Forest Restoration and Fuels Reduction: Convergent or Divergent?

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For over 20 years, forest fuel reduction has been the dominant management action in western US forests. These same actions have also been associated with the restoration of highly altered frequent-fire forests. Perhaps the vital element in the compatibility of these treatments is that both need to incorporate the salient characteristics that frequent fire produced—variability in vegetation structure and composition across landscapes and the inability to support large patches of high-severity fire. These characteristics can be achieved with both fire and mechanical treatments. The possible key to convergence of fuel reduction and forest restoration strategies is integrated planning that permits treatment design flexibility and a longer-term focus on fire reintroduction for maintenance. With changing climate conditions, long-term forest conservation will probably need to be focused on keeping tree density low enough (i.e., in the lower range of historic variation) for forest conditions to adapt to emerging disturbance patterns and novel ecological processes.

Keywords: resilience, restoration, adaptation, wildfire, convergence, forest conservation, fuel reduction

In coniferous forests of the western United States that were historically dominated by frequent (a median return interval of less than 35 years) surface fire, a host of nineteenth and twentieth century land use changes dramatically altered forest structure, function, and resilience to future disturbance (Covington and Moore 1994, Reynolds et al. 2013, Stine et al. 2014, Safford and Stevens 2017, Addington et al. 2018, Hessburg et al. 2019). These altered forest conditions, in conjunction with a changing climate, have been implicated in recent increases in the area of contiguous stand-replacing fire and drought-induced tree mortality (Miller et al. 2009, Abatzoglou and Williams 2016, Stevens et al. 2017, Young et al. 2017, Parks et al. 2018, Stephens et al. 2018a, Singleton et al. 2019), which in turn may hinder their regenerative capacity (Haffey et al. 2018, Coop et al. 2019, Dey et al. 2019, Korb et al. 2019, Stephens et al. 2020a). For over 20 years, forest fuel reduction has been the dominant silvicultural technique for mitigating the risk of large stand-replacing fires in these forests, and it is increasingly being implemented as part of the forest restoration paradigm (Moore et al. 1999, Allen et al. 2002, Fulé et al. 2012, Underhill et al. 2014, Hesburg et al. 2015).

Forest restoration in this context generally refers to reducing tree densities and surface fuels while also shifting species composition and spatial patterns to more closely resemble the historical range of variation (i.e., prior to Euro-American colonization and the onset of widespread timber harvesting, and fire exclusion and suppression). Indeed, early twenty-first century US legislation including the Healthy Forests Restoration Act provided explicit funding and policy mechanisms to accomplish fuels reduction while recognizing the link to restoration—for example, to "plan and conduct hazardous fuel reduction projects… on specified types of Federal lands… [and] to fully maintain, or contribute toward the restoration of, the structure and composition of old growth [sic] stands according to the prefire suppression old growth [sic] conditions characteristic of the forest type, taking into account the contribution of the stand to landscape fire adaptation and watershed health, and retaining the large trees contributing to old growth [sic] structure" (US Congress 2003).

Recently, there has been a growing scientific understanding of forest structure and composition in old-growth stands prior to fire suppression and logging, from a combination of historical reconstruction methods and studies of analogous contemporary frequent-fire landscapes (Fulé et al. 1997, Brown et al. 2008, Stephens et al. 2015, Merschel et al. 2019). Among these important recent developments has been the identification of generally low density, but variable forest conditions at both the stand scale (Brown and Cook 2006, Larson and Churchill 2012, Lydersen et al. 2013, Reynolds et al. 2013, Churchill et al. 2017, Battaglia et al. 2018, Lefevre et al. 2020) and across forest-dominated landscapes (Collins et al. 2015, Boisramé et al. 2017, Hagmann et al.

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Figure 1. Forest fuel reduction treatments from the Texas Hill Project, Tahoe National Forest, California (a, b), and the Meadow Valley Project, Plumas National Forest, California (c, d). Panels a and c represent nearby untreated forest to give an idea of pretreatment conditions, and b and d represent treated areas. This portion of the Texas Hill project (b) was burned multiple times following the treatment, and has retained large trees, a clumped pattern, and a diverse understory, whereas this portion of the Meadow Valley project (d) has only been pile burned since the thinning, contains a more even spaced tree pattern and less diversity and heterogeneity. The Texas Hill Project represents a greater degree of restoration than the Meadow Valley project, although both would qualify as fuels reduction. More information on these treatments is available in Stevens and colleagues (2014). Photographs: Jens Stevens.

2017, Stephens et al. 2018b). In fact, spatial and structural heterogeneity has emerged as perhaps the unifying principle guiding much of forest restoration in dry conifer forests in the western United States (North et al. 2009, Frankin and Johnson 2012, Churchill et al. 2013, Reynolds et al. 2013, Stine et al. 2014, Addington et al. 2018).

Although the nuanced understanding of the variability in historical forest conditions has been developing rapidly in the scientific literature, the practical application of these principles is lagging (but see Knapp et al. 2012, Stine and Conway 2012). At the stand scale (i.e., 10–100 hectares [ha]), conventional fuel reduction techniques of small-diameter tree removal, often targeting fire-sensitive species, and reducing surface fuels have well-known outcomes for moderating fire behavior and effects (Agee and Skinner 2005). Although these treatments may constitute forest restoration in a broad sense, they may be lacking the salient characteristic of heterogeneity (figure 1). This is partly related to the complexity in translating historical stand heterogeneity into operational treatment prescriptions.

At the landscape scale (i.e., 1000–10,000 ha), restoration via mechanical means is complicated by legal and physical constraints on mechanical access or land use (North et al. 2015a, Stevens et al. 2016), as well as limited information on variation in historical forest structure at larger spatial scales. This creates uncertainty regarding how treatments might be stitched together across landscapes, although landscape level reference conditions and guidelines on using them have been developed for some regions (Hessburg et al., 1999, 2015, Keane et al. 2009). Finally, although there is

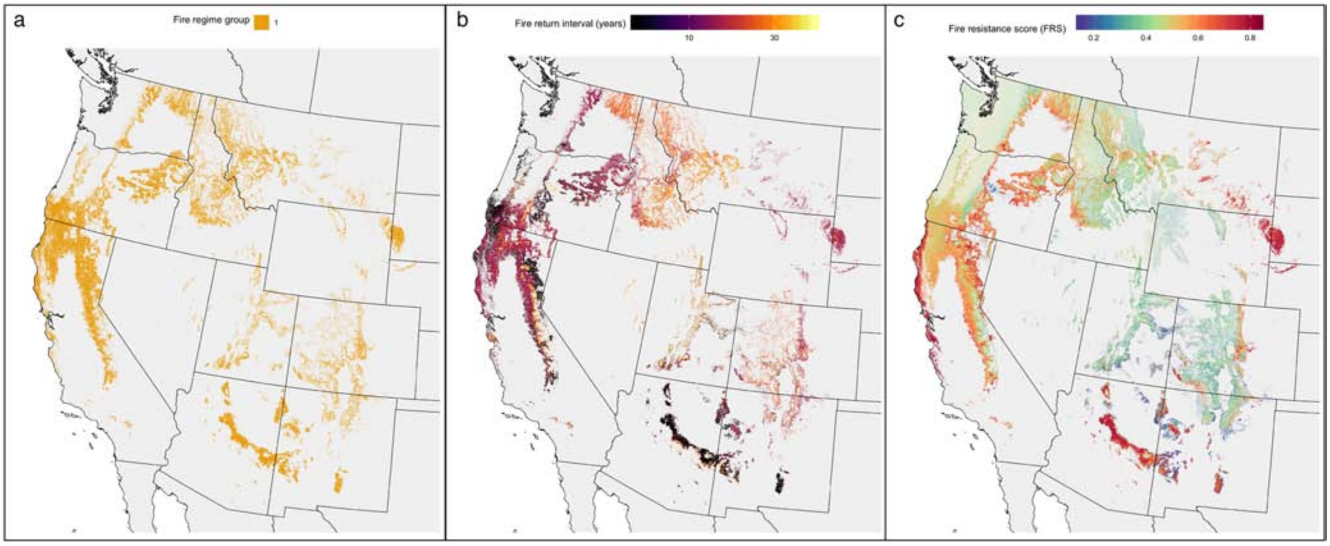

Figure 2. The geographic scope of this paper is principally aligned with regions dominated by conifer forest and classified by LANDFIRE as Fire Regime Group 1 (a), where frequent surface fire at return intervals of under 35 years (b) predominated historically. These regions generally contain the most fire-resistant conifer species (c), which are characterized by thick bark, self-pruning of lower limbs, tall tree heights, and fine litter fuels (figures modified from Stevens et al. 2020, based on data and code therein, highlighting only frequent fire forests of Fire Regime Group 1). Regions with conifer forest but a greater component of infrequent stand-replacing fire are shown in lighter transparent colors in panel c.

widespread agreement that the need for forest restoration in more mesic and cold forests with longer historical fire return intervals (e.g., more than 50–100 years) may not be as pressing as it is for drier forest types (Schoennagel et al. 2004, Schoennagel and Nelson 2011), management in these more mesic forest types may nevertheless have utility for restoring landscape scale patchworks of various forest and nonforest vegetation types (Spies et al. 2018, Hessburg et al. 2019). These landscape patchworks may also confer resilience to future disturbance in a warming climate (Stephens et al. 2013).

Given this context, our objective is to review the principles of both forest fuel reduction and forest restoration in historically frequent-fire forests of the western United States (figure 2) to explore where these two sets of principles align and the conditions in which they do not. Our motivation is to provide greater clarity to forest managers, stakeholders, scientists, and policy makers to ultimately design and implement appropriate large-scale management strategies. We recognize that fuel reduction need not always constitute ecological restoration in order to meet societal objectives (e.g., hazard reduction within and adjacent to the wildland–urban interface, WUI). Furthermore, many existing forest treatments contain elements of both principles; therefore, a rigid dichotomy between fuel reduction and restoration may not actually exist. Nevertheless, given that fuel reduction activities are often couched in terms of restoration, we argue that this review of the two concepts is needed to retain the utility and integrity of each concept independently.

Forest fuels reduction

Forest fuels reduction treatments (fuel treatments) are generally defined as "the purposeful use of any silvicultural method, including mechanical methods, managed wildfire, prescribed fire, or a combination of approaches, to intentionally alter the fuel complex in such a way as to modify fire behavior and thereby minimize the potential negative impacts of future wildfires on ecosystem goods and services, cultural resources, and human communities" (Hoffman et al. 2018). In this context, managed fire refers to permitting portions of or entire wildfires to burn in a manner such that behavior and effects of subsequent fires are mitigated (Collins et al. 2009). Although land managers can design fuel treatments to alter a number of fire behavior and effects metrics (e.g., fire rate of spread, fire-line intensity, flame length, fire severity, soil impacts), most treatments focus on reducing the likelihood of crown fire ignition and spread, because these types of fires typically have greater rates of spread and fire-line intensities, have increased fire brand generation, are more difficult to control, and can produce adverse ecological and societal effects (Scott and Reinhardt 2001, Graham et al. 2009, Hoffman et al. 2018). To reduce the likelihood of crown fire, managers often design fuel treatments to alter four aspects of the fuels complex: reducing surface fuels, increasing canopy base height, reducing canopy bulk density, and maintaining large fire-resistant trees (Agee and Skinner 2005). The first two objectives are the most critical to reduce surface fire-line intensity, decrease the risk of crown fire ignition and spread, and increase fire suppression effectiveness. The third objective reduces the potential for active crown fire spread, whereas the final objective increases tree survivability when burned.

Designing fuel treatments requires land managers identify and describe specific forest structural targets, and then develop prescriptions that accomplish the goals in a timely and economically viable manner. Posttreatment structural targets are quantified using standard forestry metrics such as surface fuel loads, residual tree basal area, tree density, crown spacing, canopy base height, canopy cover, and species composition. Strict implementation of fire hazard reduction principles commonly results in a silvicultural prescription that targets the removal of small to mid-size trees, followed by a reduction of the surface fuels by broadcast or pile burning. However, it is important to recognize that in many cases the reduction of surface fuels through prescribed fire can be postponed or never completed resulting in either no change or increased surface fuel loads for a period of time (Stephens et al. 2009). These prescriptions are commonly developed using the outputs of nonspatial fire behavior models that are converted to space-based thinning prescriptions, resulting in a residual homogenous forest with evenly spaced trees of relatively similar sizes (figure 1; e.g., Johnson 2008, Powell 2010, Kennedy and Johnson 2014). Although this is typically the desired outcome from the standpoint of fire hazard reduction, it may come at the expense of decreasing structural heterogeneity and habitat suitability for species that rely on multilayered forest conditions such as the northern flying squirrel (*Glaucomys sabrinus*; Smith 2007), the California spotted owl (*Strix occidentalis occidentalis*; Stephens et al. 2014), the Douglas squirrel (*Tamiasciurus douglasii*; Buchanan et al. 1990), and other small forest mammals (Roberts et al. 2015).

Although treatment design and assessment often occur at the stand scale, the size of contemporary wildfires in western US forests highlights the clear need for planning that extends well beyond individual forest stands to landscapes (Collins et al. 2010, Hessburg et al. 2015). Broader scale planning is needed as the spatial context of a treatment can affect both its stand-scale effectiveness as well as its ability to modify potential fire behavior beyond the treated area. Several recent studies have indicated that strategically locating treatment within a small fraction of the landscape (e.g., 18%–20%) can significantly limit landscape fire spread and severity (Finney 2001, Calkin et al. 2011, Collins et al. 2011, Ex et al. 2019, Tubbesing et al. 2019). However, the magnitude and reliability of landscape scale fuel treatment effects remains somewhat unclear because of a lack of empirical evidence and untested modeling tools. Furthermore, there are several constraints that may limit the total treated area and the location of treatments within a landscape, including limited budgets, road access, proximity to the WUI, slope restrictions, and administrative boundaries (North et al. 2015a).

Within the areas available for treatment, priority areas are often identified on the basis of a number of factors, including their fuel hazard, the expected fire behavior and fire severity, or the risk they pose to social values including homes and infrastructure (Miller and Ager 2013, Dunn et al. 2017). Factors such as site productivity, surrounding fuel conditions, and the topographic position may all interact to affect a stand's hazard level and perceived need for treatment as they influence the amount of biomass a site can sustain, the rate at which this biomass will accumulate, as well as the fire environment if a wildfire were to enter the stand. In addition, priority areas may be identified on the basis of wildfire suppression considerations, including placement on ridge tops and near roads to serve as anchor points and to facilitate suppression or burnout operations (Graham et al. 2009, Dunn et al. 2017). Such prioritization schemes may result in treatment locations that either conflict or align with other objectives such as restoration (Ager et al. 2013).

In addition to landscape scale considerations, the temporal context within which fuel reduction treatments are planned plays a key role in whether they may achieve their objectives when exposed to a wildfire. Fuel reduction treatments have a *life span* or duration during which their impacts on fire behavior can be anticipated to be effective; this life span varies with site productivity, nature of the treatment, and other factors (Stephens et al. 2012, Jain et al. 2012, Low et al. 2021). In many cases, fuel treatments may not intersect with a fire during this life span (Barnett et al. 2016); if treatments are considered as a single entry (with no subsequent treatments), such cases would represent a potential waste of resources. However, viewed in the longer term, fuel treatments can reduce costs or increase efficiency of subsequent treatment activities. In particular, mechanical treatments can be used to create lower hazard stands that can then be more easily maintained through periodic prescribed burning or managed wildfire (North et al. 2012); without such maintenance, subsequent treatments may be more expensive and less effective.

Forest restoration

Forest restoration is defined as assisting the recovery of degraded forest ecosystems by "reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems sustainability, resilience, and health under current and future conditions" (USDA Forest Service 2012). This broad definition allows for considerable overlap between forest restoration and fuel treatments, however, there are also some important distinctions. Forest restoration projects generally take a much broader approach by considering the need for resilience to a wider range of disturbance processes and stressors (e.g., drought and insect-induced mortality), and by incorporating variability in both stand structure and fuels (Franklin et al. 2013, Reynolds et al. 2013, Collins and Skinner 2014, Addington et al. 2018, Falk et al. 2019). For example, in a review of randomly selected US Forest Service restoration projects that were implemented between 2012 and 2016, all projects conducted in western US frequent-fire forests included fuels reduction as an objective, but over

Table 1. Objectives noted in the environmental analysis documents for 25 projects implemented by the US Forest Service in frequent-fire forest types in the western United States.

Objective	Number of projects	Percentage of projects
Reduce fuels	25	100
Improve forest health/Increase resilience	21	84
Improve wildlife habitat	20	80
Alter species composition[a]/Protect tree species of interest	20	80
Increase structural diversity	17	68
Improve watershed health (includes streams and meadows)	16	64
Improve recreation or public safety (includes hazard tree removal)	15	60
Maintain roads (includes road removal)	13	52
Manage plantations	12	48
Improve economic health of rural communities (includes timber production)	12	48
Increase landscape vegetation diversity	12	48
Reforest after disturbance	10	40
Reintroduce fire	7	28
Includes fire (pile or prescribed)	20	80
Postwildfire	4	16

Note: The projects were selected on the basis of location and forest type from a database of 68 projects across the entire United States that were implemented between 2012 and 2016 and randomly selected for review as part of the recently proposed restoration categorical exclusion (www.fs.fed.us/emc/nepa/revisions/includes/docs/AppendicesRestoration.pdf). All of the projects are entirely or partially composed of actions that are covered under the proposed restoration categorical exclusion.

[a]Shifting species composition to favor more fire-resistant species is also often incorporated into treatments designed to reduce crown fire potential (Agee and Skinner 2005). We count fuels reduction and shifting species composition separately in the table, because restoration may target these goals for reasons other than reducing potential fire severity.

three-quarters of the projects also targeted forest health or resilience, wildlife habitat, or tree species composition (table 1). Although the diversity of stated objectives in table 1 demonstrates that restoration projects tend to be designed with a more holistic approach that incorporates multiple elements of ecosystem function, how silvicultural prescriptions are modified to meet these objectives is unclear; additional monitoring during project implementation could help to better distinguish restoration from fuel reduction outcomes.

The conceptual underpinning behind forest restoration in western US dry conifer forests is that the forest structure and composition that developed over many centuries under an active disturbance regime are thought to be the most resilient to a range of stressors, including fire, insects and disease, and drought (Knapp et al. 2017, Hessburg et al. 2019). Therefore, the success of forest restoration treatments at meeting project goals and objectives are generally evaluated by comparing forest structural attributes (e.g., tree size class distributions, tree density, basal area) and species composition metrics (e.g., the ratio of shade-tolerant to shade-intolerant species) with historical forest conditions, as well as potential fire behavior and effects. In some cases, variability in spatial pattern (Lefevre et al. 2020) and potential fire behavior and effects are also assessed to evaluate the influence that fine-scale structural heterogeneity created by forest restoration treatments will have on future fire behavior (Parsons et al. 2017, Ziegler et al. 2017, Ritter et al. 2020). Evaluating success in achieving landscape-level restoration is more difficult because many goals are tied to longer-term responses such as benefiting wildlife populations and resistance to drought, or the ability to adapt to the changing climate, requiring ongoing monitoring (Spies et al. 2017, Liang et al. 2018).

Although historical information can be invaluable for guiding decisions related to forest restoration, it is also limited in availability, scale, and relevance under current and future climatic conditions (Millar et al. 2007, Stephens et al. 2010). Another limitation in historical reconstructions and data sets is that they rarely quantify variation in historical conditions at a landscape scale (but see Hessburg et al. 1999, Collins et al. 2015, Merschel et al. 2018, Stephens et al. 2018b). The use of data from contemporary reference sites with restored fire regimes may be more appropriate for developing restoration goals because these sites have been influenced by the recent climate (Huffman et al. 2020). However, these areas are also limited in geographic extent and may have legacy effects arising from several decades of fire exclusion prior to the reintroduction of fire (Collins and Stephens 2007, Lydersen and North 2012, Larson et al. 2013, Jeronimo et al. 2019). More challenging than restoring historical structure and composition is to restore the suite of ecological processes needed for ecosystems to sustain

Box 1. The Hartless Ridge project.

The Hartless Ridge project, on the Eldorado National Forest in the central Sierra Nevada of California, provides one example of a forest restoration project that has exhibited enhanced resilience in the face of multiple disturbance events. This project was designed to reduce the intensity and behavior of future wildfires, while also creating forest structure and species composition patterns that generally aligned with pre-Euro-American colonization conditions by reducing tree density and shifting the composition to favor pines and oaks. A requirement to retain 50% canopy cover hindered the ability of the treatments to closely mimic estimates of variable historical forest structure, resulting in relatively similar posttreatment conditions across units (Dana Walsh, US Forest Service, Placerville, California, personal communication, 17 January 2020). Although a range of target basal areas and stem densities were desired, this project was designed in 2005 before local quantitative information on historical range of variability (HRV) was available. Over 5 years (2009–2013), 375 ha of dry mixed-conifer forest was mechanically thinned and then followed with a combination of piling and burning of surface fuels, mastication of live fuels, and broadcast burning (example 11.4 ha unit shown in figure 3). Less than 5 years after treatment completion, the project area was affected by both the 2014 King Fire and the intense multiyear drought conditions that occurred from 2012–2016.

Despite the restrictions on marking guidelines, this treatment did result in a more resilient stand structure that withstood both stressors, as is evident by the remaining mature trees in the treated area. The heterogeneity introduced by the initial treatment and subsequent disturbance-related mortality resulted in a forest structure that more closely resembles the open, heterogeneous stand conditions found in pre-Euro-American forests (Dana Walsh, US Forest Service, Placerville, California, personal communication, 13 January 2020). The addition of fire was therefore complementary and additive to the initial restoration efforts. However, the 11.4 ha treated unit is also embedded within an untreated forest that burned at high severity (figure 3b; additional units of the Hartless project, not shown, were disjunct from this one but were similarly dispersed across the landscape). Although this unit now constitutes a refugium for live trees and seed for forest regeneration, and the stand-scale restoration work made it more resilient to the wildfire and drought, this example also highlights the need for contiguous restoration projects at much larger scales to promote resilience to increasingly common landscape-scale disturbances occurring across the western United States (North et al. 2015b).

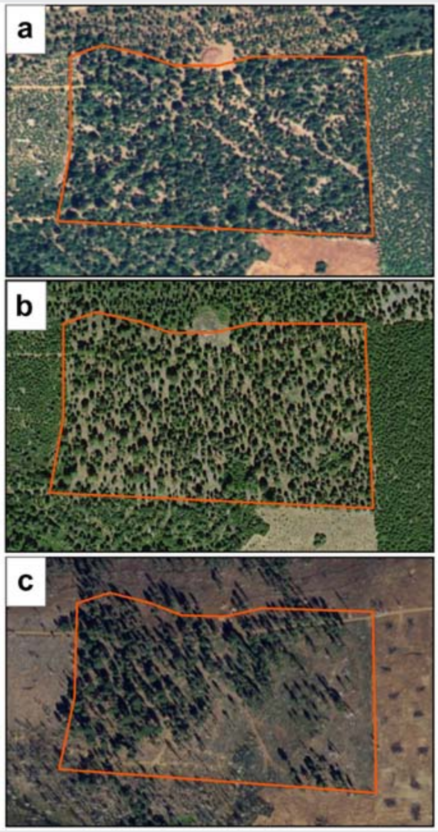

Figure 3. Example treatment unit (11.4 ha, orange outline) from the Hartless Ridge project, Eldorado National Forest, California (National Agriculture Imagery Program imagery). Pretreatment conditions (a) were characterized by dense, homogeneous forests that were determined to be at a high risk of loss from high-intensity wildfire and competition induced tree mortality. The restoration treatments implemented for this unit between 2010 and 2011, reduced surface and ladder fuels, lowered tree density, and increased the relative proportion of shade-intolerant species (b). Restoration treatments decreased fire severity during the 2014 King Fire (c), allowing for the maintenance of forest cover within portions of the landscape that experienced otherwise severe fire effects.

themselves over time (Seidl et al. 2016). For coniferous forests that have been affected by fire exclusion, restoring fire as a process is a key component of forest restoration (Hessburg et al. 2015).

One of the primary goals of forest restoration is to restore ecosystem resilience (USDA Forest Service 2012), typically defined as a system's ability to absorb disturbance and maintain the same basic ecosystem identity and function (Holling 1973). Treatments that manipulate forest structure and composition, and incorporate natural disturbance processes such as fire, may move the system closer to the desired restoration endpoint (box 1). Managing for resilience often uses the concept of the historical range of variation (HRV), recognizing that ecosystems are not static over time or space but vary in response to disturbance processes and microsite conditions at different scales (Walker et al. 2004, Keane et al. 2009, Safford and Stevens 2017). Amid concerns that forests will be unable to maintain ecosystem function under projected future climate conditions, there is growing interest in exploring the R in HRV. In other words, using our understanding of the range of historical conditions to develop targets that will help forests persist or transition into a state in which forest structure and composition align with future climate and disturbance regimes, thereby avoiding undesired states (Rissman et al. 2018).

Targeting a range of conditions allows forest restoration prescriptions to vary at both the stand and landscape scale. At the stand scale, variation can be linked to fine-scale site conditions such as topographic setting and soils (North et al. 2009, Hessburg et al. 2015, Addington et al. 2018). In addition, restoration plans can introduce variability at the tree-neighborhood scale by producing a structure that contains individual trees, varying sizes of tree clumps, and interspersed forest openings (ICO for *individual, clumps, and openings*; figure 4; Larson and Churchill 2012, Churchill et al. 2013). This approach can be used to increase both vertical and horizontal complexity within a stand. Greater within-stand variability has been demonstrated to promote tree survival and increase forest resilience to wildfire (Koontz et al. 2020).

Although most forest restoration projects have been designed and implemented at the stand scale, there is growing interest in conducting restoration planning at the landscape scale (Hessburg et al. 2015, Schultz et al. 2012). This has spurred development of tools that can evaluate tradeoffs of different management scenarios and optimize landscape restoration strategies to meet different objectives (e.g., Vogler et al. 2015, Spies et al. 2017). How to plan treatments that promote resilience outside the footprint of the treated area remains a topic in need of research (Lydersen et al. 2017). The concept of HRV can also be applied to treatments at this scale. At the landscape scale, variation in restoration targets between sites (among stands) can allow for broad differences in productivity and forest type (Stephens et al. 2018b) and account for societal needs and values (Duncan et al. 2010, Seidl et al. 2016). For example, managing for variability at the landscape scale can allow for a different forest structure in climate refugia such as cold air drainages that historically had less frequent, lower-severity fire that resulted in unique forest structure and composition (Wilkin et al. 2016).

Restoration and fuels reduction divergent

A common goal of forest restoration is to reintroduce spatial variability into both stand structure and fuels (North 2012, Franklin et al. 2013, Reynolds et al. 2013, Collins and Skinner 2014, Addington et al. 2018). Restoration treatments in frequent-fire forests commonly result in a range of tree group sizes, with variable proportions of large tree groups (more than 10 trees), moderate tree groups (5–9 trees), small tree groups (2–4 trees), and individual trees (i.e., ICO; figure 4; Churchill et al. 2013). These groups are interspersed within small (0.1 ha) to several hectares sized treeless areas. In addition, restoration areas may also maintain a component of shade-tolerant species, such as Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and grand fir (*Abies grandis)*, across a range of size classes. In contrast, fuel treatments commonly focus on the reduction of potential fire behavior by manipulating a few key elements: fuel amount, arrangement, and continuity, as well as retaining large fire-resistant trees (table 2; Agee and Skinner 2005).

Although both restoration and fuel treatment activities often have overlapping objectives (table 1), restoration projects commonly define desired outcomes using concepts of resilience as well as resistance (North 2012, Reynolds et al. 2013, Addington et al. 2018, Hessburg et al. 2019). Restoration projects often consider a wider range of disturbance processes and stressors (e.g., insects, disease, invasive species, drought, windthrow) that may affect forest structural and fuel conditions (table 2). Restoration projects often target the removal of larger diameter shade-tolerant species (*Abies* spp.) to free up space for shade-intolerant species such as pines and oaks. In addition, trees across all diameter size classes are removed to promote an uneven-age forest structure, which was common in historical frequent-fire forests (Allen et al. 2002, Reynolds et al. 2013, Churchill et al. 2017, Hagmann et al. 2017, Battaglia et al. 2018, Jeronimo et al. 2019) and is thought to increase resilience (figure 3). In contrast, fuel reduction activities typically focus tree removal on smaller diameter ladder fuels to increase stand resistance to fire, but this homogenization of forest structure may increase susceptibility to other disturbances, such as insect outbreaks that target a narrow range of tree sizes or species (Fettig et al. 2007, DeRose and Long 2014).

Because fires were an important ecological process that shaped western United States dry forests, reintroduction of fire, either through natural ignition or prescribed fire, is paramount to restoration treatments. Restoration treatments seek to restore structural and fuel conditions in which fires can burn at a range of severities allowing this process to continue to maintain and create spatial heterogeneity. Variability in stand structure and fuels can result in fine-scale variation

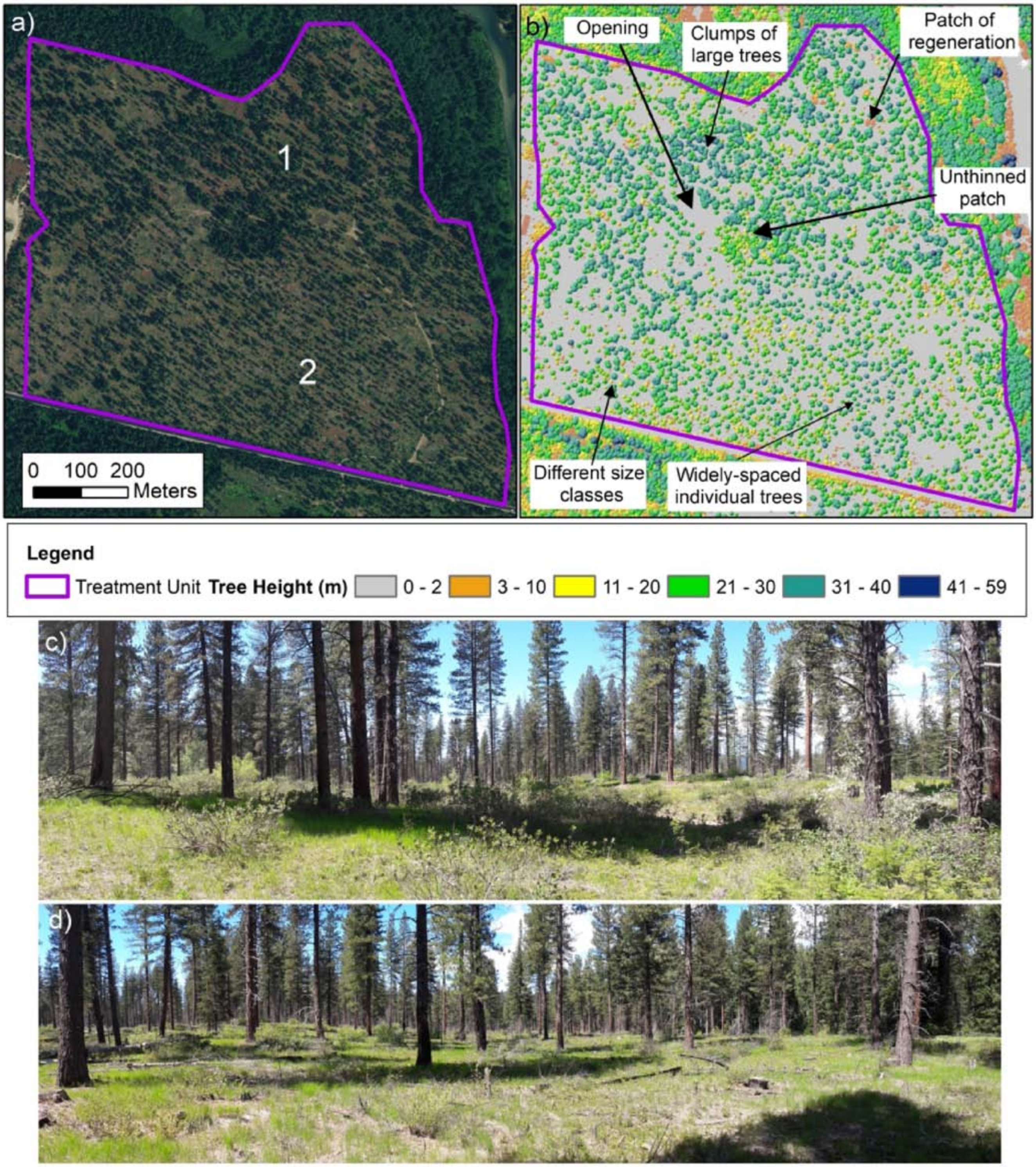

Figure 4. Aerial photograph (a), LiDAR canopy surface image (b), and panoramic photos (c, d) of a treated unit in the Okanogan-Wenatchee National Forest in central Washington, showing design elements of a restoration and fuels reduction prescription. The unit was treated with commercial thinning and prescribed fire. A more spatially variable restoration approach was used in the north half of the unit (no.1 in panel a, photo c), whereas a less variable prescription with a fuels reduction focus was used in the southern half (no.2 in panel a, photo d), which is adjacent to a highway. In photos c and d, note the separation between tree crowns and the base of the crown and the ground, as well as the recovery of understory plant communities. Photographs: Derek Churchill.

Table 2. Characteristics of fuel reduction and forest restoration treatments.

		Contextual considerations		
	Intention	Temporal	Spatial	Heterogeneity
Fuel reduction	Reduce risk of large stand-replacing fire	Shorter term: the next fire is the focus	Focus on stand, location of treatments typically driven by operational or anthropogenic concerns	Not a priority, possibly considered a liability
Forest restoration	Restore stand structure and composition to more closely resemble historical range of variation and facilitate reintroduction of fire	Longer term: next fire is one of many that together represent a regime	View of stands within a landscape context. Concern for landscape composition and variability, location of treatments more driven by past disturbance regimes, topography, or ecological considerations	Often explicit goal is to increase or restore heterogeneity in structure and composition, with understanding that this leads to variability in fire behavior and associated effects

in fire effects (box 2; Ritter et al. 2020), with small areas of torching created by moderate or high-intensity fire, as well as unburned or lightly burned areas that still maintain pre-fire seed producing mature trees, tree saplings, understory plants, and denser cover for wildlife habitat (Larson and Churchill 2012, North 2014). Furthermore, restoration in forests that historically experienced mixed-severity fires with stand-replacing fire at a range of patch sizes (up to 100 ha) requires a mixture of species and forest stand structural stages, including dense stands with multiple canopy strata, early seral stands, and low density stands with a single canopy strata (Brown et al. 1999, Hessburg et al. 2016). This range of structural conditions would not fully meet a strict interpretation of fuel treatment objectives.

Contrary to basic fuel reduction treatments, restoration treatments also seek to enhance elements that are currently missing on the landscape to help maintain ecological processes and functions. For instance, maintaining some patches of shrubby Gambel oak (*Quercus gambelii*) in the understory of ponderosa pine (*Pinus ponderosa*) forests is a common objective of restoration treatments in Colorado. However, in fuels reduction treatments, especially around the WUI, Gambel oak is generally undesirable because of its potential to vector fire vertically into adjacent tree crowns (box 3; USDA Forest Service 2017). Restoration treatments often seek to maintain moderate levels of downed coarse wood and snags to maintain site productivity and wildlife habitat (Graham et al. 1994, Brown et al. 2003), which in some cases, could be reduced to lower levels by the reintroduction of fire. In contrast, fuel treatments often focus on limiting the quantity of coarse woody fuels to reduce potential fire intensity and increase firefighter effectiveness and safety. Another common goal of forest restoration is to create various sized openings that enhance understory plant diversity and allow for regeneration of shade-intolerant tree species (York et al. 2012, Underhill et al. 2014, Addington et al. 2018). In contrast, fuel treatments often only create small openings that stimulate some understory development (Stevens et al. 2014) but generally only result in shade-tolerant tree regeneration (Bigelow et al. 2011), which may be less desirable for restoration objectives.

Finally, assessing the need for fuel treatments across a landscape may be fundamentally different than that for forest restoration (Stevens et al. 2016, Barros et al. 2019). One reason for this is that there is generally greater familiarity with the models used to assess landscape level wildfire hazard (e.g., FARSITE, Finney 1998; Flammap, Finney 2006) than there is for models of landscape restoration (e.g., Ecosystem Management Decision Support System, Reynolds et al. 2014; Envision, Spies et al. 2017). As a result, there is more confidence in recommendations for the specific fuel treatment locations and landscape treatment proportions based on the output from the more familiar fire spread and behavior models; however, Envision includes a fire model but the simulations require significant effort to parameterize and apply for a particular landscape (Ager et al. 2018).

Another reason for the differential assessment of need is that there is widespread agreement on protecting life and property from wildfire (Toman et al. 2014, Roberts et al. 2019). This means that treatments that protect the WUI and facilitate fire suppression are less likely to be challenged by the interested public and more likely to be funded by land management agencies. In contrast, the justification and objectives for restoration treatments are often more broadly defined (e.g., wildlife habitat, historical forest structure, reintroduction of fire), making it difficult to attain broad public understanding and acceptance (Stephens et al. 2016). There is no doctrine such as "life and property" that guides forest restoration.

Restoration and fuels reduction convergent

Both fuel and restoration treatments have a role in contemporary forest management and can be considered endpoints in a spectrum of possible treatments that vary across a landscape. Strict fuels reduction (i.e., decreasing surface fuels and crown density, increasing height to the live crown, and retaining large, fire-resistant species; Agee and Skinner 2005) will often need to be the priority within or adjacent to the WUI and in key strategic locations needed for fire containment. Some restoration objectives can be met within these areas with density reduction, compositional shifts in the remaining trees, and reduction in fuel loads, but reductions

Box 2. Fire simulations.

Fire simulations demonstrate an increase in the mid-flame wind speed associated with treatments, with the restoration treatment producing more variability in wind speed compared to fuel treatments (figure 5). Interestingly, surface fire rate of spread increased after restoration and fuel treatments relative to the untreated stand. This increased fire rate of spread following both treatment types is due to a combination of higher mid-flame wind speeds and a greater proportion of grass fuels, which result from reductions to canopy cover. The restoration treatment resulted in the highest overall rate of spread because of large, grass filled openings and had greater variability in fire-line intensity and increased sinuosity of the fire line relative to the fuel treatment and untreated stands (figure 5). Differences in sinuosity in the simulation are a reflection of heterogeneous surface fuel and mid-flame wind speeds (as well as more complex fire–atmosphere interactions because of small groups of trees torching that create updrafts which influence local wind velocities driving fire spread). Importantly, crown consumption, a proxy for crown fire activity, was far lower for both the fuel (10%) and restoration (13%) treatments relative to the pretreatment conditions (85%). Overall, these simulations suggest that both treatment types can be effective in reducing potential crown fire behavior. However, the retention of small trees in a restoration treatment may increase localized tree torching and mortality.

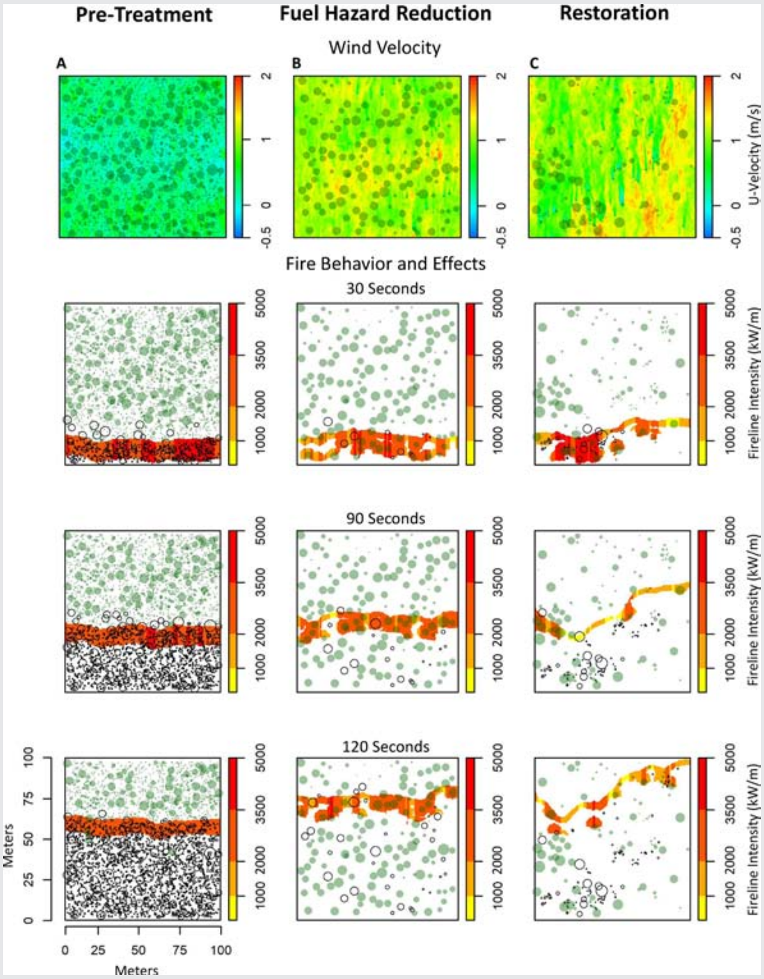

Figure 5. Simulated mid-flame windspeed, fire behavior, and effects in (a) an untreated stand, (b) a stand that received a fuel reduction treatment, and (c) a stand that received a restoration treatment on the Black Hills National Forest, South Dakota. Spatially explicit simulations were conducted using the Wildland Urban Interface Fire Dynamics Simulator (Mell et al. 2007, 2009). The instantaneous mid-flame (2-meter) wind velocity just prior to ignition is shown in the top row. Rows 2–4 show fire location and fire-line intensity (in kilowatts [kW] per meter [m]) of the surface fire after 30 seconds, 90 seconds, and 120 seconds of spread into the stands. Filled green circles represent the locations and crown widths for all live trees greater than 2.5 centimeters in diameter at breast height, and the hollow black circles represent tree crowns predicted to have sustained more than 10% crown consumption prior to the specified time step. Tree locations, height, diameter, crown width, and crown base height were based on stem-mapped data. All simulations were conducted with a 2.5 meters per second open wind speed, dead surface fuel moisture content of 6%, and a foliar moisture content of 100%.

Box 3. The Upper Monument Creek landscape restoration initiative.

The Upper Monument Creek (UMC) landscape restoration initiative, on the Pike and San Isabel National Forest in the southern Colorado Front Range, is an example of the strategic use of fuel hazard reduction and restoration treatments conducted in a compatible manner to simultaneously protect the community, and allow for the reintroduction of fire, either through natural ignition or prescribed fire (Upper Monument Creek Collaborative 2014). The UMC landscape is approximately 27,000 ha and includes several urban and smaller communities and supports a diversity of vegetation types that vary along an elevational gradient that generally increases as you move to the west and north (figure 6). About 90% of the UMC landscape consists of intermixed stands of ponderosa pine, dry mixed conifer, and mesic mixed conifer that occur throughout the middle of the elevational gradient. The rest of the UMC landscape consists of equal areas of Gambel oak shrublands at low elevation, and lodgepole pine (*Pinus contorta*) forests and subalpine grasslands at the highest elevations. Land managers used the results of landscape-scale analyses based on Low and colleagues (2010) and Calkin and colleagues (2010) to identify where fuel and restoration treatments are ecologically and socially beneficial and cost effective. Although restoration was the primary objective within the UMC landscape, fuel reduction treatments were prioritized within the WUI along the eastern boundary as well as in both the high-elevation lodgepole pine forests and low elevation Gambel oak shrublands. Although the primary goal of fuel reduction treatments within the WUI was to enhance community safety, fuel reduction treatments in lodgepole pine forests and Gambel oak shrublands were designed to reduce the risks associated with the use of prescribed and managed wildfire in ponderosa pine and mixed-conifer forests. Ultimately the integrated collaborative planning used to develop treatments within the UMC landscape used both fuel hazard and restoration treatments to create forest and shrubland structures that protect the community and watershed while fostering the reintroduction of fire within the landscape.

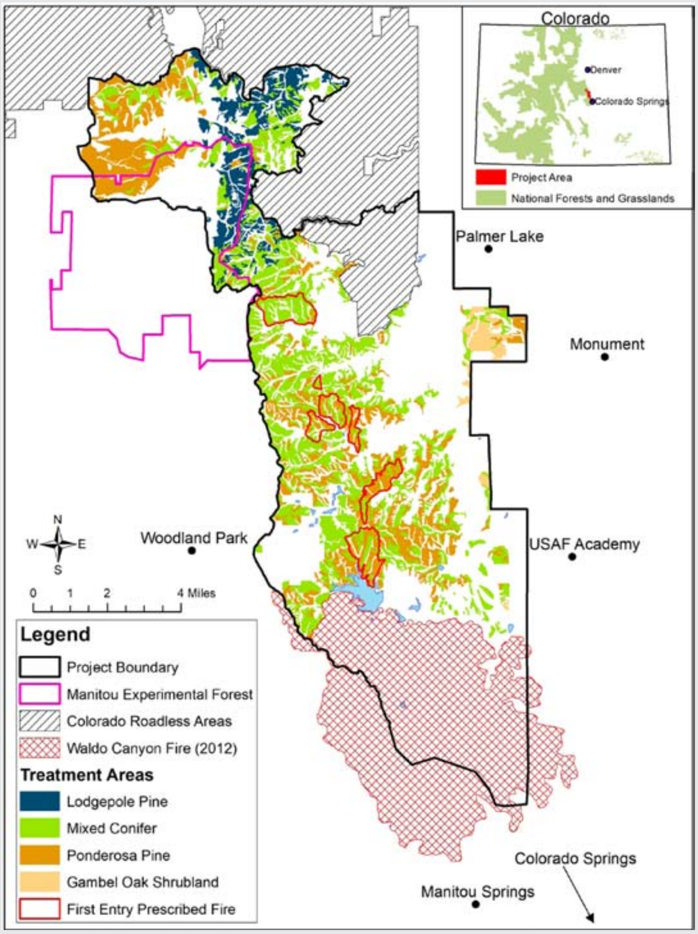

Figure 6. Proposed areas for mechanical treatments and prescribed fire for the Upper Monument Creek Landscape Restoration Initiative located on the Pike and San Isabel National Forest in Colorado. Treatment areas have been color-coded on the basis of vegetation cover type to highlight the spatial context in which fuel hazard reduction and restoration treatments are occurring. In this project area, restoration treatments are being implemented in the mixed conifer and ponderosa pine forest types with the explicit goal of reducing tree densities, increasing stand-scale spatial heterogeneity, and moving the landscape distribution of forest structures toward historical conditions. In contrast, the higher-elevation lodgepole pine forests and lower elevation Gambel oak shrublands are being treated following fuel hazard reduction principles to protect human infrastructure and to support increased use of prescribed fire and managed wildfire throughout the landscape.

in canopy density often result in regularly spaced, separated crowns (figure 1) eliminating most heterogeneity and associated ecological functions. Forest managers understandably often treat the WUI for every possible gain in reducing wildfire severity, especially in fuel breaks or areas adjacent to structures. In areas outside of the WUI, as well as portions of the WUI that are farther away from structures, fuels reduction can include a broader set of objectives, including a focus on spatial patterns such as ICO that produce greater habitat heterogeneity (figure 4). With gap creation in these areas, treatments will still reduce fire intensity under most weather conditions relative to an untreated forest (Ziegler et al. 2017).

Between these endpoints, land managers can vary treatments depending on landscape context and local knowledge. Although the need for large-scale coordinated treatments is widely accepted, it is often difficult because of concerns over smoke impacts on human communities, individual sensitive species, and agency cost and capacity limitations. If treated areas continue to be small and dispersed across a large landscape, they are prone to being overwhelmed by wildfire, drought, or other stressors (box 1; Stevens et al. 2016, Stephens et al. 2018a). With practical and cost limitations on the use of fire (i.e., prescribed and managed wildfire), consideration of an explicit design that couples silvicultural treatments and their revenue streams with whole watershed scale treatment could inform significant change in the pace and scale of treatments (box 3).

Perhaps the key element in the convergence of fuel reduction and restoration treatments is that both types promote the salient characteristics that frequent fire produced; variability in vegetation structure and composition across a given landscape and inability to support large patches of high-severity fire. These can be achieved with both fire and mechanical treatments. Decades of fire exclusion and suppression have homogenized many western US forests, making them prone to high-severity wildfire and susceptible to drought and bark beetle mortality (Stephens et al. 2018a, Voelker et al. 2019). Ideally, both types of treatments would be designed to facilitate the use of prescribed fire and managed wildfire to restore and maintain ecological objectives (Reinhardt et al. 2008, Stevens et al. 2014, Barros et al. 2018) with mechanical fuel hazard reduction treatments providing anchor points for larger fire units and increased safety around human infrastructure (box 3).

A focus on returning fire to the landscape also addresses an often overlooked need in forest treatments: future maintenance. Because regrowth in productive forests quickly reduces both fuel reduction and restoration treatment effectiveness, maintenance can rapidly subsume all management efforts and limited budgets. To leave resources available for treating additional areas, large-scale, low-cost repeat treatments could be considered once fuels become hazardous again, which can occur within one to three decades. This can be challenging for silvicultural treatments focused on fuels reduction because ingrowth of ladder and surface fuels generally are expensive to treat unless there are nearby biomass facilities that make this economically viable. Where they are practicable, restoration treatments may be less expensive to maintain using prescribed or managed wildfire (North et al. 2012, Tinkham et al. 2016, Valliant and Reinhardt 2017), although these treatments still have costs and do not provide any revenue from timber or biomass removal. With less focus on maintenance, mechanical treatment might concentrate on initial entry, where greater precision in manipulating specific structure and fuel conditions is often desired before fire is reintroduced. Mechanical treatment could also be shortly followed by fire reintroduction. Following fire's reduction in surface and ladder fuels, forest structure can have a greater range of conditions that will still favor low- to moderate-intensity surface fire, including stand structures that support restoration targets (i.e., an ICO pattern and diverse age classes of trees).

Fuel reduction and restoration treatments can be compatible at landscape levels (box 3), but research to date has been limited and practical applications rare. Certainly, part of the problem is that there are very few landscapes that have been extensively treated where both fuel reduction and ecological restoration have been achieved, let alone maintained to provide long-term effectiveness (however some areas of large wildfires can provide fuels and restoration benefits). At this scale, successful treatment includes not only fire hazard reduction and ecological restoration but also maintenance or enhancement of other ecosystem services such as provision of wildlife habitat, aquatic integrity, traditional tribal uses, recreation, stable carbon storage, water production, and long-term economic viability (Stephens et al. 2020b). Landscape planning methods, data sources, metrics, and tools that can help managers integrate these objectives, evaluate tradeoffs, and design landscape level prescriptions are being developed, but are generally still in the early stages of development. There are some notable modeling (McGarigal and Cushman 2002, Mladenoff 2004, Reynolds et al. 2008, Ager et al. 2013, Hessburg et al. 2013, Barros et al. 2019) and planning (Thompson et al. 2016, WADNR 2017, Addington et al. 2018, Leavell et al. 2018, Dunn et al. 2020) efforts that are focused on meeting this goal. However, few, if any, large-scale applications are far enough along in implementation to be evaluated. More research is needed that directly collaborates with forest managers and the interested public to facilitate large-scale treatments that meet fire risk reduction, ecological restoration, and ecosystem service objectives.

Conclusions

Despite the recognition of the importance of heterogeneity and ecological process in restoration prescriptions, encompassing natural variability into restoration planning is a challenge given the current planning process on US public land (Stephens et al. 2016). This process often involves comparing alternative strategies with explicit spatial and temporal management actions. Whether driven by the process itself or by the modeling tools used, this approach almost necessarily forces stasis in managing forests. This stasis is reinforced by real and perceived barriers to treatment, including resource protection measures (e.g., wildlife protected activity centers, wilderness, stream buffers, WUI, diverse land ownership), operability (e.g., slopes, roads), and economic considerations (Hartsough et al. 2008, Collins et al. 2010, North et al. 2015a). Although there will continue to be challenges in producing effective landscape strategies, there is strong public and management support for these actions (McCaffrey and Olsen 2012).

The good news is that fuels and restoration treatments can be designed to converge in many forests. If both fuels reduction and restoration treatments focus on leaving structures and fuels in a condition that when burned, will produce low- to moderate-severity fire effects with some small patches of high-severity fire, desired forest and fire conditions will become self-reinforcing (Koontz et al. 2020). At that point, fuels reduction and restoration treatments become convergent in creating and maintaining a resilient landscape. The possible key to aligning forest fuels and restoration objectives is integrated planning that permits treatment design flexibility in different locations and a longer-term focus on fire reintroduction for maintenance of treatments. With changing climate conditions, long-term maintenance will probably need to be focused less on static structural targets and more on keeping tree density low enough (i.e., the lower range of HRV) for forest conditions to adapt to emerging disturbance patterns and novel ecological processes.

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