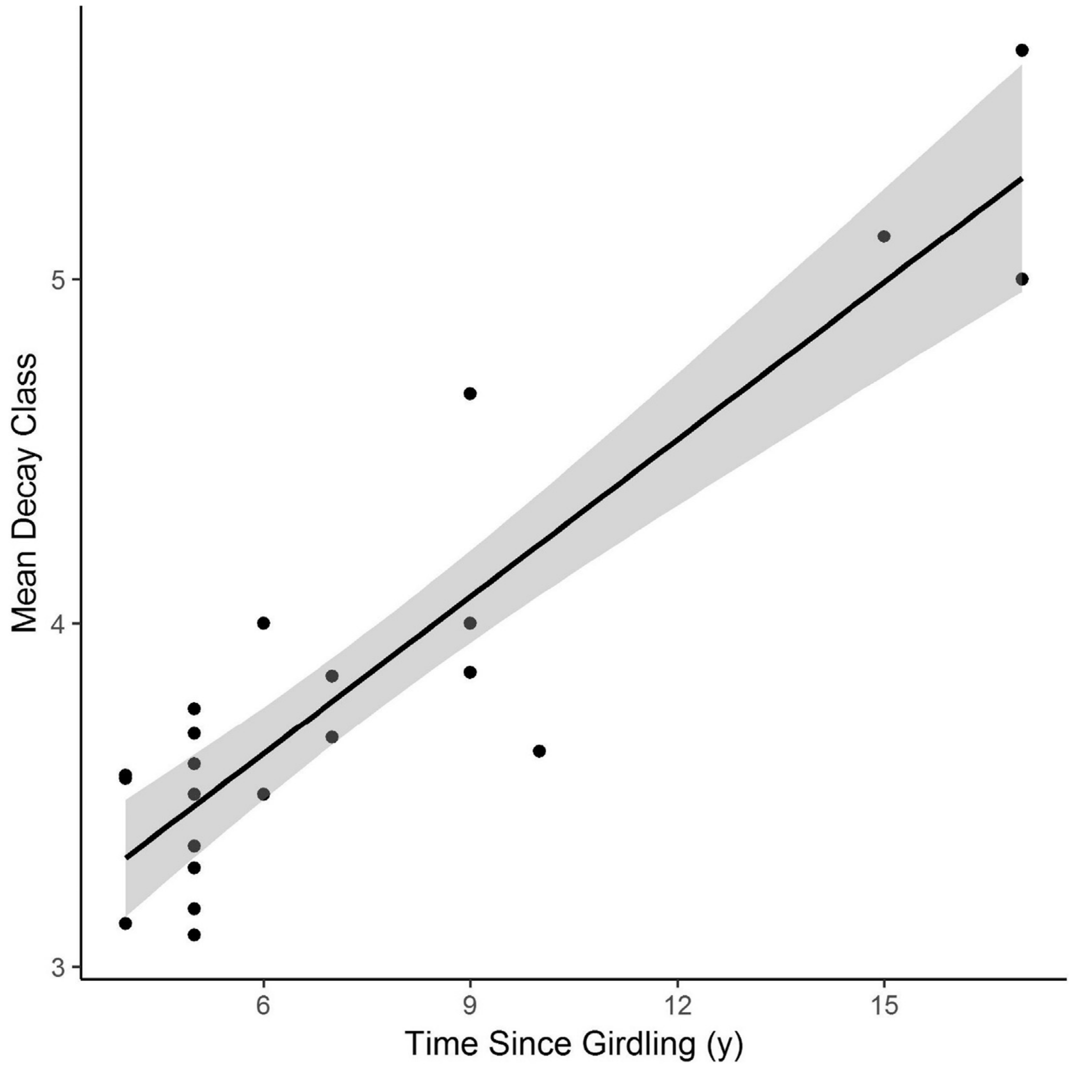


**Fig. 4.** Positive relationship between time since girdling and decay class of girdled Douglas-fir snag.

wildfire, and Douglas-fir snags that were generated by tree mortality agents over time in a second-growth forest of coastal British Columbia had a median age of 16 years (Parish et al., 2010). These other studies also found that snag longevity increased for larger diameter snags (Everett et al., 1999; Parish et al., 2010), a finding that was not detected in our study. Older girdled sites were more decayed, with girdled trees shedding fine branches and bark within 10 years. Despite concerns that chainsaw or axe cuts would facilitate more rapid snag decay and breakage, most snags were still standing after 17 years. However, chainsaw cuts that penetration deeper into the sapwood may promote premature stem failure (J. McClelland pers. obs.).

Surface fuel loading across the time since gridling gradient was persistently quite low. In comparison to another study conducted in the Bald Hills region that examined surface fuel loading within Oregon white oak woodlands that were heavily encroached by Douglas-fir (Engber et al., 2011), fine woody fuels within our study were on average 78% lower and rarely exceeded 4 Mg $ha^{-1}$. These fuel loading levels are substantially lower than slash-based fuel loads (Scott and Burgan, 2005) and would unlikely generate concerning fire behavior. Surface fuel loading was highly variable across our sites but did not vary linearly with time since girdling. We did observe a potential pulse of fine woody fuels and higher fuel bed depths within sites that were girdled 7 years ago that coincided with observations of snags with higher decay classes (> class 3), suggesting fine branch recruitment to the surface fuel profile. This pattern of increased load within 7 years after snags formed has also been observed as part of a post-fire chronosequence study of mixed-conifer forests in Oregon (Dunn and Bailey, 2015). The lack of a strong increase in 1000 hr fuels with time since girdling was somewhat unexpected. Others have found substantial increases in 1000 hr fuels within 8 years as part of a post-fire snag retention study in a ponderosa pine forest of northern California that had a similar range in snag basal area (4.7–36.3 $m^2$ $ha^{-1}$) to our study (Ritchie et al., 2013). We suspect that the greater snag longevity of Douglas-fir may explain this difference which is consistent with the persistence of snags across the 17 year timespan of our study and others (Everett et al., 1999; Parish et al., 2010). Substantial recruitment of 1000 hr fuels is expected at longer timespans (> 17 years) than what was available from our observations.

If there is an elevated fire hazard in the girdled stands examined at our study site, it may relate more to standing snags. Standing snags do have associated risk in the event of planned or unplanned fires, serving as a source for fire brands (van Wagtendonk, 2018), long-term holding concerns, and hazard tree exposure. The overall fire hazard relates to the number of girdle trees, size of the treatment units, and the adjacency of these to values at risk (e.g., likely areas of ignitions, infrastructure, boundaries of prescribed fire units, etc.). Girdled stands in the Bald Hills were isolated spatially and mostly less than 2 ha in size, and not likely to affect wildland fire risk on a landscape scale. Still, managers need to understand the risk of dead trees in relation to the wildland fire environment, and coordinate restoration efforts with fire

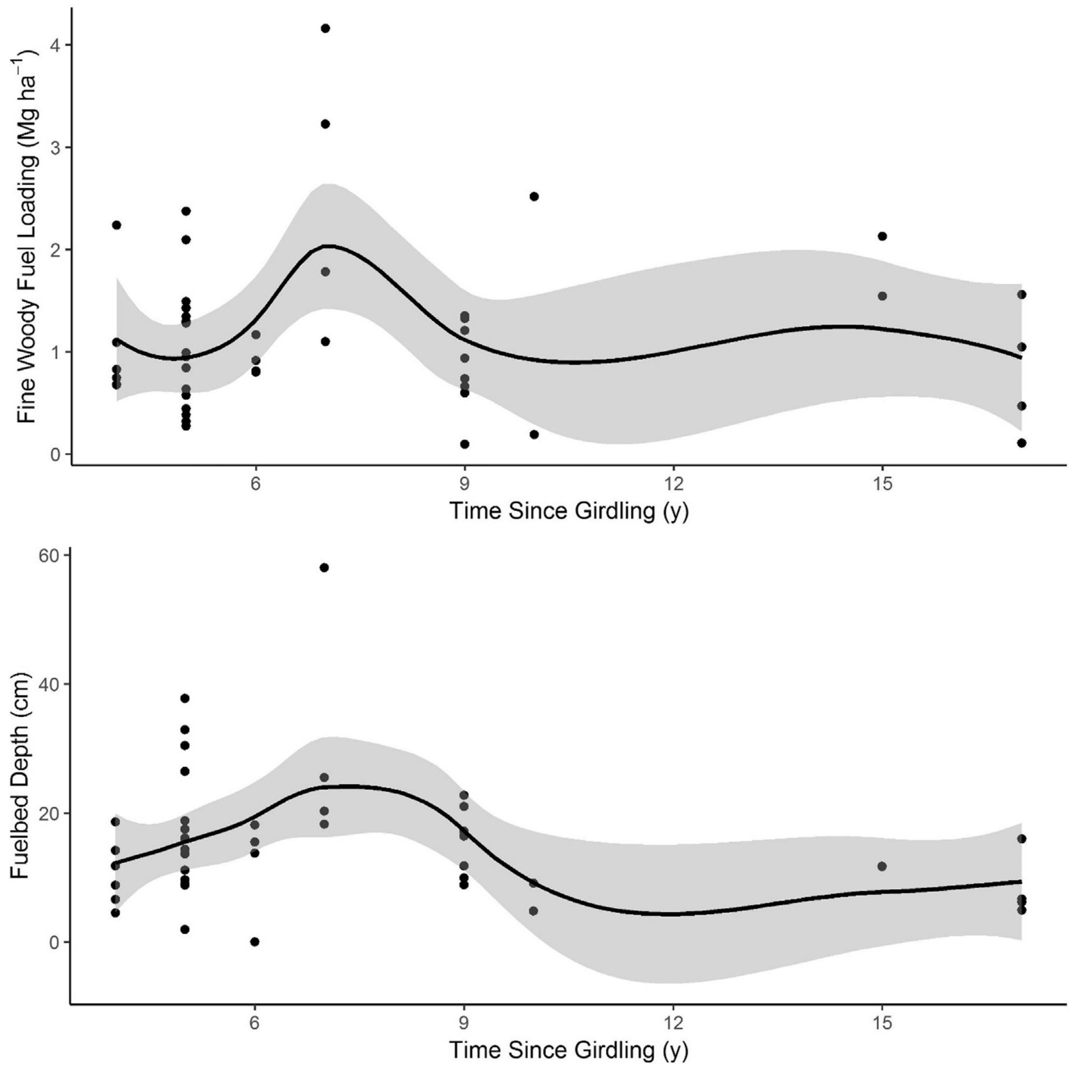


**Fig. 5.** Estimated changes in fine woody fuel loading (top) and fuelbed depth along a time since girdling gradient. Black line represents a loess smoothing function and the shaded area represents the 95% confidence intervals.

managers to mitigate these hazards.

### 4.3. Seedling regeneration

While there are plenty of documented instances where girdling can induce increased cone, and thus, seed production in conifers (e.g., Ebell, 1971; Woods, 1989), we surprisingly did not detect any evidence that girdling resulted in such an increase within our study sites. One possibility for this finding is that tree response to peel-girdling differs from partial girdling (typically a narrower girdle across half of the circumference) that is commonly used to promote masting. It is more likely that variation in Douglas-fir regeneration was related to the close proximity of mature, live Douglas-fir stands to girdled areas with more than ample seed supply to re-establish in the more open stand conditions. The maximum distance from our plots to a mature tree was only 23 m, a distance that is far less than the potential seed dispersal ability of Douglas-fir given its tall stature and winged seed (Greene and Johnson, 1989). Thus, maintaining the effectiveness of girdling over time will require subsequent treatments, such as prescribed burning. Based on our results, Douglas-fir seedlings (< 1.37 m in height) became saplings (> 1.37 m and < 25.4 cm DBH) at least 10 years after girdling. However, it is important to state that some of these saplings may represent advanced regeneration that were released following the girdling treatment. Regardless of the age of these trees, managers can expect that Douglas-fir saplings may be present 10 years after girdling, a size that is often more difficult to kill with the application of prescribed fire (Engber and Varner, 2012). Thus, managers would want to reintroduce fire well before this growth transition to the sapling stage.

Oregon white oak and California black oak regeneration was highly variable across our study but was not clearly associated with any of the girdling treatment characteristics. We expected that the girdling would increase seedling regeneration by releasing remnant oaks from the competitive effects of encroached Douglas-fir through increased acorn production (Devine and Harrington, 2006), increased growth rates (Gould et al., 2011), and increased soil moisture (Devine and Harrington, 2007). While many plots contained ample seedling densities, we did not record any oak saplings in our plots. This finding is consistent with a broader pattern observed throughout much of northwestern California oak woodlands (Schriver et al., 2018) that is possibly related to high browsing pressure from deer and elk or other factors. Managers interested in promoting seedling growth and recruitment of saplings may require additional treatments, such as mulching to increase soil water content or installing shelters to limit browse damage (Devine et al., 2007).

### 4.4. Conclusions

Girdling is an effective way to treat Douglas-fir encroachment in oak woodlands of northwestern California. Girdling method (axe or chainsaw) did not influence the level of effectiveness. However, implementing a girdle width that is equivalent or greater than the DBH of the tree, especially for larger individuals, can increase effectiveness. Girdled trees also promoted the development of persistent snags that had demonstrated use from insects and wildlife. Concerns of girdling contributing to substantial fuel accumulations or increased recruitment of Douglas-fir were not supported by our findings, however follow-up maintenance of treated sites (e.g., prescribed fire) will reduce potential conifer recruitment and maintain low fuel loads over time. Given the proportion of oak woodlands that have been encroached by Douglas-fir or other conifers, girdling can provide a clear means to improve conditions and aid in the restoration of oak woodlands with minimal impacts to fuels and regeneration.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.05.059.

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