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ARTICLE

Pyrosilviculture: Combining prescribed fire with gap-based silviculture in mixed-conifer forests of the Sierra Nevada

Robert A. York, Hunter Noble, Lenya N. Quinn-Davidson, and John J. Battles

Abstract: We used a prescribed fire study to demonstrate the concept of pyrosilviculture, defined here as (*i*) using prescribed fire to meet management objectives or (*ii*) altering nonfire silvicultural treatments explicitly in order to optimize the incorporation of prescribed fire in the future. The study included implementation of relatively hot prescribed burns in mixed-conifer forests that have been managed with gap-based silviculture. The fires burned through 12-, 22-, 32-, and 100-year-old cohorts, thus enabling an analysis of stand age influences on fire effects. Mastication and precommercial thinning were assessed as prefire treatments in the 12-year-old stands. Postburn mortality and crown scorch declined with stand age. There was a clear tradeoff between fuel consumption and high rates of tree damage and mortality in the 12-year-old stands. Masticated stands had higher levels of mean crown scorch (78%) compared with precommercially thinned stands (52%). Mortality for all 12-year-old stands was high, as nearly half of the trees were dead 1 year after the fires. Giant sequoia and ponderosa pine had relatively high resistance to fire-related mortality. When applying the concept of pyrosilviculture, there may be opportunities to combine prescribed fire with regeneration harvests that create a variety of gap sizes to sustain both low fire hazard and promote structural heterogeneity and sustainable age structures that may not be achieved with prescribed fire alone.

Key words: prescribed fire, giant sequoia, mixed conifer, crown scorch, tree mortality.

Résumé : Nous avons utilisé une étude de brûlage dirigé pour démontrer le concept de pyrosylviculture, définie ici comme (*i*) l'utilisation du brûlage dirigé pour atteindre des objectifs d'aménagement ou (*ii*) la modification de traitements sylvicoles n'impliquant pas le feu expressément pour qu'ils puissent optimiser l'incorporation du brûlage dirigé à l'avenir. L'étude comprenait l'application de brûlages dirigés relativement intenses dans des forêts mixtes de conifères qui ont été aménagées à l'aide d'une sylviculture fondée sur les trouées. Les brûlages ont eu lieu dans des peuplements âgés de 12, 22, 32 et 100 ans, ce qui a permis d'analyser l'influence de l'âge du peuplement sur les effets du brûlage. Le déchiquetage de la végétation et l'éclaircie précommerciale appliquées avant le brûlage ont aussi été évalués dans les peuplements âgés de 12 ans. Après l'application du brûlage, la mortalité des arbres et le roussissement des cimes ont diminué avec l'âge du peuplement. Il y avait clairement un compromis entre la quantité de matière organique brûlée et les taux de dommages aux arbres et de mortalité dans les peuplements de 12 ans. Les peuplements dont la végétation avait été déchiquetée avaient des niveaux plus élevés de roussissement des cimes (78 %) que les peuplements soumis à une éclaircie précommerciale (52 %). La mortalité était élevée dans tous les peuplements de 12 ans et atteignait près de la moitié des arbres un an après le brûlage. Le séquoia géant et le pin ponderosa étaient relativement résistants à la mortalité induite par le brûlage dirigé. Lors de l'application du concept de pyrosylviculture, il pourrait être possible de combiner le brûlage dirigé à des coupes de régénération créant diverses tailles de trouées afin de maintenir un faible risque de feu et de favoriser une hétérogénéité structurelle et des structures d'âge durables, ce qui serait difficile à obtenir en utilisant uniquement le brûlage dirigé. [Traduit par la Rédaction]

Mots-clés : brûlage dirigé, séquoia géant, forêts mixtes de conifères, roussissement des cimes, mortalité des arbres.

Introduction

Pyrosilviculture definition

The fundamental rationale and techniques for prescribed burning in fire-adapted forests were articulated over three decades ago by Biswell (1989), who stated "fire is natural to wildland environments and must be used." Following Biswell's assertion, the results of many experiments applying prescribed fire in the western United States have confirmed their efficacy for meeting the objectives of ecological restoration and fire hazard management (e.g., Agee and Skinner 2005; Schwilk et al. 2009). While there are some isolated instances of private landowners who have succeeded in sustaining prescribed fire programs over time (York et al. 2020*a*), the use of prescribed fire at meaningful scales remains an ideal but not a reality in California forests. Likewise, the limited use of prescribed fire on federal forestlands has contributed to a substantial backlog of forest area that is vulnerable to high-severity fire (North et al. 2012). In 2015 — the most recent year for which data have been published — approximately 48 600 ha of private forestland in California were harvested commercially with nonfire silvicultural methods (Brown et al. 2018). The majority of these treatments were not designed to reduce fire severity and therefore were not likely to result in reduced fire severity potential (Stephens and Moghaddas 2005*a*). By contrast, in the 2016–2017 fiscal year,

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state agency burning (including pile burning and grassland burning) occurred on less than 5700 ha statewide (Brown et al. 2018). While mechanical-only treatments in forests can be effective in reducing fire severity if applied properly (Agee 2007), broadcast burning via prescribed fire is often preferred because it can accomplish a comparatively fast and effective reduction of high-severity fire potential (Stephens and Moghaddas 2005*b*).

Currently, land managers perceive a wide variety of barriers to the use of prescribed fire (Miller et al. 2020). Yet, even when these barriers are not present, windows of opportunity to apply prescribed fires during conditions that would allow for effective consumption of fuels remain narrow because of regulatory constraints (York et al. 2020*b*). On private timberlands, there is an additional obstacle: the perception that prescribed fire causes damage to timber and therefore cannot complement timber-focused objectives. Skepticism that prescribed fire and timber management can coexist is deeply seated, dating back to the original reports (Show and Kotok 1924) that led to current fire-suppression policies (Stephens and Ruth 2005). More recently, the balance of the negative effects of prescribed fire on stand growth with the positive effects of protection from wildfire may still sway managers away from prescribed fire if timber growth and yield is the primary objective and wildfire probabilities are low (Foster et al. 2020). The dramatic expansion of wildfire damage to timberlands in 2020 in California and other western states, however, will likely bring a renewed interest in prescribed fire, even where prescribed fire may compromise other objectives in the short term.

In forests, the use of prescribed fire should qualify as a silvicultural treatment according to any of the variety of definitions of silviculture because it is a treatment done to achieve one or multiple objectives (Ashton and Kelty 2018). Prescribed fire is distinct from other silvicultural treatments, however, because its inherent variability makes it a blunt tool for meeting objectives (Hartsough et al. 2008). The unique nature of prescribed fire suggests that it be viewed as a distinct type of silviculture, especially in forests where its use is rare compared with what is desired. We suggest the term "pyrosilviculture" to help articulate the need to manage forests in new ways that will make the use of fire more common. We define pyrosilviculture as the design of treatments in forests to (*i*) use fire directly to meet management objectives or (*ii*) alter nonfire silvicultural treatments explicitly so that they can optimize the incorporation of prescribed fire in the future. Including the use of prescribed fire in this definition actively claims it as a silvicultural practice wherever burns are done to meet specific management objectives, such as reducing surface fuels or wildfire severity, as opposed to burning for less-quantifiable objectives such as improving resilience or forest health. If a prescribed fire is viewed as a silvicultural treatment, then it is more likely that silviculturalists or foresters are centrally involved in defining burn objectives and actively involved in burn operations. This may help to protect against the "problem-isolation paradigm" (Charland 1996), where different forest treatments are isolated and handled separately by different experts. If a prescribed fire is planned and carried out by fire professionals but not silviculturalists, there is arguably more risk that forest management objectives will not be met and will be misaligned with long-term objectives.

Importantly, our definition also considers any nonfire treatment to be pyrosilviculture if there is an objective to include prescribed fire at some future time. If prescribed fire is the primary desired treatment, but opportunities to conduct them are limited because of various social or physical factors, then nonfire treatments become essential to increase future opportunities to conduct prescribed fires within acceptable societal contexts. Practically speaking, this implies that a goal of pyrosilviculture is to create conditions so that the next fire that occurs will be a prescribed fire and not a wildfire. For example, in California mixed-conifer forests, where fall burning is ecologically ideal but practically challenging (York et al. 2020*b*), pyrosilviculture treatments could facilitate future burning by promoting low canopy densities (Levine et al. 2020) or litter layers with low bulk densities (Knapp and Keeley 2006), thus enabling prescribed burns that could occur during wetter times of year, when burning is more socially feasible. Another example is the suggestion for a staggered mechanical plus fire treatment, where a mastication of mid-story trees is performed with the intent of conducting a prescribed fire several years later following decomposition of activity fuel (Stephens et al. 2012). Pyrosilviculture is more than preparing a stand for a prescribed burn by modifying the fuel structure shortly before a prescribed fire. Rather, preparation treatments in a pyrosilviculture context may occur decades prior to burning through the application of regeneration and intermediate treatments designed through the prescription-writing process to meet the long-term objective of incorporating fire at various phases of stand development. Here, we present the results of a prescribed fire study whose objective was to evaluate the influence of stand age and prefire mechanical treatments on canopy tree damage and mortality. The study is placed in the broader context of a pyrosilvicultural framework to provide an example of how the concept may be applied wherever it is desirable to increase the use of prescribed fire.

Testing the interaction of prescribed fire with young stands and gap-based silviculture

In California mixed-conifer forests that have burned with high-severity fires, natural regeneration may not occur within acceptable time frames because of limited seed supply and competing vegetation, and stands will require human intervention to reestablish desired forest structure (Goforth and Minnich 2008; Welch et al. 2016; Crotteau et al. 2014; Stephens et al. 2020). A wide variety of interventions are available to manage stands postfire, including traditional silvicultural treatments such as systematic planting on a grid, thinning, and herbicide application (Stewart 2020). Alternative treatments that focus on building general components of resilience through variable planting designs and the application of fire to young stands have also been proposed (North et al. 2019). Neither traditional nor newly proposed alternatives for reforestation and young stand management have been critically evaluated with respect to how they interact with prescribed fire during young stand development because the majority of prescribed fire studies have been done in mature stands.

Even-aged regeneration harvests (i.e., planted clear-cuts or shelterwood-regenerated stands) also create young stands in mixed-conifer forests, creating patches up to ∼10 ha in size. In a review of early 1900s descriptions of mixed-conifer forests, Safford and Stevens (2017) found that authors consistently described historical fire-maintained forest structures as "uneven-aged" and "patchy." While even-aged silviculture can therefore be viewed as mismatched with past fire-maintained structures, the management and ecological benefits of even-aged methods are arguably significant. Benefits include increased operational efficiencies, control of genetic and species compositions in stands that were previously high graded (York 2015), high species richness (Battles et al. 2001), and the potential to mimic the portion of the Sierra Nevada fire regime that includes young stands initiated by locally intense fires (Collins and Stephens 2010). The long-term sustainability of traditional even-aged stands dominated by one or two species and a homogenous structure, however, is disputed given fire behavior predictions and recent observations of elevated fire severity in even-aged stands (Stephens and Moghaddas 2005*a*; Odion et al. 2004; Lydersen et al. 2014; Zald and Dunn 2018). To avoid the potential downsides of even-aged methods while still retaining their benefits, managers may turn to the practice of gap-based silviculture. Here, the term gap-based silviculture is defined as the creation of distinct canopy gaps through harvesting to create coarse-scale structural heterogeneity or to regenerate new cohorts in support of sustainable age structures. If the disturbance regime is used as a guide for gap-based silviculture (Seymour et al. 2002), then harvests in mixed-conifer forests would create a distribution of canopy gap sizes, with a generally negative relationship between gap frequency and gap size — that is, many small gaps and fewer large gaps (Collins and Stephens 2010). In the context of silvicultural treatments, each canopy gap is a "stand," a relatively continuous structure occurring across an area where a treatment such as planting or thinning would be applied (sensu Helms 1998). Gap-based silviculture that initiates young forests developing in distinct canopy openings provides an option for restoring the coarse-scale structural heterogeneity that existed prior to fire suppression and exclusion (Lydersen et al. 2016; York et al. 2012). In the Sierra Nevada, stands ranging from 0.5 to 1.0 ha in size are large enough to regenerate all mixed-conifer species and can be expected to maximize young stand growth rates that are similar to those in larger, even-aged plantations (York and Battles 2008).

Combining prescribed fire and gap-based silviculture treatments at the same location over time merges two systems that are already relatively complex on their own. Yet, if the two treatments can be implemented in ways that complement each other, it represents an appealing strategy for managers seeking to build and maintain both low fire hazard and high structural variability. Of foremost concern for managers will be the risks associated with prescribed fire, including widespread damage to surviving trees and unacceptably high mortality in young cohorts established from previous regeneration harvests. Also of interest will be the interaction of young stand density treatments such as precommercial thins, which will influence prescribed fire outcomes when they eventually occur.

In our study, we conducted prescribed fires under relatively dry conditions on the same day across a matrix of stand ages and prefire treatments. Specifically, we burned through 12-, 22-, 32-, and 100-year-old stands to determine the relationship between stand age and crown damage and mortality. We also compared mastication and precommercial thinning in the 12-year-old stands to evaluate these two prefire treatment options with respect to the resulting crown damage and mortality.

Methods

Site description

This study was performed at the University of California Blodgett Forest Research Station (Blodgett Forest), located in the north-central Sierra Nevada near Georgetown, California, USA. Blodgett Forest is between 1100 and 1410 m a.s.l. in the Sierra Nevada mixed-conifer forest type. Tree species in this area are typical for this forest type: sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), white fir (*Abies lowiana*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), and California black oak (*Quercus kelloggii*). Soils are deep-weathered sandy loams (mean 85–115 cm) overlain by an organic forest floor horizon, with trees reaching heights of 31 m in 50 years. The climate at Blodgett Forest is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive most of the precipitation, which averages 160 cm. Mean temperatures in January range between 0 and 8 °C. Summer months are hot, with mean August temperatures between 10 and 29 °C; infrequent summer precipitation comes from thunderstorms (averaging 4 cm over the summer months from 1960 to 2000). Fire was common in the mixed-conifer forests of Blodgett Forest before the policy of fire exclusion began early in the 20th century (Stephens and Collins 2004). Blodgett Forest was logged in 1915, initiating a cohort that now constitutes the upper canopy. Starting in 1974, giant sequoia (*Sequoiadendron giganteum*) was included in planting practices along with the other native conifer species. Young stands at Blodgett are diverse, with all six conifer species typically present from both planting and natural regeneration.

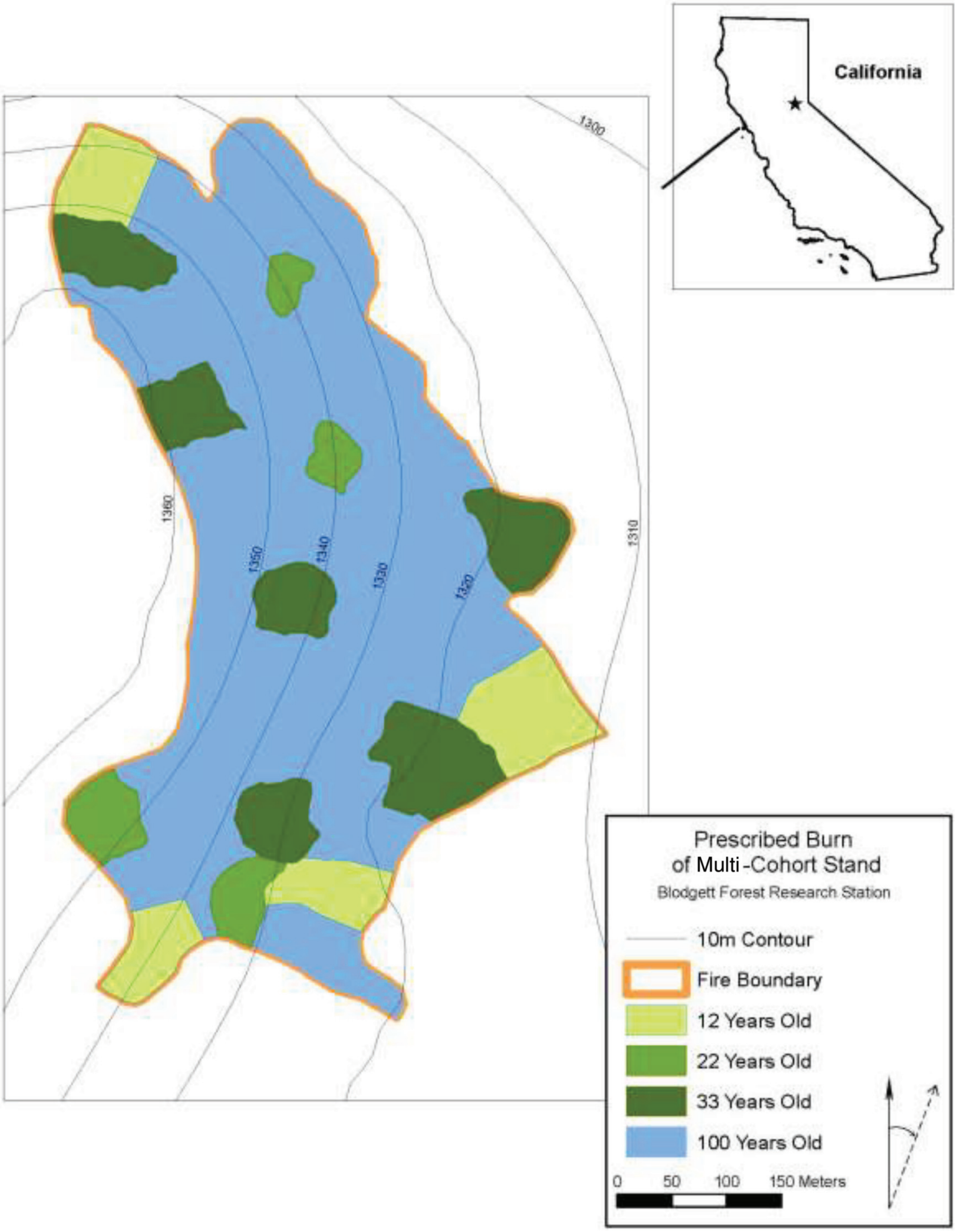
The young stands in this study were developed using a gap-based silviculture approach (Fig. 1), whereby new cohorts are initiated in several discrete gaps covering 10% of the stand area every ~10 years (i.e., a 100-year planning rotation). Canopy gaps ranging in size from 0.2 to 0.5 ha were created by clear-felling all trees within discrete areas. General reforestation objectives following harvests included reducing harvest-related fuels and initiating mixed-species stands of rapidly growing and well-stocked trees. Logging slash was piled and burned, followed by planting of all six Sierra mixed-conifer species (sugar pine, ponderosa pine, Douglas-fir, white fir, incense-cedar, and giant sequoia) in equal proportions and at a total density of 890 trees·ha^{-1}. A relevant note is that this reforestation approach reflects more recent practices of managing for high tree species diversity as a hedge against both timber market volatility among species and against species-specific pathogens and climatic stressors. Multi-species plantations are currently more common than the traditional planting regimen of one or two species, commonly ponderosa pine (e.g., Reiner et al. 2009). With the exception of Bellows et al. (2016), the few studies of prescribed burning in young forests that have been established in the past 40 years (e.g., North et al. 2019) are limited to more traditional stands that are on the older side of this 40-year range and less diverse than the stands in this study. The stands used in this study are more relevant to current reforestation practices, where species diversity and structural heterogeneity are high priorities. Standard vegetation management practices were applied during stand development, including herbicide applications where needed to limit shrub cover to <10% at 2–3 years postharvest. Between 6 and 10 years of age, stands were precommercially thinned to ~450 trees·ha^{-1} (4.9 m spacing). Commercial thins begin at about age 30. This suite of treatment activities prior to the prescribed burns reflects an overall objective of accelerating the development of well-stocked, diverse stands with low surface fuel. In these stands, the objectives include timber production as well as reducing wildfire severity, building resistance to climatic stress, and accumulating carbon in biomass.

Experimental design

Eight 12-year-old stands were randomly assigned to one of two forms of manipulation prior to the fires: a precommercial thin (PCT) or mastication. Prior to the treatments, stem density was >890 trees·ha^{-1}, originating from both planted and natural regeneration. The eight stands are distributed across two larger 20 ha areas that are within 1 km of each other in Blodgett Forest. In the summer of 2017, the PCT-designated stands were thinned with chainsaws to ~4.9 m spacing between residual trees, while leaving vigorous trees of all species. Following standard fire hazard mitigation practices, limbs of cut trees were severed so that fuel height was less than 1 m above the ground, and stems were cut into lengths <3 m long. Masticated stands were treated in 2017 and 2018 using an excavator with a vertically mounted masticating head. Guidelines for mastication applied the same spacing and retention specifications as those used for the PCT treatment. The two treatments created the same tree canopy structure and composition but different surface fuel structures. Mastication creates much smaller pieces (<0.5 m long) of dead surface fuel than PCT, and distributes the fuel in a more low-profile, uniform manner.

In October 2018, the two 20 ha areas containing all study sites were burned over two consecutive days that had similar weather conditions. The moisture content of 10 h fuel (1.3 cm diameter sticks) measured between 5% and 6%, with relative humidity varying between 23% and 39%. All burning occurred within the prescription used at Blodgett Forest for the general objective of maximizing consumption of surface fuel while limiting damage

Fig. 1. One of the study areas that was managed with gap-based silviculture and burned with prescribed fire at Blodgett Forest, California, USA. All cohorts were burned on the same day. The 12-year-old cohorts had a precommercial thin (PCT) or mastication pretreatments randomly assigned. Developed with ESRI ArcMap and USGS base map. [Colour online.]



of canopy trees. The prescription range has been developed through a combination of fire behavior modelling and observed fire effects over 15 years of annual prescribed burning. Notably, these burns occurred on the dry end of the prescription. Slightly lower fuel moisture or lower relative humidity would have put conditions out of prescription and would have caused the burns to be cancelled. Ignition via drip torches began at approximately 1000 h and concluded by 1600 h, with strip and dot head fire ignition patterns. Where possible, fires were allowed to back down slopes if the rate of spread was adequate for finishing the burns within 1 day.

Because the prescribed fires occurred in stands that had been managed with gap-based silviculture in the past, several age classes were available to burn. Seven 22-year-old stands and seven 32-year-old stands were burned in the same prescribed fires during relatively dry conditions (i.e., all stands were burned over

2 days). All stands had the same regeneration history and were of the same size (0.2–0.5 ha) as the 12-year-old stands. The mature matrix forests surrounding the younger stands were also burned at the same time, thus contributing a 100-year-old cohort to the distribution of ages that were burned. These mature stands had been harvested with a commercial thin from below to a target basal area in 2001, followed by a mastication and prescribed burn in 2002, with a second mastication of shrubs in 2017 and 2018 prior to the second burn in 2018. This sequence of treatments follows a "mechanical + burn" pyrosilviculture approach, where mechanical treatments are done with the specific objective of facilitating the next prescribed fire and achieving low fire hazard immediately following the burn treatment. The strategy with respect to facilitating the prescribed fires involved creating low canopy density with the earlier commercial thin, reducing midstory density from the prefire mastication, and inputting dry surface fuel from the mastication that would help carry the fire. All of the young stands used for this study had not been burned before. While the age of the oldest regenerated stands (32 years) is still far younger than that of the mature stands surrounding them (100 years old), thus creating a wide gap between ages, this 32-year vintage is old relative to common ages of stands initiated with modern harvesting practices in Sierra Nevada mixed-conifer forests. Plantations in the mixed-conifer forest have only been common within the past 40 years. Kitzmiller and Lunak (2012), for example, sampled 96 maturing plantations from what was available on industrial lands across the mixed-conifer forest, finding a mean stand age of 21 years. It is not yet possible to study a well-distributed range of cohort ages between zero and a rotation age used for maximizing yield, let alone between zero and maximum tree life spans of 200–300 years. This study therefore represents a management scenario where the practice of gap-based silviculture to create a wide variety of small yet distinct stands of different ages is well advanced compared with what is available across the landscape.

Data collection

Crown damage and mortality following very young stand burning

Prior to conducting the prescribed burns, 7.32 m wide belt transects were established in the eight 12-year-old stands. Belt transects ran from the south edge to the north edge driplines, through the center of each stand. Within the belt transects, all codominant and dominant trees that made up the canopy were identified by species, tagged, and measured for diameter at breast height. Transects had a mean length of 65 m, and the mean number of trees per transect was 34. Surface fuels were measured before and after the fires to provide reference information about consumption levels of the fires. At each transect midpoint, two Brown's planar intersects (11.34 m) were measured using standard protocols (Brown 1974) to estimate the change in prefire versus postfire fuel load. Transects were remeasured shortly after the prescribed burns. Consumption of litter and 1 h (<0.6 cm diameter sticks), 10 h (0.6–2.5 cm), and 100 h (2.5–7.6 cm) fuel size classes was considered for these young stands, as they do not have high proportions of duff. Consumption of 1000 h (>7.6 cm logs) fuel was not considered because of the harvests and site preparation activities that were used to establish new cohorts.

We focused on assessing damage to canopy trees, which we defined as either codominant (in the main canopy layer and receiving direct light from above) or dominant (receiving light from above and from one or more sides). Crown damage was assessed visually, estimating percent crown volume scorch (PCVS) to the nearest 5%. PCVS is a widely used (Woolley et al. 2012) indicator of future growth potential because it reflects the degree to which a fire reduces photosynthetic capacity. Given previous experience that prescribed fire-related mortality is often quite low, we chose to conduct 100% surveys of fire-related mortality. We did this by visiting all canopy trees in the 12-year-old stands that had been masticated or thinned with a PCT. This resulted in the assessment of 1251 trees across the eight stands. The mortality surveys were conducted 1 year after the fires.

Crown damage and mortality in stands of different ages

For the 22- and 32-year-old stands, we applied the same sampling methodology as that used in the 12-year-old stands. Belt transects were used to measure postfire PCVS, and 1-year postburn mortality was assessed using a 100% census of all codominant and dominant trees. In the ~100-year-old mature stands, a previously established grid of circular 0.04 ha permanent plots was used instead of transects to sample PCVS. The plots represented a 6% sampling intensity. This sampling scheme resulted in a total of 4991 observations of tree mortality; of these observations, 1251 came from the 12-year-old cohorts, 989 from the 22-year-old cohorts, 1068 from the 32-year-old cohorts, and 1683 from the 100-year-old cohort.

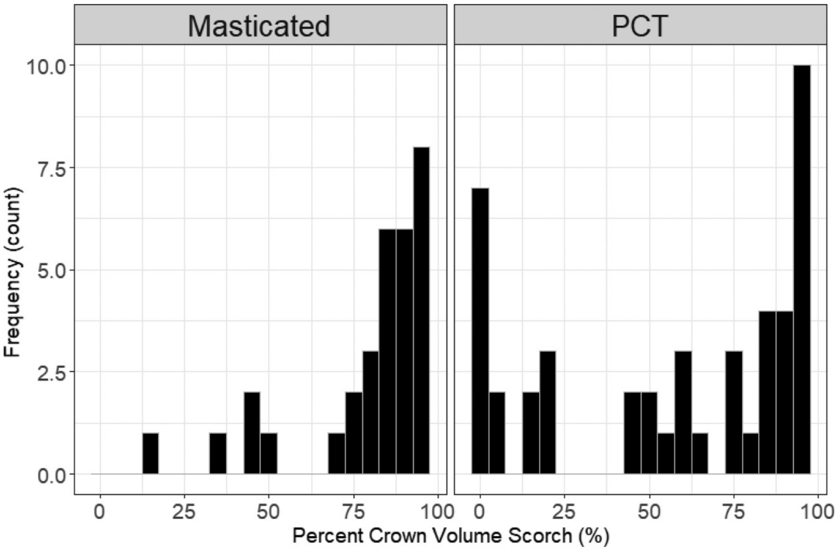
Analysis

We quantified differences in the effect of treatments (i.e., PCT versus mastication) on fire damage in very young stands (i.e., 12-year-old stands) by comparing the PCVS of surviving trees ($n = 76$). PCVS was measured as a continuous proportion bounded between 0 and 1 (i.e., 0%–100%). The distribution of this data was asymmetric, with the modal value at 95% (Fig. 1). To accommodate the nature of our data and its distribution, we used beta regression to test for treatment effects (Eskelson et al. 2011; Douma and Weedon 2019). Specifically, we used the library "betareg" in the R statistical environment (R Core Team 2017). We developed three models to predict PCVS: a null model with only an intercept, a treatment model, and an additive model with treatment plus species effects. For all models, the precision term in the beta regression was fit as a function of stand to account for random spatial variation. Given the propensity of maximum likelihood methods to introduce bias in beta regression parameters (Douma and Weedon 2019), estimates were bias corrected. We ranked the models by the Akaike information criterion for small samples ($\mathrm{AIC_c}$) to compare performance between model forms. $\mathrm{AIC_c}$ imposes a stronger penalty on model complexity than AIC and was chosen to avoid fitting models that were overly complex given the size of the dataset (Burnham and Anderson 2002).

To assess the effect of stand age and species on PCVS, we again relied on beta regression with model selection via $\mathrm{AIC_c}$. The three models we evaluated were a null model with only an intercept, an age model, and an additive model with age plus species effects. As above, the precision term in the beta regression was allowed to vary among stands, and estimates were based on maximum likelihood with bias correction.

We calculated the postburn mortality as a discrete rate variable (Sheil et al. 1995) and summarized species-specific cohort data by treatment (12-year-old stands) and stand age (all stands). Since mortality was assessed 1 year after the prescribed fire, it represents the immediate impact of fire and not the long-term trend. Every canopy tree was assessed for mortality across all age classes burned. Uncertainty was estimated using maximum likelihood. Specifically, we obtained confidence intervals (CI) of mortality using profile likelihood as outlined by Eitzel et al. (2015). This approach correctly weights stands with different numbers of trees as well as instances with complete mortality or no mortality. To test for significance differences in mortality among species and treatment in the very young stands, we fit a logistic regression using a generalized linear mixed-effects model (function "glmer"; Bates et al. 2015), with species and treatment as fixed

Fig. 2. Distribution of percent crown volume scorch by treatment in 12- to 13-year-old stands at Blodgett Forest Research Station. Treatments include mastication of stands prior to prescribed fire (masticated) and precommercial thinning prior to prescribed fire (PCT). $n = 76$ trees.



effects and stand as a random effect. A similar model was used to quantity differences in mortality among species and stand age. In this case, the fixed effects were species and stand age, and stand was included as a random effect.

Results

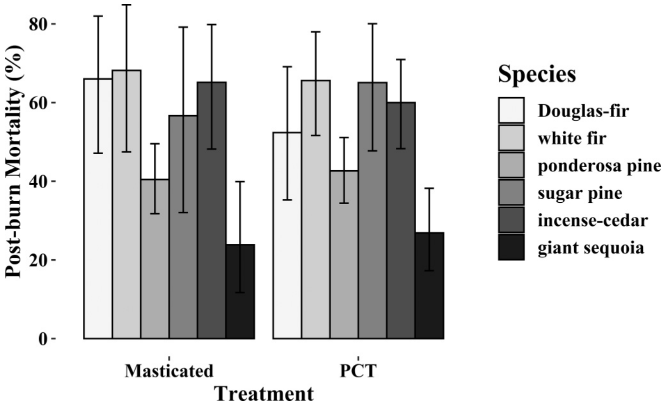
Crown damage and mortality in PCT versus masticated young stands

As intended from using identical thinning guidelines, the mastication and the PCT treatments were similar in the degree to which live canopy material was converted to dead surface fuel. Total fuel load averaged 44 $\mathrm{Mg \cdot ha^{-1}}$ following mastication and 46 $\mathrm{Mg \cdot ha^{-1}}$ following PCT, with the heaviest fuel category being litter for both treatments. Litter in masticated stands made up 41% of the total fuel, and litter in PCT stands made up 56%. As expected, given the operational differences (masticator versus chainsaws), fuels in the masticated stands were prostrate and continuous, whereas PCT fuel was concentrated into taller accumulations. Prefire and postfire measurements of fuel transects confirmed that the fires met objectives of reducing surface fuel. The prescribed fires, which were conducted during relatively dry conditions, reduced surface fuel in all size categories. Total surface fuel load was reduced by a mean of 75% across all stands.

In the 12-year-old stands, crown scorch was substantial, with significant differences between treatments (Fig. 2). The additive model with treatment and species was indistinguishable in terms of fit from the simpler treatment-only model ($\Delta\mathrm{AIC_c}$ = 1.1). Both were superior to the null model ($\Delta\mathrm{AIC_c} > 16$). The treatment-only model also had no evidence of heteroscedasticity based on inspection of a plot of standardized residuals against fitted values. Results from the treatment-only model estimated a 50% increase in crown scorch with mastication: 78% PCVS in masticated stands versus 52% PCVS in PCT. There was limited evidence of differences in scorch by species, but the treatment effect was significant ($p < 0.001$).

Despite the differences in crown damage, there were no treatment differences in mortality (Fig. 3; Supplementary Table S1[1]). Postburn mortality averaged about 48% in both treatments and the fixed effects term for treatment in the logistic regression ($p = 0.84$). However there were differences in species (Fig. 2). Both giant sequoia and ponderosa pine had significantly ($p < 0.001$) less mortality.

Fig. 3. One-year postburn mortality by treatment and species at Blodgett Forest Research Station. Results are from the 12-year-old stands. Error bars represent 95% confidence intervals of the mean survival rate.



Stand age versus fire effects

Crown damage from the prescribed fire declined with stand age (Fig. 4). The beta regression from the age-only model was clearly a better fit than the age + species model ($\Delta\mathrm{AIC_c}$ = 10.6) and the null model ($\Delta\mathrm{AIC_c}$ = 24.4). Again, there was no evidence of trends in the variance structure. Results from the age-only model predicted a steady decline in crown damage with age for the younger stands. PCVS decreased from 64% in 12-year-old stands to 59% in 32-year-old stands, a reduction in damage at an absolute rate of $1\% \cdot \mathrm{year^{-1}}$. The absolute rate slowed from the younger stands to the mature stands (100 years old), where the mean PCVS was 41%.

Tree mortality following the prescribed fire decreased consistently with stand age (Fig. 5; Supplementary Table S2[1]). Overall mortality ranged from 48% (95% CI: 44%–52%) in 12-year-old

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[1] Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2020-0337.

Fig. 4. Distribution of percent crown volume scorch by stand age class at Blodgett Forest Research Station. Stand ages include 12-year-old stands (12), 22-year-old stands (22), 32-year-old stands (32), and mature stands approximately 100 years old (100). *n* = 329 trees.

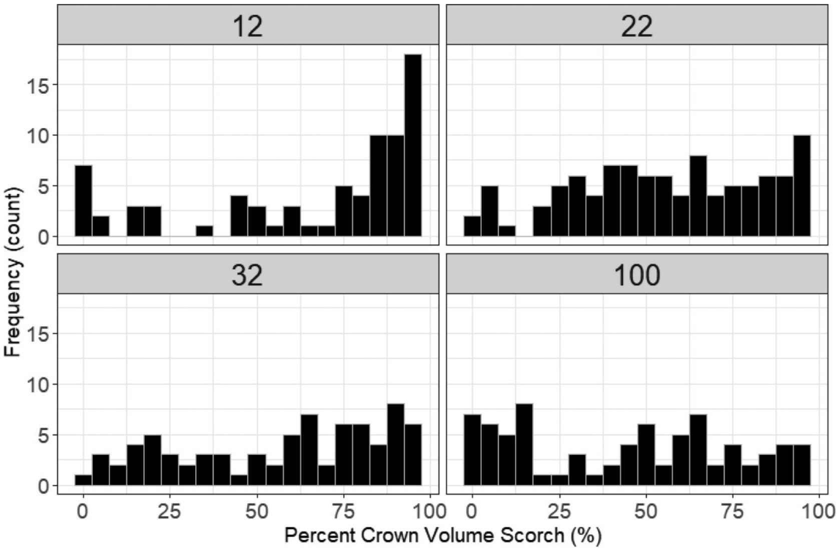
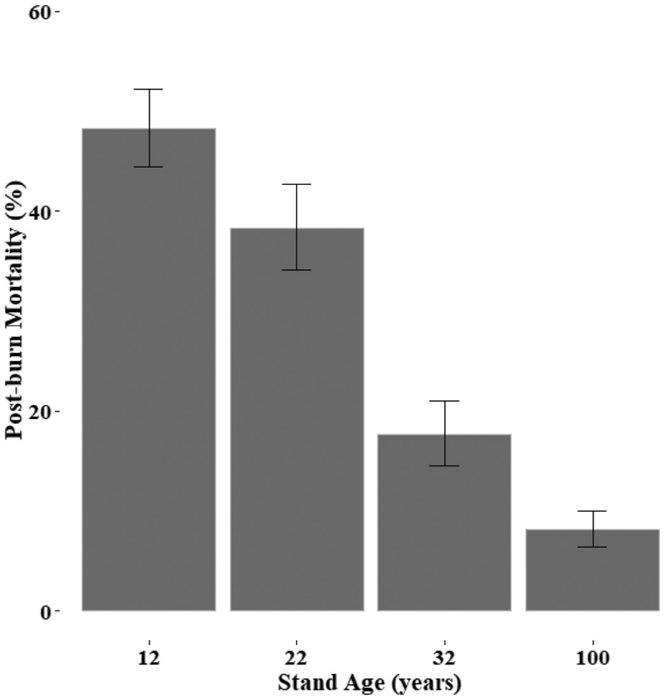


Fig. 5. One-year postburn mortality of all trees in each stand age class at Blodgett Forest Research Station. Error bars represent 95% confidence intervals.



stands to 8% (95% CI: 6%–10%) in 100-year-old stands (Fig. 5). All species had similar age-related trends in mortality, but species vulnerability to fire varied. Specifically, giant sequoia and ponderosa pine had consistently lower rates of mortality ($p < 0.001$, Fig. 6) while incense-cedar and white fir had consistently higher mortality rates ($p < 0.01$, Fig. 6). Giant sequoia had the highest survival rate of all species across three younger stand ages (this species is not present in the mature stands on Blodgett Forest), and its relative resistance to mortality was most noticeable in the youngest stands.

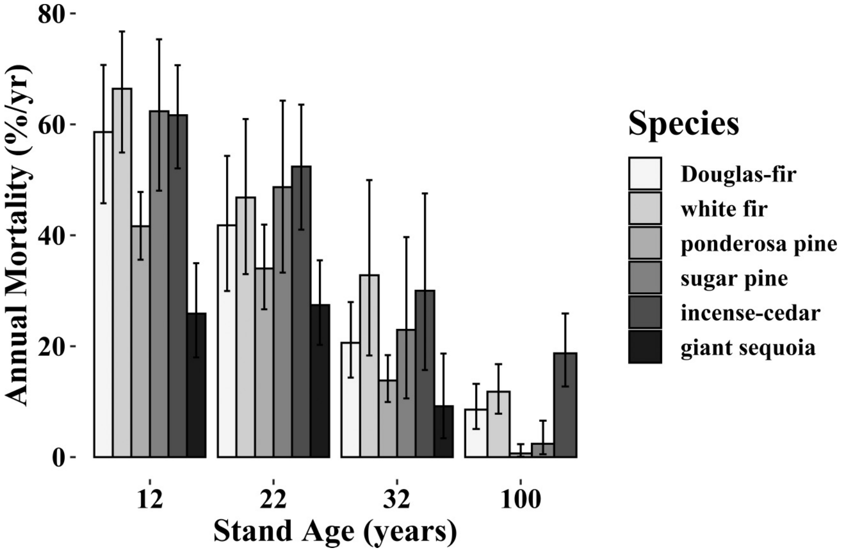
Discussion

Merging versus replacing nonfire with prescribed fire treatments

Conducting harvests and other mechanical treatments that manipulate the spatial arrangement and density of trees is an important component of efforts currently underway to prepare forests in the dry western United States for the impacts of climate change and high-severity fire (Stephens et al. 2020). In addition to following long-standing principles of surface fuel management to decrease fire severity (Agee and Skinner 2005), a variety of approaches to create structural variability in live fuels can also be used (York et al. 2012; Churchill et al. 2013). An appealing vision for proponents of fire restoration is that, following treatments, forests will be "turned over" to prescribed fire or wildfire in perpetuity (e.g., North et al. 2012). In many forests, especially those that are privately owned, this vision is arguably not practical. Even if current social and regulatory obstacles surrounding prescribed fire are overcome, prescribed fires in dry forests are typically low severity by design and are therefore not hot enough to create the discreet canopy gaps (North et al. 2007) that would be necessary for maintaining heterogeneity. Even the fires in this study, which were hot and required significant resources to contain, did not create distinct canopy gaps near the size found to be relevant for promoting resilience to wildfire (Koontz et al. 2020). Thus, turning dry forests over to a fire-only strategy risks accomplishing one of two extremes: a reinforcement of canopy homogeneity through repeated low-severity prescribed fires or an eventual high-severity fire — because of increasing probabilities that wildfires will occur during extreme fire weather conditions — and the homogeneous structure that typically follows (Collins 2014).

Because pyrosilviculture is inclusive of both fire and nonfire treatments (including regeneration harvests), it may be used to create coarse-scale heterogeneity where fire alone cannot. Furthermore, harvests do not have to be viewed as one-off treatments. In many cases they will be necessary to sustain heterogeneity over time. For example, the areas used for this study were regenerated with gap-based silviculture by converting 10% of the stand area into young cohorts three times over a 33-year period, equating roughly to a 100-year rotation age (Fig. 1). It was this scheduling of harvests, and not the prescribed fires, that created genuinely coarse-scale structural variability. The prescribed burns then

Fig. 6. One-year postburn mortality by stand age class for each species at Blodgett Forest Research Station. Error bars represent 95% confidence intervals of the mean survival rate. Note that giant sequoia is not present in the mature 100-year-old stands on Blodgett Forest, and hence it is missing a bar for this age class.



reduced fuels and further enhanced the heterogeneity and resiliency of the stands.

Merging fire with nonfire treatments in perpetuity also has relevance for the financial sustainability of prescribed fire programs. While the cost of prescribed burning compares favorably to other noncommercial mechanical surrogates (Hartsough et al. 2008), it nonetheless represents a net cost to the landowner. Forestland previously managed for sustainable timber cannot be turned over to fire as the sole management tool without substantial losses of revenue. Alternatively, harvest revenue from periodic timber harvests may be used to support a pyrosilviculture approach that helps offset or cover prescribed fire costs. Interestingly, it was foresters focused on protecting commercial timber from wildfires who originally advocated for but failed to secure policies allowing for a "light burning" approach to timber management nearly a century ago (Agee 2007).

Applications for facilitating coexistence of timber and prescribed fire

In this study, the application of prescribed fire was done within the physical and social context of stands that were also managed for timber and carbon accumulation. The prescribed fires reduced the risk of high-severity wildfire effects substantially. Their immediate effects, however, were in many ways contrary to timber management goals. Most of the timber and value of the stands were in the 100-year-old mature forests that surrounded the younger cohorts. While 8% mortality in the mature stands was low relative to what was observed in the younger stands, it is still likely to be viewed as a significant cost of the fires. Prior to the burn, the mature stands were commercially thinned from below and also had submerchantable trees masticated previously. The resulting structure was dominated by a large, vigorous canopy trees, all of high value for timber and carbon. Even minor fire-related losses are likely to be viewed as unacceptable within this context of stands where substantial investments have been made to increase the value of individual trees. More important than mortality is likely the prescribed fire-related crown damage. On average, the large 100-year-old trees lost half of their crowns to scorching effects from the fire, representing future losses in stand-level growth.

Adopting a pyrosilviculture approach would, rather than reject the use of fire because of its negative effects in this case, identify ways in which future management may be adjusted to mitigate conflict between objectives. There are at least three ways to adjust future burning operations so that fire can still be used. The obvious response is to adjust the burning prescription so that fire effects are not as severe. Given that masticated fuel beds can increase fireline intensity immediately following treatments (Stephens and Moghaddas 2005*b*); prescription parameters may need to be adjusted to increase acceptable low-end fuel moisture and humidity when burning masticated fuel. Alternatively, if prescribed burning is done within the context of a timber management program, then the option of salvage logging following particularly hot burns can be built into management plans. Salvage logging plans could consider snag recruitment targets for wildlife habitat (Knapp 2015) as well as economic recovery goals. Finally, an approach that can take advantage of masticated fuel's tendency to burn hot is to save burning for the winter period or episodic periods of higher fuel moisture and (or) lower air temperatures. Winter burning is a largely unexplored option in mixed-conifer forests, but may represent significant opportunities to expand what are currently extremely narrow fall-burning windows (York et al. 2020*b*).

The results of the study also underscore the importance of timing the merging of prescribed fire with a silvicultural system so that fires do not conflict unacceptably with regeneration and recruitment goals. Four distinct cohorts, ranging in age from 12 to 100 years, were present in these stands. The spatial patterns of prescribed fire-related mortality were directly related to this particular age structure. The high levels of damage and mortality that we observed in the 12-year-old stands were unacceptable within the context of timber and carbon accumulation objectives because cohort establishment had been planned in the past to replace larger trees that would eventually be harvested for timber. The only other study that has conducted burns in stands as young as those considered here is Bellows et al. (2016), who burned using the same prescription, but burned in the middle of the prescribed range of acceptable weather parameters and not on the hot end. They found only 5% mortality 1 year following fall burns in masticated stands and 8% mortality following fall burns in untreated stands. Our results therefore do not suggest that young stands will always be at risk for high mortality from prescribed burns. Rather, the findings suggest that the use of fire as a tool may be even blunter when applying it to young compared with mature stands.

There are three possible alternatives for adjusting future burning so that it can be merged with a gap-based silvicultural regime that has initiated multiple cohorts from past harvests. If tolerance for young tree mortality is low, then an obvious approach would be to physically exclude young cohorts from burn areas. This would involve the construction of surface fuel breaks (i.e., firelines) around each gap that contained a young cohort. The results here suggest that cohorts less than ~22 years old in productive forests may be considered for exclusion from prescribed fires under a low-mortality tolerance scenario, but that older cohorts may have a considerable capacity to resist mortality even from relatively hot burns like the ones conducted here. A second alternative is to increase cutting cycle lengths and then apply prescribed fires just prior to scheduled regeneration harvests. If ~20 years is thought to be the age at which developing stands can avoid mortality risk, then a cutting cycle of 20 years or more would avoid burning through any vulnerable young stands.

Finally, the third alternative is to use fire instead of mastication or PCT as the density management tool. While a thinning-with-fire approach may be viewed as antithetical to the concept of pyrosilviculture, it is arguably not for two reasons. The first is that our definition of pyrosilviculture includes any use of prescribed fire if it used for meeting specific objectives (in this case, thinning a dense, young stand). The second is that given the inherent long-term view that pyrosilviculture promotes, it is arguably the reforestation practices implemented 12 years prior that are the nonfire treatments that set up the opportunity to use fire as the thinning tool. The young stands in this study were thinned from a density of 890 to 416 trees·ha^{-1} — a percent reduction in density that was similar to the reduction caused by the prescribed fire. It is notable that the fires preferentially removed smaller trees, just as the PCT and mastication treatments did. Following the fires, live canopy trees were on average 5.6, 8.1, 8.6, and 16.3 cm larger than dead canopy trees for the 12-, 22-, and 32-year-old and mature stands, respectively. The prescribed fires, therefore, did what the mechanical treatments achieved but at a lower cost. An important caveat is that even if mortality rates as high as 50% from prescribed fire are acceptable in dense stands, the high levels of crown damage may be unacceptable because of the probability of lower growth associated with damaged crowns. As with mortality, our results probably represent the extreme end of other prescribed fire outcomes because burning was conducted on the hot end of the prescription. Bellows et al. (2016) measured a mean of 39% PVCS after burning though nine young stands during more moderate conditions, compared with 77% in our PCT stands and 91% in our masticated stands (Fig. 4).

Mastication as a prefire treatment caused more fire-related damage than PCT in young stands. Our result adds to the growing evidence that mastication can increase vulnerability to prescribed fire when the burns occur shortly after mastication operations (Kobziar et al. 2009; Knapp et al. 2011; Reiner et al. 2012). In mixed and young stands that were most similar to those used in this study, however, Bellows et al. (2016) found no reduction in crown scorch or survival (i.e., no benefit) when masticating compared with not masticating prior to burning. Mastication is generally expensive, ranging from \$612·ha^{-1} to over \$2450·ha^{-1} (USD; Fitzgerald and Bennett 2013). Thus, we advise against using mastication as a pyrosilvicultural treatment for fall-season prescribed burns in young stands. As suggested above for mature stands, mastication may have some benefit for facilitating winter burning in young stands.

Reforestation practices for facilitating prescribed fire

Basic information about how reforestation practices interact and influence prescribed fires in young stands are not well understood because most studies have focused on mature stands (North et al. 2019). Our study highlights the influence of species selection during planting. While there were minimal differences in crown scorch, species varied greatly in fire-caused mortality. Giant sequoia stood out as a superior survivor among the six species, resisting mortality despite moderate levels of crown scorch. Bellows et al. (2016) also found young giant sequoia to be resistant to mortality. Mature giant sequoia have been observed to resist mortality despite high levels of crown scorch (Stephens and Finney 2002). The extremely thick bark characteristic of mature giant sequoia (Weatherspoon 1990) is not present on young trees. However, the thicker bark of giant sequoia at young ages relative to that of other species at the same age (York 2019) possibly offers resistance to fire-related mortality. Ponderosa pine also demonstrated a relatively high resistance to fire-related mortality. Despite having the highest amount of crown damage, it had the second lowest level of mortality. This capacity in ponderosa pine was also suggested following a hot backfire during wildfire suppression that was conducted in a plantation, albeit one that was relatively old (53 years; Zhang et al. 2019). However, Bellows et al. (2016) found a relatively high mortality of ponderosa pine in young stands, possibly related to an interaction of spring burning with bark beetles. Incense-cedar and white fir were not as resilient in the sense of having the capacity to recover from fire-related damage. The lack of resilience to crown scorch in these young trees is actually at odds with what has been found in mature trees, where both incense-cedar and white fir are predicted to have relatively low probabilities of mortality for given levels of crown scorch (Smith and Cluck 2011). Despite lower crown damage, however, more trees of these species died following the burns. Collectively, these results suggest that prescribed fire effects in young stands may be expected to be different from those in mature stands. Furthermore, young stands dominated by ponderosa pine and giant sequoia would be expected to have a higher capacity to survive prescribed fires compared with mixed stands where the other species were more abundant. Both planting and young stand thinning treatments could be designed to favor these species to reduce mortality following future prescribed fires during young stand development.

Conclusion

Prescribed fire in forests is fundamentally a silvicultural treatment because it aims to achieve defined objectives through the planned manipulation of structure and species composition. Given the increasing frequency of high-severity fires in western US forests, it is arguably essential to develop a widespread practice of prescribed burning to reduce fire severity and associated losses of mixed-conifer forests. It will take considerable time, however, as it has been nearly a century since burning practices have been excluded (Show and Kotok 1924), and several intractable barriers to using prescribed fire still limit its use (Miller et al. 2020; York et al. 2020*b*). Here, we argue that pyrosilviculture may be one framework to help increase the use of prescribed fire. We demonstrated fire hazard reduction, timber, and carbon as examples of multiple objectives that could be considered when applying pyrosilviculture. Other goals such as water yield, wildlife habitat, or native species diversity may be more important than timber or carbon for a given landowner. But the concept of pyrosilviculture can still be applied regardless of specific objectives. The essence of pyrosilviculture is to apply and then adjust prescribed burning applications so that burns augment, rather than conflict with, other forest management goals. Importantly, it also suggests what may be significant alterations to current nonfire treatments so that they can facilitate prescribed fire many decades beyond when the treatments are applied. Because the practice of silviculture is designed to consider and then plan for long-term objectives, it should not be at the periphery but instead at the center of efforts to increase prescribed fire.

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