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Merging prescribed fires and timber harvests in the Sierra Nevada: Burn season and pruning influences in young mixed conifer stands

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ABSTRACT

In dry, productive forests where historically infrequent high-severity fires are now common, new silvicultural systems will be needed to better align management activity with the ecosystem's dependent disturbance regime of frequent low and moderate-severity fires. Merging timber harvests with prescribed fire programs can be advantageous because each disturbance provides benefits that the other cannot provide alone. We conducted a study aimed at providing information to managers interested in merging gap-based silviculture with frequent prescribed fire. We studied the influence of burn season (spring versus fall) on canopy mortality and damage by conducting prescribed burns in 13-14 year old stands that had been regenerated with gap-based silviculture. We also pruned sugar pine (*Pinus lambertiana*) and incense-cedar *(Calocedrus decurrens*) prior to burns to evaluate the influence of pruning on fire related mortality and damage. Fall (21%) and spring (19%) burns resulted in similar amounts of mortality two years following burns, but the fall burns consumed considerably more fuel compared to spring burns. Percent volume crown scorch was greater in spring burns and greater when crown bases were low to the ground. Fall burns were generally favorable assuming a management context where fuel consumption and survival is desirable. However, either burn season may be acceptable using fire as a thinning mechanism is desired to encourage the development of low-density, mature stands. As a pre-fire treatment, pruning did not clearly reduce fire-related mortality or crown damage. Considering that pruning itself is a form of crown damage, it could be considered counterproductive as a pre-fire treatment because of increased heat entering pruned crowns as a result of increased surface fuel and the loss of heat-buffering lower branches. Merging gap-based silviculture with prescribed fires in perpetuity may be initially complex operationally in the Sierra Nevada, but it offers managers a disturbance regime-guided method for sustaining heterogeneity at fine and coarse scales while maintaining low surface fuels. The timing of introducing fires into young stands as well as traditional timber management tools such as rotation ages and harvest intervals can be altered depending on exact objectives.

1. Introduction

Silvicultural systems that create distinct canopy gaps have been used in many forest types to regenerate and sustain diverse tree communities of both shade tolerant and intolerant species over long periods (Rogers et al. 2021). Regeneration of multiple species occurs when gap sizes are sufficiently large to meet resource availability needs for all species (Lhotka 2013). In dry forests where the historic disturbance regime included fires that burned with local intensities hot enough to kill groups of canopy trees, gap-based silvicultural systems can also help meet restoration objectives or achieve concepts of resilience. For managers whose highest priority is restoring ecological processes, hot prescribed fires are arguably the ideal silvicultural tool for creating canopy gaps in a manner that most closely resembles a disturbance regime that has been interrupted by prolonged fire suppression. However, there are numerous intractable challenges involved with conducting prescribed fires that are hot enough to create distinct gaps greater than ∼0.1 ha in size (York et al. 2021a). In dry forests with summer wildfire seasons, gap-generating prescribed fires would have to occur in the summer or early fall when fuel moisture is low. One of numerous challenges related to burning during dry conditions is that fire managers with enough experience to conduct hot burns are not available, either because they

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are assigned to work on wildfires or they need to maintain availability to respond to wildfires as they occur (Striplin et al. 2020). Unless current approaches to wildfire and prescribed fire management change fundamentally, the creation of canopy gaps via timber harvests is likely to be the best available tool for creating desired canopy heterogeneity in most forest management scenarios.

While utilizing prescribed fire to create canopy gaps and regenerate new cohorts has several challenges, it may be a more useful tool for maintaining low surface fuel loads and for guiding stand development once cohorts are established. In mixed conifer forests of the western US, the application of prescribed fire in young stands is an area of uncertainty with many research needs (North et al. 2019). However, some studies have begun to inform emerging prescribed fire programs that include young stand burning. Factors of prescribed fire effects that have been studied recently include stand age (York et al. 2021a), pre-fire manipulations of fuel (Busse and Gerrard 2020), and tree species composition (York et al. 2021b). A factor that remains largely unaddressed with field experiments is season of burn. Burn season studies have been done for mature stands (e.g. Knapp et al. 2005), but only limited work (Bellows et al. 2016) has been done for young stands. Because multiple constraints limit the use of prescribed fires broadly (Schultz et al. 2019), understanding tradeoffs between burning at different times of year is important for ensuring that each burn meets objectives. While there may be more opportunities to burn in the spring because wildfires are not as prevalent and personnel are therefore more available, spring burns may be less desirable than fall burns if they do not consume adequate amounts of fuel (Knapp et al. 2005) or if they result in unacceptable levels of tree mortality (Bellows et al. 2016). Historically, spring fires were also less frequent than fall fires when reconstructed from studies of fire scars (e.g. Beaty and Taylor 2008), suggesting that spring prescribed burns are less aligned with the seasonality of the inherent disturbance regime.

In addition to controlling the timing of burns to occur in optimal seasons, it is often possible to influence fire-related mortality by manipulating fuel and vegetation structures prior to burning. For example, surface fuel “jackpots” and/or ladder fuels can be removed if they are directly beneath canopy trees to lower the probability of crown torching. In mature stands, commercial thinning projects with heavy equipment can be effective in both reducing fire hazard and cost when they generate revenue from the sale of forest products (Hartsough et al. 2008). Manipulative treatments in young stands, however, are relatively expensive because there is typically no capacity to recover costs from the sale of forest products given the small size of trees. Treating stands with expensive manipulations prior to burning defeats one of the primary purposes of using prescribed fire- managing fuels at low cost (Hartsough et al. 2008). Pruning of lower branches prior to conducting prescribed burns is one of the few relatively low-cost treatments that may reduce prescribed fire-related mortality. Costs are relatively low because branches are quickly severed from the lower portions of crowns, and there is no physical moving of material within or from the stand. In theory, pruning to modify vertical configurations of fuel reduces fire hazard because crown base heights become taller (Hevia et al. 2018). However, the lifting of crown bases comes at the cost of an increase in surface fuels directly beneath crowns and adjacent to boles. Very little research exists to demonstrate the actual effectiveness, or lack thereof, of pruning. Meanwhile, pruning is generally recommended in mixed conifer forests as a way to reduce fire hazard (CAL FIRE 2019) despite a lack of evidence for its effectiveness. In mixed species stands, pruning as a preparation for prescribed fires may be cost-effective for all species present or only when it is targeted at particular species. This may occur because certain species are easier to prune or because pruning-related benefits only occur for certain species that are more vulnerable to fire when young (York et al. 2021a). If pruning only has marginal value as a pre-treatment before prescribed fires, meeting other longer-term objectives that are not related to prescribed fires could make it worthwhile. In young mixed conifer stands, sugar pine (*Pinus lambertiana*) and incense-cedar (*Calocedrus decurrens*) benefit from pruning in distinct ways. Removing lower branches can reduce the incidence of white pine blister rust (*Cronartium ribicola)* (Lehrer 1982), an exotic pathogen that has impacted populations of sugar pine. Young incense-cedar crowns are made of very dense, small branches (Cox 2021), the removal of which can result in significant gains in knot-free wood production when managing for timber. For any extra value to be realized after prescribed fires, however, pruning at the very least should not increase the probability of prescribed fire-related damage and mortality.

The long-term study, Treatment Alternatives for Young Stand Resilience (TAYSR; Bellows 2016) provided a context and location to further develop the concept of pyrosilviculture and study the factors of burn season (fall versus spring) and pruning on prescribed fire effects in young, mixed-species stands of the Sierra Nevada, California. We conducted a prescribed fire experiment intended to be relevant to forest managers who desire to develop silvicultural systems that rely on coarse structural heterogeneity and canopy gap creation as central components (e.g. Churchill et al. 2013). More specifically, it applies to managers who want to use pyrosilviculture, which in this case involves the planning of timber harvests and prescribed fires to complement and strengthen each other. Our study questions were: 1) Was fuel consumption, mortality, or crown damage different between spring and fall burns?; 2) For sugar pine and incense-cedar trees, did pruning prior to prescribed fires influence prescribed fire effects, or did it interact with season of burn to reduce mortality or crown damage? Via integration of these results with other young stand burning studies, we provide suggestions for the design of pyrosilvicultural systems that use harvests to regenerate forests via canopy gaps and then fire to maintain them.

2. Methods

2.1. Study area and regeneration context

Burns were completed at Blodgett Forest Research Station (BFRS) in the mixed conifer forest on the western slopes of the central Sierra Nevada California range, which has a Mediterranean climate. From 1994 to 2020, the mean total precipitation during the wet season was 145 cm yr^{-1}. Mean daily temperature was 6.2°C, mean daily low was 2.6°C, and mean daily high was 10.9°C. Climate data were collected directly from a weather station at BFRS. The prescribed burn program at BFRS has been active for the past 20 years, during which burns have occurred across a variety of seasons, age classes, and silvicultural systems. Experimentally applying treatment alternatives, including fire and non-fire treatments, in young stands began in 2012 when the TAYSR study started.

We use the term “stand” to apply to areas of young forest where structure, age, and management history is continuous across a given area (Society of American Foresters 2018). We specify this definition because, within the context of gap based-silviculture, the term stand can also be used to refer to larger planning areas over which cohorts of many different ages may be developed using a predetermined schedule (O'Hara and Nagel. 2013). The young stands that we burned at different seasons were regenerated by clearfelling in the summers of 2006 and 2007 to create distinct canopy gaps ranging in size from 0.3 to 0.8 ha. The harvests resulted in a commercial sale of sawlogs, via conventional harvesting and ground-based yarding methods. Our reforestation objectives following harvests were to represent landowners who desire cohorts of mixed species that are established and growing at or near maximum potential following a disturbance (i.e. disturbances caused by harvests, wildfires, or insects/pathogens). Site preparation, a common practice in this region (Stewart 2020), was used; tops and limbs of felled trees were piled and burned the fall after harvests. Stands were reforested with combinations of planting seedlings at a density of 420 seedlings / ha and relying on natural regeneration from surrounding mature trees. Six trees native to the mixed conifer forest were planted: white fir (*Abies lowiana),* incense-cedar, sugar pine, ponderosa pine *(Pinus* *ponderosa),* Douglas-fir (*Pseudotsuga menziesii),* and giant sequoia *(Sequoiadendron giganteum)*. Because they have higher survival rates in resource-rich environments (York et al. 2007), *P. ponderosa* and *S. giganteum* were planted at half the frequency of the other species. Following planting, the common practices of vegetation control and precommercial thins to control density were done prior to burns. Vegetation control was done with herbicide applications (4% concentration of glyphosate) two years after planting. Herbicide was targeted to reduce competitive shrub cover to approximately 10%. Thins were done five years after planting and reduced density to approximately 420 trees per hectare. The thins had the objectives of increasing vigor of remaining trees, balancing species composition, and maintaining lower canopy densities than would otherwise develop without thinning. This lowering of canopy density is done primarily to facilitate prescribed burns via increased drying of surface fuels. Stands at BFRS are empirically known to be able to maintain 420 trees per hectare with low mortality until they can be commercially thinned at approximately 30 years.

2.2. Prescribed burns

The burns were conducted in 13 to 14 year old stands. We targeted this stand age for the TAYSR study since it is aligned with the median fire return interval of 6 to 14 years at the 3-5 ha spatial scale for BFRS (Stephens and Collins 2004) and is most likely similar to when young stands would have been first exposed to fire before the current era of fire exclusion and suppression. From experience burning in other young stands at BFRS, we have observed that it takes roughly this many years of stand development for surface fuels to develop enough continuity to carry a prescribed fire. Prescribed fires attempted in younger stands (if they have been site prepared) have typically not carried fire due to lack of continuous fuel.

We identified eight stands across BFRS that met the age requirement and had a similar management history (harvest, site preparation, plant, vegetation control, and thin). We randomly assigned half of these eight stands (n=4 replicates of each treatment) to be burned either in the spring or fall seasons. Fall burning is defined as occurring after the summer drought, but prior to the saturation of fuels from multiple winter storms. Generally, this occurs at BFRS in October or November, following one or two storms but prior to accumulating 13 cm of total precipitation. Spring burning is defined as occurring following heavy winter storms but prior to the drying out of fuels in the early summer to a point that precludes burning within a predetermined fuel moisture prescription. An important factor of spring burning that is not necessarily related to fuel moisture is the onset of wildfire season that is declared by fire suppression agencies. Typically, this is May 1st for this region. While conditions for burning are often appropriate and burn permits can be issued after the onset of wildfire season, usually they are suspended for the entire summer season across the entire region until significant precipitation occurs in the fall (York et al. 2020).

In all eight stands every sugar pine and incense-cedar tree that was at least 3.6 m tall was located and designated as a study tree. Each tree was then randomly assigned to be either pruned before the burns or to remain unpruned. To avoid the potential for one tree’s pruned branches to influence fire intensity near an adjacent tree, study trees were excluded if they were closer than 5 meters from an existing study tree. Pruning occurred in the summer prior to burning, about 4 months before fall burns and about 9 months before spring burns. Trees were pruned by hand with bypass loppers, removing all branches up to a height 1.8 m above the ground. Because study trees had to be at least 3.6 m tall, this meant that no more than 50% of crown lengths were removed. This method of pruning to an ergonomically comfortable height while avoiding excessive crown removal is a typical method when used for a “first-lift” prune where the objective is clear wood production (Hartsough and Parker 1996). From our observations it also represents the standard practice when pruning is done as a pre-fire treatment to reduce fire-related crown damage. Also as standard practice, pruned limbs were left on the ground where they fell once cut.

Fall burning occurred in October 2019. Ten-hour fuel moisture was 8 to 9%, relative humidity was 36 to 40%, and temperature was 13 to 17°C. Spring burning occurred five months later during similar conditions that occurred in April 2020. Ten-hour fuel moisture was 8 to 10%, relative humidity was 34 to 48%, and temperature was 12 to 23°C. Ignitions were done with drip torches and strip-head firing, progressing slowly as a best management practice to minimize torching of canopy trees. We ensured that all prune study trees had fire beneath them, meaning that if the fire was not carrying towards them on its own, we ignited beneath them with one dot of drip torch fuel. Fuel consumption for burns was observed to be patchy across the stands, which in our experience is typical for young stands that have had previous site preparation treatments. Shrubs typically did not torch, and individual tree torching was limited to occasional smaller trees. Generally, fire intensity was related to local conditions, mostly influenced by the amount of sun exposure and fuel load in areas less than 1 m^2. This is typical of fire behavior that we have observed in young stand TAYSR burns over the past decade.

2.3. Measurements

For each stand, a 7.3 m-wide belt transect oriented south-north was established prior to burning. Transects were laid out so that they spanned the diameters of the stands between the driplines of surrounding mature canopies. This transect orientation was used to capture the gradient of edge effects from surrounding overstory trees (York et al. 2003). Within each transect, all conifers over 1.37 m tall were tagged and measured. Species, diameter at breast height (DBH; cm), tree height (m), crown class (intermediate, co-dominant, dominant), and height to crown base (HTCB; m) were recorded for each tree. Mortality, percent crown volume scorch (PCVS; %), and scorch height (m) were recorded following the burns.

At the center of each stand, a permanent 0.04 ha circular plot was established and fuels were measured along two transects before and after each burn using the planar intercept method (Brown 1974). One-hour (0 – 0.64 cm) and ten-hour (0.64 – 2.54 cm) fuels were tallied between 0 and 1.8 m, 100-hour (2.54 – 7.62 cm) fuels were tallied between 0 and 3.0 m, and 1000-hour (>7.62 cm) fuels were tallied between 0 and 11.3 m along each transect. Duff and litter depths (cm) were measured at 3.0 and 9.1 m along each transect.

Throughout the entire stand areas, prune study trees were tagged and identified as having been pruned or not pruned prior to the burns. In addition to the measurements collected for trees in the belt transects, we measured additional parameters related to fire behavior that we thought could be related to prune status: the percent of the ground beneath crowns that was covered with ash was visually estimated to the nearest 5%; the percent of the basal circumference that was charred was visually estimated to the nearest 5%; and bole char height was measured to the nearest 0.1 m.

To help potentially explain pruning results and to collect pilot data for future experiments designed to understand the mechanisms of pruning-fire relationships, we instrumented 10 trees with Type-K, fiberglass insulated thermocouple sensors rated for temperatures up to 482°C prior to burning. These included five pairs of pruned and unpruned trees. Each pair was in the same stand and was burned on the same day during the spring burns. Three of the pairs were incense-cedar and two of the pairs were sugar pine trees. Each tree had a data logger that was protected with fire-resistant insulation and a fire shelter strapped to the bole of the tree at 1.8 m height. Three thermocouples were deployed from each logger to measure heat at 0.9m (beneath crowns of pruned trees), 1.8 m (at the base of pruned tree crowns), and at 2.7 m (in the crowns of pruned trees). Unpruned trees had the same deployment, with all sensors in the crowns but at the same heights above ground. Sensors were placed near the boles of trees.

2.4. Analysis

Fuel loads were calculated for each transect using the Rfuels package (Foster et al. 2018) in R version 4.1.0 (R Core Team 2021). Fuel loads for the two transects in each stand were averaged together to estimate stand-level fuel load. To evaluate whether or not the burns accomplished meaningful reductions of surface fuels, we used paired left-sided t-tests from the emmeans package in R (Lenth 2021) to determine whether the difference between post-burn and pre-burn fuel load was significantly less than zero after controlling for season. This was done for each fuel class individually. To evaluate if consumption was different between fall and spring seasons, we used ANOVA in R to test for the effect of season on the difference between post-burn and pre-burn fuel load.

We used a linear mixed-effects model with a binomial distribution and a logit link to model two-year canopy tree mortality using the lme4 package in R (Bates et al. 2015). We defined canopy trees as all dominant and codominant trees that were at least 3.8 cm DBH from the belt transects. This resulted in sample sizes averaging 18 trees per transect (8 total transects, one from each stand). Although they were mixed-species stands, the composition was not evenly balanced among species. 40% of the canopy trees analyzed were ponderosa pine, 19% were incense-cedar, 12% were giant sequoia, and 10% were Douglas-fir. Sugar pine and white fir both made up 9%. The null model included an intercept and a random stand effect. Predictors tested included season, PCVS, DBH, HTCB, species, and an interaction term between season and PCVS. AICc and likelihood ratio tests were used for backwards model selection. Following model selection, variance inflation factors were checked to ensure that multicollinearity was not present. For this and other modelling described below, residuals were checked using a simulation-based approach from the DHARMa package in R (Hartig 2021).

Following York et al. (2021a) and Douma and Weedon (2019), we used a beta regression model with a logit link to test the effect of season on canopy tree PCVS using the glmmTMB package in R (Brooks et al. 2017). PCVS was transformed using the formula $p^* = (p(n-1) + 0.5)/n$ to make all observations fall within the open interval (0,1) as required by beta regression (transformation recommended by Douma and Weedon 2019). p^* is the transformed proportional data value; p is the proportional data value; n is the total number of observations in the data set. We investigated zero-inflated and zero-one-inflated beta regression models but found them too complex to be worthwhile, especially since the beta regression model seemed sufficient for the data. The precision term for the beta regression model was set to stand to account for non-independent observations taken within each stand and to capture stand heteroscedasticity. Backwards model selection was done based on AICc and likelihood ratio tests. The null model had an intercept and stand as the precision parameter. Predictors tested included season, DBH, HTCB, species, interactions between season and all other fixed effects, and a random stand effect.

We modeled mortality of pruned and unpruned trees the same way as described above. Predictors in the full model included season, prune status, species, PCVS, DBH, HTCB, percent ground burned, stand, interactions between season and all other fixed effects, and interactions between prune status and all other fixed effects. Stand was initially included as a random effect but was excluded due to singularity issues brought about by lack of mortality and subsequent small sample size. Scorch height, bole char height, and percent basal char were not included as variables of interest because they were highly correlated with PCVS and percent ground burned, and PCVS and ground burned seemed the most ecologically informative. AICc and likelihood ratio tests were used for backwards model selection.

As described above, we used a beta regression model with a logit link to analyze pruning effects on PCVS. The precision term for the beta regression model was again set to stand for all models. Predictors tested included season, prune status, species, DBH, percent ground burned, interactions between season and all other fixed effects, interactions between prune status and all other fixed effects, and a random stand effect. Scorch height, bole char height, and percent bole charred were again not included for reasons described above. Backwards model selection was performed based on AICc and likelihood ratio tests.

The thermocouple data were not analyzed since the intent was not to replicate enough to make statistical inferences. We evaluated two outputs from the thermocouple measurements that are generally important factors of foliage damage: maximum heat and duration of heat (Dickinson and Johnson 2001). First, we recorded the maximum temperature that was measured by each thermocouple during burning in order to see if there were any large differences in heat delivery between pruned and unpruned trees. Second, to see if there were large differences in the duration of elevated heat levels, we summed the number of seconds during which each thermocouple recorded temperatures greater than 60 degrees C as a rough approximation for persistence of heat delivery and potential for leaf mortality (Bär et al. 2019). We averaged these two measurements across pruned and unpruned groups and at each sensor height. We compared the heating of pruned versus unpruned trees for incense-cedar and sugar pine separately.

3. Results

3.1. Seasonal effects on fuel consumption, mortality, and crown damage

The fall burns were generally productive in meeting the objective of fuel consumption (Fig. 1). In this forest type, a reduction of 50% in total surface fuels with the majority of reduction occurring in fine fuel categories would be seen as desirable from a fire hazard perspective. However, lower amounts of fuel reduction may be acceptable for burn programs that plan on a high frequency of entries if fuel consumption keeps up with rates of recovery in between fires. There was a detectable ($p<0.05$) decrease in fuel load following fall burns for all fuel categories except 1000+hour fuels ($p=0.07$). Total fuel load declined substantially following fall burns, from 92 to 18 Mg / ha. The spring burns, in contrast, had comparatively little fuel consumption. Across all fuel categories and for total fuel load, there was no detectable consumption. The ANOVA analysis that tested for a seasonal effect indicated that consumption was greater in the fall compared to the spring for total fuel load ($p=0.02$), but did not detect a difference for individual size classes of duff ($p=0.28$), litter ($p=0.06$), fine woody debris ($p=0.47$), or 1000+ hour fuel ($p=0.15$). Two notable characteristics of the fuels measurements likely influenced the capacity to detect significance within size classes. By chance, the stands burned in the fall had higher pre-burn fuel loads than the spring burns (Fig. 1) despite the random assignments of burn season. Second, the 1000-hour fuels increased following the spring burns. This occurred because of a doubling of 1000 hour fuels in one of the stands where a large fuel concentration fell onto a transect following

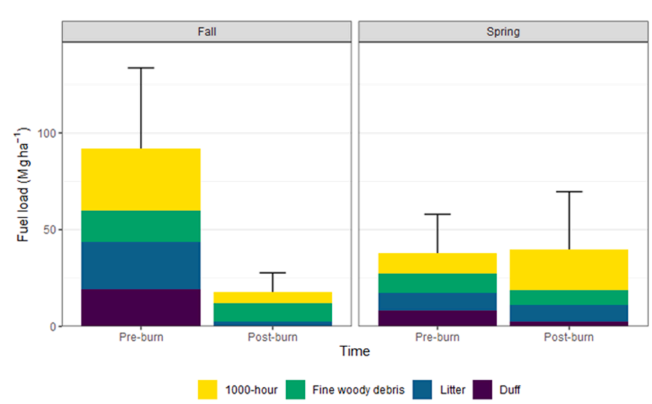

Fig. 1. Average fuel load change (Mg ha−1) by fuel class and season. Fine woody debris is composed of 1-, 10-, and 100-hour fuel loads. Error bars are standard deviations for total fuel load.

the fire.

Two-year mortality of canopy trees was notably similar between spring and fall seasons. 21% of trees died following spring burns and 19% of trees died following fall burns. The best-fit model predicting mortality included season, PCVS, an interaction term between season and PCVS, and stand as a random effect. Species was not found to be a relevant predictor. Probability of mortality increased as PCVS increased for both fall and spring burns (Fig. 2; $p = 0.015$). While overall the level of mortality between fall and spring burns was similar, mortality from fall burns was predicted to occur at lower levels of crown scorch ($p = 0.025$ at 0% PCVS, $p = 0.044$ at 45% PCVS). While fall burning led to slightly increased mortality at low levels of crown scorch compared to spring burning, at higher levels of crown scorch there was little difference in mortality. The discrepancy between observed mortality (very little difference due to season) and predicted mortality (higher mortality from fall burns at low PCVS) can be partly explained by the distribution of crown scorch that occurred during the spring burns. Spring burns had more trees that had 100% scorch, and these were the vast majority of trees that died (Fig. 3). By contrast, fall burns had mortality occur in trees that had lower levels of PCVS.

The best performing model predicting crown damage included season and HTCB. Crown damage was higher in the spring, when the estimated marginal mean PCVS was 36%. Comparatively, PCVS in fall burns was 26% (Fig. 4A; $p = 0.024$). The relationship between crown scorch and HTCB was inverse and slight, with crown scorch decreasing as HTCB increased (Fig. 4B; $p = 0.013$). This trend was parallel between fall and spring burns.

3.2. *Influence of pruning*

The best-fit model predicting mortality in the pruning study trees included season, prune status, species, PCVS, DBH, and percent ground burned (Table 1). The best-fit model also had an interaction between season and PCVS, an interaction between prune status and species, and an interaction between prune status and ground burned. Strongly supported factors of mortality, however, were difficult to distinguish presumably because mortality was not particularly high within a given category (Table 2).

Given the moderate amount of mortality, most confidence intervals overlapped when evaluating effect differences. The two factors that were the most useful in terms of inferences were the effects of DBH (Fig. 5) and percent ground burned (Fig. 6). For both fall and spring burns, the probability of mortality decreased slightly as DBH increased ($p=0.034$), approaching zero probability at diameters above about 20 cm. Probability of mortality increased as the percent of the ground burned beneath crowns increased (Fig. 6; $p = 0.009$). This general relationship was the case for both pruned and unpruned trees, but

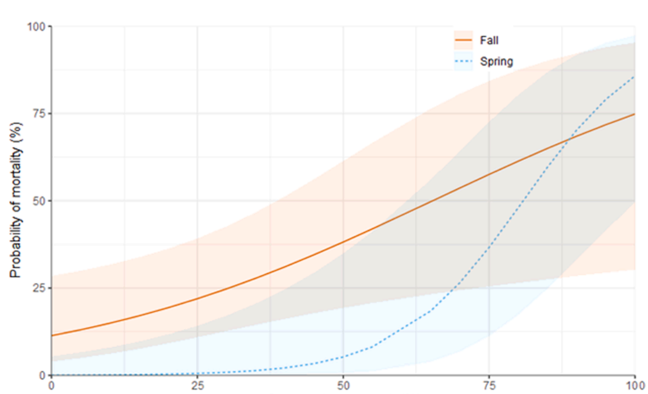

Fig. 2. Model estimates of probability of mortality by season and PCVS. Lines are estimated marginal means and shaded ribbons are 95% confidence intervals.

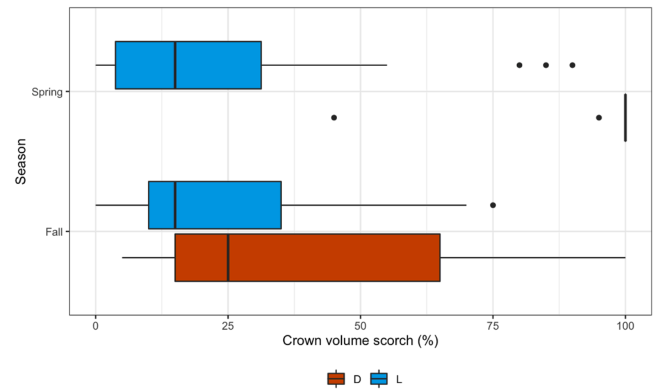

Fig. 3. Box plots of crown scorch that occurred for dead and live trees burned in fall and spring seasons. Live trees are shown on top (blue) and dead trees on the bottom (red). Most of the trees dying in the spring were 100% scorched.

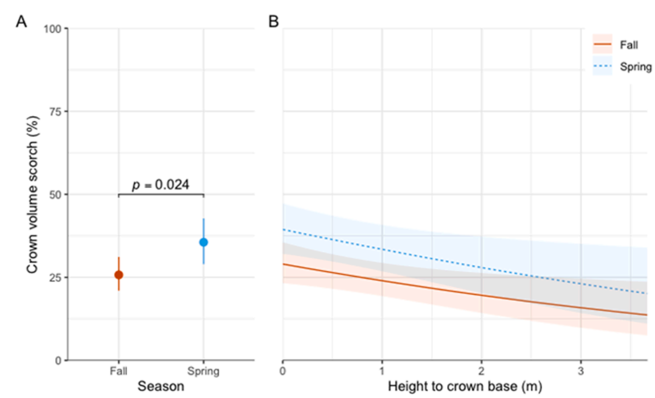

Fig. 4. A. Model estimates of PCVS by season with HTCB held constant at its average value. Points are estimated marginal means and lines are 95% confidence intervals. B. Model estimates of PCVS by season and HTCB. Lines are estimated marginal means and shaded ribbons are 95% confidence intervals.

mortality of pruned trees was higher as the percent of the ground that burned approached 100%.

The best-performing model predicting crown damage included prune status, species, and ground burned (Fig. 7). Season, an interaction between season and prune status, and an interaction between prune status and ground burned did not significantly improve the model. While effects were significant, they were generally not large. A post-hoc test of pairwise comparisons by species and prune status (using the emmeans package in R (Lenth 2021) showed that for a given species, unpruned trees had about 13 percentage points higher PCVS than pruned trees ($p < 0.001$). Estimated marginal mean PCVS for incense-cedar was 36% compared to 29% for sugar pine ($p = 0.012$), meaning that incense-cedar scorched more given the same prune status and ground burned. Generally, and as would be expected, PCVS increased as the percent of the area beneath crowns burned more.

On the small number of trees that had thermocouple sensors, temperatures were hotter and for longer durations at all three heights (0.9, 1.8, and 2.7 m above ground) when trees were pruned (Table 3). For the three pairs of pruned and unpruned incense-cedar trees, the average max temperature at 0.9 m (below the crown) on pruned trees was 247% hotter than unpruned trees. This difference decreased with sensor height. Pruned trees became 172% hotter at 1.8 m (at the base of the live crown) and 135% hotter at 2.7 m heights (in the live crown). The time during which temperatures were greater than 60°C was also much longer for incense-cedar pruned trees compared to unpruned trees. This was the case at all three sensor heights (0.9m = 777%; 1.8m = 828%; 2.7m = 300% longer). For the two pairs of sugar pine trees,

Table 1
Means and standard errors (SE) of crown damage, tree size, and percent ground burned by species, pruning treatment, and status of trees that were either pruned or not-pruned prior to conducting prescribed fires.

Species	Treatment	Status	PCVS (%) Mean	SE	DBH (cm) Mean	SE	Ground burned (%) Mean	SE
Incense-cedar	Pruned	Live	35	3.2	10.4	0.5	79	3.3
		Dead	55	5.4	9.8	1.0	98	0.6
	Unpruned	Live	22	2.5	10.8	0.5	32	3.7
		Dead	87	6.0	9.2	1.4	96	2.4
Sugar pine	Pruned	Live	19	5.3	9.4	0.8	64	7.7
		Dead	42	6.8	9.0	0.6	91	2.9
	Unpruned	Live	26	4.0	9.1	0.5	60	4.9
		Dead	38	11.1	8.6	1.0	72	12.3

Table 2
Number of pruned and unpruned trees that survived or died within two years of prescribed fires.

Species	Treatment	Fall Dead	Live	Spring Dead	Live
incense-cedar	pruned	25	47	7	26
	unpruned	10	51	1	32
	Total	35	98	8	58
sugar pine	pruned	26	10	2	7
	unpruned	8	29	1	12
	Total	34	39	3	19

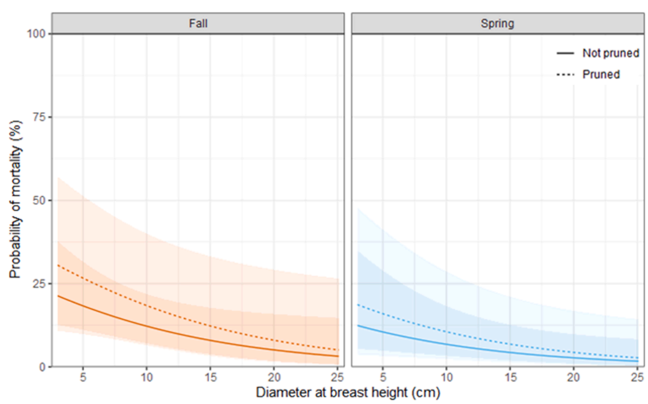

Fig. 5. Model estimates for probability of mortality by season, prune status, and DBH with species, PCVS, and percent ground burned held constant. Lines are estimated marginal means and ribbons are 95% confidence intervals.

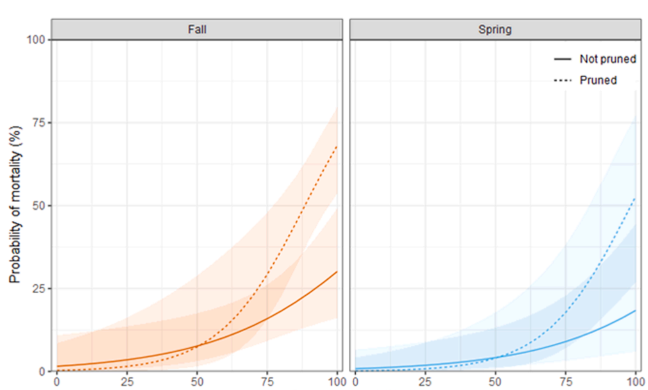

Fig. 6. Model estimates for probability of mortality by season, prune status, and percent ground burned with species, PCVS, and DBH held constant. Lines are estimated marginal means and ribbons are 95% confidence intervals.

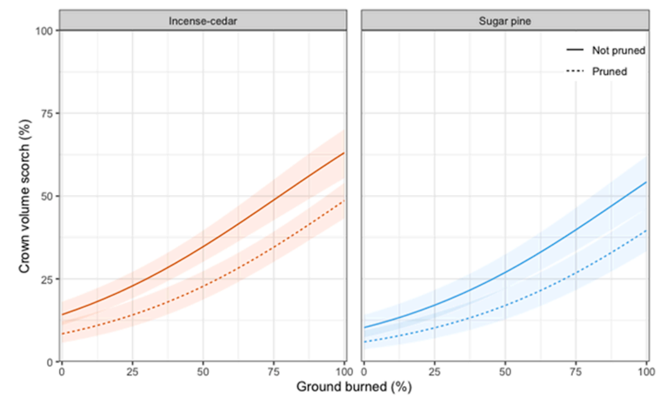

Fig. 7. Model estimates of PCVS by species, prune status, and ground burned. Lines are estimated marginal means and shaded ribbons are 95% confidence intervals.

Table 3
Maximum temperatures and durations of heat going into pruned and unpruned trees, measured with thermocouples during prescribed burns. For unpruned trees, thermocouples were placed below (0.9m), at the base of (1.8m), and within (1.8m) tree crowns.

			Mean maximum temperature (°C)			Mean number of seconds when temp > 60°C		
Species	Treatment	n	0.9 m	1.8 m	2.7 m	0.9 m	1.8 m	2.7 m
Incense-cedar	Pruned	3	372	203	155	272	167	64
	Unpruned	3	94	63	55	31	18	16
Sugar pine	Pruned	2	203	52	57	24	1	15
	unpruned	2	49	43	41	0	0	0

temperatures were also hotter and for longer on pruned trees compared to unpruned trees. Compared to incense-cedar, however, maximum temperatures and seconds when temperatures exceeded 60°C were generally lower. For the two unpruned sugar pine trees, temperatures never exceeded 60°C at any height.

4. Discussion

4.1. Merging prescribed fire with timber harvests

While silvicultural systems do not necessarily need to have timber harvests as part of them (Ashton and Kelty 2018), those that do can provide a feasible way of restoring coarse canopy heterogeneity that fires once created but currently do not. Likewise, the use of prescribed fire can provide risk reduction ecological process benefits that harvests alone cannot provide. Merging gap-based silviculture with prescribed fire (i.e. pyrosilviculture) is therefore appealing conceptually in dry mixed conifer forests, but there is uncertainty in several aspects of how to merge timber harvests with prescribed fire, including how and when to introduce fire in young stands (North et al. 2019). Prescribed fires in mature stands can consume large amounts of fuel without causing meaningful changes to the canopy (e.g. Stephens and Moghaddas 2005), resulting in canopy and basal area densities that increase over time and lead to high levels of competition. By contrast, even low-intensity fires can result in density reductions in young stands. The average 20% mortality that we found is roughly in between the only two other two studies we could find that have used prescribed fire at similar stand ages in this forest type. Bellows et al. (2016) measured 6 and 9% mortality following fall burns done during moderate fuel moisture conditions and York et al. (2021a) measured 48% mortality during relatively dry conditions. High variability in fire-related mortality among burns is a characteristic of burning young cohorts across forest types, as mortality has been observed to be very low (e.g. Knapp et al. 2011), moderate (e.g. Zhang et al. 2019), and quite high (e.g. Wade 1993). Tree size is commonly found as an important factor of mortality (Harrington 1987; Wade 1993; Battaglia et al. 2009). Small trees, because of their proximity to the ground and low crown volume, are especially sensitive to increases in ambient air temperature (Wade and Johansen 1986), and flame lengths (Battaglia et al. 2009). While there is likely some inevitable mortality that managers should expect when burning in young stands, experience with burning within local conditions and constraints should reveal factors of mortality that can be controlled. In the southeast US, where burning in young cohorts has been practiced for much longer than in the western US, various best practices have been developed when attempting to influence fire-related mortality (Wade and Johansen 1986). Of particular relevance in the western US will be to understand the importance of site preparation prior to young cohort establishment (Lyons-Tinsley and Peterson 2012) because of the variability in post-harvest (e.g. pile and burn) and post-wildfire preparations (e.g. salvage) that currently occur across landowner types.

In some management contexts, prescribed fire related mortality may be tolerated or even preferred. Using fire periodically during stand development may be used as an approach to maintain targeted stocking conditions at or well below timber growth maximization levels. Exceptionally low stocking levels could arguably be more sustainable even for timber objectives because of the need to maintain high individual tree vigor via low stand density during periods of climatic stress (North et al. 2022). Using fires, as opposed to chainsaws, to control density presents several stand growth tradeoffs. For example, prescribed fires can cause tree damage from local concentrations of fuel that result in high peak fire intensities. This can result in lower growth rates of surviving mature trees despite reductions in competition for resources (Seifert et al. 2017). . Via exposure to fires, however, trees can build up physiological mechanisms for resisting drought-related bark beetle attacks in the future (Hood et al. 2015). Increases in resin ducts, which builds resistance to secondary mortality agents, can occur even following low intensity prescribed fires (Sparks et al. 2017). As with mechanical thinning, individual tree growth can increase as a response to fires because of reductions in competition for water in dry, mature forests (Alfaro-Sánchez et al. 2016; Wenderdott et al. 2022). Nitrogen fertilization may be a fire-specific benefit to growth, but fire intensities may need to be particularly high in order to observe this effect (Alfaro-Sánchez et al. 2016).

While reducing density with low intensity prescribed fires can occur in young stands even when it is not desired, intentionally reducing density with fire in mature stands is much more difficult. Using fire alone in mature stands can decrease surface fuels without reducing canopy tree density (Stephens and Moghaddas 2005), highlighting one of the limitations of prescribed fire compared to mechanical thinning as a tool for increasing tree vigor prior to climate stress (Zald et al. 2022). An advantage of regenerating cohorts with a silvicultural system and then using prescribed fire during stand development is to reduce density before reaching the phase of stand maturity when higher severity prescribed fires are difficult. This can be an approach for preparing stands for the future climate that may necessitate even lower levels of stocking than what existed prior to fire suppression (Bernal et al. 2022). If repeated prescribed fires killed 20% of the canopy trees each time, density would be roughly half the starting density by the end of the third burn. More likely, prescribed fire related mortality will decline greatly with future burns because trees will develop size-related resistance and because those individuals or species that are more fire-sensitive will have been selectively removed by fire previously. If frequent prescribed fire maintains stocking levels as low as is suggested by the many studies that have used archived data to describe pre-fire suppression conditions (Bernal et al. 2022), the use of fire could significantly reduce or even eliminate the need to mechanically thin developing stands before a desired rotation age is reached. The pyrosilviculture approach invoked by this study – harvesting to regenerate cohorts and then burning early, frequently, and with low intensity – is not necessarily a "one-off" harvesting approach, however. Mature forests surrounding canopy gaps (i.e. the matrix forest) would need to be regenerated over time to sustain canopy heterogeneity as long as prescribed fires are not hot enough to create discrete gaps. Scheduling gap creation can be done using standard forest management principles of frequency and rotation age that are guided by the historic fire regime. In the mixed conifer forest, for example, 10% of an area could be converted to canopy gaps approximately every 15 years, resulting in a ~150 year rotation age. This rotation age could be adjusted depending on objectives of optimizing growth versus large tree values such as wildlife habitat.

4.2. Fuel consumption, mortality, and crown damage differences between spring and fall burns

We found that fall burns were more effective at reducing surface fuels, which is most likely related to lower fall fuel moisture in the duff and 1000-hour categories (Kauffman and Martin 1989). In fact, the spring burns in this case damaged and killed canopy trees without evidence of meeting the objective of surface fuel reduction at all. Adjusting spring burn prescriptions to burn when fuel moisture is lower would result in more consumption, but this would likely be traded off with even higher tree mortality and crown damage. The 100% crown scorches that occurred during the spring burns may have been from higher air temperatures during the burns, although we are unsure why we observed these high crown scorches given the low surface fuel consumption. Others have found the spring period to be a time when trees are sensitive to crown scorch (e.g. Harrington 1993). Burning during higher winds in the spring may result in more surface fuel consumption without causing additional scorch if heat is dissipated enough horizontally by winds, but this would present a tradeoff with containment effort. If using fire as a tool for reducing density is an objective and low amounts of surface fuel consumption is acceptable, then the spring burns were effective. This could be the case in young stands that were previously site prepared, and therefore do not have high amounts of surface fuel. We did not analyze the effect of these burns on tree structure, but a visual display of the change in diameter distributions (Fig. 8) confirms that, as expected, smaller trees were preferentially removed by the fires. Very small trees that were not measured (i.e. saplings less than 1.37 m tall) were likely reduced to a much larger extent, which would inhibit ladder fuel development and reduce wildfire future severity. Future surveys of TAYSR burns in the coming decades should be able to evaluate the impact that young stand burning has on guiding long-term development of forest structure and composition.

Unlike Bellows et al. (2016), whose two spring burns resulted in mortality that was 40 percentage points higher than fall burns that used the same prescription, we found very little difference in mortality between fall and spring burns. Notably, we improved upon experimental power compared to Bellows et al. (2016) by replicating spring burns four times instead of two. Bellows et al. (2016) also observed increased bark beetle activity as a factor that was likely important in causing higher spring mortality, and they also had slightly higher crown scorch in

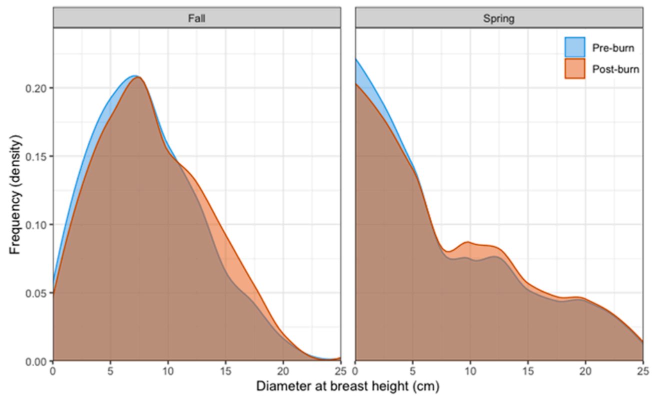

Fig. 8. Pre- and two-year post-burn diameter distribution by season in smoothed 2.5 cm size classes, averaged over stands for all canopy trees.

spring burns. We did not observe elevated bark beetle activity in our case, which may be related to the timing of our burns being more out of sync with seasonal bark beetle activity. While effects were not large, we did find that mortality was higher given low levels of scorch for fall burns compared to spring burns. Given that fall burns consumed more fuel compared to spring burns, there could have been hotter soil or cambial heating that was associated with the fall burns. Regardless of the reasons, our finding of very little difference in mortality between fall and spring burns suggests that managers should not expect consistently higher mortality in spring compared to fall burns. However, some spring burns may result in occasional high levels of tree mortality.

Crown damage has varied considerably when researchers have burned in young stands. The crown scorch that we observed is comparatively on the low end of what has typically been observed. When broadening "young" to mean stand age less than 60 years, several studies have found average crown scorch greater than 50% (Knapp et al. 2011, Reiner et al. 2012, Bellows et al. 2016, York et al. 2021a). We found that spring burns resulted in more crown scorching (Fig. 3), but effect size was not large (36% versus 26%). Elevated crown scorch may have been related to the slightly higher air temperatures during which we conducted the spring burns, but again this difference was small. Alternatively, it may be related to phenology. In the spring, trees typically have higher moisture contents, which can make leaves more vulnerable to damage given the same amount of heating (Harrington 1993). If given the option, burning in the fall may result in marginally less crown damage if that is a concern. Or, given the small effect size, it could also be interpreted that spring burning windows should not be passed up given the myriad of other constraints on burning. The negative relationship between height to crown base and crown scorch is one that we expected. As height to crown base increases with stand age, crown damage from fires should also decline. A reduction of 1% PCVS per year was found across stand ages from 12 to 32 years old (York et al. 2021a), meaning that managers can wait to burn until stands get older and likely experience less crown damage. The relationship between stand age and PCVS, however, may be very different in stands that have already been burned. Presumably, repeat fires will have considerably less scorch because earlier fires would have removed the lower portions of crowns that would be more available to scorch.

4.3. Influence of pruning and season on sugar pine and incense-cedar

Because pruning is a common method prescribed to reduce fire hazard and given that young trees tend to have low crown bases that are near flames during burns, it was reasonable to expect that pruning would "save" trees from mortality. However, there was no clear indicator in our study that pruning sugar pine and incense-cedar reduced fire-related mortality. The only result involving pruning status where confidence intervals did not overlap was with percent ground burned, where pruning increased mortality when most of the ground beneath trees burned (Fig. 5). We interpret this to mean that pruning in some cases may be counterproductive if the fuel that is left beneath crowns from pruning results in enough heat to overcome the fact that pruned crowns are farther away from the ground. Although we did not replicate enough trees to do a formal analysis, the results from the thermocouple measurements support this interpretation that pruned fuel increases temperatures in crowns considerably during prescribed fires. While pruning created a clear separation between surface fuels and the live crowns, it also clearly created more heat going into crowns.

Pruning did reduce crown scorch for incense-cedar, and somewhat for sugar pine, but again effect sizes were not large. It is important to note that the pruning treatment essentially pre-damaged crowns, removing up to 50% of live crown lengths. Hence the net effect of pruning plus fire was a much larger reduction of live crown area compared to just using fire without pruning. Percent ground burned, which generally would be expected to be higher with pruning, had the larger effect on crown scorch. While it may be possible to remove branches when they are pruned, or move them away from beneath crowns, this would be an additional cost for a benefit that so far we have observed is marginal at best. Another alternative is to prune and then burn the fuel added from pruning during relatively wet and cool conditions when very little crown scorch can be expected (Fig. 9). The lack of clear benefits from pruning that we found, plus the fact that we could not find other studies with which to compare our results, suggest the need for further study. Experimentally controlling the amount of fuel beneath crowns as well as the time since pruning, and then measuring heat transfer into crowns (Banerjee et al. 2020) with and without pruning may help clarify whether pruning is a worthwhile treatment. Season of prune studies, similar to what has been done for southeastern US pine species (Weise et al. 2016), can also help clarify if there is a season of prune interaction with prescribed fire treatments.

4.4. Conclusion

The merging of prescribed fire with other silvicultural treatments has been proposed in western US forests as a means to reduce wildfire severity at the stand scale (York et al. 2021a) and to modify fire behavior at the landscape scale (North et al. 2021). Here, we describe a version of this pyrosilvicultural approach that considers the positive synergy that can occur between gap-based silviculture and prescribed fire. The creation of distinct canopy gaps can offer several benefits that prescribed fire cannot: 1) revenue from wood products utilized from larger trees (i.e. sawlogs), which can support prescribed fire costs; 2) the creation of coarse heterogeneity (0.1 to 1.0 ha) at the stand scale that prescribed fire is unable to accomplish wherever hot fires are challenging; 3) regeneration of preferred or underrepresented species by planting in canopy gaps; and 4) sequestration of carbon in wood products to offset

Fig. 9. This stand of young ponderosa pine was pruned and then burned in the winter, resulting in very little crown damage and consumption of primarily just pruned branches. Credit: Craig Ostergaard

emissions from prescribed fires. Likewise, prescribed fire offers several benefits that gap-based silviculture cannot: 1) low-cost and effective reduction of surface fuels to decrease wildfire severity; 2) reintroduction of a critical ecosystems process; 3) inhibition of ladder fuel development via fire-caused mortality of seedlings; and 4) restoration of fine-scale heterogeneity (<0.1 ha) in overstory and understory vegetation.

Details of how gap-based silviculture and prescribed fire could be merged will depend on objectives. In our study, we only burned within 13 and 14 year old gaps in order to focus on the study questions. It is more likely that managers would try to burn across larger areas, especially within the mature matrix forest that surrounded canopy gaps where fuel load is higher. If harvest-created canopy gaps are site prepared (i.e. pile and burn) as they were in this study, then surface fuel loads within gaps are likely to remain low during the early phases of development. Burning through young cohorts in gaps that have been site prepared may not have the objective of reducing surface fuel. Rather, it could be done as a density management tool or because it is too costly to construct fuel breaks surrounding many small gaps in order to keep fire out during burning of surrounding areas. If a timber objective is important, our results may influence a manager to avoid prescribed fire in young cohorts completely in order to avoid fire-related damage and mortality to what will be future "crop" trees. In this case, fire could be avoided within canopy gaps until they are mature enough to withstand prescribed fire without undesirable mortality and damage. In a similar site, 32 year old cohorts were resistant to mortality even during relatively hot burns (York et al. 2021a).

The timing of burning versus harvesting would also have to be planned carefully and in a way that reflected specific objectives. Rather than have fire selectively remove certain species more than others, commercial thins could be done within gap-created cohorts once they reach a viable commercial size. Following thins, prescribed fires could be used as a follow up treatment to reduce activity fuels that came from the thin and to inhibit understory growth responses to the thin. Likewise, mature forests surrounding gaps could have thins and prescribed fires planned to occur in a specific order that made sense with objectives. For example, hot prescribed burns that are particularly effective in reducing fuels could be done initially, with salvage harvests occurring following burns if overstory tree mortality is outside of desired levels for wildlife habitat. Conversely, commercial thins in the mature matrix could be done prior to prescribed burns in order to lower canopy density so that fuel consumption is more complete (Levine et al. 2020).

Declaration of Competing Interest

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

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