RESEARCH ARTICLE

Using prescribed fires in young forests: A pyrosilvicultural approach

Prescribed burns can mitigate wildfires' impacts, and pre-fire treatments as part of a pyrosilviculture regime can facilitate prescribed burning in young stands.

by Hunter Noble and Robert A. York

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Abstract

Prescribed burning is an effective treatment to reduce the risk of very severe wildfires. Many forests, however, are ill-suited for prescribed fire, because of high fuel loads, high tree densities, or young stands that are vulnerable to low intensity fires. Utilizing prescribed fire in reforested stands established after high-severity fires can protect against further losses from subsequent wildfires ("reburn" fires). Only a handful of studies provide practical guidance on how and when to burn young forests. We apply the concept of "pyrosilviculture" to suggest ways in which pre-fire silvicultural treatments can make prescribed burns more effective across a variety of age classes and structures. We also update results from a study in which several age classes of stands (12-, 22-, 32-, and 100-year-old) were burned experimentally on the same day. This focuses on a key question for managers: how to determine the right stand age at which prescribed fires may become feasible. As expected, older stands were more resistant to damage and had higher survival rates. If tree survival during prescribed fires is a primary objective, then a conservative approach is to wait until stands are age 30 before instituting prescribed fire. This is likely an overestimate of the minimum age, given that the prescribed fires applied in this study occurred during especially dry conditions. Under different objectives, higher mortality may be considered beneficial if it creates low-density, high-complexity stands that are similar to historic conditions.

Sierra mixed conifer (SMC) forests occupy over 7.4 million acres (3 million hectares) of land in California, providing a wide range of critical ecosystem services. Historically, SMC forests experienced frequent fires (less than 12-year intervals), mainly of low to moderate severity, which sustained spatially complex forest structures with generally low stocking densities (North et al. 2022) and low fuel loads (McKelvey et al. 1996; Van de Water and Safford 2011). More recently, wildfires have increased in size and severity, resulting in substantial negative impacts to ecosystem services on private and public lands (Li and Bannerjee 2021; Williams et al. 2019). Significant portions of wildfire areas often experience fire effects that are low or moderate in severity; such fires may even be beneficial, depending on the management objectives (North et al. 2021). However, large, high-severity patches can cover entire properties and watersheds which can undermine most ecosystem management objectives.

The primary reason for viewing wildfires as negative is that most or all trees die. This is because SMC conifer species have not evolved adaptive traits for high-severity fires, such as sprouting or cone serotiny (releasing seeds after a fire). What was previously forested land may not regenerate at all or within desired time frames

This 12-year-old stand, which was burned during relatively dry conditions, burned hot enough to alter structure and species composition while still maintaining tree dominance. Reforestation treatments done 10 to 12 years prior influenced fire effects. *Photo*: Robert York.

following high-severity fires; this is because a changing climate, shrub competition, and a lack of seed sources can prevent the development of a forested structure (Collins and Roller 2013; Davis et al. 2019; Tubbesing et al. 2021).

Of these constraints on regeneration, climatic variables are especially challenging because managers have no control over the climate. However, the phase of regeneration that is the most sensitive to harsh climatic conditions is germination and establishment (Davis et al. 2019). This phase can be bypassed by planting seedlings with pre-established roots. In California, the ecological and technical frameworks of reforestation have been well developed so that, even on harsh environmental sites, reforestation can be successful. The practice of reforestation has been developed for the past half-century (Schubert and Adams 1971) out of necessity to meet growth objectives and to comply with regulatory requirements following clearcut harvesting.

If done properly, active reforestation can provide a high probability of establishing post-fire cohorts of trees that are capable of developing into mature forest structures; important factors include seed collection, nursery tending, seedling handling, site preparation, and planting timing (Stewart et al. 2020). Managing competing vegetation (shrubs and grasses) in young stands can further increase development rates of tree size and bark thickness, which are two of the primary mechanisms that trees have for surviving fires. These practices, while originally designed to meet timber objectives, can also be applied as a means of ecological restoration to address the disruption of ecosystem functioning due to high-severity fires in SMC forests.

If human effort to exclude and suppress fire was the original cause of the disruption of ecosystem functioning, then the reintroduction of fire as soon as possible is likely to be an important method of restoration. In fact, for landowners who want to either restore fire or protect planted forests from high-severity wildfire, reforestation is logically viewed as complete only once fire has been reintroduced.

The reintroduction of fire is likely to be most feasible in young stands when their structures are managed so that fires with low-severity effects can be prescribed (York et al. 2021a). As such, young forest management is a strategy to facilitate the use of prescribed fire as soon as possible, in order to maximize the probability that the next fire will be a prescribed fire, rather than a wildfire that could undercut reforestation efforts. Despite the increasing occurrence of high-severity fires, there is still a reasonably high likelihood of managers achieving this "prescribed fire first" outcome given the probability of wildfire occurrence (Starrs et al. 2018).

Prescribed fire in young stands

Most of the research on the use of prescribed fire has focused on mature forests, the results of which are not readily applied to young stands (Bellows et al. 2016).

Low fuel moistures and relative humidities during the burn resulted in torching of small trees and crown scorching of larger, mature trees. *Photo*: Hunter Noble.

Because of a lack of both management and research attention, much is unknown about the relationship between stand age and prescribed fire in terms of effects on tree damage and mortality. It is this stand age-fire effects relationship that is most critical to the management strategy of reintroducing fire as quickly as possible. Heat from fires, even when low-intensity, can cause significant damage and mortality when trees are young (Stephens 1998). Young trees are inherently vulnerable to fire because of their undeveloped insulating bark, low height-to-crown base, and much lower crowning and torching indices compared to mature stands (Van Mantgem and Schwartz 2004). For these reasons, despite the ubiquity of fire in mixed conifer forests prior to fire exclusion, prescribed fire is seldom used in young stands (e.g., where trees have not developed fire-resistant characteristics such as thicker bark and higher height-to-crown bases) due to concerns about high mortality risk.

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For managers, there is a threshold age when it is "too early" to burn because the risk of crown damage and mortality is unacceptable. In general, the expected relationship between tree damage and stand age is negative. As trees get older their crown bases move upward and their bark thickens, thereby reducing risk of scorching and death. However, there is little research to define the parameters of this relationship in young stands (Smith et al. 1997; Thompson et al. 2011). Only a few studies have experimentally attempted to study prescribed fire effects in young stands (Bellows et al. 2016; York et al. 202lb; York et al. 2022). Further, only one study conducted prescribed fires across several age classes on the same day under the same conditions (York et al. 2021b).

The role of pyrosilviculture

The concept of pyrosilviculture as it relates to California forests was recently defined at the scale of individual forest stands (York et al. 2021b) and was then expanded to be inclusive of landscape-scale planning (North et al. 2021). While management at the landscape scale aims to prioritize the placement of treatments so that they can combine to allow more beneficial large fires (whether they are prescribed or wildfires), management at the stand scale aims to design treatments so that prescribed fires can be used to meet specific management objectives. If stand-scale objectives are to be effective at landscape scales, these objectives must include reducing wildfire severity. However, they can also include other specific objectives such as timber production, positive net revenue to support future treatments, or wildlife habitat. Through a sequence of planned treatments, pyrosilviculture can be used to create forest stand conditions that will increase the likelihood that prescribed fires will be carried out, and also will increase the chances that prescribed fire effects are in line with management objectives once they finally occur. To achieve stand-level objectives, however, more important is the sequence of treatments that alter stand development long before any specific point in time of stand development (Ashton and Kelty 2018). Here, we follow up on York et al. (2021b) by providing updated results on the relationship between age and mortality from prescribed fire. We further develop the conceptual approach of "pyrosilviculture" by discussing ways in which both young and mature forests can be managed in order to increase the use of prescribed fire in the future.

Hot and dry conditions

The study occurred at the University of California Blodgett Forest Research Station (Blodgett Forest), located in the north-central Sierra Nevada. This study area has a history of harvesting that has created a mosaic of age classes. The burned areas included replications of three distinct cohorts: 12, 22, and 32 years old. The stands were all planted with the five SMC species: white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana)*, Douglas fir (*Pseudotsuga menziesii)*, incense cedar (*Calocedrus decurrens)*, and giant sequoia (*Sequoiadendron giganteum*). Table 1 describes the average species composition and density of each stand age prior to burning.

In October 2018, all age classes were prescribe burned over two consecutive days. The fires were conducted under conditions that were at the hot and dry end of prescriptions for fall prescribed fires at Blodgett Forest. Ten-hour fuel moisture was between 5% and 6%; relative humidity was between 23% and 39%. The conditions under which these burns were conducted are of particular importance, as dead fuel moisture (and relative humidity, which impacts fuel moisture) are important influences on fire behavior (Graham and McCarthy 2006). Most prescribed fires would be expected to result in less mortality than what we observed in this study, since they would burn under cooler and/or wetter conditions. For managers considering using prescribed fires in young stands, therefore, our results suggest a "worst case" scenario in terms of mortality that can be expected from prescribed fires.

Follow-up data were collected by surveying trees within defined 24-foot-wide belt transects running north to south in the young stands (20 stands total). A mixed effects logistic regression model was performed to assess the effect of stand age on mortality rates two years after the burns. Independent variables initially included were stand age, species, percent volume crown scorch, and stand density, but the final model only included stand age and density due to non-converging models. Detailed site information and sampling methodology can be found in York et al. (2021b).

Post-fire mortality

Tree mortality following prescribed burns is an important consideration for managers evaluating prescribed burn effects and for those considering post-fire treatments. Such treatments may include salvage harvesting of timber or felling and pile-burning of standing dead trees. York et al. (2021b) reported average stand survival rates one year post-burn of 52% (12-year-old stands), 62% (22 year), and 82% (32 year). In our remeasurement, we found that delayed mortality was especially important in the 12-year-old stands, where survival after two years was only 31% compared to

TABLE 1. Average species composition by percentage of total trees per acre per stand, averaged across stands of each age class

Stand age (years)	Percent Douglas fir	Percent giant sequoia	Percent incense cedar	Percent ponderosa pine	Percent sugar pine	Percent white fir	Average TPA
12	9%	14%	17%	43%	7%	10%	187
22	12%	29%	12%	29%	5%	12%	186
32	24%	12%	1%	56%	3%	5%	124

Density in trees per acre (TPA) is averaged across each stand of each age class.

pre-fire levels (fig. 1). Survival in the 22-year-old stands remained virtually unchanged (63% after two years), and the 32-year-old stands also did not change substantially, falling slightly to 78% survival after two years.

Reporting only immediate post-fire mortality is common in prescribed fire studies. However, our study points out the importance of additional surveys in order to capture delayed mortality, especially when studying younger stands. The logistic regression model that used two-year mortality surveys found stand age to be significant ($P < 0.05$), while stand density was not. These findings underscore the overwhelming importance of stand age as a factor of tree mortality following prescribed burns.

Similar to what would be expected in mature stands, the fires preferentially removed smaller trees, resulting in an increase in average post-fire diameter for all age classes. Average live tree diameter at breast height (DBH) was greater for all stand ages (5.2, 10.6, and 15.8 inches, respectively) than average diameter of trees killed (3.3, 7.4, and 10.9 inches, respectively; see fig. 2). Overall, average tree diameter increased across all age classes post-burn as a result of smaller trees being killed. As reported in York et al. (2021b), mortality was also dependent on species, with giant sequoia and ponderosa pine exhibiting more resistance to prescribed fire mortality compared to the other SMC species.

In this study, which occurred under low relative humidity and 10-hour fuel moisture, the level of damage and mortality in the two youngest ages may be considered unacceptable. However, what is "unacceptable" will be determined by management objectives and pre-burn stand conditions. For example, in a young stand with 350 trees per acre (865 trees per hectare), 50% mortality may be considered desirable given the starting density. A conservative approach for management contexts that are intolerant of prescribed fire-related mortality is to wait roughly three decades, given that survival rates can be 80% or more after this time, even with particularly intense prescribed fires.

Burns in young stands have been done with much lower mortality than what we found in this study. For example, Bellows et al. (2016) conducted fall burns in 12- to 13-year-old stands and found mortality ranging from 0% to 24% after two to three years. The overall lower mortality rates of Bellows et al., when compared to the mortality reported in this study, may be a result of the higher 10-hour fuel moisture during their burns (6% to 7% versus 5% to 6% in this study). As such, this study is likely near or at the highest levels of expected mortality that would result from a prescribed fire. Given that California has long wildfire seasons, numerous regulatory boundaries, and limited time before rain begins in the fall or when fuels are dry enough before wildfire season starts in the spring, managers often have extremely limited burn opportunity windows. This may lead to burning during conditions at the more extreme ends of an established prescription, or it may lead to widening the prescription on both ends of the spectrum. Being ready to burn at any given time may be the best way to take advantage of burning windows to achieve objectives and limit damage to trees

The presence of white and gray ash after the burn is a qualitative indicator of the relatively high intensity and "hot" temperatures that occurred. A topic for future studies is to understand the interaction between stand age and below-ground impacts of prescribed fire. *Photo*: Hunter Noble.

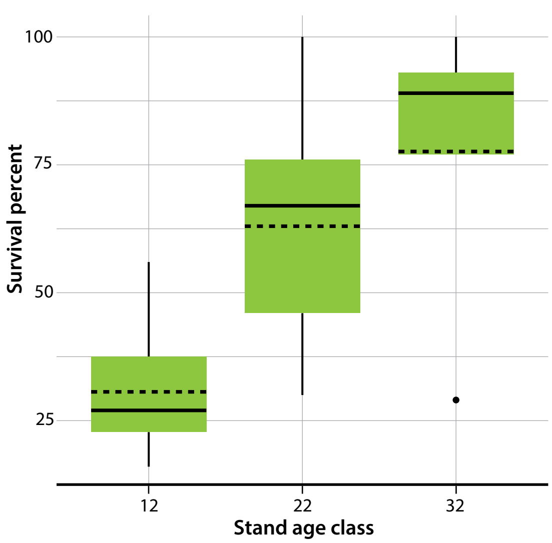

FIG. 1. Two-year post-burn stand level survival by age class. Boxes represent the interquartile range, solid black line the median, black dashed line the mean, and whiskers 1.5 times the interquartile range. Black dots represent outliers in the data.

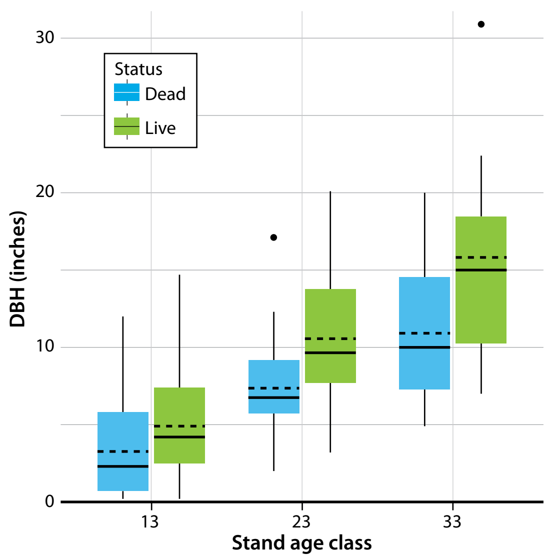

FIG. 2. Mean, median, and range of the DBH of live and dead trees of each age class. Solid black line represents the median, dashed line the mean, boxes the inter-quartile range, and whiskers 1.5 times the interquartile range. Black dots are outliers in the data.

TABLE 2. Pyrosilviculture* example treatments, effects, and mechanisms

Pyrosilviculture treatment†	Effect on prescribed burns	Mechanism	References
Reduce canopy density	Increases surface fuel consumption during winter and spring burns	Drying of surface fuels via radiation input through canopy	York et al. 2021a
Plant long-leaved conifers (e.g., ponderosa pine and giant sequoia)	Increases continuity of consumption	Longer leaves/ needles have less bulk density and are more receptive to combustion	Anderson et al. 1976
Reduce canopy cover substantially but retain large, fire-resistant trees (ponderosa pine and incense cedar)	Decreases fire-related mortality of overstory and increases consumption during fall burns	Light penetration can dry out fuels, enabling more thorough consumption while avoiding high fire-related mortality	Levine et al. 2020
Mastication	Increases fire spread during winter burns	Small woody pieces increase fireline-intensity	Stephens and Moghaddas 2005
Pruning in young stands	Increases fire intensity directly below trees during winter burns	Branches and foliage from pruned materials can provide small diameter fuel to facilitate consumption	Bellows et al. 2016
Remove mid-story via whole tree biomass harvest	Less torching during dry conditions and increased surface fuel consumption during winter and spring	Increase gusty winds at the micro-scale during wet conditions; remove ladder fuels during hot conditions	Banerjee et al. 2020
Site preparation (pile and burn) following harvests	Increases continuity of burn intensity and reduces mortality during dry fall burns	Fewer "jackpots" of fuel that result in locally intense fire	Lyons-Tinsley and Peterson 2012
Thinning with whole tree yarding	Improves ergonomics of burning	Less slash to climb over during burns	Hartsough et al. 2008
Increase rotation age	Increases the number of burns that could be done in a mature forest, prior to regenerating	Less area will be comprised of < 30-year-old stands, where prescribed fire could be avoided	York et al. 2021b
Place stands to treat and burn adjacent to previously burned stands	Reduces risk of escape	Spotting into previously burned areas will not spread and will be easier to contain	R. York personal observation
During timber harvests, use equipment to build containment lines	Lowers preparation costs	Cost of equipment is relatively low since it is on-site already	R. York personal observation
Place treated areas on south-facing slopes	Increases consumption during winter and spring burns	More direct radiation, drying out fuels more quickly	R. York personal observation
Periodically salvage harvest along roads and likely prescribed fire boundaries	Lowers preparation costs and improves safety	Standing dead trees along burn unit perimeters are a safety and escape risk	R. York personal observation

* Pyrosilviculture includes both the use of prescribed fire for objective-based management, as well as tailoring non-fire treatments to support prescribed fire in the future.
† These treatments can occur years or decades before prescribed fire.

(Quinn-Davidson 2019). Applying our results to this strategy suggests including several stand ages in burn plans. In this way, a particular stand age can be chosen from a group of available stands in order to minimize expected mortality.

Implementing pyrosilviculture

As the size and frequency of high-severity wildfires increases in California, forest managers will increasingly face a question to which there is no obvious answer. Do they allocate limited resources to treating yet-unburned mature forests and leave alone areas that have been burned with high-severity fires? Or do they seek to reforest areas that were burned with high-severity fires and invest in young stand treatments that can eventually restore forest structures that are more likely to burn with low severity during wildfires? For those who consider reforestation as a worthwhile investment, the coinciding efforts of encouraging rapid growth of seedlings and maintaining low fuel loads with prescribed fire is a best-bet strategy for preparing stands for inevitable wildfire occurrence under extreme weather conditions. Because this approach requires active investments in the form of reforestation and prescribed burning prior to the next wildfire, it is probably not practical that it will be practiced everywhere. Reasons include a lack of funding and a lack of expertise in conducting prescribed fires. Where investments in ecological restoration cannot be sustained or where logistical constraints may prohibit prescribed fire, then alternative reforestation practices that assume the next fire will be a wildfire (as opposed to a prescribed fire) may be more feasible (North et al. 2019). But for managers viewing prescribed fire as the most effective tool of ecological restoration, whether in young or mature stands, then all treatments should be critiqued in terms of the extent to which they improve the chances of conducting a prescribed fire as soon as possible and with desirable outcomes.

In mixed conifer forests, these can be a variety of treatments (table 2), some of which may occur several decades preceding a prescribed fire. Such treatments may also meet additional objectives besides supporting prescribed fire usage. As was demonstrated in this study, reforestation methods can affect the outcome of prescribed fires in young stands because they influence tree size, species composition, and age cohorts present when fires occur. Intermediate treatments, such as precommercial thins and pruning, should also be expected to influence prescribed fire effects based on how these treatments influence forest structure, i.e., reducing densities and raising crown base heights (Agee and Skinner 2005). In addition, the silvicultural system that is applied to forests once they do achieve maturity (i.e., even-aged versus uneven-aged methods) will be of critical importance to long-term sustainability. Transformation silviculture, which is the process of transitioning single-aged stands into multi-aged stands (O'Hara 2001), can eventually create diverse and multi-age stands from what — for now — must be single-aged plantations that follow high-severity wildfires. But to reach that point will likely require a combination of traditional reforestation management and innovative practices for conducting prescribed fire in young forests.

The right conditions

With increasing threats of high-severity wildfire in young stands, managers must design novel approaches to ecological restoration that will enable young forests to reach maturity. Prescribed fire is desirable because it restores a basic ecological process, but it is also a blunt tool with highly variable outcomes. Still, prescribed fire is the most effective tool for fuel reduction; fundamentally, it is the most direct form of ecological restoration to address the negative impacts of fire suppression and exclusion that have occurred over the past century (Knapp et al. 2017). Utilizing prescribed fire in young stands under the right conditions and/or stand development stages can result in positive outcomes for reducing fuels and fire hazard without significant mortality. However, as demonstrated, high levels of mortality can occur under drier burning conditions, where the acceptable level of mortality will be determined by management objectives and pre-burn stand structure. Ultimately, active pyrosilvicultural treatments in stands of various ages can create more favorable conditions for implementing prescribed fire in order mitigate the effects of wildfires. CA

H. Noble is Forest Manager, Whittell Forest and Wildlife Area, University of Nevada, Reno; R. York is Associate Professor of Cooperative Extension, Department of Environmental Science, Policy, and Management, UC Berkeley.

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