Pyrosilviculture Needed for Landscape Resilience of Dry Western U.S. Forests

North, M.P.[1], R.A. York[2], B.M. Collins[3,4], M.D. Hurteau[5], G.M. Jones[6], E.E. Knapp[7], L. Kobziar[8], H. McCann[9], M.D. Meyer[10], S.L. Stephens[2], R.E. Tompkins[11], and C.L. Tubbesing[2].

1) USDA Forest Service, PSW Research Station, Mammoth Lakes, CA. 93546
2) Department of Environmental Science, Policy and Management, 130 Mulford Hall, University of California, Berkeley, CA. 94720
3) Center for Fire Research and Outreach, University of California, Berkeley, CA. 94720
4) USDA Forest Service, PSW Research Station, Davis, CA. 95618
5) Department of Biology, University of New Mexico, Albuquerque, N.M. 87131
6) USDA Forest Service, Rocky Mountain Research Station, Albuquerque, N.M. 87102
7) USDA Forest Service, PSW Research Station, Redding, CA. 96002
8) College of Natural Resources, University of Idaho, Moscow, ID. 83844.
9) Public Policy Institute of California, San Francisco, CA. 94111
10) USDA Forest Service, Region 5 Ecology Program, Southern Sierra Province, Bishop, CA. 93514
11) University of California Cooperative Extension, Plumas-Sierra, Quincy, CA. 95971

Acknowledgments: We thank Thomas Flowe, F.S. Region 5 Remote Sensing, for Figure 2, and Steve Oerding of Oerding Illustrated, Dixon, CA for creating Figures 3 and 4. We’re grateful to the Eldorado N.F. Amador R.D. for funding and ideas from working on the Power Fire, and Taro Pusina and Jon Regelbrugge, both Inyo N.F., for discussions about ‘managed’ wildfire and manuscript review and suggestions, respectively. We also thank two anonymous reviewers whose suggestions and edits greatly improved the manuscript.

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.

Abstract

A significant increase in treatment pace and scale is needed to restore dry western US forest resilience to increasingly frequent and severe wildfire and drought. We propose a pyrosilviculture approach to directly increase large-scale fire use and to 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 burns and managed wildfires 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 U.S. forests and pyrosilviculture focuses on proactively shifting more of that fire into managed large-scale burns needed to restore ecosystem resilient.

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

Over the last several decades, dry conifer forests in the western U.S. have experienced high mortality from severe drought and wildfire. Past logging practices and on-going fire suppression have significantly decreased average tree size while increasing fuel loads and continuity, stand density, and canopy cover (Scholl and Taylor 2010, Collins et al. 2011, Knapp et al. 2013), conditions which 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 review). 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 U.S. 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 U.S., prescribed fire has been used mostly for site preparation for replanting, fuels 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 U.S. 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 paper broadens the concept of pyrosilviculture from the stand (York et al. in pressA) 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 multi-ownership 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 how fire managers set objectives and assess outcomes. Pyrosilviculture does not change the need to provide forest

---

[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 impacted by stresses or disturbances (Holling 1973, Hessburg et al. 2019).

products 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). The paper 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 how 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 fuels reduced areas. In addition to fuels reduction, new measures for setting objectives and evaluating large-scale fire use are suggested. Finally, the paper 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 U.S., 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 burned, 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. While 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 paper is on forests that historically had frequent, low to moderate severity fire regimes, as these are most in need of fuels 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).

While more than 95% of wildfire ignitions in dry western U.S. 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 U.S. forests to adapt to changing disturbance and climate conditions requires a significant expansion of low to moderate severity fire.

Almost all global change change models (GCCMs) suggest a significant increase in the pace and scale of fuels 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 (Westerling 2016, Abatzoglou and Williams 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 impacted 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 U.S. 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), fuels 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 (LTBMU) 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 which historically had a frequent low to moderate severity fire regime that requires active management (i.e., periodic fuels reduction) and one which 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 M acres in the Sierra Nevada, fires historically reduced fuels at an average rate of 631,000 ac/yr (≈ 5%) in the twelve 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 F.S. 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 F.S. 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 acres of treatments were burned by wildfire between 2011 and 2020, or an average of 20,244 acres per year. This is likely an underestimate because we only included treatments from 2007 onward (to reflect when fuels 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 2017-2020, wildfire burned a total of 1,432,989 ac, of which 152,842 acres 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 non-overlapping, 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 fuels 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

---

[2] There are some inconsistencies in how wildfires were designated as ‘managed’, including wildfires the authors knew 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”).

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 at increasing treatment acreage: 1) leveraging a wildfire's low and moderate severity burn areas as initial 'treatments'; 2) identifying managed wildfire zones; and 3) 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 FS 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 post-burn 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 post-wildfire management is concentrated on areas that burned at high severity (>75% 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 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" upon 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 Chruchill 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 post wildfire that facilitate faster fuel drying, prescribed fires could carry under a broader range of weather conditions (York et al. In PressB) while minimizing overstory tree mortality and reducing surface fuels. Generally, these burns would have low fuel loads 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 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 N.F.'s are amongst the eight 'early adopter' National Forests to develop fifteen-year plans in response to the new forest planning rule (USDA-FS 2012). Each of these N.F.'s 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 fuels 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 N.F. 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 on 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 N.F.s and 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 (>5000 ac) overlapping wildfires burning in topographically complex forest landscapes (Meyer 2015, Meyer et al. 2019, Huffman et al. 2020). While managers will certainly face constraints and agency reservation (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 are a range of mechanical thinning treatments designed to affect fire and some of these are broadly classified as strategically placed area treatments (SPLATs), designed to slow fire spread rate and reduce intensity across a landscape, and defensible fuel profile zones (DFPZs) intended to act as holding points for fire containment and suppression (Finney 2001). While 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, that serve to expand burn coverage for ecological benefit while retaining key ecosystem attributes, and that serve to 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 fuels 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 the paper 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 using an organizational or "box" tactic commonly used in the Wildfire Decision Support System (i.e., WFDSS). 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 fuels 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). While 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 pre-treated to reduce fuels and moderate burn intensity when fire is re-introduced. 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 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 U.S., 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 since 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 multi-day 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), 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 post-treatment 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 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 U.S. 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)*

Each year, the southern US (hereafter 'the South') accomplishes more prescribed fire treatment acres (e.g. over 7M 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 U.S. (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 like 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 fuels 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 N.F.'s 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 post-treatment becomes pre-treatment 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 for 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 U.S., 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. In spite of this, Fire Management Officers in the Sierra Nevada often work with targets of no more than 5-10% overstory tree mortality, while 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 acre) 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, Steele et al. 2021). Managed fire is not as surgical as mechanical thinning and in some locations may kill large, overstory trees that managers 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 individual trees, clumps of trees, and openings (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, 2015b). 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 amongst 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 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 U.S. 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 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 and possibly up to 50,000 acres 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 fuels 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 fuels 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 U.S. 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 one area, the 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, 2019b, Schultz and Mosley 2019). A key 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 2013, 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 how federal and state wildland fire agencies work together through Geographic Area Coordination Centers (GACC). A western prescribed fire center could specifically train crews in applying fire for ecological benefit rather than a focus on suppression, while providing 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. While 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 more of an operational and safety emphasis (Schultz et al. 2019b). Broadening prescribed 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).

While 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 twenty year period they studied. Working to adjust these procedures so that they are congruent with scientific understanding of fire would have ecological benefits while supporting 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.

While it is unlikely that society will ever fully restore historical fire regimes in western U.S. 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." 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.

Literature Cited

Abatzoglou, J.T., and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences 113:11770–11775.

Agee, J.K. and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211:83-96.

Agee, J.K. 1996. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. Ecological Applications 12: 1418-1433.

Arno, S.F., and C.E. Fiedler. 2005. Mimicking nature’s fire: restoring fire-prone forests in the West. Island Press, Washington, D.C. 242pp.

Barnett, K., S.A. Parks, C. Miller, and H.T. Naughton. 2016. Beyond fuel treatment effectiveness: Characterizing interactions between fire and treatments in the US. Forests 7:237.

Beaty, R.M., and A.H. Taylor. 2007. Fire disturbance and forest structure in old-growth mixed conifer forests in the northern Sierra Nevada, California. Journal of Vegetation Science 18:879-890.

Berkey, J.K., R.T. Belote, C.T. Mahoer, and A.J. Larson. 2021. Structural diversity and development in active fire regime mixed-conifer forests. Forest Ecology and Management 479:118548.

Bigelow, S., North, M.P., and Salk, C. 2011. Using light to predict fuels-reduction and group-selection effects on succession in Sierran mixed-conifer forest. Canadian Journal of Forest Research 41:2051-2063.

Bigelow, S. and M.P. North. 2012. Microclimate effects of fuels-reduction and group-selection silviculture: Implications for fire behavior in Sierran mixed-conifer forests. Forest Ecology and Management 264:51-59.

Blakey, R.V., R.B. Siegel, E.B. Webb, C.P. Dillingham, R.L. Bauer, M. Johnson, and D.C. Kesler. 2019. Space use, forays, and habitat selection by California Spotted Owls (*Strix occidentalis occidentalis*) during the breeding season: New insights from high resolution GPS tracking. Forest Ecology and Management432:912-922.

Boisramé, G.F.S., S. Thompson, M. Kelly, J. Cavalli, K.M. Wilkin, and S.L. Stephens. 2017. Vegetation change during 40 years of repeated managed wildfires in the Sierra Nevada, California. Forest Ecology and Management 402:241-252.

Boisramé, G.S., S. Thompson, and S.L. Stephens. 2018. Hydrologic responses to restored wildfire regimes revealed by soil moisture vegetation relationships. Advances in Water Resources 112:124-146.

CAL FIRE FRAP. 2015. California Department of Forestry and Fire Protection Vegetation (fveg)— [ds1327]

Calkin, D.E., K.M. Gebert, J.G. Jones, and R.P. Neilson. 2005. Forest Service large fire area burned and suppression expenditure trends, 1970-2002. Journal of Forestry 103: 179-183.

Chiono, L.A., D.L. Fry, B.M. Collins, A.H. Chatfield, and S.L. Stephens. 2017. Landscape-scale fuel treatment and wildfire impacts on carbon stocks and fire hazard in California spotted owl habitat. Ecosphere 8:e01648.

Collins, B.M., M. Kelly, J.W. van Wagtendonk, and S.L. Stephens. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecology 22: 545-557.

Collins, B.M. and S.L. Stephens. 2010. Stand-replacing patches within a ‘mixed severity’ fire regime: quantitative characterization using recent fires in a long-established natural fire area. Landscape Ecology 25:927-939.

Collins, B.M., S.L. Stephens, J.J. Moghaddas, and J. Battles. 2010. Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. Journal of Forestry 108:24-31.

Collins, B.M., R.G. Everett, and S.L. Stephens. 2011. Impacts of fire exclusion and managed fire on forest structure in an old growth Sierra Nevada mixed-conifer forest. Ecosphere 2:51.

Collins, B.M., J.M. Lydersen, R.G. Everett, D.L. Fry, and S.L. Stephens. 2015. Novel characterization of landscape-level variability in historical vegetation structure. Ecological Applications 25:1167-1174.

Collins, B.M., J.T. Stevens, J.D. Miller, S.L. Stephens, P.M. Brown, and M.P. North. 2017. Alternative characterization of forest fire regimes: incorporating spatial patterns. Landscape Ecology 32:1543-1552.

Collins, B.M., J.M. Lydersen, R.G. Everett, and S.L. Stephens. 2018. How does forest recovery following moderate-severity fire influence effects of subsequent wildfire in mixed-conifer forests? Fire Ecology 14:1-14.

Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M.P. North, M.A. Parisien, S. Prichard, and K.C. Rodman. 2020. Wildfire-driven forest conversion in Western North American landscapes. Bioscience 70:659-673.

Coppoletta, M., K.E. Merriam, and B.M. Collins. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications 26:686–699.

De Frenne, P., F. Rodríguez-Sánchez, D.A. Coomes, L. Baetenh, G. Verstraeten, M. Vellend, M. Bernhardt-Romermann, C.D. Brown, J. Brunet, J. Cornelis, G.M. Decocq, H. Dierschke, O. Eriksson, F.S. Gilliam, R. Hedl, T. Heinken, M. Hermy, P. Hommel, M.A. Jenkins, D.L. Kelly, K.J. Kirby, F.J.G. Mitchell, T. Naaf, M. Newman, G. Peterken, P. Petrik, J. Schultz, G. Sonnier, H. Van Calster, D.M. Waller, G. Walther, P.S. White, K.D, M. Wulf, B.J. Graae, and J. Verheyen. 2013. Microclimate moderates plant responses to macroclimate warming. Proceedings of the National Academy of Sciences 110:18561-18565.

Earles, J.M., M.P. North, and M.D. Hurteau. 2014. Wildfire and drought dynamics destabilize carbon stores of fire-suppressed forests. Ecological Applications 24: 732-740.

Falk, D.A., M.A. Palmer, and J.B. Zelder. 2006. Foundations of restoration ecology. Island Press, Washingotn, DC. 363p.

Fettig, C.J., A. Wuenschel, J. Balachowski, R.J. Butz, A.L. Jacobsen, M.P. North, S.M. Ostoja, R.B. Pratt, and R.B. Standiford. 2019. Drought management recommendations for California. P. 71-93 in: Drought impacts on U.S. forests and rangelands: Translating science into management responses, Vose, J., T. Patel-Weynand, D.L. Peterson, and C.H. Luce, (eds.) WO-GTR-98. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47:219-228.

Freeman, J.E. and L.N. Kobziar. 2011. Tracking postfire successional trajectories in a plant community adapted to high-severity fire. Ecological Applications 21: 61-74.

Fricker, G.A., N.W. Synes, J.M. Serra-Diaz, M.P. North, F.W. Davis, and J. Franklin. 2019. More than climate? Predictors of tree canopy height vary with scale in complex terrain, Sierra Nevada, CA (USA). Forest Ecology and Management 434:142-153.

Fry, D.L, S.L. Stephens, B.M. Collins, M.P. North, E. Franco-Vizcaino, and S.J. Gill. 2014. Contrasting spatial patterns in active-fire and fire-suppressed Mediterranean climate old-growth, mixed conifer forests. PLOS ONE, DOI: 10.1371/journal.pone.0088985

Goodwin, M.J., M.P. North, H.S.J. Zald, and M.D. Hurteau. 2020. Changing climate reallocates the carbon debt of frequent-fire forests. Global Change Biology 26:6180-6189.

Hartsough, B.R., S. Abrams, R.J. Barbour, E.S. Drews, J.D. McIver, J.J. Moghaddas, D.W. Schwilk, and S.L. Stephens. 2008. The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and fire Surrogate Study. Forest Policy and Economics 10:344-354.

He, T., B.B. Lamont, and J.G. Pausas. 2019. Fire as a key driver of Earth's biodiversity. Biological Reviews 94:1983-2010.

Hiers, J.K., J.J. O'Brien, R.E. Will, and R.J. Mitchell. 2007. Forest floor depth mediates understory vigor in xeric *Pinus Palustris* ecosystems. Ecological Applications 17:806-814.

Hessburg, P., D. Churchill, A. Larson, R. Haugo, C. Miller, T. Spies, M.P. North, N. Povak, R. T. Belote, P. Singleton, W. Gaines, R. Keane, G. Aplet, S. Stephens, P. Morgan, P. Bisson, B. Rieman, R. B. Salter, and G. Reeves. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landscape Ecology 30:1805-1835.

Hessburg, P.F., C.L. Miller, N.A. Povak, A.H. Taylor, P.E. Higuera, S.J. Prichard, M.P. North, B.M. Collins, M.D. Hurteau, A J. Larson, C.D. Allen, S.L. Stephens, H.R. Huerta, C. Stevens-Rumann, L.D. Daniels, Z. Gedalof, R.W. Gray, V.R. Kane, D.J. Churchill, R.K. Hagmann, T.A. Spies, S.A. Parks, C.A. Cansler, R.T. Belote, T.T. Veblen, M.A. Battaglia, C. Hoffman, C.N. Skinner, and H.D. Safford. 2019. Climate, environment, and disturbance history govern resilience of western North American forests. Frontiers in Ecology and Evolution 7: 239 (doi: 10.3389/fevo.2019.00239).

Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck. 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. Proceedings of the National Academy of Sciences, 115:E8349-E8357.

Hollings, C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1-23.

Huffman, D.W., J.P. Roccaforte, J.D. Springer, and J.E. Crouse. 2020. Restoration applications of resource objective wildfires in western US forests: a status of knowledge review. Fire Ecology 16: 18. https://doi.org/10.1186/s42408-020-00077-x

Hurteau, M.D. and M.P. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Frontiers in Ecology and the Environment 7:409-414.

Hurteau, M.D., S. Liang, K.L. Martin, M.P. North, G.W. Koch, and B.A. Hungate. 2016. Restoring forest structure and process stabilizes forest carbon in wildfire-prone southwestern ponderosa pine forests. Ecological Applications 26:382-391.

Hurteau, M.D., M.P. North, G.W. Koch and B.A. Hungate. 2019. Managing for disturbance stabilizes forest carbon. Proceedings of the National Academy of Sciences 116:10193-10195.

Innes, J., M.P. North and N. Williamson. 2006. Effect of thinning and prescribed fire restoration treatments on woody debris and snag dynamics in a Sierran old-growth mixed-conifer forest. Canadian Journal of Forest Research 36:3183-3193.

Jain, P., X. Wang, and M.D. Flannigan. 2018. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. International journal of wildland fire. 26:1009-1020.

Jeronimo, S.M.A., V.R. Kane, D.JU. Churchill, J.A. Lutz, M.P. North, G.P. Asner, and J.F. Franklin. 2019. Forest structure and pattern vary by climate and landform across active-fire landscapes in the montane Sierra Nevada. Forest Ecology and Management 437:70-86.

Jones, G.M., R.J. Gutierrez, D.J. Tempel, S.A. Whitmore, W.J. Berigan, and M.Z. Peery. 2016. Megafires: an emerging threat to old-forest species. Frontiers in Ecology and the environmental 14:300-306.

Jones, G.M., J.J. Keane, R.J. Gutiérrez, and M.Z. Peery. 2018. Declining old forest species as a legacy of large-tree lost. Diversity and Distributions 24: 341-351.

Jones, G.M. 2019. Fire, Forest Restoration, and Spotted Owl Conservation in the Sierra Nevada, CA. Univ. of Wisconsin, Madison, Ph.D. dissertation.

Jones, G.M., H.A. Kramer, S.A. Whitmore, W.J. Berigan, D.J. Tempel, C.M. Wood, B.K. Hobart, T. Erker, F.A. Atuo, N.F. Pietrunti, R.J. Gutiérrez, and M.Z. Peery. 2020. Habitat selection by spotted owls after a megafire reflects their adaptation to historical frequent-fire regimes. Landscape Ecol 35:1199–1213.

Jose, S., E.J. Jokela, and D.L. Miller (eds.). 2006. The Longleaf Pine Ecosystem: Ecology, Silviculture, and Restoration. Springer.

Kane, V.R., C.A. Cansler, N.A. Povak, J.T. Kane, R.J. McGaughey, J.A. Lutz, D.J. Churchill, and M.P. North. 2015a. Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography and forest structure. Forest Ecology and Management 358:62-79.

Kane, V.R., J.A. Lutz, C.A. Cansler, N.A. Povak, D.J. Churchill, D.F. Smith, J.T. Kane, J.T. and M.P. North. 2015b. Water balance and topography predict fire and forest structure patterns. Forest Ecology and Management 338:1-13.

Kane, V.R., B.N. Bartl-Geller, M.P. North, J.T. Kane, J.M. Lydersen, S.A. Jeronimo, B.M. Collins, and L M. Moskal. 2019. First-entry wildfires can create opening and tree clump patterns characteristic of resilient forests. Forest Ecology and Management 454:e117659.

Keane, R.E., P.F. Hessburg, P.B. Landres, and F.J. Swanson. 2009. The use of historical range and variability (HRV) in landscape management. Forest Ecology and Management 258: 1025– 1037.

Keegan, C.E., T.A. Morgan, K.M. Gebert, J.P. Brandt, K.A. Blatner, and T.P. Spoelma. 2006. Timber-processing capacity and capabilities in the Western United State. Journal of Forestry 104: 262-268.

Knapp, E.E. and J.E. Keeley. 2006. Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. International Journal of Wildland Fire 15: 37-45.

Knapp, E.E., C.N. Skinner, M.P. North, and B.L. Estes. 2013. Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed-conifer forest. Forest Ecology and Management 310:903-914.

Knapp, E.E, J.M. Lydersen, M.P. North, and B.M. Collins. 2017. Efficacy of variable density thinning and prescribed fire for restoring forest heterogeneity to mixed-conifer forest in the central Sierra Nevada, CA. Forest Ecology and Management 406:228-241.

Knapp, E.E.; Carlson, R.L.; North, M.P.; Lydersen, J.L.; Collins, B.M. 2020. Restoring forest heterogeneity with thinning and prescribed fire: Initial results from the central Sierra Nevada, California. In: Pile, L.S.; Deal, R.L.; Dey, D.C.; Gwaze, D.; Kabrick, J.M.; Palik, B.J.; Schuler, T.M., comps. The 2019 National Silviculture Workshop: a focus onforest management-research partnerships. Gen. Tech. Rep. NRS-P-193. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station: 216-226. https://doi.org/10.2737/NRS-GTR-P-193-paper28.

Knapp, E.E., A.A. Bernal, J.M. Kane, C.J. Fettig, and M.P. North. 2021. Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. Forest Ecology and Management 479: doi.org/10.1016/j.foreco.2020.118595.

Koontz, M.J., M.P. North, C.M. Werner, S.E. Rick and A.M. Latimer. 2020. Local forest structure variability increases resilience to wildfire in dry western U.S. coniferous forests. Ecology Letters. doi: 10.1111/ele.13447.

Koontz, M.J., A.M. Latimer, L.A. Mortenson, C.J. Fettig and M.P. North. 2021. Cross-scale interaction of host tree size and climatic water deficit governs bark beetle-induced tree mortality. Nature Communications: 12: 129.

Kramer, A., G.M. Jones, S.A. Whitmore, J.J. Keane, F.A. Atuo, B.P. Dotters, S.C. Sawyer, S.L. Stock, R.J. Gutiérrez, M.Z. Peery. 2021. California spotted owl habitat selection in a fire-managed landscape suggests conservation benefit of restoring historical fire regimes. Forest Ecology and Management 479:118576.

Larson, A.J. and D. Churchill. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. Forest Ecology and Management 267: 74-92.

Levine, J.I., B.M. Collins, R.A. York, D.E. Foster, D.L. Fry, and S.L. Stephens. 2020. Forest stand and site characteristics influence fuel consumption in repeat prescribed burns. Internation Journal of Wildland Fire 29:148-159.

Liang, S., M.D. Hurteau, and A.L. Westerling. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. Frontiers in Ecology and the Environment 16:207–212.

Long, J.W., L.W. Tarnay, and M.P. North. 2018. Aligning smoke management with ecological and public health goals. Journal of Forestry 116:76-86.

Lydersen, J. and M.P. North. 2012. Topographic variation in active-fire forest structure under current climate conditions. Ecosystems 15:1134-1146.

Lydersen, J.M., M.P. North, E.E. Knapp, and B.M. Collins. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: reference conditions and long-term changes following fire suppression and logging. Forest Ecology and Management 304:370-382.

Lydersen, J., North, M. and Collins, B. 2014. Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. Forest Ecology and Management 328: 326-334.

Ma, S., A. Concilio, B. Oakley, M.P. North, and J. Chen. 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. Forest Ecology and Management 259:904-915.

Mallek, C., H. Safford, J. Viers, and J. Miller. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. Ecosphere 4: 1-28.

Maloney, P.T., C. Smith, C. Jensen, J. Innes, D. Rizzo, and M.P. North. 2008. Initial tree mortality, and insect and pathogen response to fire and thinning restoration treatments in an old growth, mixed-conifer forest of the Sierra Nevada, California. Canadian Journal of Forest Research 38:3011-3020.

Martinson, E.J., and P.N. Omi. 2013. Fuel treatments and fire severity: a meta-analysis. Research Paper RMRS-RP-103WWW, U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Melvin M. 2018. 2018 National prescribed fire use survey report. Technical Report 03-18 Coalition of Prescribed Fire Councils, Inc.

Meyer, M., D. Kelt, and M.P. North. 2007. Microhabit associations of northern flying squirrels in burned and thinned stands of the Sierra Nevada. American Midland Naturalist 157: 202-211.

Meyer, M.D. 2015. Forest fire severity patterns of resource objective wildfires in the southern Sierra Nevada. Journal of Forestry 113, 49–56.

Meyer, M.D., B.L. Estes, A. Wuenschel, B. Bulaon, A. Stucy, D.F. Smith, and A.C. Caprio. 2019. Structure, diversity and health of Sierra Nevada red fir forests with reestablished fire regimes. International Journal of Wildland Fire 28:386–396.

Meyer, M.D. and M.P. North. 2019. Natural range of variation of red fir and subalpine forests in the Sierra Nevada Bioregion. PSW-GTR-263. USDA Forest Service, Pacific Southwest Research Station, Albany, CA. 135pp.

Meyer, M.D., J.W. Long, H.D. Safford, S.C. Sawyer, M.P. North, and A.M. White. 2021. Principles of postfire restoration. Pages 1-30 in M.D. Meyer, J.W. Long, and H.D. Safford (eds.) Postfire restoration framework for National Forests in California. USDA Forest Service, PSW-GTR-270. 204 pp.

Miller, C. and G.H. Aplet. 2016. Progress in wilderness fire science: Embracing complexity. Journal of Forestry 114: 373–383.

Miller, R.K., C.B. Field and J.J. Mach. 2020. Barriers and enablers for prescribed burns for wildfire management in California. Nature Sustainability 3:101-109.

Mitchell, R.J., J.K. Hiers, J.O'Brien, and G. Starr. 2009. Ecological forestry in the Southeast: Understanding the ecology of fuels. Journal of Forestry 107:391-397.

Murphy, J.S., R. York, H. Rivera Huerta, and S.L. Stephens. 2021. Characteristics and metrics of resilient forests in the Sierra de San Pedro Martír, Mexico. Forest Ecology and Mangement 482:118864.

NIFC. 2020. National Interagency Fire Center, Statistics Center. Accessed February 2021. https://www.nifc.gov/fire-information/statistics/wildfires

Ng, J., M.P. North, A.J. Arditti, M.R. Cooper, and J.A. Lutz. 2020. Topographic variation in tree group and gap structure in Sierra Nevada mixed-conifer forests with active fire regimes. Forest Ecology and Management 472:118220.

Norris, C., P. Hobson and P.L. Ibisch. 2012. Microclimate and vegetation function as indicators of forest thermodynamic efficiency. Journal of Applied Ecology 49:562-570.

North, M.P., P. Stine, K. O'Hara, W. Zielinski, and S. Stephens. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. USDA Forest Service, PSW General Technical Report. PSW-GTR-220.

North, M.P. and M.D. Hurteau. 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. Forest Ecology and Management 261:1115-1120.

North, M.P., B.M. Collins, and S.L. Stephens. 2012. Using fire to increase the scale, benefits and future maintenance of fuels treatments. Journal of Forestry 110: 392-401.

North, M.P., A. Brough, J. Long, B. Collins, P. Bowden, D. Yasuda, J. Miller and N. Suighara. 2015a. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. Journal of Forestry 113:40-48.

North, M.P., S. Stephens, B. Collins, J. Agee, G. Aplet, J., Franklin, and P. Fulé. 2015b. Reform forest fire management: Agency incentives undermine policy effectiveness. Science 349:1280-1281.

North, M.P., B. Collins, H. Safford, and N. Stephenson. 2016. Montane Forests. Pages 553-578 in Ecosystems of California, H. Mooney and E. Zavelta, (eds.) U.C. Press, Berkeley, CA. 984 pp.

North, M.P., J.T. Kane, V.R. Kane, G.P. Asner, W. Berigan, D.J. Churchill, S. Conway, R.J. Gutiérrez, S. Jeronimo, J. Keane, A. Koltunov, T. Mark, M. Moskal, T. Munton, Z. Peery, C. Ramirez, R. Sollmann, A.M. White, S. Whitmore. 2017. Cover of tall trees best predicts California spotted owl habitat. Forest Ecology and Management 405:166-178.

North, M.P., J.T. Stevens, D.F. Greene, M. Coppoletta, E.E. Knapp, A.M. Latimer, C.M. Restaino, R.E. Tompkins, K.R. Welch, R.A. York, D.J.N. Young, J.N. Axelson, T.N. Buckley, B.L. Estes, R.N. Hager, J.W. Long, M.D. Meyer, S.M. Ostoja, H.D. Safford, K.L. Shive, C.L. Tubbesing, H. Vice, D. Walsh, C.M. Werner, and P. Wyrsch. 2019. Tamm Review: Reforestation for resilience in dry western U.S. forests. Forest Ecology and Management 432:209-224.

O'Connor, C.D., M.P. Thompson, F. Rodriguez y Silva. 2016. Getting ahead of the wildfire problem: quantifying and mapping management challenges and opportunities. Geosciences 6: 35.

O'Connor, C.D. and D.E. Calkin. 2019. Engaging the fire before it starts: A case study from the 2017 Pinal Fire (Arizona). Wildfire. 28: 14-18.

Oswalt, S.N.; B.W. Smith, P.D. Miles, and S.A. Pugh, 2019. Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 223 p. https://doi.org/10.2737/WO-GTR-97.

Parks, S.A., C. Miller, C.R. Nelson, and Z.A. Holden. 2013. Previous fires moderate burn severity of subsequent wildland fires in two larger western US wilderness areas. Ecosystems 17: 29-42.

Parks, S.A., C. Miller, J.T. Abatzoglou, L.M. Holsinger, M.-A. Parisien, and S.Z. Dobrowski. 2016. How will climate change affect wildland fire severity in the western US? Environmental Research Letters 11:035002.

Pausas, J.G. 2015. Evolutionary fire ecology: lessons learned from pines. Trends in Plant Science 20: 318-324.

Prichard, S.J., P.F. Hessburg, K. Hagmann, D.J. Chruchill, S. Dobrowski, R.W. Gray, D. Huffman, M.D. Hurteau, V. Kane, R.E. Keane, L. Kobziar, M.P. North, H.D. Safford, J. Stevens, C. Kolden, S. Parks, and L. Yokum. In review. Adapiting western U.S. forest to wildfires and climate change: Ten Misconception. Ecological Applications.

Pyne, S. 2020. Fire fundamentals: A primer on wildland fire for journalists. http://www.stephenpyne.com/attachments/fire_primer_for_journalists_(june_2020).pdf.

Reinhardt, E.D. R.E. Keane, D.E. Calkin, and J.D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256: 1997-2006.

Restaino, C., D.J.N. Young, B. Estes, S. Gross, A. Wuenschel, M. Meyer and H. Safford. 2019. Forest structure and climate mediate drought-induced tree mortality in forests of the Sierra Nevada, USA. Ecological Applications 29:e01902.

Ritchie, M.W., C.N. Skinner, and T.A. Hamilton. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire. Forest Ecology and Management 247:200-208.

Ritchie, M.W., E.E. Knapp, C.N. Skinner. 2013. Snag longevity and surface fuel accumulation following post-fire logging in a ponderosa pine dominated forest. Forest Ecology and Management 287:113-122.

Ritchie, M.W., and E.E. Knapp. 2014. Establishment of a long-term fire salvage study in an interior ponderosa pine forest. Journal of Forestry 112:395-400.

Ritter, S.M., C.M. Hoffman, M.A. Battaglia, C.S. Stevens-Rumann, and W.E. Mell. 2020. Fine-scale fire patterns mediate forest structure in frequent-fire ecosystems. Ecosphere 11:e03177.

Roberts, S.L., J.W. van Wagtendonk, A.K. Miles, and D. A. Kelt. 2011. Effects of fire on spotted owl site occupancy in a late-successional forest. Biological Conservation 144:610-619.

Roberts, S.L., D.A. Kelt, J.W. van Wagtenkonk, A.K. Miles, and M.D. Meyer. 2015. Effects of fire on small mammal communities in frequent-fire forests in California. Journal of Mammology 96:107–119.

Ryan, K.C., E.E. Knapp, and J.M. Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practices, and challenges. Frontiers in Ecology and the Environment 11: e15-e24.

Safford, H.D., M.P. North, and M.D. Meyer. 2012. Climate change and the relevance of historical forest conditions. P. 23-45 in Managing Sierra Nevada Forests, M. North (ed.) General Technical Report PSW-GTR-237. USDA Forest Service, Pacific Southwest Research Station, Albany, CA. 184 pp.

Safford, H.D. and K.M. van de Water. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on national forest lands in California. USDA Forest Service Research Paper PSW-RP-266. Albany, CA. 59pp.

Safford, H.D. and J.T. Stevens. 2017. Natural Range of Variation for Yellow Pine and Mixed-Conifer Forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA. USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-256.

Schofield, L.N., S.A. Eyes, R.B. Siegel, and S.L. Stock. 2020. Habitat selection by spotted owls after a megafire in Yosemite National park. Forest Ecology and Management 478:118511.

Scholl, A.E. and A.H. Taylor. 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. Ecological Applications 20:362-380.

Schultz C.A., H. Huber-Stearns, S. McCaffrey, D. Quirke, G. Ricco, and C. Moseley. 2018. Prescribed fire policy barriers and opportunities: a diversity of challenges and strategies across the West. Ecosystem Workforce Program, Institute for a Sustainable Environment, University of Oregon.

Schultz, C.A. and C. Moseley. 2019. Collaborations and capacities to transform fire management. Science 366:38-40.

Schultz, C.A., S.M. McCaffrey, and H.R. Huber-Stearns. 2019a. Policy barriers and opportunities for prescribed fire application in the western United States. International Journal of Wildland Fire 28: doi.org/10.1071/WF19040.

Schultz, C.A., M.P. Thompson, and S.M. McCaffrey. 2019b. Forest Service fire management and the elusiveness of change. Fire Ecology 15: 13.

Schwartz, M.W., J.H. Thorne, B.M. Collins, and P.A. Stine. 2020. "Forest mismanagement" misleads. Science 370:417.

Smith, T., D. Rizzo and M.P. North. 2005. Patterns of mortality in an old-growth mixed-conifer forest of the southern Sierra Nevada, California. Forest Science 51:266-275.

Sneeuwjagt, R.J., T.S. Kline, and S.L. Stephens. 2013. Opportunities for improved fire use and management in California: lessons from Western Australia. Fire Ecology 9:14-25.

Soung-Ryoul, R., A. Concilio, J. Chen, M.P. North, and S. Ma. 2009. Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. Forest Ecology and Management 257:1324–1332.

Steel, Z.L., H.D. Safford, and J.H. Viers. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6: 1-23.

Steel, Z.L., B. Campos. W.F. Frick, R. Burnett, and H.D. Safford. 2019. The effects of wildfire severity and pyrodiversity on bat occupancy and diversity in fire-suppressed forests. Scientific Reports 9:16300.

Steel, Z.L., M.J. Goodwin, M.D. Meyer, G.A. Fricker, H.S.J. Zald, M.D. Hurteau, and M.P. North. 2021. Do forest fuel reduction treatments confer resistance to beetle infestation and drought mortality? Ecosphere 12: e03344.

Stephens, S.L., R.E. Martin, and N.E. Clinton. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. Forest Ecology and Management 251:205-216.

Stephens, S.L., Collins, B.M, and Roller, G. 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 285:204-212.

Stephens, S.L., Bigelow, S.W., Burnett, R.D., Collins, B.M., Gallagher, C.V., Keane, J., Kelt, D.A., North, M.P., Roberts, S.J., Stine, P.A., Van Vuren, D.H. 2014. California spotted owl, songbird, and small mammal responses to landscape fuel treatments. Bioscience 64: 893-906.

Stephens, S.L., B.M. Collins, E. Biber, and P.Z. Fulé. 2016a. U.S. federal fire and forest policy: emphasizing resilience in dry forests. Ecosphere 7:e01584.

Stephens, S.L., J.D. Miller, B.M. Collins, M.P. North, J.J. Keane, and S.L. Roberts. 2016b. Wildfire impacts on California spotted owl nesting habitat in the Sierra Nevada. Ecosphere 7: e01478. 10.1002/ecs2.1478.

Stephens, S.L., B.M. Collins, C.J. Fettig, M.A. Finney, C.M. Hoffman, E.E. Knapp, M.P. North, H. Safford, and R.B. Wayman. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience 68:77-88.

Stephens, S.L., L. Kobziar, B.M. Collins, R. Davis, P. Fulé, W. Gaines, J. Ganey, J. Guldin, P. Hessburg, K. Hiers, S. Hoagland, J. Keane, R Master, A. McKellar, W. Montague, M.P. North, and T. Spies. 2019. Is fire "for the birds"? How two rare species drive fire management across the United States. Frontiers in Ecology and the Environment 17:391-397.

Stephens, S.L., M.A. Battaglia, D.J. Churchill, B.M. Collins, M. Coppoletta, C.M. Hoffman, J.M. Lydersen, M.P. North, R.A. Parson, S.M. Ritter, and J.T. Stevens. 2020a. Forest restoration and fuels reduction: Convergent or divergent? Bioscience doi:10.1093/biosci/biaa134

Stephens, S.L., A.L. Westerling, M.D. Hurteau, M.Z. Peery, C.A. Schultz, and S. Thompson. 2020b. Fire and climate change: conserving seasonally dry forests is still possible. Frontiers in Ecology and the Environment 18:354-360.

Stevens, J.T., H.D. Safford, S. Harrison, and A.M. Latimer. 2015. Forest disturbance accelerates thermophilization of uunderstory plant communities. Journal of Ecology 103:1253-1263.

Stevens, J.T., B.M. Collins, J.W. Long, M.P. North, S.J. Prichard, L.W. Tarnay, and A.M. White. 2016. Evaluating potential trade-offs among fuel treatment strategies in mixed-conifer forests of the Sierra Nevada. Ecosphere 7:e01445. 10.1002/ecs2.1445.

Stevens, J.T., B.M. Collins, J.D. Miller, M.P. North, and S.L. Stephens. 2017. Changing spatial patterns of stand-replacing fire in California conifer forests. Forest Ecology and Management 406:28-36.

Stevens J.T., M.M. Kling, D.W. Schwilk, J.M. Varner, and J.M. Kane. 2020. Biogeography of fire regimes in western U.S. conifer forests: A trait-based approach. Global Ecology and Biogeography 29:944–955.

Striplin, R., S.A. McAfee, H.D. Safford, and J.J. Papa. 2020. Retrospective analysis of burn windows for fire and fuels management: an example from the Lake Tahoe Basin, California, USA. Fire Ecology 16: article 13.

Tempel, D.J., R.J. Gutierrez, J.J., Battles, D.L. Fry, Y.J. Su, Q.H. Guo, M.J. Reetz, S.A. Whitmore, G.M. Jones, B.M. Collins, S.L. Stephens, M. Kelly, W.J. Berigan, and M.Z. Peery. 2015. Evaluating short- and long-term impacts of fuels treatments and simulated wildfire on an old-forest species. Ecosphere 6:19.

Thompson M.P., D.E. Calkin, J.W. Gilbertson-Day, and A.A. Ager. 2011. Advancing effects analysis for integrated, large-scale wildfire risk assessment. Environmental Monitoring Assessment 179: 217–239.

Thompson, M.P., P. Bowden, A. Brough, J.H. Scott, J. Gilbertson-Day, A. Taylor, J. Anderson, and J.R. Haas. 2016. Application of wildfire risk assessment results to wildfire response planning in the Southern Sierra Nevada, California, USA. Forests 7:64.

Thompson, M.P.; K.L. Riley, D. Loeffler, and J.R. Haas. 2017. Modeling fuel treatment leverage: Encounter rates, risk reduction, and suppression cost impacts. Forests 8:469.

Tingley, M.W., V. Ruiz-Gutierrez, R.L. Wlherson, C.A. Howell, and R.B. Siegel. 2016. Pyrodiversity promotes avian diversity over the decade following forest fire. Proceedings of the Royal Society 283:1840.

USDA-FS. 2012. The Forest Planning Rule. Available online at www.fs.usda.gov/detail/planningrule.

USDA-FS. 2021. Forest Service FEIS for Sierra and Sequoia forest plans. https://www.fs.usda.gov/detail/r5/landmanagement/planning/?cid=STELPRD3802842

Vaillant, N.M. and E.D. Reinhardt. 2017. An evaluation of the Forest Service hazardous fuels treatment program—Are we treating enough to promote resiliency or reduce hazard? Journal of Forestry 115:300-308.

van de Water, K. and M.P. North. 2010. Fire history of coniferous riparian forests in the Sierra Nevada. Forest Ecology and Management 260:384-395.

van de Water, K. and M.P. North. 2011. Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA; a comparison of current and reconstructed conditions. Forest Ecology and Management 262:215-228.

van Wagtendonk, J.W., J.A. Fites-Kaufman, H.D. Safford, M.P. North, and B.M. Collins. 2018. Sierra Nevada Bioregion. Pages 249-278 in J.W. van Wagtendonk, N.G. Sugihara, S.L. Stephens, A.E. Thode, K.E. Shaffer, and J.A. Fites-Kaufman (eds) Fire in California's Ecosystems. 2nd edition. U.C. Press, Oakland, CA.

Wayman, R. and M.P. North. 2007. Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. Forest Ecology and Management 239:32-44.

Westerling, A.L., M.G. Turner, E.A. H. Smithwick, W.H. Romme, and M.G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences 108:13165–13170.

Westerling, A.L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150178.

Wood, C.M. and G.M. Jones. 2019. Framing management of social-ecological systems in terms of the cost of failure: the Sierra Nevada, USA as a case study. Environmental Research Letters 14:105004.

Young, D.J N., J.T. Stevens, J M. Earles, A. Ellis, A. Jirka, J. Moore, and A.M. Latimer. 2017. Long-term climate and competition explain forest mortality patterns under extreme drought. Ecology Letters 20:78-86.

Young, D.J.N., M. Meyer, B. Estes, S. Gross, A. Wuenschel, C. Restaino, and H.D. Safford. 2020a. Forest recovery following extreme drought in California, USA: natural patterns and effects of pre-drought density reduction. Ecological Applications 30:e02002.

Young, J.D., A.M. Evans, J.M. Inguez, A. Thode, M.D. Meyer, S.J. Hedwall, S. McCaffrey, and P. Shin. 2020b. Effects of policy change on wildland fire management strategies: Evidence for a paradigm shift in the western US? International Journal of Wildland Fire 29: 857–877.

York, R.A., J. Levine, D. Foster, S. Stephens, and B. Collins. In PressA. Silviculture can facilitate prescribed burn programs. California Agriculture.

York, R.A., H. Noble, L. Quinn-Davidson, and J.J. Battles. In pressB. Pyrosilviculture: Combining prescribed fire with gap-based silviculture in mixed-conifer forests of the Sierra Nevada. Canadian Journal of Forest Research: doi.org/10.1139/cjfr-2020-0337.

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

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 management.

Table 3: Total acres and acres by severity class for wildfire activity from 2011-2020 for the nine National Forests and Lake Tahoe Basin Management Unit in the Sierra Nevada. Acres of fuel reduction treatments burned are calculating from the intersection of wildfires with treatment areas from the FACTs database.

Table 4: Average annual acreage of F.S. 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 2011-2020.

Figure Legends

Figure 1: Distribution of the twelve 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 the 2020 Castle Fire perimeter.

Figure 2: Left panel (a) 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 (b) shows areas that have been designated for wildfire restoration (yellow) and maintenance (blue) in the Sierra NF'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.

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 fuels 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.

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, spacely 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.

Figure 5: An example of coupled mechanical thinning and mastication treatments with fire in southern forests that most effectively meets ecological, silvicultural, and wildlfire 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, while 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.

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)

Figure 1 revised

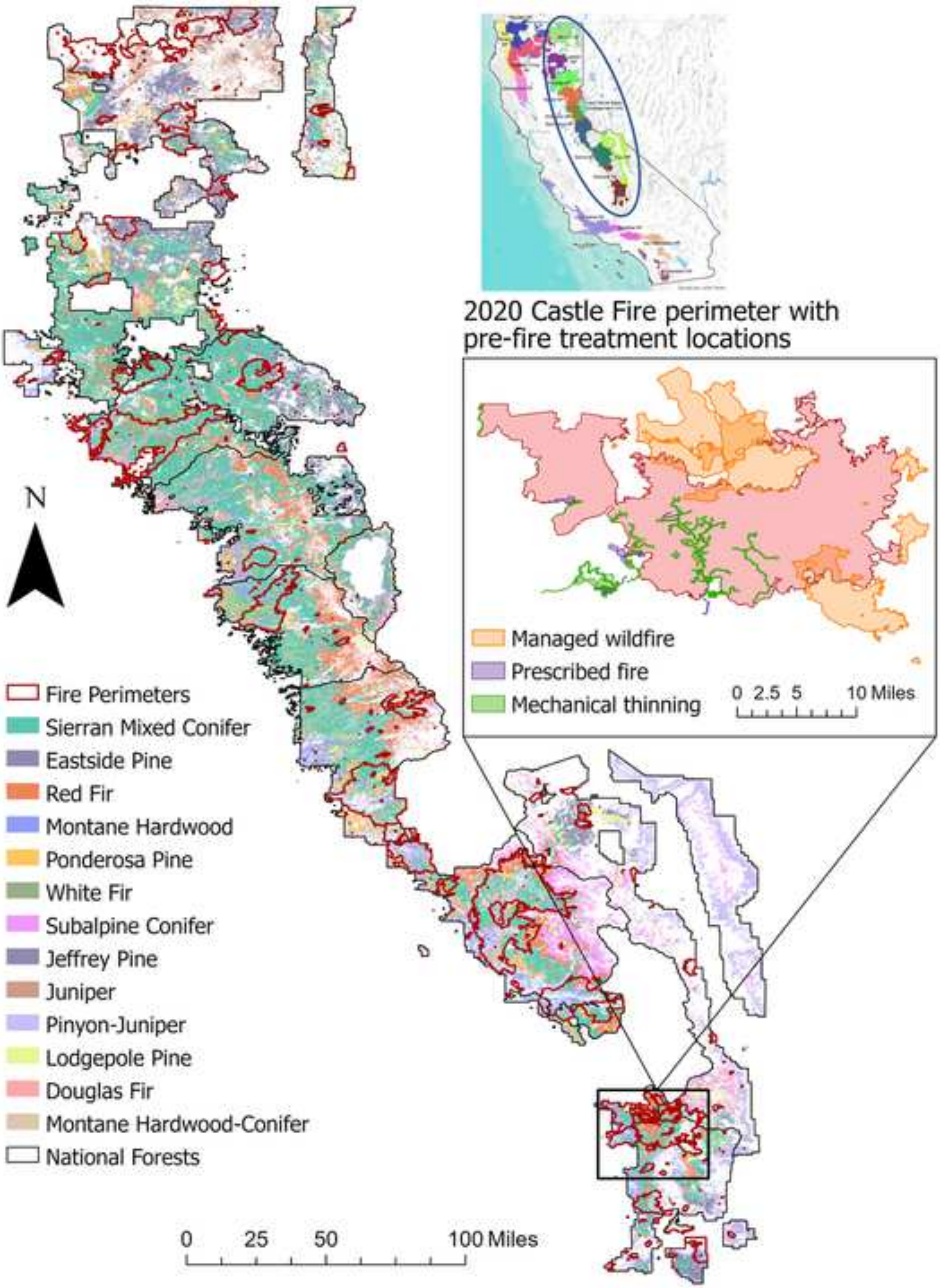

Figure 2 revised

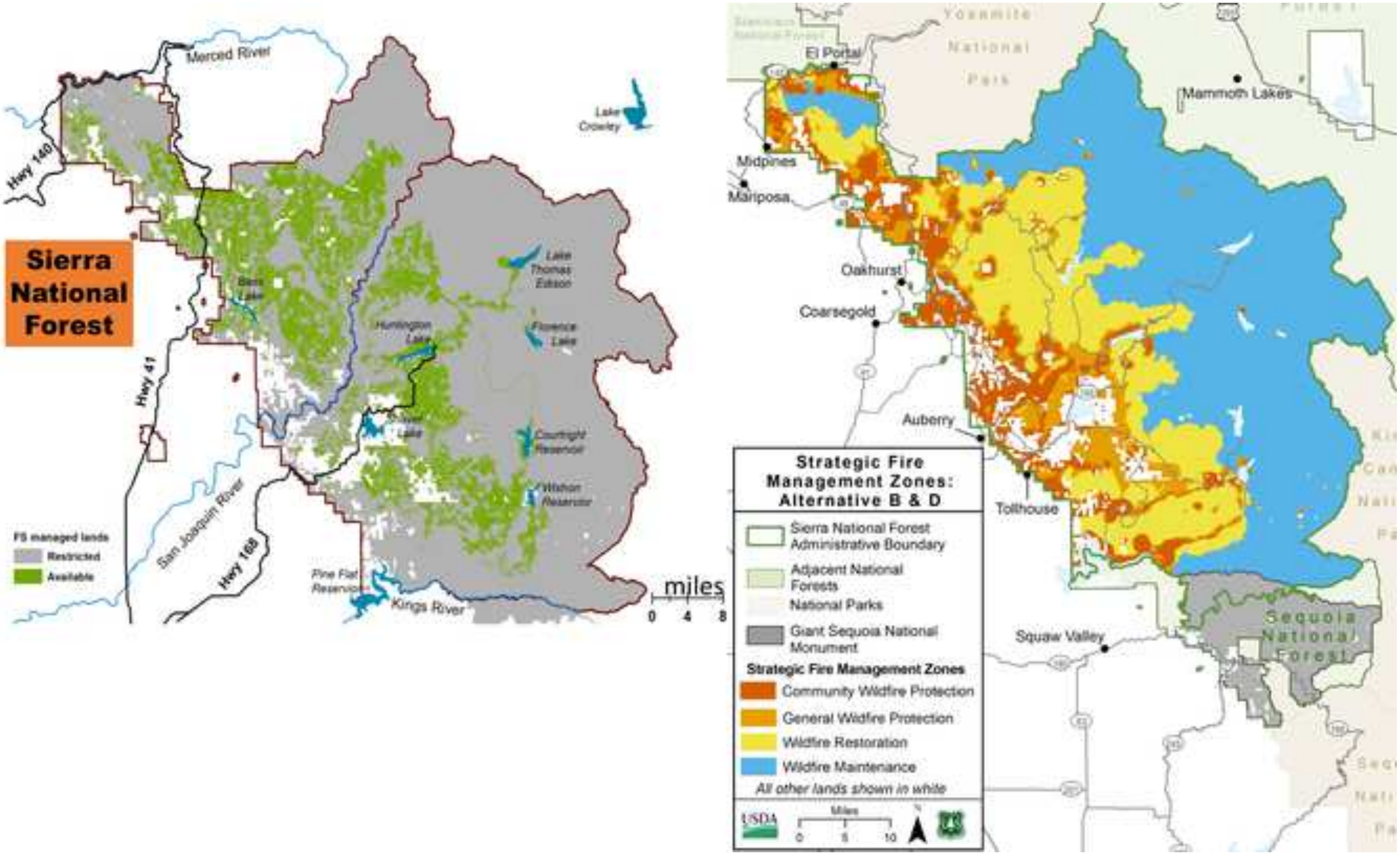

Figure 3 revised

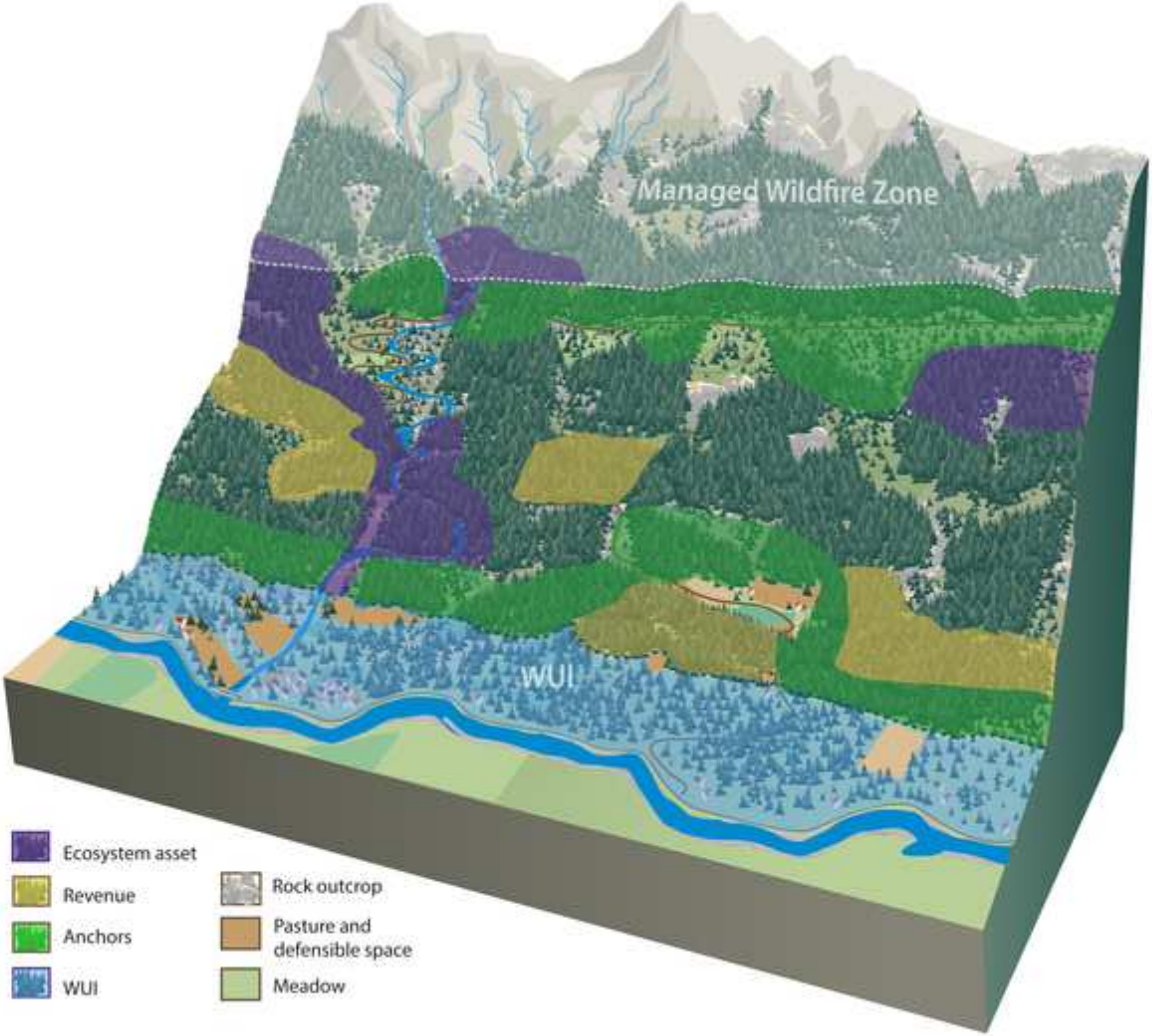

Figure 4 revised

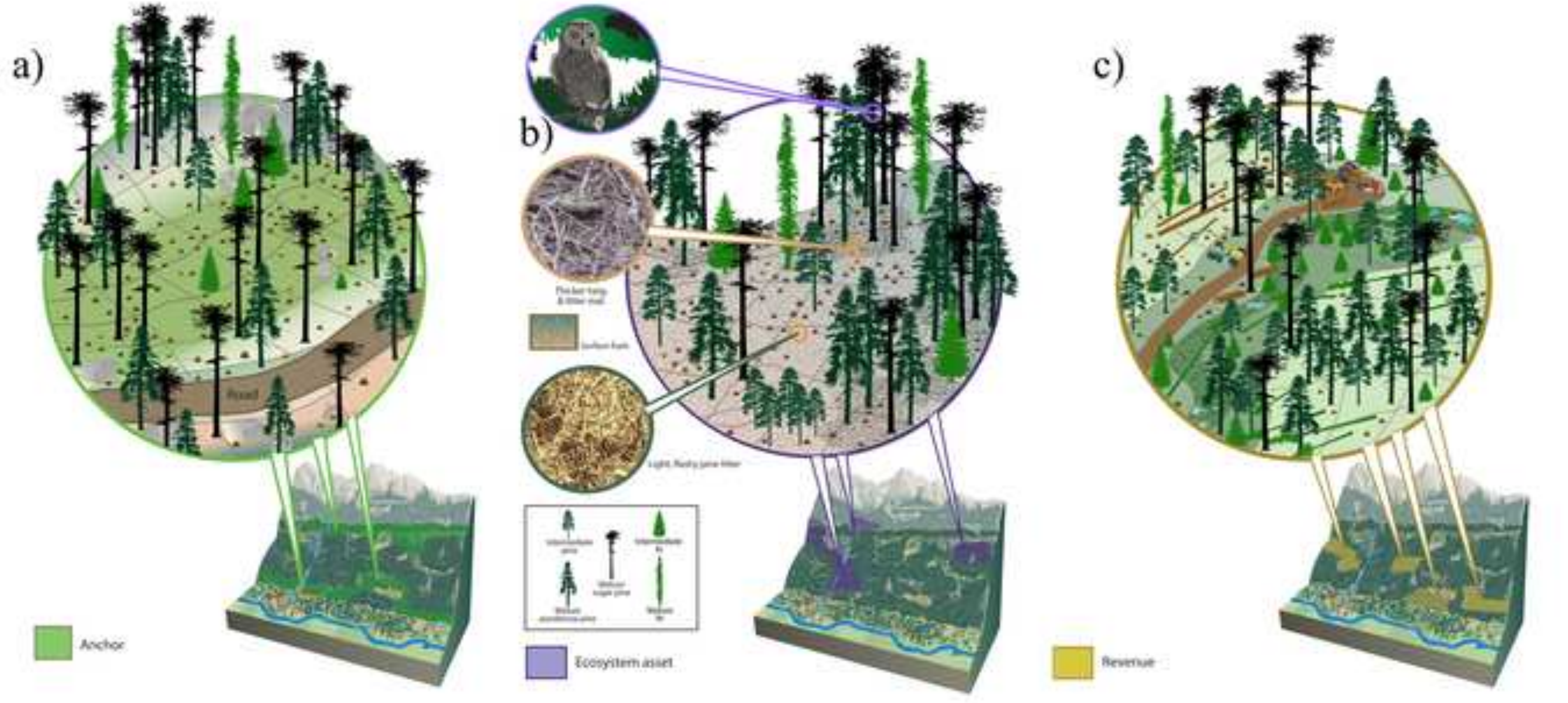

Figure 5 revised

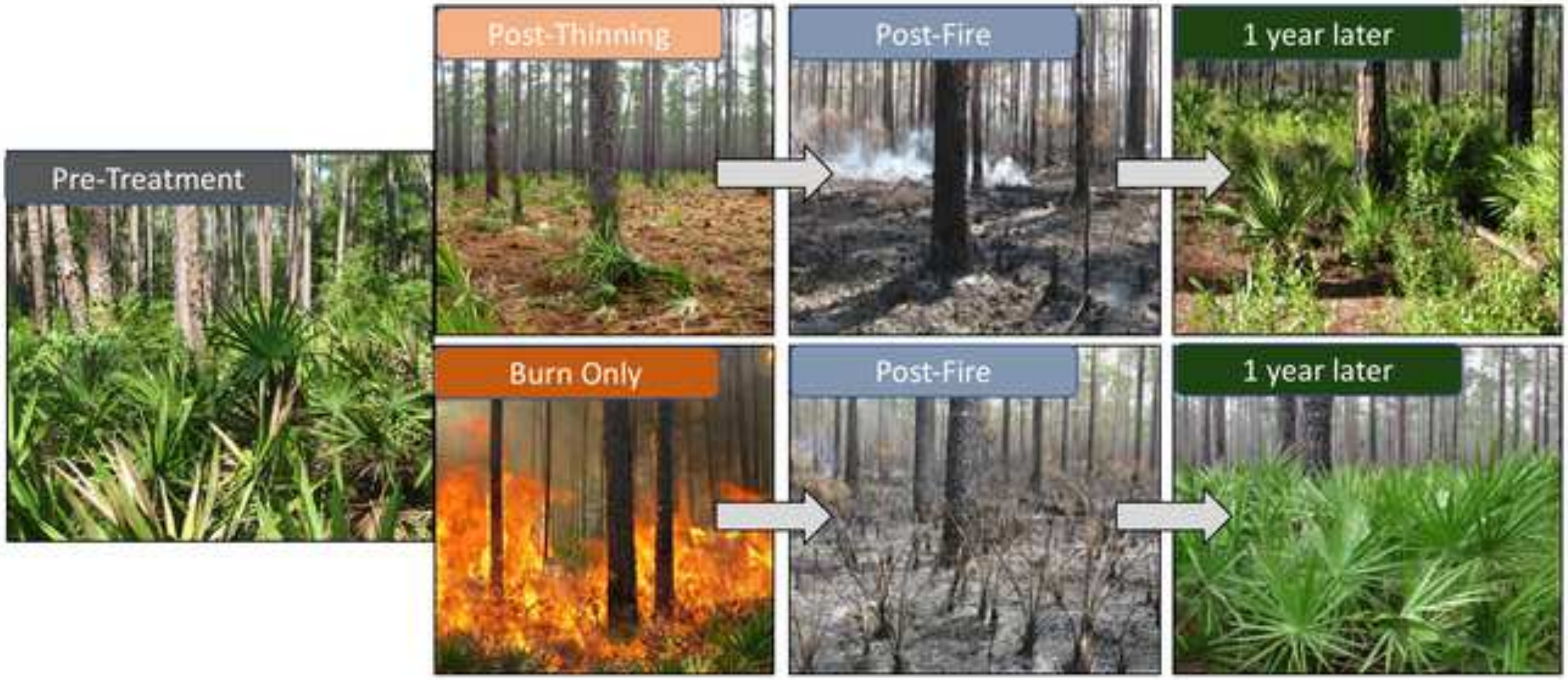

Figure 6 revised

Figure 7 revised

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

Pyrosilviculture		
Attributes:	Stand*	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 Natural Range of Variation (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	• Treat landscapes while providing habitat for sensitive species

	• 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	• 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

* York et al. (In pressB)

[1] Given changing climate and disturbance conditions, 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)

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 management.

Total FS Acreage	13,015,888		
Forest Type (FT):	Area (ac)	MFRI	Avg 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/)

Table 3 revised

Table 3: Total acres and acres by severity class for wildfire activity from 2011-2020 for the nine National Forests and Lake Tahoe Basin Management Unit in the Sierra Nevada. Acres of fuel reduction treatments burned are calculating from the intersection of wildfires with treatment areas (including managed wildfire) from the 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*	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*	NA	NA	NA	NA	10,977
2020	902,991*	NA	NA	NA	NA	104,804
Avg/yr	227,245	29,699^ (16.8%)	66,042^ (36.4%)	45,973^ (25.9%)	34,656^ (20.9%)	20,244[+]

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

* Totals in 2011 and 2019 are from CalFire's FRAP dataset, which for 2012-2018 were within 2% of MTBS totals for each year. The total for 2020 is from National Interagency Fire Center (NIFC 2020) data.

^ Average acres by severity class are for 2012-2018 only.

[+] Average treated acres intersected by wildfire are calculated for 2017-2020 only.

Table 4 revised

Table 4: Average annual acreage of F.S. 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 2011-2020.

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 (0.1-5,249)	13	4623
Prescribed Burn (Rx)	11,861	22,214	40 (0.1-1,298)	13	
Managed Wildfire (Man)	18,919	20,138	2,877 (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.