Journal of Forestry, 2021, 520–544
doi:10.1093/jofore/fvab026
Practice of Forestry - fire & fuels management
Received December 16, 2020; Accepted April 6, 2021
Advance Access publication May 21, 2021

Practice of Forestry - fire & fuels management

Pyrosilviculture Needed for Landscape Resilience of Dry Western United States Forests

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Abstract

A significant increase in treatment pace and scale is needed to restore dry western US forest resilience owing to increasingly frequent and severe wildfire and drought. We propose a pyrosilviculture approach to directly increase large-scale fire use and modify current thinning treatments to optimize future fire incorporation. Recommendations include leveraging wildfire's "treatment" in areas burned at low and moderate severity with subsequent pyrosilviculture management, identifying managed wildfire zones, and facilitating and financing prescribed fire with "anchor," "ecosystem asset," and "revenue" focused thinning treatments. Pyrosilviculture would also expand prescribed-burn and managed-wildfire objectives to include reducing stand density, increasing forest heterogeneity, and selecting for tree species and phenotypes better adapted to changing climate and disturbance regimes. The potential benefits and limitations of this approach are discussed. Fire is inevitable in dry western US forests and pyrosilviculture focuses on proactively shifting more of that fire into managed large-scale burns needed to restore ecosystem resilience.

Study Implications: A management paradigm shift in fire use is needed to restore western forest landscape resilience. We propose a "pyrosilviculture" approach with the goals of directly increasing prescribed fire and managed wildfire and modifying thinning treatments to optimize more managed fire. Changes include leveraging low- and moderate-wildfire burn areas as treatments, identifying managed wildfire zones, and three thinning treatments designed to expand and finance prescribed fire to connect dispersed treatments. We also suggest that large-scale fire be used to reduce forest density, increase structural heterogeneity, and select for tree species and phenotypes adapted to changing climate and fire conditions.

Keywords: forest fuels, managed wildfire, prescribed fire, spotted owl, structural heterogeneity, treatment pace and scale

Published by Oxford University Press on behalf of the Society of American Foresters 2021.

Over the last several decades, dry conifer forests in the western US have experienced high mortality from severe drought and wildfire. Past logging practices and ongoing fire suppression have significantly decreased average tree size and increased fuel loads and continuity, stand density, and canopy cover (Scholl and Taylor 2010, Collins et al. 2011, Knapp et al. 2013), conditions that have made forests susceptible to these stresses (Restaino et al. 2019, Young et al. 2020a, Knapp et al. 2021). Many of these forests show signs of potential ecological "unraveling" with loss of sensitive species (Jones et al. 2016), type conversion (Coop et al. 2020), and carbon loss that contributes to global warming (Hurteau et al. 2019, Goodwin et al. 2020). Researchers and managers have widely documented these changes and identified forest treatments that alleviate forest degradation and loss (Ritchie et al. 2007, Stephens et al. 2018, Prichard et al. In Press). The pace and scale of these treatments, however, has never matched the enormity of the problem. For example, analyses of what is annually treated by the US Forest Service compared to historical levels of fuel reduction from pre-European fire regimes have documented an order-of-magnitude shortfall in treatment rates (North et al. 2012, Valliant and Reinhardt 2017).

Contributing to treatment inertia is a sometimes-contentious political and press debate about whether public land agencies can only effectively increase pace and scale by fully committing to either extensive mechanical thinning or broad-scale application of managed fire (i.e., prescribed burns and wildfires managed for resource benefit). On their own, however, each of these approaches has inherent limitations. The scale of mechanical treatments is limited by constraints including administrative and topographic thresholds where mechanical equipment can be used (North et al. 2015a), cost (Hartsough et al. 2008), insufficient log and biomass processing facilities (Stephens et al. 2016a), and the low market value of the majority of material that needs to be removed to reduce potential fire and drought severity (Schwartz et al. 2020). Many factors limit widespread prescribed fire use, which Miller et al. (2020) broadly classified into three types of barriers: risk-related (fear of liability and negative public perceptions), resource-related (limited funding, crew availability, and experience) and regulations-related (poor weather and air quality conditions for burning and environmental regulations). For managed wildfires, additional barriers include evolving national and local policies (e.g., restrictive forest plans), constraints related to political boundaries (e.g., transmission of fire risk), environmental changes (e.g., extended drought, widespread fuel continuity), and weather and seasonality when a natural ignition occurs (Young et al. 2020b). With these constraints, forest managers work to apply whatever treatment they can within the limits of available burn windows, funding, personnel, and a host of forest management, air quality, liability, and environmental regulations (Schultz and Moseley 2019).

This paper suggests the two dominant forest-treatment tools, silvicultural thinning and fire, can be better integrated to work at larger scales needed for landscape resilience[1] and reduce forest loss to type conversion. We propose the adoption of "pyrosilviculture" as a management paradigm; an approach where the two disciplines expand beyond the current use of each individual tool to affect large-scale ecological restoration. In the western US, prescribed fire has been used mostly for site preparation for replanting, fuel reduction, and for maintenance of strategic fuelbreaks (Ryan et al. 2013). In western US forests, silviculture's use of mechanical thinning is often to create fuel discontinuity (particularly for vertical flame transfer), increase radial growth through density reduction, and shift species composition (Reinhardt et al. 2008). There is, however, a broader potential for coordinated use of mechanical thinning, prescribed burning, and managed wildfire to effect forest resilience from larger scale treatments than are presently used. Most of the 155 US Forest Service National Forests are developing or have recently released new forest plans, and without increasing treatment pace and scale, many fire-dependent forests in the western US face continued degradation and type conversion.

Pyrosilviculture's principle goal is to directly increase fire use in dry western conifer forests by coordinating and consolidating prescribed burn, managed wildfire, and modified mechanical treatments to reduce fuels and tree density at large scales. This article broadens the concept of pyrosilviculture from the stand (York et al. In PressB) to the landscape scale, and expands the concept of fire use to include managed wildfire (Table 1). It also focuses much of its discussion on federal forest lands, although the principles would apply to any large landowner or collaborative effort in multiownership landscapes. When used over large areas, fire is a blunt tool for modifying forest conditions (Hartsough et al. 2008), and as such, its large-scale application will require modified silviculture treatments and expanding the ways fire managers set objectives and assess outcomes. Pyrosilviculture does not change the need to provide forest products

Table 1. Comparison of stand and landscape scale attributes of pyrosilviculture.

Pyrosilviculture Attributes:	Stand[a]	Landscape
Definition	• Use fire to directly meet management objectives. • Alter silvicultural treatments to better incorporate future prescribed fire.	• Coordinate and consolidate mechanical, prescribed burn, and managed wildfire treatments to reduce fuels and tree density to moderate large-scale stressors.
Objectives	• Create conditions (structures and species compositions) such that future prescribed fires can more feasibly be applied. • Apply prescribed fire as the preferred tool for reducing surface fuels. • Sustain fuel conditions, so that a higher proportion of wildfires burn with predominantly low-moderate severity in treated stands.	• Treat large forested areas where the beneficial effects of prescribed fire, managed wildfire, and mechanical treatments are synergistic. • Fire occurs on a scale such that its function as a crucial ecosystem process is restored. • Limit high-severity wildfire extent such that type conversion is minimized.
Operational means	• Increase near- and long-term opportunities for future fire use by adjusting planting and thinning prescriptions. • Apply prescribed fires at stand scales (<125 ac). • Prescribed fire schedules are designed around specific management objectives.	• Leverage low and moderate severity areas in wildfires as initial 'treatments.' • Identify managed wildfire zones. • Implement anchor, ecosystem asset, and revenue treatments. • Expand fire objectives to include density reduction, heterogeneity and species/phenotypic selection.
Measures	• Fuel-load monitoring • Wildfire behavior modeling • Fire effects that are identified as enhancing objectives (e.g. minimizing crown damage).	• General objectives[1] derived from NRV[2] for: • Forest conditions—tree density, structure, composition, and spatial pattern. • Fire behavior—percentage and patch size of high-severity fire.
Limitations	• Risk, resource, and regulatory barriers around fire use. • Outcomes are variable compared to non-fire treatments. • Perception of fire's incompatibility with timber objectives.	• Crew and equipment availability for large operations. • Increased days of smoke production • Potential liability • Institutional caution
Opportunities	• Use traditional tools, such as leaf area index and relative density index to manage stand structure. • Small burns can be done during short opportunity windows, which may occur during winter droughts or cool summer nights. • Hedge bets against variable environmental conditions by having multiple stand types ready to burn on any given day.	• Treat landscapes while providing habitat for sensitive species. • Develop a network of thinned anchors and ecosystem assets for increasing fire-use opportunities. • Dynamically work with fire, 'pushing' it into low fuel areas during adverse conditions and 'pulling' it across the landscape under optimal weather and smoke dispersal settings.

[a] York et al. (In pressB)

[1] Given changing climate and disturbance conditions, natural range of variation (NRV) is used for general guidelines, not for strict numerical targets.

[2] Many western forests have literature summaries of NRV (i.e., Keane et al. 2009, Safford and Steven 2017, Meyer and North 2019)

and their economic returns or ignore managing forests for a range of ecosystem services including maintenance or enhancement of habitats for sensitive species.

A paradigm shift in using fire as a management tool in western US forests begins with acknowledging that our current approach to building resilient forest ecosystems is insufficient given observed rates of forest loss from recent fire and drought (Stevens et al. 2017, Young et al. 2017). This article first outlines the need for a new approach and then examines current treatment rates and wildfire patterns in the Sierra Nevada, as an example, providing insight into the ways by which current practices might be modified. It then discusses how pyrosilviculture could be operationalized by using some wildfire areas as a "treatment," identifying managed wildfire zones, and implementing modified silvicultural treatments to help finance prescribed fire used to expand and connect fuel-reduced areas. In addition to fuel reduction, new measures for setting objectives and evaluating large-scale fire use are suggested. Finally, the article discusses the potential wider benefits (i.e., wildlife and ecosystem services) of this approach and current limitations and opportunities in applying pyrosilviculture.

The Need for a New Approach

Many forests are susceptible to wildfire, but in the drier portions of the western US, several forest types (i.e., ponderosa pine, Jeffrey pine, mixed conifer, some hardwood/evergreen) evolved with and benefit from frequent predominantly low-to-moderate-severity fire that reduces forest floor fuels and preferentially thins smaller understory trees (North et al. 2016, van Wagtendonk et al. 2018). Higher elevation, more mesic forests (i.e., whitebark pine, mountain hemlock, subalpine) also occasionally burn, but, in general, experience more infrequent (generally >80 years) higher-severity fire, often in large patches (Agee 1996). Modern forest management that suppresses most fires has had less of an impact on these upper elevation forests, but has substantially changed forest and fuel conditions at lower elevations where higher productivity has rapidly led to increased tree densities and fuel loads (Mallek et al. 2013, Lydersen et al. 2014, Steel et al. 2015). When such lower-elevation forests burn, fire is often carried into the tree crowns, killing large overstory canopy trees. Although historical fires in these forest types did occasionally "crown out," the size of high-severity patches was generally small (often <10 ac) (Collins et al. 2007), producing openings where bordering green trees could provide wind-dispersed seed for new cohorts of shade-intolerant species such as pines (Collins and Stephens 2010). Our focus in this article is on forests that historically had frequent low-to-moderate-severity fire regimes, as these are most in need of fuel- and density-reduction treatments to restore ecological processes and enhance their resilience to fire and drought events (Allen et al. 2002, Arno and Fiedler 2005, Hessburg et al. 2015).

Although more than 95% of wildfire ignitions in dry western US conifer forests are suppressed before they reach 10 ac in size (Calkin et al. 2005, North et al. 2015b), most such forests eventually burn, often in large wildfires with significant overstory mortality. These forests are primarily process-driven ecosystems (Falk et al. 2006), meaning that frequent (i.e., at least every 10–35 years) low-to-moderate-severity burns once maintained ecosystem functions and integrity. Although beneficial, structural restoration with mechanical thinning does not fully reestablish the underlying ecological functions (Stephens et al. 2020a), such as nutrient cycling, soil respiration, decomposition, or large snag creation associated with habitat niches for a variety of wildlife species (Meyer et al. 2007, Soung-Ryoul et al. 2009, Roberts et al. 2015, Tingley et al. 2016, He et al. 2019, Steel et al. 2019). The resilience needed for dry western US forests to adapt to changing disturbance and climate conditions requires a significant expansion of low-to-moderate-severity fire.

Almost all global climate change projections suggest that a significant increase in the pace and scale of fuel treatments is needed to mitigate against changing wildfire conditions (Westerling et al. 2011, Parks et al. 2016, Liang et al. 2018). There is a strong positive relationship between temperature and wildfire area burned because higher temperatures increase the length of fire season and decrease fuel moisture, increasing forest flammability (Abatzoglou and Williams 2016, Westerling 2016). In a study evaluating the influence of the pace of treatment implementation on fire severity and carbon dynamics, Liang et al. (2018) found that restoring fire to the frequent-fire forests of the Sierra Nevada over the first half of the 21st century would decrease carbon losses and the area affected by severe fire significantly more than distributing the treatments across the 21st century. Accelerated treatment implementation, which will require widespread use of managed fire, would have substantially greater benefits for reducing intense adverse wildfire.

Under current practices, many western US forests have implemented fuel- and density-reduction treatments, but their extent and maintenance is often so limited that encounters between wildfire and effective treatments are infrequent (Barnett et al. 2016, Thompson et al. 2017). Despite being incorporated in large overall project areas (>5,000 ac), fuel-treated areas tend to be dispersed and fairly small in size (<100 ac) (Collins et al. 2010). Treated areas can locally reduce severity (Koontz et al. 2020, Ritter et al. 2020), but may not reduce fire severity much beyond the treatment unit because they are imbedded in a high-density, fuel-loaded landscape matrix (Stevens et al. 2016). The need for larger consolidated treatments in designed projects may be masked by current operational fire-spread models that considerably underpredict the growth and behavior of recent large fire events (e.g., Chiono et al. 2017). Taken together these realities may, in part, explain our current inability to alter the increasing trends in wildfire activity.

Historical Fire, Current Wildfire, and Treatment Acreage in the Sierra Nevada

To investigate these treatment patterns using publicly available data, we quantified the acreage of historical fire, current (2011–2020) wildfire, and US Forest Service treatment rates for the nine national forests (Modoc, Lassen, Plumas, Tahoe, Eldorado, Stanislaus, Sierra, Sequoia, and Inyo) and the Lake Tahoe Basin Management Unit that encompass California's Sierra Nevada range. First, we used CalFire's Fveg (CALFIRE FRAP 2015) to tally and map the distribution of dominant forest types across the study area (Figure 1). Then, to establish a baseline comparison, we used previously published methods (Stephens et al. 2007, North et al. 2012) to estimate the Sierra Nevada acreage on US Forest Service lands that would have been burned each year during the historical fire regime active before the arrival of Europeans. We separate the forest types into two groups, one that historically had a frequent low-to-moderate-severity fire regime that requires active management (i.e., periodic fuel reduction) and one that historically had an infrequent, high-severity fire regime that is typically passively managed (North et al. 2012). We estimated that across the Forest Service's 13 million acres in the Sierra Nevada, fires historically reduced fuels at an average rate of 631,000 ac/yr (≈5%) in the 12 largest forest types (Table 2), with 622,000 ac/yr burning in the nine frequent fire forest types.

We then examined the recent (2011–2020) area burned by wildfire on Sierra Nevada Forest Service land by year and severity level (when available) using the Monitoring Trends in Burn Severity (MTBS) (2012–2018), CalFire's Fire and Resource Assessment Program (FRAP) dataset (2011, 2019), and the National Interagency Fire Center data (NICF 2020). We also calculated the size and locations of Forest Service treatment areas (this included wildfires managed for resource benefit), using the Forest Activity Tracking System (FACTS) database, and which of these treatments were intersected (burned through and just abutted) by wildfire (Table 3). On average, 227,245 ac of forest were within wildfire perimeters each year and 36.4% burned at low, 25.9% burned at moderate, and 20.9% burned at high severity (Table 3). We found that a total of 202,440 ac of treatments were burned by wildfire between 2011 and 2020, or an average of 20,244 ac per year. This is likely an underestimate because we only included treatments from 2007 onward (to reflect when fuel program accomplishment reporting was performed through FACTS) that were completed and subsequently burned by wildfire. Depending on forest type and productivity, treatment efficacy for reducing fire severity is about 10–15 years (Agee and Skinner 2005, Stephens et al. 2012, Martinson and Omi 2013), meaning early years (2011–2016) in our tally would miss potentially effective treatments completed from 1996 to 2006. Focusing on more recent years that reduce this data limitation, we found that between 2017 and 2020, wildfire burned a total of 1,432,989 ac, of which 152,842 ac had been treated or about 10.7% of the total wildfire acreage (Table 3).

Over the 2011–2020 period, an average of 63,357 ac/yr of nonoverlapping, distinct treatments, including mechanical, prescribed burn, and managed wildfire[2] (each determined by coding in the FACTS database), and combinations thereof, were implemented (Table 4). The total footprint of these treatments, a measure of treatment progress across the landscape, averaged 10% of the historical fuel-reduction rate in forest types with low-to-moderate severity-fire regimes (Table 4). When accounting for all treatment acres, including overlapping treatments, the total area treated averaged 92,726 ac/yr or 15% of historical rates in frequent-fire forests (Table 4). The mean treatment size for managed wildfire (2,877 ac) was approximately 75 times larger than the mean mechanical (36 ac) and prescribed fire (40 ac) treatment sizes (Table 4). Furthermore, individual treatment units (mechanical and prescribed fire) were separated by an average of 0.88 miles, which taken with the relatively small unit sizes, indicates a much more dispersed pattern than that for an individual managed wildfire. This analysis forms the basis for three pyrosilvicultural approaches that could be effective for

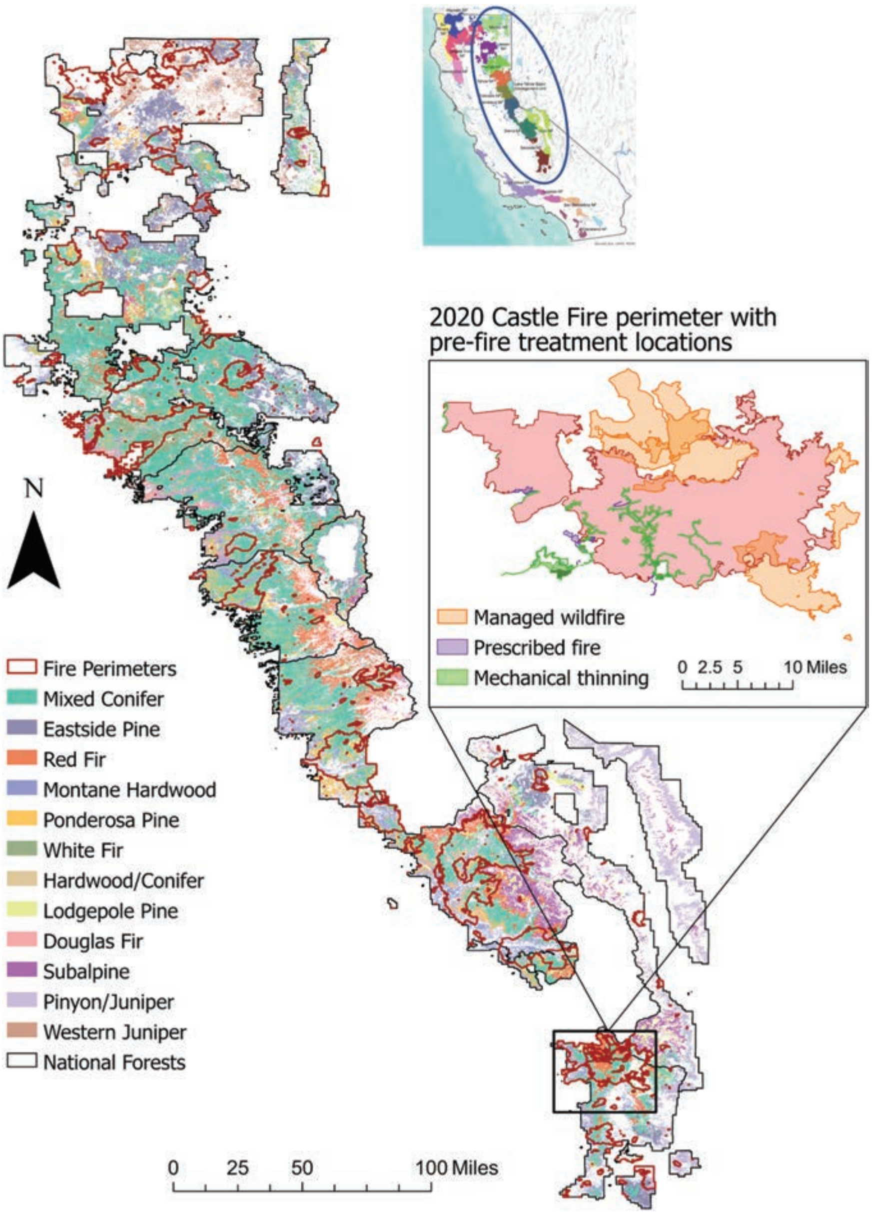

Figure 1. Distribution of the 12 most common forest types and wildfires (2011–2020) for the nine national forests and Lake Tahoe Basin Management Unit. Inset shows three principle treatment types and their locations within and adjacent to the 2020 Castle fire perimeter.

increasing treatment acreage: (1) leveraging a wildfire's low- and moderate-severity burn areas as initial treatments, (2) identifying managed wildfire zones, and (3) using thinning treatments designed to facilitate and be connected by prescribed fire or managed wildfire.

Leveraging Wildfire Treatments

Currently, wildfire has a much larger average annual impact (227,245 ac) on Sierra Nevada Forest Service lands than the combined total of mechanical, prescribed-burn, and managed wildfire treatments (63,357–92,726 ac). Given this pattern, adding a new focus to how postburn areas are managed could help facilitate pyrosilviculture's objective of preparing the landscape for more fire. In forest types that historically had frequent fire regimes, wildfire areas that burned at low-to-moderate severity are helping restore a key ecological process that can increase forest resilience. At present, most postwildfire management is concentrated on areas that burned at high severity (>75 percent mortality of overstory trees) (Meyer et al. 2021), which, in our analysis, made up 21% of the area within wildfire perimeters. Much of the fire footprint, however, includes areas of low-to-moderate-severity

Table 2. Acreage of dominant forest types[a], mean fire return interval (MFRI)[b], and estimate of the historical (pre-European) burn levels for the nine US national forests and Lake Tahoe Basin Management Unit in the Sierra Nevada. Forest types are grouped by historical fire patterns as either a frequent low-to-moderate-severity fire regime (MFRI < 50 years) generally requiring active management (i.e., fuels reduction), or as an infrequent high-severity fire regime (MFRI > 80 years), generally being passively managed.

Total forest service acreage	13,015,888		
Forest type	Area (ac)	MFRI	Average burned (ac/yr)
Mixed conifer	3,052,375	14	218,027
Eastside pine	1,102,164	6	183,694
Red fir	755,787	40	18,895
Montane hardwood	630,241	11	57,295
Ponderosa pine	469,630	5	93,926
White fir	452,755	25	18,110
Hardwood/conifer	307,891	14	21,992
Lodgepole pine	226,415	37	6,119
Douglas-fir	87,125	24	3,630
Total: Frequent low- to mod-severity fire regime	**7,084,383**		**621,688**
Sub alpine	408,466	132	3,094
Pinyon/juniper	364,181	150	2,428
Western juniper	277,939	83	3,349
Total: Infrequent high-severity fire regime	**1,050,586**		**8,871**
Total: All forest types	**8,134,969**		**630,559**

[a] Forest types with >70,000 ac

[b] Based on Safford and van de Water (2014), and the Fire Effects Information System (https://www.feis-crs.org/feis/)

effects (62% in our analysis area) where wildfire has reduced live-tree density and surface fuels. Managers could leverage the wildfire's low-to-moderate-severity burned areas as an initial treatment on which subsequent thinning and prescribed-fire applications increase resilience. For example, shortly after the wildfire, thinning could be used to "harden" low-to-moderate-severity burn areas against crown fire by removing any remaining problematic ladder fuels (Collins et al. 2018). It could also be used to create the spatial pattern characteristic of frequent-fire forests, individual trees, clumps of trees and openings (ICO), that helps reduce fire intensity (Larson and Churchill 2012). Later, prescribed fire could be applied to reduce larger surface fuels such as snags that often fall to the ground 7–20 years after the wildfire (Ritchie et al. 2013, Ritchie and Knapp 2014). With lower canopy densities postwildfire that facilitate faster fuel drying, prescribed fires could carry under a broader range of weather conditions (York et al. In pressA) while minimizing overstory tree mortality and reducing surface fuels. Generally, these burns would have low fuelloads, reducing smoke output, lessening escape risk, and, under dry conditions, could reduce recalcitrant fuels such as dense fir litter (Knapp and Keeley 2006, Parks et al. 2013). Both treatment types can be iteratively applied to fine-tune low-to-moderate-severity burn areas for future fire. This approach could be particularly effective when incorporated into a landscape-scale postfire management strategy (Meyer et al. 2021). In our Sierra Nevada analysis, treating and including low-and moderate-severity burn areas, on average, could have added up to 141,000 ac/yr to treatment rates, increasing current levels by 252–323%.

Identifying Managed Wildfire Zones

At present, managers often have clearly quantifiable objectives for prescribed burning and thinning at the stand level but may lack coordinated strategies for scaling up stand-level treatments to retain ecosystem services while effecting landscape-level resilience. To implement pyrosilviculture at larger spatial scales, an initial step would be to identify areas where mechanical fuel reduction is most practical (i.e., the wildland-urban interface [WUI] and areas with existing roads), and which areas, due to mechanical constraints or remote location, will require treatment with some type of managed fire (North et al. 2015a). This type of planning analysis is widely used in western national forests to help set two treatment bounds within a landscape

Table 3. Total acres and acres by severity class for wildfire activity from 2011 to 2020 for the nine national forests and Lake Tahoe Basin Management Unit in the Sierra Nevada. Acres of fuel reduction treatments burned are calculated from the intersection of wildfires with treatment areas (including managed wildfire) from the Forest Activity Tracking System (FACTS) database.

Year	Total fire ac	Unburned ac (%)	Low-severity ac (%)	Moderate-severity ac (%)	High-severity ac (%)	Treated acres intersected by wildfire
2011	35,765[a]	NA	NA	NA	NA	1,622
2012	132,033	18,311 (13.9)	49,695 (37.6)	36,139 (27.4)	27,888 (21.1)	2,506
2013	237,497	35,038 (14.8)	80,889 (34.1)	72,085 (30.4)	49,485 (20.8)	11,293
2014	189,505	16,281 (8.6)	53,185 (28.1)	51,983 (27.4)	68,056 (35.9)	15,139
2015	162,574	40,329 (24.8)	52,877 (32.5)	42,172 (25.9)	27,196 (16.7)	3,900
2016	82,086	13,467 (16.4)	22,529 (27.4)	20,840 (25.4)	25,250 (30.8)	15,136
2017	186,232	37,565 (20.2)	94,824 (50.9)	37,071 (19.9)	16,772 (9.0)	25,350
2018	244,654	46,900 (19.2)	108,292 (44.3)	61,520 (25.1)	27,942 (11.4)	11,711
2019	99,112[a]	NA	NA	NA	NA	10,977
2020	902,991[a]	NA	NA	NA	NA	104,804
Avg/yr	227,245	29,699[b] (16.8)	66,042[b] (36.4)	45,973[b] (25.9)	34,656[b] (20.9)	38,211[c]

NA: Severity levels were not available for 2011, 2019 and 2020.

[a] Totals in 2011 and 2019 are from CalFire's Fire and Resource Assessment Program (FRAP) dataset, which for 2012–2018 were within 2% of Monitoring Trends in Burn Severity (MTBS) totals for each year. The total for 2020 is from National Interagency Fire Center (NIFC 2020) data.

[b] Average acres by severity class are for 2012–2018 only.

[c] Average treated acres intersected by wildfire are calculated for 2017–2020 only.

and identify the intermediate zone where a combination of thinning and prescribed fire can be coordinated using pyrosilviculture approaches described below (Thompson et al. 2011, 2016, O'Connor et al. 2016). Identified nonmechanical areas can be considered as potential zones for treating natural ignitions as managed wildfires for resource benefit.

In the southern Sierra Nevada, three national forests recently revised their forest plans and have developed strategic fire-management zones that greatly expand opportunities to manage wildfires for resource objectives (Figure 2). The Inyo, Sequoia, and Sierra National Forests are among the eight "early adopter" national forests to develop 15-year plans in response to the new forest planning rule (USDA-FS 2012). Each of these national forests has identified strategic fire-management zones by proactively assessing the benefits and risks of wildfires within a landscape of interest. An initial step in this process was applying a wildfire risk assessment of anticipated fire effects on high-valued resources and assets (e.g., WUI, ecosystems, habitats) (Thompson et al. 2016). With higher risk areas identified, a second step was to identify more remote and lower risk areas where mechanical fuel reduction was often constrained, requiring some form of managed fire to reduce fuels and improve forest resilience (Figure 2a). With areas defined that effectively prioritize mechanical and managed fire treatments, each national forest delineated four fire management zones. Two of these zones, wildfire restoration and maintenance, use unplanned ignitions to restore and maintain ecosystem resilience, whereas in the two other zones, community and general wildfire protection, the focus is on the protection of life, property, and other resources (Figure 2b).

Nearly three-quarters (74%; range: 66–84%) of the Inyo, Sierra, and Sequoia National Forests are currently mapped in the wildfire restoration and maintenance zones, and the remaining 26% are located within wildfire protection zones. The wildfire maintenance zone, which is the least constrained and most supportive of managing wildfires for resource objectives under the broadest range of environmental (e.g., weather, fuels) conditions, represents nearly half (48%; range: 39–58%) of the total area of these national forests. Across all fire management zones, approximately 65% of the treated area on the Inyo, Sierra, and Sequoia National Forests could be accomplished by wildfires managed for resource objectives over the next 15 to 20 years. This could effectively double the area currently treated by managed wildfire in the southern Sierra Nevada national forests and

Table 4. Average annual acreage of Forest Service treatments by type tallied by unique footprint[1] and accomplishment[2] size, mean and median treatment size, and median distance between treatment units within a project[3] for the nine national forests and Lake Tahoe Basin Management Unit in the Sierra Nevada between 2011 and 2020.

Treatment type	Unique footprint[1] (acres)	Total accomplished[2] (acres)	Mean size in acres (range)	Median size (acres)	Median distance (ft) between treatments within a project[3]
Mechanical (Mech)	21,211	50,374	36 (0.1–5249)	13	4623
Prescribed burn (Rx)	11,861	22,214	40 (0.1–1298)	13	
Managed wildfire Man)	18,919	20,138	2877 (0.8–82,230)	295	
Mech & Rx	10,861	(23,200[4])			
Rx & Man	58	--			
Mech & Man	341	--			
Mech/Rx/Man	105	--			
Total:	63,357	92,726[5]			

[1] Stacked treatment polygons are condensed into one footprint.

[2] Total treatment acreage tallied regardless of overlap

[3] Treatments within a project are identified by having the same NEPA project number, name or decision id (total of 687 projects). This analysis excluded records for which NEPA decision statuses were "CE no DM," "Default or Not Required," and "NEPA Pending." Distance is calculated between treatment centroids.

[4] Overlapping acres of treatment (i.e., the same area was thinned and then burned)

[5] Note that even after subtracting the 23,200 overlapping acres, the total remaining accomplishment acreage (69,526) is larger than the footprint acres (63,357) because repeat treatments sometimes extend beyond the first treatment's area. This method of summing every unique pair of treatment efforts also explains why the Mech & Rx acreage is larger than the prescribed burn acreage.

more than triple the overall restoration-treatment rate (USDA-FS 2021). Although there are several barriers that could limit these anticipated rates of managed wildfires for forest restoration (see Introduction section), this approach will help diminish the restoration treatment "backlog" on national forestlands, especially in areas inaccessible to mechanical treatment (North et al. 2015a) and located in more remote landscapes (Meyer 2015). Fire-severity patterns in these managed wildfires are likely to fall within the natural range of variation and improve forest ecosystem integrity and diversity, even for large (>5,000 ac) overlapping wildfires burning in topographically complex forest landscapes (Meyer 2015, Meyer et al. 2019, Huffman et al. 2020). Although managers will certainly face constraints and agency reservations (North et al. 2015b), these designations at least provide support for allowing wider use of managed wildfire when conditions allow.

Silvicultural Treatments to Expand Prescribed Fire

There is a range of mechanical thinning treatments designed to affect fire, and some of these are broadly classified as strategically placed area treatments, designed to slow fire spread rate and reduce intensity across a landscape, and defensible fuel profile zones, intended to act as holding points for fire containment and suppression (Finney 2001). Although all acres can't be treated to meet the same objective, greater diversity in treatment types can help meet landscape treatment goals. In particular, for fire to have a more dynamic role in landscapes, treatments are needed that serve as planned ignition points, expand burn coverage for ecological benefit while retaining key ecosystem attributes, and provide economic support. The strategic objective of these treatments is to facilitate rather than suppress fire, using it as an integrating process between treatment units to connect and give inertial mass to fuel reduction and restoration efforts across the landscape (Figure 3).

To meet these pyrosilviculture objectives, three types of thinning treatments are needed: anchors, ecosystem assets, and revenue. The concept of anchors as fire-control features in a landscape has been proposed (O'Connor and Calkin 2019) and this article builds on that concept by suggesting they can also be strategically located areas from which fire can be expanded into the adjacent landscape. Anchor locations might be identified

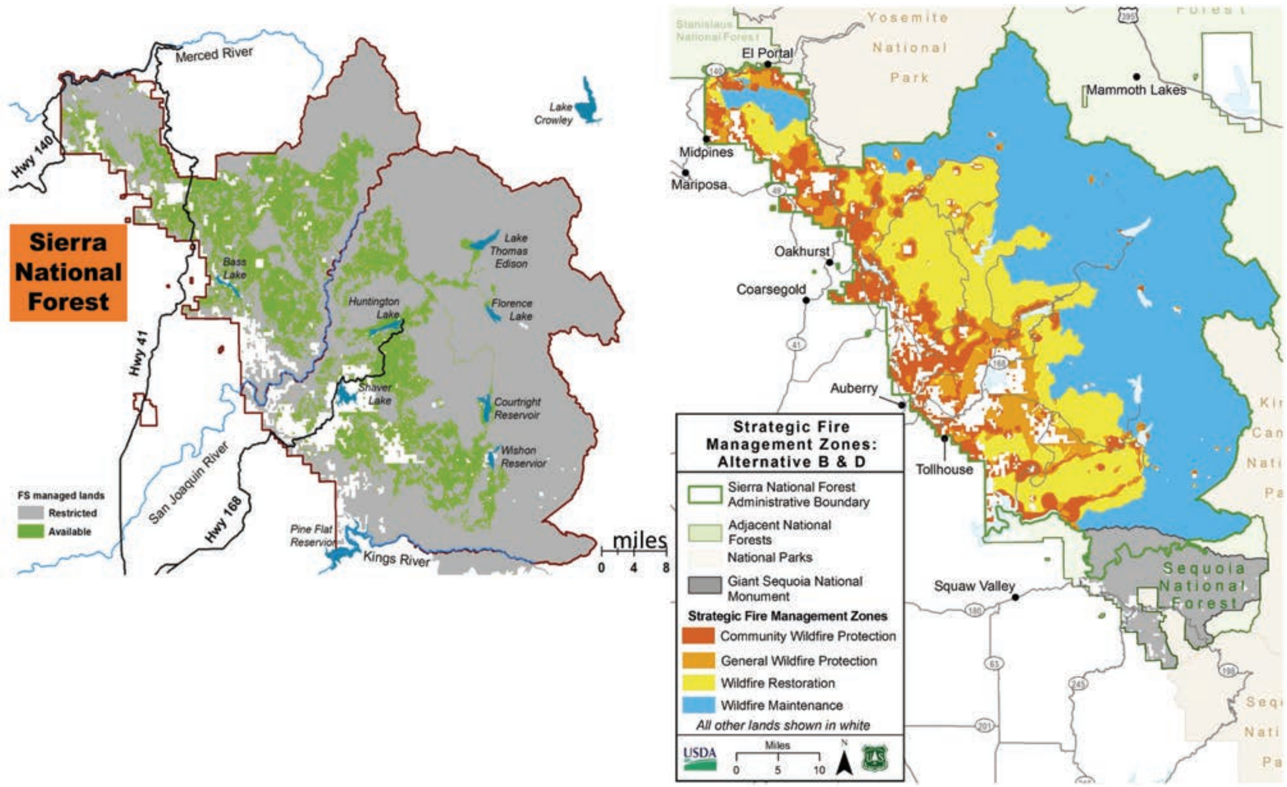

Figure 2. Left panel shows the area available for mechanical treatment (green shading) within the Sierra National Forest after identifying and removing areas of nonproductive forest land, those with legal (i.e., wilderness, etc.), topographic (too steep, too distant from a road), and administrative (i.e., spotted owl, riparian, etc.) constraints (following North et al. 2015a). The right panel shows areas that have been designated for wildfire restoration (yellow) and maintenance (blue) in the Sierra National Forest's new forest plan. In these areas, which generally match the nonmechanical grey area in the left panel, natural ignitions will be primarily managed to maintain or restore more resilient forest conditions.

using an organizational or "box" tactic commonly used in the Wildfire Decision Support System. The box usually is defined as generously large enough to contain different fire responses and its size is often determined by fire growth models, topography, resource assets, and strategic infrastructure that provide landscape level containment locations (i.e., roads and past forest and fuel management treatments). Anchors would help define the fire-use perimeter, acting as both ignition and control points for connecting and moderating landscape-level prescribed fire treatment. Before applying prescribed fire, fuels are heavily reduced on the anchor edge adjacent to a road or WUI to provide a hard backstop and more lightly reduced toward the box interior, ensuring low-to-moderate-severity fire spreads into the adjacent forest (Figure 4a). This approach has worked well in western Australia, where anchor networks have allowed fire managers to burn about 385,000 ac (7%) of a 5.5 million ac landscape each year (Sneeuwjagt et al. 2013). The heavier fuel reduction, particularly in the backstop, can generate revenue to help support prescribed burns and lighter thinnings used in other locations.

Ecosystem assets are areas where fuel and density reductions are needed but important ecosystem services (i.e., spotted owl [*Strix occidentalis*] nests, large carbon stores, riparian corridors) warrant more precise control over fire effects (van de Water and North 2010, 2011, North and Hurteau 2011) (Figure 4b). Although fire exclusion has generally been the rule in these areas, retaining and restoring ecosystem assets in dry, frequent-fire forest types requires careful fire reintroduction. Ecosystem assets would be mechanically pretreated to reduce fuels and moderate burn intensity when fire is reintroduced. In many cases, large overstory trees contribute to the ecosystem asset, so traditional ladder-fuel reduction might remain a priority. In ecosystem asset areas, an additional pyrosilvicultural goal would be a focus on horizontal fuel continuity, particularly of pine litter, which helps with fire spread, especially in wetter conditions (Mitchell et al. 2009, Levine et al. 2020, York et al. In pressB), facilitating more extensive burn coverage for ecosystem benefit and restoration.

Finally, the potential to generate revenue from forest products would also be a consideration in locating and

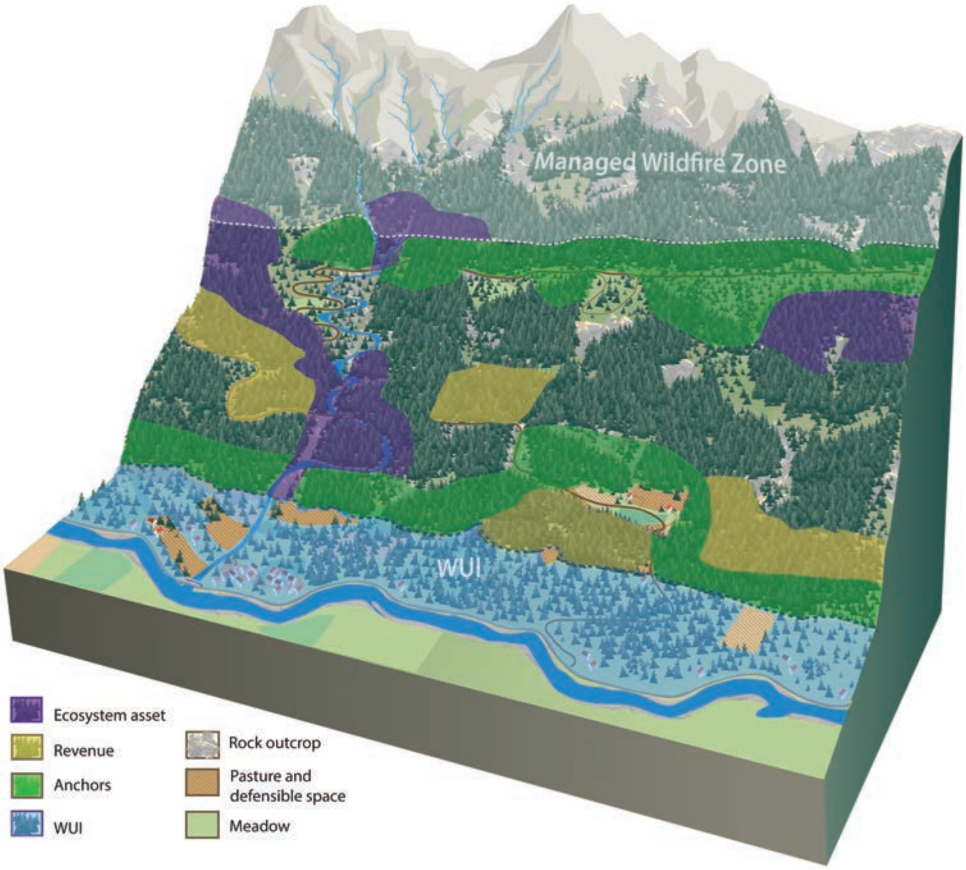

Figure 3. Schematic of how anchors, ecosystem assets, and revenue thinnings might be placed in a landscape. Providing a boundary 'box', anchors back to roads or the WUI and are ignition locations for expanding prescribed fire between anchors. Managers have the option of letting prescribed fire continue up through or managed wildfire burn down through the upper string of anchors under favorable conditions. Ecosystem assets are located where fuel reduction is needed to maintain particular ecological values, and revenue thinnings are in locations where larger shade-tolerant fire-sensitive species can be removed to restore resilience and provide sawlog revenue.

designing silvicultural treatments. Commitment to generating revenue from sawlogs and biomass might provide enough certainty to increase harvesting and wood processing infrastructure in some areas of the western US, which currently is a significant constraint on increasing treatments (Keegan et al. 2006). Concern that fire will negatively affect the timber base and lack of funding have consistently limited the use of prescribed fire (Schultz et al. 2019a). The wider use of both prescribed burning and managed wildfire require a supporting revenue stream, particularly as large-scale applications may require incident-management-team logistics and resources (i.e., aerial resources, a host of hand crews, engines and heavy equipment, and multiday resource dedication). Infilling from fire suppression has widely increased stand density and ladder fuels (Innes et al. 2006), but in productive locations (i.e., with greater soil moisture), it has also produced larger, commercially sized trees of the more fire-intolerant species (North et al. 2016, Fricker et al. 2019, Knapp et al. 2020). Removal of some of the larger fir and cedar can help restore stands to historical densities (Lydersen and North 2012, Collins et al. 2015, Knapp et al. 2017) and increase water availability and drought resilience for retained trees (Smith et al. 2005), and their revenue could be directed to support local application of prescribed fire and managed wildfire (Figure 4c).

These three thinning strategies focus on how posttreatment fuel conditions affect fire behavior, and how that in turn can affect forest vegetation. This approach may seem roundabout compared to how most thinning directly creates specific stand structures. In process-driven ecosystems, however, fuel manipulation influences combustion, and fire is what's driving changes in forest conditions, ecosystem processes, and effecting landscape resilience. Recent research suggests

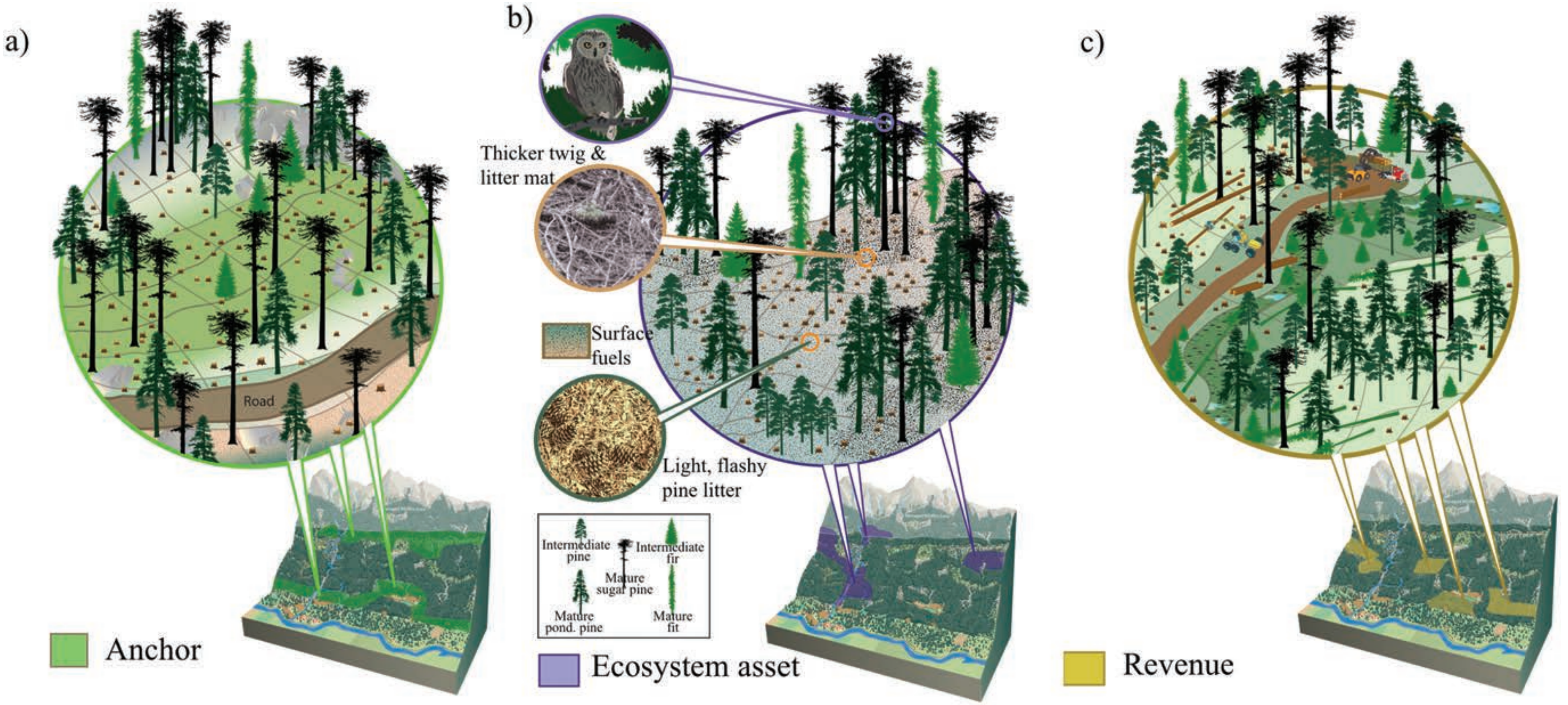

Figure 4. Stand-level schematics of the three thinning treatments: a) an anchor, showing near the road, the backstop (heavy fuels reduction leaving only large spatially separated pines) grading into a more mixed-species forest with a fire resistant spatial pattern (i.e., individual trees, clumps of trees and openings [ICO]) where the fire leaves the anchor; b) an ecosystem asset where most thinned trees are ladder-fuel size, an ICO pattern is created, and pine litter is dispersed in openings to facilitate fire spread; and c) a revenue thinning where intermediate and larger fire-sensitive fir are removed for sawlog processing.

fire-dependent forests may not have a set seral development pattern and stand structures can vary widely, depending largely on fire history rather than tree age (Berkey et al. 2021). This structural variability helps create the heterogeneity associated with greater fire resilience (Koontz et al. 2020). The difference is perhaps best summarized in noted research in the southeastern US, where prescribed fire is extensively used: "Fuels are the bridge between the combustion environment and vegetation response" (Hiers et al. 2007, Mitchell et al. 2009).

Pyrosilviculture Lessons from the Southern US

> "Heretofore, the thinking has been largely that of fitting fire into forest-land management, but those experienced in fire use are beginning to see that certain forestry practices might be altered to fit into prescribed burning, thus making better use of this tool than is possible under present management." -H. Biswell, reflecting on differences between forest management in Georgia and California (1958) Journal of Range Management 11: 293.

Each year, the southern US (hereafter the South) accomplishes more prescribed fire treatment acres (e.g. over 7 million ac in 2018; [Melvin 2018]) than anywhere else on the planet—an area that approaches or exceeds the total acreage burned in all US wildfires annually. This is achieved while also harvesting more lumber from both private and public lands than either the west or northern regions in the contiguous US (Oswalt et al. 2019). In the South, pyrosilviculture has been embraced historically, culturally, and politically for multiple decades, even if the term is not yet widely used. As is now the case in the West, the scale of fire treatments didn't always meet the need, and enacting new perspectives for the role managed fire could play was an iterative and deliberate silviculture-based process. In states such as Florida, with extensive forest coverage, wildland-urban-interface, and year-long natural and anthropogenic ignitions, proactive solutions were driven by necessity. Although there are multiple ways the South and the West differ that affect ease of access for equipment and scales of contiguous wildlands, fire managers in southern states have for decades responded to significant wildfire risk across diverse landscapes by employing fuel treatments that encompass the objectives of anchors, ecosystem assets, and revenues. In long-unburned longleaf pine (*Pinus palustris*) forests, where species selection and density reduction are key to providing habitat for sensitive wildlife species (Stephens et al. 2019), thinning ladder fuels (hardwoods) is often a first-entry approach along forest-unit borders, which serve as initial anchors (Jose et al. 2006). This is followed by iterations of prescribed burning that slowly reduce surface and ground fuel buildup under successively drier conditions, widening the prescription window with each fire iteration and making the next burn (either prescribed or managed wildfire) easier to plan, less resource-intensive to execute, and creating larger and larger anchors.

Longleaf pine uplands and sandhills occur within the context of a landscape of forest types, each with their unique wildfire hazard. For example, at the landscape scale, Central Florida's longleaf pine-dominated uplands are interspersed with more mesic (and productive) slash pine flatwoods, and even drier sand pine scrub forests—an ecosystem that harbors many threatened species and is dependent on stand-replacing fire (Freeman and Kobziar 2011). The analogy to western forests provides a compelling example of how anchors (longleaf pine stands), revenues (slash pine flatwoods), and ecosystem assets (sand pine scrub) can each be achieved by using specific mechanical and prescribed fire techniques within the same landscape. This approach results in a heterogenous landscape where wildfires that occur in any of the treated forests can be managed using the proximity and fuel structure of the other forest types, and where extensive ecotones allow for the inherent imprecision of some fire.

Policy providing protection against liability for managers who make the hard choices to employ fuel treatments across ecosystems and throughout a management landscape has also been critical in expanding options for what was possible in southern fire management. For example, when legal precedents raised significant liability concerns for forest managers and reduced prescribed fire use, stakeholders worked with the public and the legislature to codify the need for prescribed fire in the Florida Prescribed Fire Act of 1990 (now State Statute 590.125[3]). The Act was reiterated in 2000 to further enhance liability protection and sign into law the economic, ecological, and social benefits of fire. Backed by this landmark policy, fire management officers on each of Florida's three national forests now set and achieve annual quotas for prescribed burned acres that rival the total number of acres treated in the western US.

The fuel ecology of many southern forests also drives the support for proactive pyrosilviculture approaches that benefit ecosystems, economies, and the public. The speed of fuel and hazard recovery after pyrosilviculture treatments in the South is such that posttreatment becomes pretreatment within only a few years (Figure 5). If forests had been fire-suppressed for a century in the South as they have been in the West, many of the world's most biologically diverse ecosystems would no longer exist. The pace of change associated with the process of fire in southern forests is a powerful imperative; the effects of fire suppression are easily witnessed within a human lifetime. Although it took nearly 75 years for the results of fire suppression in the West to become widely recognized, the incentive to broaden perspectives of how forested landscapes can be treated is underscored by regions like the South, where pyrosilviculture has succeeded in mitigating many wildfire challenges.

Objectives for Assessing Expanded Fire Use

In the western US, prescribed fire has most often been used to moderate future fire severity by reducing surface and ladder fuel loads, disposing of logging slash, and for preparing sites prior to planting. To expand the use of prescribed fire and managed wildfire, burn objectives and successful implementation are best not measured against the precision that silvicultural treatment could have produced. Fire is only partly manageable and its effects on vegetation are influenced by many factors, some of which managers have little control over. Despite this, fire management officers in the Sierra Nevada often work with targets of no more than 5–10% overstory tree mortality, whereas variable weather conditions and limited crews make such precision difficult or result in restrictive burn windows that narrow the probability of implementation. Fire effects on forest conditions at any particular location may not meet such strict targets, especially on larger fires. However, as several western national parks have shown, in aggregate, managed fire can increase structural diversity and promote forest resilience at large scales (Boisramé et al. 2017). Scaling up pyrosilviculture on national forest lands will, in part, hinge on relaxing stand-level structural targets and focusing on broader landscape objectives. For example, after the 2018 Lions managed wildfire on the Inyo and Sierra National Forests produced moderately large (200–450 ac) high-severity patches, some managers and public stakeholders questioned its "resource benefits." Yet overall, the fire extensively reduced fuels, produced fire effects that were largely within the natural range of variability, and two years later, helped check the 380,000 ac Creek Fire from reaching the town of Mammoth Lakes.

Three additional managed fire objectives, density reduction, enhancing spatial heterogeneity, and species and phenotypic selection (Figure 6) will further improve landscape resilience. Reducing forest density will decrease water competition, thereby increasing resistance to drought stress and bark beetles (Maloney et al. 2008, Boisramé et al. 2017, Fettig et al. 2019, Koontz et al. 2021, Steel et al. 2021). Managed fire is not as surgical as mechanical thinning and in some locations may kill large overstory trees that managers

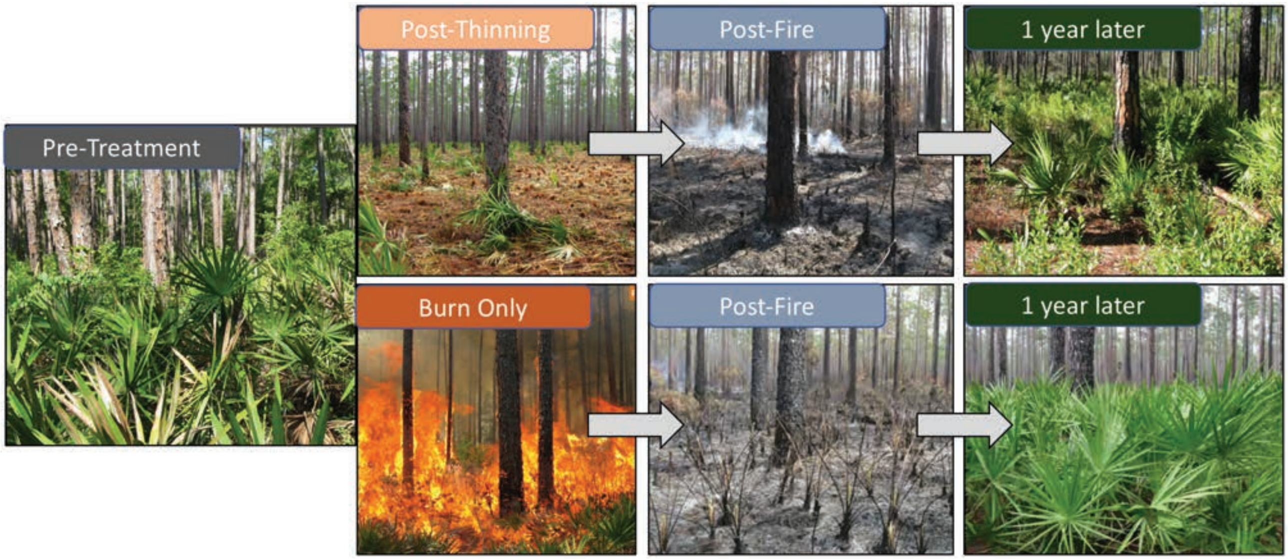

Figure 5. An example of coupled mechanical thinning and mastication treatments with fire in southern forests that most effectively meets ecological, silvicultural, and wildfire hazard reduction objectives.

Figure 6. Examples of the three metrics suggested for assessing ecologically beneficial fire. A: managed wildfire reducing stand density, killing some overstory trees, and leaving gaps for regeneration; B: spatial heterogeneity with individual trees, clumps of trees and openings (i.e., an ICO pattern); and C: forest composition where hardwoods and fir have survived in the shallow wetter drainage in the background, and large pines, possibly individuals with thick bark, persist in the foreground despite extensive fire scarring. All photos were taken in fire-restored Yosemite National Park forests.

would most like to retain (Figure 6a). However, the opportunities for more targeted density reduction, such as biomass removal and service contracts for cutting and piling small trees, are scale-limited by shrinking infrastructure and budgets. In many areas, large-scale density reduction can be accomplished for much lower costs and more extensively with managed fire, albeit with less precision than mechanical thinning (Hartsough et al. 2008).

Creating spatial heterogeneity in forest conditions is another pyrosilviculture objective that capitalizes on the less precise shaping of forests by fire (Figure 6b). Spatial heterogeneity can provide a self-reinforcing pattern that makes forests more resilient to future wildfires (Jeronimo et al. 2019, Kane et al. 2019) and drought (Knapp et al. 2021, Murphy et al. 2021). This pattern (Figure 6b) of ICO (Larson and Churchill 2012) also has ecological benefits. Heterogeneous complex forests are characterized by highly variable microclimates (Ma et al. 2010, Norris et al. 2012), with different temperature and moisture niches leading to high-understory-plant diversity (Wayman and North 2007, Stevens et al. 2015). This microclimate diversity may be key for facilitating species persistence under climate change (De Frenne et al. 2013). Variable spatial structure is often produced in burns with a range of intensities or pyrodiversity (He et al. 2019). The size and frequency of different severity patches, however, should be aligned, where possible, with conditions under historical frequent-fire regimes (Safford et al. 2012). High-severity patches can create gaps needed to foster shade-intolerant regeneration (Bigelow et al. 2011, Bigelow and North 2012), but in frequent-fire forests, the size of these gaps should ideally be consistent with fire patterns that in the past facilitated forest regeneration (i.e., most <8 ac [Collins and Stephens 2010, Lydersen et al. 2013, Fry et al. 2014]). Big gaps created by many modern wildfires are much larger than the seed-dispersal capabilities of most conifers (Collins et al. 2017, Stevens et al. 2017) and can promote type conversion for several decades or longer (Coppoletta et al. 2016, Coop et al. 2020).

Repeated use of managed fire can help select for phenotypic traits that enhance fire resistance and shift species composition so it is more congruent with topographic conditions (i.e., steepness, aspect, soil moisture, etc.) that influence local fire intensity (North et al. 2009, Kane et al. 2015a, b). With repeated burns, fire-tolerant species such as pines should, on average, have higher survival than other less fire-tolerant species on steep warm aspect slopes where fire burns more frequently and intensely (Ng et al. 2020). Fire-sensitive species such as fir and cedar would be expected to persist in areas with more mesic conditions that have a reduced burn probability or burn at lower severities (Beaty and Taylor 2007) (Figure 6c). Within a species, there are substantial differences among individual trees in bark thickness, branch abscission timing, cambium heat tolerance, and foliage flammability (Pausas 2015, Stevens et al. 2020). Currently, these traits are not being evaluated in planting stock, and developing saplings are not exposed to early fire to help select for more fire-resistant phenotypes (North et al. 2019). Regular burning would select for individuals with phenotypic characteristics that are more fire resistant, which should help reduce forest loss to type conversion as climate and disturbance regimes continue to change.

Pyrosilviculture Benefits

In forests that have historically burned frequently, one of the most difficult challenges in multiple-use management is to balance the need for fuel reduction treatments with the provision of wildlife habitat, particularly for some sensitive species associated with denser forest conditions. In western US forests, the spotted owl has been the most impactful of these species (Stephens et al. 2014). Spotted owl populations benefit from greater landscape availability of forests containing large trees and a closed overstory canopy (North et al. 2017, Jones et al. 2018) and often select these features when foraging for prey (Blakey et al. 2019). However, owl populations are declining across several Sierra Nevada national forests characterized by dense homogenized forest structure resulting from fire suppression (Jones et al. 2018), landscapes that have a high risk of owl habitat loss through type conversion (Figure 7b) (Jones et al. 2016, Stephens et al. 2016b, Wood and Jones 2019). Innovative approaches for promoting wildlife habitat through the restoration of natural processes, and local- and landscape-scale structural variability are needed (Stephens et al. 2020b).

Recent research suggests that provision, maintenance, and recruitment of wildlife habitat—and spotted owl habitat specifically—may align with the expansion of pyrosilvicultural practices. In Sierra Nevada national parks where prescribed- and managed-fire use have been common practice for decades, spotted owl populations are stable (Jones et al. 2018). In those landscapes, owls showed strong preference for extensive areas that have experienced low-severity fire within the previous 15 years (Kramer et al. 2021), suggesting a conservation benefit of frequent low-severity fire restoration across broader landscapes. In both national forests and national parks, owls have continued to occupy and reproduce in landscapes that have experienced

Figure 7. A: Female spotted owl with a nestling owl in a burned snag on the Eldorado NF. Fire created the nesting habitat by burning a small forest patch at high severity, but nearby (B) destroyed owl habitat in a fuel-loaded forest when burning created extensive high-severity areas. (Photo credits Sheila Whitmore)

predominately low- to moderate-severity fire (Roberts et al. 2011, Jones et al. 2016, Schofield et al. 2020). Owls do use severely-burned forests for foraging activities but usually only when patches are smaller than the historical maximum patch size for dry frequent-fire forests (e.g., 10–100 ha; Safford and Stevens 2017) (Figure 7), suggesting spotted owls are well adapted to pyrodiverse conditions at appropriate scales (Jones et al. 2020). Pyrosilviculture has the potential to promote owl habitat in the short-term by expanding the footprint of low-severity fire that is preferred by owls, and over the long-term by recruiting key habitat structures (e.g., large trees and snags) and reducing direct habitat loss to extensive stand-replacing fire that can be detrimental to owl populations (Tempel et al. 2015, Jones et al. 2016, Jones 2019).

Pyrosilviculture's significant pace and scale increase may be beyond current procedural constraints that can limit mechanical treatments, but changes in prescribed fire planning may allow much wider use. Some national forests, including several in the Sierra Nevada, are developing burn plans for the entire national forest that would allow large-scale use of prescribed fire and ease regulatory hurdles. Thinning projects often go through 3–5 years of development and review before any treatment occurs, and most are limited in spatial extent to a maximum of several hundred to a couple thousand acres. In contrast, a national-forest-wide burn plan would allow 10,000 to 15,000 ac, and possibly up to 50,000 ac, annually of prescribed fire to achieve forest-restoration objectives. Coupled with natural ignitions that may provide opportunities to manage wildfires for resource objectives, prescribed fire and managed wildfire could dramatically increase the speed of forest-restoration efforts.

It is difficult to predict exactly what stand structures are best adapted to future climate conditions, and managers should not assume that fuel reduction will increase tree resilience to increasingly severe and frequent droughts (Steel et al. 2021). However, a benefit of pyrosilviculture is its reintroduction of a key process that may give forests more flexibility to adapt to changing climatic and disturbance conditions. Fire has been a strong historical influence on dry western forests and its repeated application under current fuel and climate conditions is likely to build great adaptability into ecosystems than traditional thinning treatments focused on producing a target stand density and diameter distribution. Additionally, studies in forests with restored fire regimes suggest improvements for many ecosystem services, including water production (Boisramé et al. 2018), stabilization of large carbon stores (Hurteau and North 2009, Hurteau et al. 2016), increases in microclimate diversity (Norris et al. 2012), and provision of sensitive species habitat.

Increases in prescribed fire and managed wildfire can help with a large backlog of maintaining fuel-reduced conditions in existing treatments (North et al. 2012). In productive forests, fuels quickly accumulate and forests with fuels left untreated for longer than two historical fire-return intervals generally have a higher likelihood of crown fire. For many dry low- to mid-elevation western forest types, this means re-treating the forest every 10–35 years or needing to treat about 3–10% of these fire-dependent western US forests each year. In practice, to even make a dent in this annual maintenance acreage, a significant increase in the use of prescribed fire and managed wildfire is needed.

Limitations and Opportunities

New research is needed in many areas on how to best apply pyrosilviculture. However, in the area of most significant impediments to prescribed fire, recent studies have shown the main limitations are reduced work-force capacity and a lack of funding, together with varying degrees of local leadership and institutional support for fire use (Schultz et al. 2019a, b, Schultz and Moseley 2019). A key time window for fire use in the western US is the late summer to early fall (August through October) when burns may best meet ecological objectives for fire-adapted forest types. However, increasingly large late summer wildfires, combined with droughty fall conditions, have extended fire-season length in recent years (Jain et al. 2018, Holden et al. 2018), making it difficult to acquire crews, many of which have been sent to wildfires or are held in preparation for being deployed. Two changes might help with these problems. Agencies could dedicate some crews to just work on prescribed burns and managed wildfire and could train and share work forces across agencies and jurisdictions through a western US prescribed-fire center (Miller and Aplet 2016). An interagency center could pool resources and be more nimble deploying crews to follow optimal burn conditions, moving to areas and applying fire as fuel moistures and weather conditions align to enable fire use to meet resource objectives. Increasing drought conditions may enable more burning in winter or early spring, requiring year-round prescribed-fire personnel to take advantage of these periods.

Drawing from the example of the Prescribed Fire Training Center in Florida, the western center could provide the critical training and experience-based education required to grow fire-use workforce capacity and skills across the region. Such a center could also coordinate, allocate, and deploy equipment and crews similar to the way in which federal and state wildland fire agencies work together through Geographic Area Coordination Centers. A western prescribed-fire center could specifically train crews in applying fire for ecological benefit rather than a focus on suppression, as well as provide leadership and institutional support for broader managed fire use. Presently, many fire managers come up through the ranks from suppression crews and have varying degrees of ecological- and forestry-related training. Although agency silviculturists are required to complete an intensive education program and certification process in order to approve proposed treatments and prescriptions, burn planning and implementation is handled by fuel specialists and fire-management officers whose training programs understandably have a more operational and safety emphasis (Schultz et al. 2019b). Broadening prescribe-fire training to include more emphasis on ecology- and forestry-related curriculum and create greater commonality between these programs may help bridge the organizational divide between fire and silviculture in some federal land agency locations (Schultz et al. 2018).

Although forest-wide burn plans may help increase the future pace and scale of prescribed fire, current practices are not scaled to achieve the acreage or density reduction proposed with pyrosilviculture. Prescribed burns are often implemented at the stand level, resulting in an arrangement much like jigsaw-puzzle pieces across the landscape over time. Implementation at this scale is often completed on a local project level and this approach generally includes daytime firing operations at a constrained scale. The scale is often defined by daily containment lines to manage the number of acres burned, stay within smoke allowances, and reduce the need for extended resources. A recent analysis of prescribed fire windows in the Lake Tahoe Basin (Striplin et al. 2020) found that there were few 2–3 day burn windows during the preferred burning season (August through October) and longer burn windows were very rare. Landscape-scale prescribed burning will require more fluid management where daytime and nighttime operations are continuous.

A more practical approach for working with prescribed fire might follow practices sometimes used in Yosemite National Park. Using localized weather and smoke dispersal forecasts, Yosemite has used a push-pull approach to burning where the fire is pushed into low fuels areas (i.e., anchors, previous burns, granite outcrops, etc.) during adverse weather and smoke conditions, and then pulled out across the landscape needing treatment during more optimal conditions. This means having more open-ended burn windows, keeping the fire contained and smoldering until conditions align for extensive consumption, and lofting smoke away from populated areas. This would require a change in permitting procedures. Striplin et al. (2020) found that a 2008 change in California Air Resources Board procedures was associated with an increase in burn-window length during the 20-year period they studied. Working to adjust these procedures so that they are congruent with scientific understanding of fire would have ecological benefits and support the public's need to know about potential smoke before it reaches populated areas.

Conclusion

Given all the limitations on using fire, is pyrosilviculture really practical? Under current constraints it is difficult to imagine how beneficial fire use could be significantly increased, particularly in densely populated areas (i.e., much of California) and states with highly restrictive air quality regulations (i.e., Washington and Oregon). However, if fire is inevitable and likely to increase with changing climate, any practical future management scenario has to include a paradigm shift toward greater proactive human influence on the fire that does occur (Young et al. 2020b). This shift would have widespread benefits, including better predictability and dispersal control of smoke (Long et al. 2018), less structure loss and human casualties, and enhanced ecosystem services (i.e., water quantity and quality [Boisramé et al. 2018], sensitive species habitat [Jones et al. 2016], and secure carbon storage [Earles et al. 2014, Stephens et al. 2019, 2020b]). Incorporating pyrosilviculture's wider use of managed fire is a practical recognition of the inevitability of fire continuing to be the largest influence on dry western forests.

Although it is unlikely that society will ever fully restore historical fire regimes in western US forests, pyrosilviculture can help realign current and historical fire regimes and improve landscape resilience in a rapidly changing environment. Pyne (2020) noted "Because it is a reaction, fire synthesizes its surroundings: it takes its character from its context" (p.1). Facilitated by revenue-generating, strategic thinning treatments, fire's responsiveness to context may accelerate adaptation of fire-restored forests to future climate conditions. The real issue is whether we continue to focus on suppression, propagating more 'feral' fire, or become the agents of more beneficial fire under our terms and objectives.

Acknowledgments

We thank Thomas Flowe and Jon Regelbrugge, both of USFS Pacific Southwest Region, for Figure 2 and manuscript review, respectively. We also thank Steve Oerding of Oerding Illustrated, Dixon, California, for creating Figures 3 and 4. We're grateful to the Eldorado National Forest Amador Ranger District for funding and ideas from working on the Power Fire, and Taro Pusina of Inyo National Forest, for discussions about 'managed' wildfire. We also thank two anonymous reviewers whose suggestions and edits greatly improved the manuscript.

Endnotes

1. In the context of this paper, forest resilience and resistance are defined as the ecosystems' allied capacities to regain and retain, respectively, their structure, composition, and functions when affected by stresses or disturbances (Hollings 1973, Hessburg et al. 2019).
2. There are some inconsistencies in how wildfires were designated as 'managed', including wildfires the authors know were initially treated as suppression events, but which included days and areas where the fire was left to burn for 'resource benefit'. In the end, we used the FACTS domain designations 1116 (Wildland Fire Use used through 2009) and 1117 (Wildfire-Natural Ignition used 2010 on), but within these two designations included only portions (acreage and polygons) that were identified with a keypoint designation of "6" ("meets planned objectives for fuels treatments") and did not include the portions of wildland fires with a keypoint of "0" ("no hazardous fuel benefit" or "do not meet objectives").

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