Hood et al. Fire Ecology (2022) 18:33
https://doi.org/10.1186/s42408-022-00157-0

Fire Ecology

Association for Fire Ecology

TECHNICAL NOTE

Open Access

A framework for quantifying forest wildfire hazard and fuel treatment effectiveness from stands to landscapes

Sharon M. Hood[1*], J. Morgan Varner[2], Theresa B. Jain[3] and Jeffrey M. Kane[4]

Abstract

Background: Wildland fires are fundamentally landscape phenomena, making it imperative to evaluate wildland fire strategic goals and fuel treatment effectiveness at large spatial and temporal scales. Outside of simulation models, there is limited information on how stand-level fuel treatments collectively contribute to broader landscape-level fuel management goals. Our objective here is to present a framework designed to measure fuel treatment effectiveness from stands to landscapes to inform fuel treatment planning and improve ecological and social resilience to wildland fire.

Results: Our framework introduces the concept of a fuel management regime, an iterative and cumulative evaluation from the stand to the landscape of fire hazard, fuel treatments, and wildland fire behavior and effects. We argue that the successfulness of fuel treatments within this regime must be evaluated based on pre-treatment fire hazard and post-wildland fire fuel treatment outcomes over large spatial and temporal scales. Importantly, these outcomes can be evaluated from the stand level to across a landscape through time, based on preidentified management objectives that define condition-based criteria that account for social values and environmental and ecological indicators used to determine the effectiveness of fuel treatments within a fuel management regime.

Conclusions: Evaluating the cumulative ability of fuel treatments to change landscape patterns of fire behavior and effects is challenging. By quantifying fire hazard, followed by evaluating outcomes of wildfires on environmental and ecological indicators and social values, it becomes possible to assess how individual fuel treatments placed within the context of a fuel management regime are effective based on desired conditions that address management objectives. This conceptual framework offers a much-needed middle-ground planning, monitoring, and reporting approach between overly simplistic annual reporting summaries of the area treated, number of fires, and burned area and detailed fire simulation modeling outcomes by putting individual treatments and fires in the context of current and desired vegetative conditions and social values. Our fuel treatment effectiveness framework examines the state of fuels through the lens of fire hazard and connects fuels to subsequent fire behavior and effects over time and space. The framework provides a way to focus regional and national fuel management planning efforts toward creating fuel management regimes that increase social and ecological resilience from wildfire.

Keywords: Forest management, Fuel management regimes, Social and ecological resilience, Wildfire resilience

*Correspondence: sharon.hood@usda.gov

[1] USDA Forest Service Rocky Mountain Research Station, Missoula, MT 59808, USA
Full list of author information is available at the end of the article

Resumen

Antecedentes: Los incendios son fundamentalmente fenómenos del paisaje, haciendo imperativo evaluar objetivos estratégicos del fuego a escalas temporales y espaciales amplias. Por fuera de los modelos de simulación, hay una cantidad limitada de información sobre cómo los tratamientos de combustible a nivel de rodal contribuyen en forma colectiva a objetivos de manejo más amplios a nivel de paisaje. Nuestro objetivo aquí es presentar un marco de trabajo diseñado para medir la efectividad de los tratamientos del combustible desde rodales a paisajes para informar sobre la planificación de estos tratamientos y mejorar la resiliencia ecológica y social de los incendios naturales.

Resultados: Nuestro marco de trabajo introduce el concepto de régimen de tratamiento de combustibles, una evaluación iterativa y acumulativa del peligro del fuego desde el rodal hasta el paisaje, tratamientos de combustible, y comportamiento de fuegos naturales y sus efectos. Argumentamos que el éxito de los tratamientos del combustible dentro de este régimen debe ser evaluado basándose en el peligro del fuego previo al tratamiento, y en los resultados posteriores de esos tratamientos después de incendios naturales en escalas temporales y espaciales grandes. Es de destacar, que estos resultados pueden ser evaluados desde el nivel de rodal hasta de paisaje a través del tiempo, basados en objetivos de manejo pre-identificados que definen criterios basados en condiciones que tienen en cuenta los valores sociales e indicadores ambientales y ecológicos, utilizados para determinar la efectividad del tratamiento de los combustibles dentro de un régimen de manejo de los mismos.

Conclusiones: Evaluar la habilidad de acumulación de los tratamientos de combustible para cambiar el comportamiento del fuego y sus efectos en los patrones del paisaje es desafiante. Cuantificando el peligro del fuego, seguido por la evaluación de los resultados de incendios sobre indicadores ambientales y ecológicos y valores sociales, es posible determinar cómo los tratamientos individuales de los combustibles ubicados dentro del contexto de un régimen de manejo de los mismos, son efectivos basados en condiciones deseadas que cumplan con los objetivos de manejo. Este marco conceptual ofrece un abordaje de planificación intermedia muy necesaria, de monitoreo y de información, por sobre resúmenes anuales simples del área tratada, número de fuegos, y áreas quemadas y resultados de detallados modelos de simulación de fuego, colocando tratamientos individuales y fuegos naturales en el contexto de condiciones deseadas de la vegetación y de valores sociales. La efectividad del tratamiento de combustible de nuestro marco de trabajo examina el estado de los combustibles a través de la lente del peligro del fuego y conecta los combustibles con el subsecuente comportamiento del fuego y sus efectos a través del tiempo y del espacio. Este marco de trabajo provee una forma de enfocar los esfuerzos hacia la creación de regímenes de manejo de combustible que incrementen la resiliencia social y ecológica del fuego.

Introduction

Wildland fires burn millions of hectares annually, with both beneficial and detrimental ecological, economic, and societal effects (Bowman et al. 2009). Although many ecosystems in the United States (US) are ecologically dependent on fire (Collins and Greenberg 2021), severe and uncharacteristic wildfire seasons are lengthening and increasing across much of the west (Jolly et al. 2015; Stephens et al. 2014). The annual average area burned by wildfire in the US in the past 10 years (2011–2020) was over three million hectares, with annual suppression costs of $2.45 billion US (https://www.nifc.gov/fire-information/statistics). While staggering, these direct suppression costs account for a small fraction of total short- and long-term wildfire costs (Barrett 2018). In the last 15 years, over 89,000 structures in the US have been lost in wildfires, with 62% of these losses occurring from the recent large wildfire events in 2017, 2018, and 2020 (https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire). These effects do not include the additional impacts of evacuations, smoke exposure, and loss of human life, which are also increasing (Burke et al. 2021), or post-wildfire mitigation and restoration actions (Robichaud et al. 2009). Given climate change forecasts, wildfire costs and detrimental effects are likely to continue increasing without proactive fuel mitigation over large spatial extents.

National and state agencies recognize the important role of wildland fire in fire-adapted ecosystems and the need for landscape-scale management, balanced with the need to effectively manage wildland fires to ensure public safety and to reduce unsustainable costs associated with wildfire suppression (State of California 2021; Stephens et al. 2016; USDOI and USDA 2014; USFS 2012). To meet these goals, treating hazardous fuels is a primary strategy used to modify fire behavior by changing wildland fuel conditions through mechanical treatments and prescribed fire (Agee et al. 2000; Agee and Skinner 2005). These treatments ultimately seek to create forest and rangeland conditions that mitigate potential negative impacts from wildfire in support of land management goals. Fuel treatments are implemented widely across the

US on millions of hectares annually both directly through mechanical treatment or prescribed fire or wildfires that meet resource objectives (https://www.doi.gov/wildlandfire/fuels; https://www.forestsandrangelands.gov/). In 2022, the USDA Forest Service, which stewards approximately 78,104,000 hectares of forests and rangelands, has a targeted goal of treating hazardous fuels on 1.295 million hectares, not including areas burned by wildfires managed for resource benefit (https://tinyurl.com/yxp7vw5f). Yet there is still a fire deficit, especially in forests, with only about half the area of USDA Forest Service administered land treated annually with either fuel treatments or resource objective wildfires than is needed to control fuel accumulations (Vaillant and Reinhardt 2017). In contrast, many rangelands and grasslands have increased fire frequency and severity due to invasive grass species, where fuel treatments are used to reduce the area burned through decreasing fire spread and allowing more effective fire suppression tactics (Shinneman et al. 2019).

Wildland fires are a landscape phenomenon, and this is also the scale at which national strategic goals are evaluated, making it imperative to better understand how stand-level fuel treatments function within landscapes to determine if fuel management programs are achieving broad goals, such as increased ecological and social resilience to wildfire and reduced suppression costs. While numerous studies have shown fuel treatments are effective at the stand level in reducing fire intensity and severity (Fulé et al. 2012; Hunter and Robles 2020; Martinson and Omi 2013), ecological and societal losses (Kalies and Yocom Kent 2016), and suppression costs (Sánchez et al. 2019), few focus at a landscape scale except for model simulation studies. In a report of landscape fuel treatment effectiveness, Jain et al. (2021) compiled results from empirical, modeling, and case studies. Of the approximately 2100 papers evaluated, McKinney et al. (2022) found only 26 studies that used empirical data to examine fuel treatment effectiveness at the landscape scale, Urza et al. (in press) found 15 case study papers, and (Ott JE, Kilkenny FF, Jain TB: Fuel treatment effectiveness at the landscape scale: A systematic review of simulation studies comparing treatment scenarios in North America, in review) found 85 simulation model studies. An example of a national effort to evaluate fuel treatment effectiveness is the Fuel Treatment Effectiveness Monitoring application (FTEM, https://tinyurl.com/3z6n4msv), which is a multi-agency collaboration to spatially document wildfire intersections with fuel treatments. FTEM allows users to input additional information, such as if the treatment contributed to suppression efforts or changed fire behavior. While FTEM is a useful step towards understanding fuel treatment effectiveness, the detailed monitoring information is optional, and a large percentage of the listed wildfire-treatment intersections have little-to-no information associated with them. Results are often impossible to summarize over large areas beyond simple metrics such as "yes" or "no" the fire behavior changed because of the treatment. These shortcomings highlight the need for more research and dialog about how to best manage wildlands over large scales to mitigate against detrimental effects of uncharacteristic wildland fire and to determine appropriate evaluation measures of landscape-level treatment effectiveness.

Our goal here is to present a framework that provides meaningful measures to evaluate fuel treatment effectiveness from stands to landscapes to improve ecological and social resilience to wildland fire. We use a coarse definition of landscape, thinking of it not as a fixed extent, but as a large spatial mosaic of ecosystems and landforms irrespective of ownership or other artificial boundaries to reflect the behavior and effects of large fires that often have human communities embedded in the matrix (Ager et al. 2016; Hagmann et al. 2021). The appropriate area of a landscape analysis is also dependent on the prevalent fire size. For example, the scale of landscape-level evaluation will likely be smaller in regions where most fires are <15,000 hectares compared to areas where individual fires routinely burn >40,000 hectares. Our framework provides a more informative approach for determining multiple fuel treatment outcomes over larger spatial and longer temporal scales compared to current simple reporting statistics (e.g., https://www.nifc.gov/fire-information/statistics), but is less complex and time intensive than fire simulation modeling (Scott et al. 2013). Importantly, the framework puts stand-level projects in a landscape context of current and desired ecological conditions and social values.

Fuel treatments: a primer

Fuel treatments are designed to alter live and dead fuels to moderate potential fire behavior and effects. Successful fuel treatments are integrated with land management objectives to increase ecological (e.g., wildlife habitat, carbon storage, biodiversity) and social (e.g., providing forest products and recreation opportunities) resilience to wildland fire. Fuel treatment designs incorporate the following tenets (Agee and Skinner 2005; North et al. 2012; Prichard et al. 2020; Stevens et al. 2016): (1) fire behavior is dictated by an interaction of fuels, weather, and topography, with fuels being the only manageable component; (2) since wildfire is a landscape disturbance, a multi-scale, all-jurisdictional approach is needed to inform strategic placement of fuel treatments; (3) the particular ecosystem, climate, ownership, and topographic diversity will dictate how much of a landscape can be treated, but in general, the greater percentage of a landscape that is treated, the more pronounced the effectiveness on fire behavior and related outcomes (Ager et al. 2020; Ager et al. 2010).

Fuel treatment designs typically focus on two general fire management objectives that relate to reducing hazardous fuels—creating conditions that reduce resource damage from wildfire (proactive) and that aid fire suppression efforts such that the fire is easier to control (reactive) (Deal 2018; NWCG 2014) (Fig. 1). Fuel treatment prescriptions are highly variable and dictated by the context of vegetation (e.g., composition and structure), topography, soils, and spatial locations (e.g., land designation, proximity to urban areas and infrastructure). In addition, knowledge of historical fire regimes (i.e., the cumulative effects of multiple disturbances over space and time, described by distributions of fire frequency, patch size, and fire severity; Turner 2010), fire ecology, and contemporary fire behavior provide essential context to guide fuel treatment prescriptions and other management objectives, including restoration (Blankenship et al. 2021; Greenberg and Collins 2021). However, contemporary climate, biological invasions, and social constraints often drive decisions and fuel treatment alternatives. In these situations, fuel treatments may or may not overlap with ecological restoration goals that focus on the recovery of degraded systems (Palmer et al. 2016; Stephens et al. 2020) (Fig. 1). For example, intensive treatments designed to reduce ignition potential and fire spread and to create favorable conditions for direct fire suppression tactics may be warranted in the wildland-urban interface (WUI) zone regardless of forest type to reduce risk to homes and make it safer to fight fire near communities. Such treatments often require frequent, routine maintenance of fuels. Outside of the WUI within the larger landscape, fuel treatment planning typically incorporates a broader range of objectives (e.g., ecological restoration, wildlife and plant species diversity, water quality, recreation, forest products) that can constrain treatment options (Ager et al. 2016; North et al. 2015). For example, forests dependent on frequent, low-severity fire may justify treating larger proportions of the landscape and require frequent maintenance of fuels to restore and sustain open forests that foster low-severity wildfire. In contrast, fuel treatments in ecosystems with historical fire regimes of infrequent, high-severity fires (e.g., high-elevation cold forests) and mixed-severity fires (e.g., moist and mesic mixed-conifer forests) may emphasize heterogenous mosaics of species composition and forest structural stages that will vary over time and space and require less frequent treatment maintenance.

When planning fuel treatments, horizontal and vertical fuel arrangement, fuel component, and fuel loads are targeted to meet fuel treatment objectives for an anticipated fire weather condition (Keane 2015). Typically, these treatments are designed to endure if a fire were to occur during extreme fire weather and low fuel

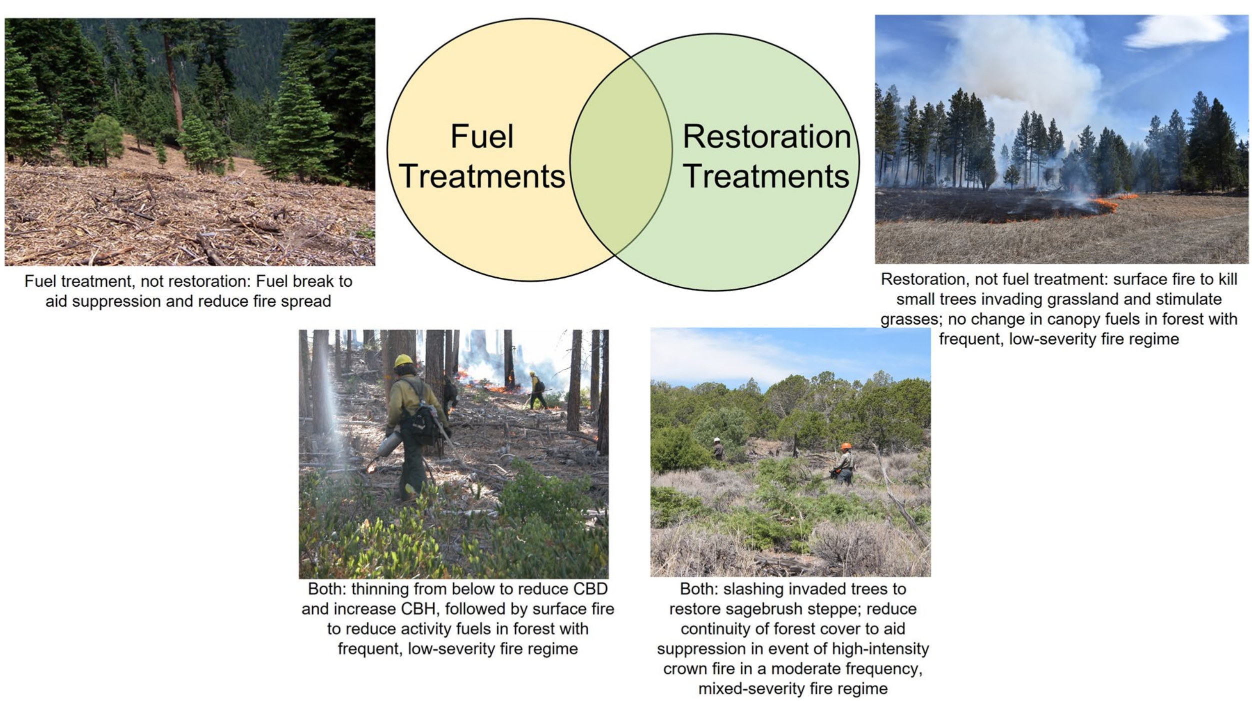

Fig. 1 Fuel treatments and ecosystem restoration treatments can be independent of each other (left and right photo examples) or overlap (center photos) based on management objectives, ecosystem, and fire regime. Fuel treatments primarily aim to reduce hazardous fuels, while the main goal of restoration treatments is promoting the recovery of a degraded ecosystem. CBD–canopy bulk density, CBH–canopy base height

moisture levels based on local climatology (Bradshaw and McCormick 2000; Finney 2005). In dry forests, fuel treatments commonly reduce surface fuels, increase canopy base height, decrease canopy bulk density, and retain/increase growth of large trees of fire-resistant species (Agee and Skinner 2005).

Beyond stand-level attributes, the spatial and temporal configurations of fuel treatments at a landscape level are an essential aspect of meeting fuel management goals (Prichard et al. 2021; Stephens et al. 2010). Specific principles of fuel treatment effectiveness at a landscape level are still developing but considerations will inevitably include concepts from landscape ecology. Primary landscape fuel treatment principles include extent, spatial arrangement, type, intensity, and timing of stand-level fuel treatments (Finney 2005; Hessburg et al. 2005; McKenzie et al. 2011; Ott JE, Kilkenny FF, Jain TB: Fuel treatment effectiveness at the landscape scale: A systematic review of simulation studies comparing treatment scenarios in North America, in review). Extent refers to the proportion of a given landscape that has received fuel treatments. The effectiveness of fuel treatments will also depend on the spatial arrangement and positioning of fuel treatments on a particular landscape (Ager et al. 2010). Additionally, the type (e.g., thinning, broadcast burning) and intensity (i.e., amount of live and dead fuels removed) of fuel treatments, or more importantly, the resultant fuel structures following treatment, will be important landscape parameters that influence effectiveness (Finney 2003; Finney et al. 2005; Prichard et al. 2021). Since fuel treatments vary in their timing of implementation and fuels recover over time, the temporal application of fuel treatments across a landscape also need to be considered (Prichard et al. 2017).

Evaluating fuel treatment effectiveness

Determining fuel treatment effectiveness first requires clearly defined, quantifiable management objectives and associated short- and long-term desired conditions that are applicable across spatial and temporal scales; however, the ambiguity around measuring fuel treatment effectiveness creates confusion (Prichard et al. 2021). For example, a fuel treatment could be considered effective if fewer ignitions occurred in an area, resource damage was mitigated in the event of a fire, or it was easier to suppress a wildfire. These three metrics of effectiveness could all co-occur, but there could also be examples where they may have opposing results. Fuel treatments in forests with a historically frequent, low-severity fire regime could mitigate the likelihood of a high-severity fire, while also making it easier to directly suppress subsequent wildfires that may provide resource benefits, forcing frequent maintenance treatments. We acknowledge that this is a simplistic example, but it illustrates the ever-present challenge of managing lands to improve resilience over long time spans and the immediate pressure to manage existing wildfires for current smoke and other negative impacts to communities and resources balanced with the need to allow wildfires for resource benefit when feasible.

We suggest a method is needed to evaluate fuel treatment effectiveness in the context of a fuel management "regime" that is an iterative and cumulative process composed of three, linked components: changing fuels, changing fire behavior under specified weather and topographic conditions, and changing fire effects within larger landscapes over time (Fig. 2). Similar to a disturbance regime that describes the cumulative effects of multiple disturbance events over space and time, a fuel

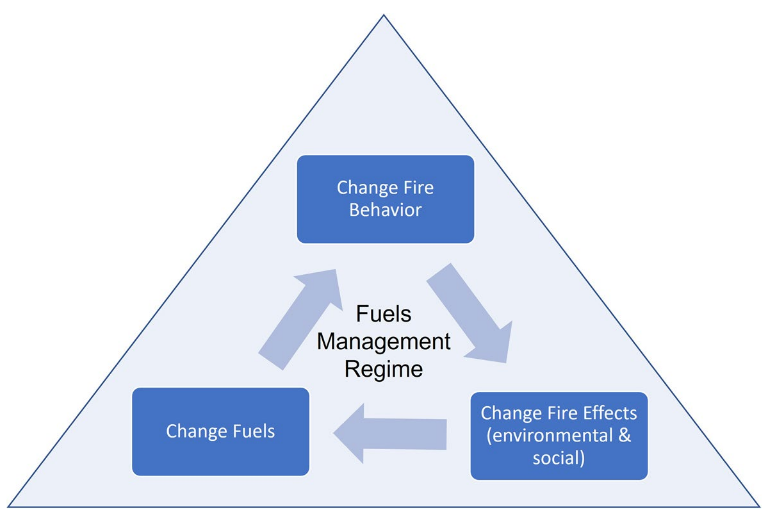

Fig. 2 Fuel management regime triangle consists of changing fuels to achieve desired fire behavior that will result in desired ecological and social fire effects, whether at stand or landscape scales

management regime describes the cumulative effects of fuel treatments over space and time. The advantage of the fuel management regime triangle is that it places the emphasis on how to achieve desirable fire effects by proactively changing fuels and subsequent fire behavior. Land management agencies' and organizations' goals are centered on creating resilient ecosystems that provide multiple ecological benefits and social services (State of California 2021; Stephens et al. 2016; Urgenson et al. 2017; USDOI and USDA 2014). Therefore, a fuel management regime that links fuels, fire behavior, and fire effects explicitly should be more successful in attaining goals than an approach that focuses primarily or solely on reducing fire behavior. We think of this as an adaptive feedback process, where fuel treatment prescriptions and placement change over time and areas are prioritized for social resource protection and ecological resource management (North et al. 2021).

We argue that the successfulness of a fuel management regime must be evaluated in two ways: fire hazard (defined in the section below) and actual wildfire outcomes (Table 1). This approach is placed within defined management objectives and desired conditions and will help resolve confusion about how to evaluate fuel treatments by separately quantifying hazard state attributes of vegetation and then quantifying fire effect outcomes of actual fires. Importantly, these outcomes can be evaluated at the scale of a stand or single fire or across a landscape over time based on preidentified objectives to determine the effectiveness of fuel treatments and fuel management regimes. By separating the components of a fuel treatment into how fuels, fire behavior, and fire effects were individually altered relative to untreated areas, it becomes easier to evaluate both how and to what extent fuels across a landscape are changing due to treatments, as well as resulting fire behavior and effects when wildfires do occur. This ability is especially important outside of modeling exercises and research, where treatments are often only documented by the general activity that occurred (e.g., thinning, burning) but do not report vegetation and fuel characteristics (e.g., fuel loading, tree density) (Vaillant and Reinhardt 2017).

Hazard state evaluations

Reducing fuels and altering fuel arrangement can moderate fire hazard. Hazard is characterized by fuels that, together with weather and topography, determine fire behavior (Hardy 2005). Hazard describes the condition of live and dead fuels from objective quantification, as well as the subjective prediction of potential fire behavior

Table 1 Metrics to quantify realized (i.e., actual) and potential effectiveness of stand and landscape fuel treatments. Attributes of interest are dictated by preidentified objectives, desired conditions, and landscape boundaries; not all attributes will be pertinent for every evaluation. Hazard state attributes describe the fuel conditions based on actual vegetation and fuels and the subjective prediction of potential fire behavior and effects (i.e., severity) based on the best-available modeled output. Realized fuel treatment effectiveness is based on actual fire behavior and effect attributes and can be compared against no-treatment and alternative treatment outcomes

Evaluation of hazard	Stand attributes	Landscape attributes
Hazard state	Data-derived, actual:	
	Surface fuel load	Fire return interval departure distribution
	Canopy base height	Structural stage/age class distribution
	Canopy bulk density	Fire regime condition class (% of classes)
	Fire-resistant trees and species	Treatment extent (% treated)
	Modeled output, potential:	
	Fire behavior fuel model	Potential flame length distribution
	Potential flame length	Potential fire type[a] distribution
	Potential rate of spread	Potential severity distribution
	Potential fire type[a]	
	Potential severity	
Evaluation of fuel treatment effectiveness	**Stand attributes**	**Landscape attributes**
Environmental and ecological indicators	Fire severity	Total area burned
	Fire size	Extent burned (%)
	Strategic point protection ability	Characteristic fire severity (% of trees killed)
	Fire progression/rate of spread	Characteristic patch size (%)
Social values	Fire suppression opportunities	Structures lost
	Suppression costs	Evacuations (# days and people)
	Individual homes	Suppression costs
		Smoke production
		Smoke exposure

[a] Surface, torching, crowning

and effects based on the best-available modeled output (Table 1). Numerous quantifiable stand-level attributes exist to characterize the fire hazard state (Table 1). Managers can measure stand and fuel characteristics and analysts can use these values in fire behavior and effects models to calculate attributes of potential fire behavior (e.g., potential flame length, rate of spread) and potential fire effects (e.g., severity, exposure) for given weather scenarios (Ottmar et al. 2007; Scott et al. 2013).

Fire hazard affects how a fire may burn through an area, but it does not address the likelihood of loss or benefit from a fire—that is quantified by fire risk. Fire risk is the expected net value change given the likelihood of a fire at a given intensity and has three components: likelihood of ignition or burn probability, expected fire intensity, and fire effects based on the expected fire intensity (Ager et al. 2019; Finney 2005; Scott et al. 2013; Thompson and Calkin 2011). Fire hazard is therefore a component of fire risk, as hazard is composed of fire intensity and fire effects. This concept of risk draws on the actuarial definition and builds on the simpler definition described by Hardy (2005) where risk is "the chance that a fire might start, as affected by the nature and incidence of causative agents." An area may have high fire hazard but a very low probability of ignition, reducing the overall fire risk. The likelihood of fire of a certain intensity dictates an area's exposure and susceptibility to fire effects. Fire effects may be positive, negative, or neutral response functions (sensu Scott et al. 2013), such that a fire of a given intensity could have both desirable and undesirable outcomes. Our evaluations do not include the more detailed analyses required to create risk assessments that consider hazard attributes coupled with burn probabilities and expected responses (Scott et al. 2013).

Fuel treatment effectiveness evaluations

Our evaluation of fuel treatment effectiveness is determined after a fire occurs based on observed fire behavior and effects. Effectiveness again relates back to preidentified objectives of the treatment—typically related to desired fire effects that are a combination of environmental and ecological outcomes and social values that are identified in the planning process (Table 1). Extreme weather or topography will greatly influence fire behavior and effects; therefore, the effects of fuel treatments will ideally be quantified relative to untreated areas (Prichard et al. 2020; Safford et al. 2012). Environmental and ecological attributes commonly include fire severity, often quantified as the percentage of tree mortality from fire, and fire size, or area burned. Remote sensing methods allow estimates of changes in vegetation to classify severity for individual large fires (Eidenshink et al. 2007; Wimberly et al. 2009). Examples of social values of interest are the number of structures lost, suppression costs, evacuations, or public health outcomes and loss of life.

Evaluations of effectiveness over space and time

Landscape is a loosely used term to describe the general characteristics of a large areal extent. Population density, road density, forest cover, forest type, topographic complexity, climate, and land ownership influence historical and contemporary fire regimes and management options (see Spies et al. 2018). For fire planning efforts, several mapping alternatives exist to characterize fire and resources over large areas (Evers et al. 2020; Scott et al. 2017; Thompson et al. 2020) that could be used as landscape boundaries. To assess trends in fire hazard and fuel treatment effectiveness, we propose examining vegetation, environmental and ecological outcomes, and identified social values across large spatial and temporal scales using boxplots (as visual and statistical aids (Fig. 3). Landscape attribute values are estimated by either weighting areas by vegetation types or creating separate boxplots by vegetation type. The advantage of boxplots or violin plots is that they can create a dashboard of indicators that allow visualization of the underlying data distribution of attributes of interest and naturally incorporate the range of variation that will invariably exist within diverse landscapes. For example, in frequent, low-severity fire regimes, patches of high severity are expected. Boxplots put these high-severity patches in the context of the desired range of variation and help to determine if long-term trends are moving in the desired direction.

Our dashboards summarize individual stands within the landscape of interest and provide several statistics, including boxes of first and third quartiles, medians, 1.5 inter-quartile ranges (whiskers), and outliers. Using readily available or attainable vegetation and modeled fire behavior and effects output allows the creation of boxplots for attributes that characterize the distribution of pre-fire hazard states. Using observed environmental, ecological, and social indicator outcomes allows the determination of fuel treatment effectiveness over time and space. To change the landscape hazard state, land management agencies and stakeholders can identify desired values for the median and upper and lower bounds (green boxes and median lines in Fig. 3), allowing measurable objectives within any one stand that is also couched in the larger landscape context. Overall fuel treatment effectiveness is evaluated over time as an iterative process to determine how management is shifting the distribution of stand attributes over time and the trajectory toward identified goals. This method recognizes that when managing complex landscapes for a broad range of ecological and social objectives under changing climate, a range of stand conditions on the landscape is typically

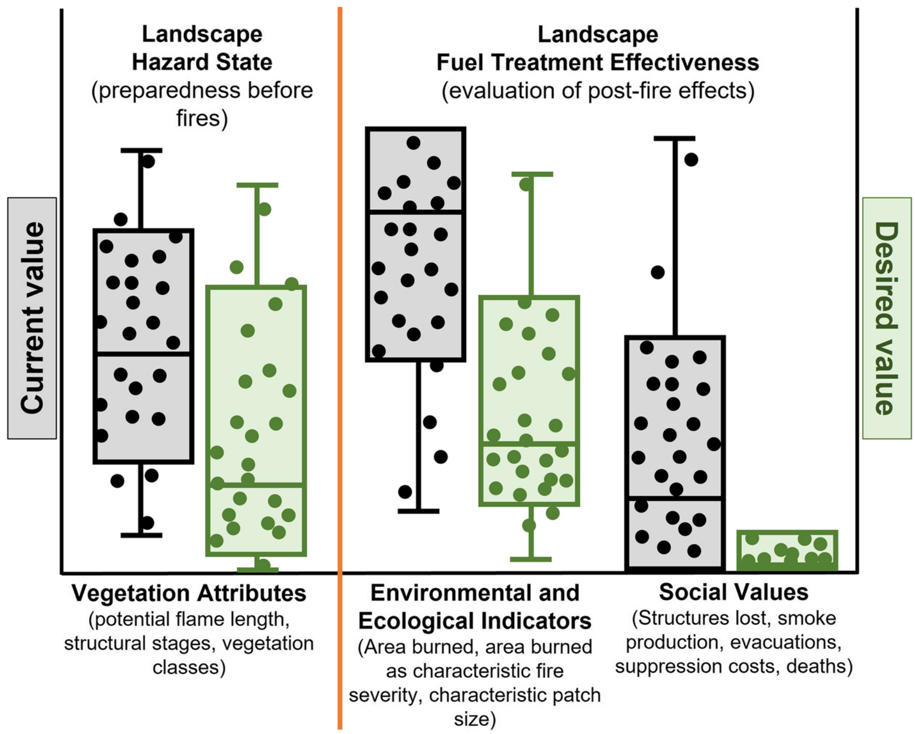

Fig. 3 Fuel treatment dashboard indicators (black = current; green = desired). The distribution of individual stand and fire attributes (black and green dots) within a landscape quantifies the state of pre-fire landscape hazard. Landscape fuel treatment effectiveness is evaluated post-fire based on preidentified environmental and ecological indicators and social values of interest. Overall fuel treatment effectiveness is evaluated over time as an iterative process to determine how management is shifting the distribution of stand attributes and in the direction of identified goals

desired and 100% effectiveness for all attributes and all fires is an unrealistic goal. It also requires that users identify feasible desired conditions for vegetation and environmental and ecological indicators, which include the changing conditions under projected future climate by depicting desired conditions over different timescales. Importantly, through the process of identifying ranges for desired conditions and comparing against the ranges of current conditions, our method fosters communication across resource disciplines and collaborative groups. This approach enables adaptive management—if no change in the distribution of landscape fuel treatment effectiveness is observed over time, even as hazard state distribution changes, then fuel treatment prescriptions can be refined such that burned outcomes in treated areas are more desirable over larger scales.

Hazard will change depending on the time since treatment or the time since a previous disturbance (e.g., wildfire, insect outbreaks) and will vary from one stand to the next and by vegetation type over the landscape. Calculating fire hazard metrics within stands over large spatial extents and routinely updating over time allows the creation of landscape hazard states (Table 1; Fig. 3). While stand and landscape attributes that define hazard states are similar, landscape attributes allow an assessment of cumulative impact at a scale appropriate to those on which fires operate. Landscape attribute values are estimated by weighting area by vegetation types, and existing databases such as LANDFIRE can provide historical fire return intervals and characteristic fire severity (Blankenship et al. 2021). Landscape assessments provide a broader context of the relative influence of one treatment prescription or placement relative to the whole region.

By defining objectives across spatial scales, with temporal boundaries, it becomes tenable to choose metrics that allow the determination of fuel treatment effectiveness. Time is an important component because of inherent variability in annual weather and other disturbances. While a single fuel treatment may fail to reduce fire severity during one incident, it is essential to examine the overall success rate of fuel treatments challenged by wildfire within and across years at the regional and national levels to detect if treatments are having the desired impact and in the context of extreme fire seasons where there is widespread regional drought and high fire danger. Again, the importance of preidentified objectives is essential to evaluate effects.

Discussion

Despite the widespread consensus that fuel treatments are effective at both reducing fire effects (Fulé et al. 2012; Hunter and Robles 2020; Kalies and Yocom Kent 2016; Prichard et al. 2020; Safford et al. 2012; Stephens et al. 2012) and assisting suppression efforts (Sánchez et al. 2019; Thompson et al. 2017; Thompson et al. 2013), evaluating the cumulative impacts of these treatments to change landscape patterns of fire behavior and effects is challenging. Our proposed method of quantifying fire hazard states, followed by evaluation of actual outcomes of fires on environmental and ecological indicators and social values, allows assessment of how individual fuel treatments and fuel management regimes are effective based on predetermined objectives. We envision that this method can be used in conjunction with large-scale pre-fire planning efforts that identify fire management areas such as the Potential Wildfire Operational Delineations (PODS) (Thompson et al. 2020; Thompson et al. 2022) or FireSheds (Evers et al. 2020). Our dashboard indicators could potentially also be used to summarize data within the FTEM database.

We acknowledge our framework is focused on US ecosystems and policies; however, this approach could be evaluated outside of the US or compared to approaches used in other countries. Thompson and Calkin (2011) describe examples of risk assessment approaches from several countries, and studies have identified the challenges of developing successful fire management programs over landscape scales in Europe (Fernandes et al. 2013; Moreira et al. 2020; Tedim et al. 2016) and Australia (Burrows and McCaw 2013). Results indicate the need to develop methods to improve reporting and evaluation of fire management programs.

Our method is relatively simple to implement and understand, but it does not explicitly account for landscape metrics such as connectivity and spatial placement or disturbance processes such as contagion (each of which needs synthesis and future incorporation). Instead, it offers a much-needed communication bridge between too simplistic reporting values such as area treated and area burned that are disconnected from ecological or social outcomes and more complex, time-intensive fire simulation modeling. To determine the underlying causes of detrimental or undesirable outcomes in treated vs. untreated areas after fires, additional spatial state-and-transition vegetation and fire modeling will be required. These more detailed efforts can then be used to adapt treatment prescriptions, amount of area treated, and strategic placement of treatments to reduce landscape hazard and risk in the future (Ager et al. 2010; Kennedy et al. 2019; Koontz et al. 2020; Tubbesing et al. 2019). We argue that our method offers a way to place individual treatments in the context of landscape fuel management regimes that emphasize desired outcomes of fires. It provides easily assessable indicators of vegetation conditions and fire outcomes over time to help evaluate fuel treatments and management regimes. The landscape dashboards can also foster conversations between stakeholders and resource managers about tradeoffs and scenario gaming of treatment methods, placement, and total area treated.

Our method also does not incorporate uncertainty around model predictions. This is a known deficiency in fire behavior modeling and simulations due to the inherent complexity of predicting outcomes of wildland fires (Benali et al. 2017; Cai et al. 2019; Ciri et al. 2021; Cruz and Alexander 2013; Thompson and Calkin 2011). We attempt to circumvent potential unavoidable errors introduced in modeling exercises by calling to evaluate fuel treatment effectiveness using only actual wildfire outcomes and separating attributes of fire hazard by data-derived, realized values versus modeled values (Table 1, Fig. 3). Better accounting of uncertainty into fire behavior and effects models is a needed and active area of research to provide planners and managers with more accurate assessments of potential wildland fire behavior and effects.

We know enough to act now to implement large-scale fuel treatments within fuel management regimes, while continuing to adapt fuel management with changing conditions and as new research becomes available (Hessburg et al. 2021). History has shown that removing fire by attempting to suppress all fires is impossible. Furthermore, it also creates a “fire paradox” in which suppressing the majority of fire causes increasingly detrimental outcomes and the wildland fire problem becomes ever more exacerbated by increasing fuel loads over time and shifting fires to the highest burn potential days (Finney 2005; Thompson et al. 2018). Failure to act will almost certainly result in increasingly worse outcomes as climate change causes extreme fire weather to be more common.

Strategically placed fuel treatments can also amplify their impact on the landscape by allowing more resource objective wildfires in the future (Huffman et al. 2017; North et al. 2021; Thompson et al. 2018). These fires are unplanned ignitions that are managed to achieve resource benefits with minimal threat to infrastructure and humans. Allowing more resource objective fires when beneficial outcomes are likely and pose little safety concerns can further reduce landscape hazard (North et al. 2012). The footprint of these fires can regulate the size and severity of subsequent fires (Parks et al. 2015; Parks et al. 2014) and meet ecological restoration-related objectives (Huffman et al. 2017). The intensive planning required for fuel treatments limits the feasibility of treating large areas of land annually, making increased use of resource objective wildfires all the more essential towards achieving resilient, fire-adapted landscapes.

Conclusion

Not all fuel treatments will be effective, but our framework and dashboard allow the outcomes of single fires to be put in the context of landscape trends. We posit that 100% effectiveness is an unreasonable expectation given that wildfire is inherently a dynamic process heavily influenced by weather, climatic conditions, and topography. Legal, administrative, and operational designations dictate the total area that is treatable, which may influence the feasibility of fuel treatments to change landscape-level patterns of fire behavior and severity (Ager et al. 2020; North et al. 2015; Prichard et al. 2021). For example, places with vast wilderness areas preclude most management options except resource objective wildfires, while other places offer more flexibility to implement a range of fuel treatments. Our dashboard of boxplots that shows underlying data distributions of environmental and social effects of fire can help put extreme fire events in perspective and provide a counterpoint to cherry picking individual fire outcomes that fail to "see the landscapes for the stands." We hope that our fuel treatment framework to examine the state of fuels through the lens of fire hazard and connecting fuels to subsequent fire behavior and effects over time and space focuses the picture of regional and national fuel management programs towards increasing social and ecological resilience from wildfire.

Acknowledgements
We thank the many people that provided thoughtful critiques and fruitful discussions over the years about how to quantify fuel treatment effectiveness. This paper is an outgrowth of all those exchanges with researchers and practitioners. We thank the two anonymous reviewers whose comments improved the final manuscript.

Authors' contributions
SH: conceptualization, writing—original draft preparation, and writing—review and editing; JMV: conceptualization, writing—original draft preparation, and writing—review and editing; TJ: conceptualization, funding acquisition, project administration, and writing—review and editing; JK: writing—review and editing. The authors read and approved the final manuscript.

Funding
We acknowledge funding from the Joint Fire Science Program under project JFSP 19-S-01-2.

Availability of data and materials
Not applicable—no data are presented.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]USDA Forest Service Rocky Mountain Research Station, Missoula, MT 59808, USA. [2]Tall Timbers Research Station, Tallahassee, FL 32312, USA. [3]USDA Forest Service Rocky Mountain Research Station, Moscow, ID 83843, USA. [4]Wildland Fire Laboratory, Department of Forestry, Fire, and Rangeland Management, California State Polytechnic University, Humboldt, Arcata, CA 95521, USA.

Received: 20 April 2022 Accepted: 16 November 2022
Published online: 21 December 2022

References

Agee, J.K., B. Bahro, M.A. Finney, P.N. Omi, D.B. Sapsis, C.N. Skinner, J.W. van Wagtendonk, and C.P. Weatherspoon. 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* 127: 55–66.

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

Ager, A.A., A.M.G. Barros, R. Houtman, R. Seli, and M.A. Day. 2020. Modelling the effect of accelerated forest management on long-term wildfire activity. *Ecological Modelling* 421: 108962. https://doi.org/10.1016/j.ecolmodel.2020.108962.

Ager, A.A., M.A. Day, P. Palaiologou, R.M. Houtman, C. Ringo, and C.R. Evers. 2019. *Cross-boundary wildfire and community exposure: A framework and application in the western U.S. Gen. Tech. Rep. RMRS-GTR-392*. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Ager, A.A., M.A. Day, K.C. Short, and C.R. Evers. 2016. Assessing the impacts of federal forest planning on wildfire risk mitigation in the Pacific Northwest, USA. *Landscape and Urban Planning* 147: 1–17.

Ager, A.A., N.M. Vaillant, and M.A. Finney. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* 259: 1556–1570.

Barrett, K. 2018. *The full community costs of wildfire*, 50. Headwaters Economics.

Benali, A., A.C. Sá, A.R. Ervilha, R.M. Trigo, P.M. Fernandes, and J.M. Pereira. 2017. Fire spread predictions: Sweeping uncertainty under the rug. *Science of the Total Environment* 592: 187–196.

Blankenship, K., R. Swaty, K.R. Hall, S. Hagen, K. Pohl, A. Shlisky Hunt, J. Patton, L. Frid, and J. Smith. 2021. Vegetation dynamics models: A comprehensive set for natural resource assessment and planning in the United States. *Ecosphere* 12: e03484. https://doi.org/10.1002/ecs2.3484.

Bowman, D.M.J.S., J.K. Balch, P. Artaxo, W.J. Bond, J.M. Carlson, M.A. Cochrane, C.M. D'Antonio, R.S. DeFries, J.C. Doyle, S.P. Harrison, F.H. Johnston, J.E. Keeley, M.A. Krawchuk, C.A. Kull, J.B. Marston, M.A. Moritz, I.C. Prentice, C.I. Roos, A.C. Scott, T.W. Swetnam, G.R. van der Werf, and S.J. Pyne. 2009. Fire in the Earth system. *Science* 324: 481–484. https://doi.org/10.1126/science.1163886.

Bradshaw, L., and E. McCormick. 2000. *FireFamily Plus user's guide, Version 2.0. Gen. Tech. Rep. RMRS-GTR-67WWW*. Ogden.

Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara. 2021. The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America* 118.

Burrows, N., and L. McCaw. 2013. Prescribed burning in southwestern Australian forests. *Frontiers in Ecology and the Environment* 11: e25–e34. https://doi.org/10.1890/120356.

Cai, L., H.S. He, Y. Liang, Z. Wu, and C. Huang. 2019. Analysis of the uncertainty of fuel model parameters in wildland fire modelling of a boreal forest in north-east China. *International Journal of Wildland Fire* 28: 205–215.

Ciri, U., M.M. Garimella, F. Bernardoni, R. Bennett, and S. Leonardi. 2021. Uncertainty quantification of forecast error in coupled fire–atmosphere wildfire spread simulations: Sensitivity to the spatial resolution. *International Journal of Wildland Fire* 30: 790–806.

Collins, B., and C.H. Greenberg. 2021. *Fire ecology and management: Past, present, and future of US forested ecosystems*. Springer Nature.

Cruz, M.G., and M.E. Alexander. 2013. Uncertainty associated with model predictions of surface and crown fire rates of spread. *Environmental Modelling & Software* 47: 16–28. https://doi.org/10.1016/j.envsoft.2013.04.004.
Deal, R. 2018. *Dictionary of forestry*. 2nd ed. Bethesda: Society of American Foresters.
Eidenshink, J., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard. 2007. A project for monitoring trends in burn severity. *Fire Ecology* 3: 3–21.
Evers, C.R., C.D. Ringo, A.A. Ager, M.A. Day, F.J. Alcasena Urdíroz, and K.J. Bunzel. 2020. *The Fireshed Registry: Fireshed and project area boundaries for the continental United States*.
Fernandes, P.M., G.M. Davies, D. Ascoli, C. Fernández, F. Moreira, E. Rigolot, C.R. Stoof, J.A. Vega, and D. Molina. 2013. Prescribed burning in southern Europe: Developing fire management in a dynamic landscape. *Frontiers in Ecology and the Environment* 11: e4–e14. https://doi.org/10.1890/120298.
Finney, M.A. 2003. Calculation of fire spread rates across random landscapes. *International Journal of Wildland Fire* 12: 167–174.
Finney, M.A. 2005. The challenge of quantitative risk assessment for wildland fire. *Forest Ecology and Management* 211. https://doi.org/10.1016/j.foreco.2005.02.010.
Finney, M.A., C.W. McHugh, and I.C. Grenfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* 35: 1714–1722. https://doi.org/10.1139/x05-090.
Fulé, P.Z., J.E. Crouse, J.P. Roccaforte, and E.L. Kalies. 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *Forest Ecology and Management* 269: 68–81.
Greenberg, C.H., and B. Collins. 2021. *Fire ecology and management: Past, present, and future of US forested ecosystems vol 39*. Springer International Publishing. https://doi.org/10.1007/978-3-030-73267-7.
Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz. 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*: e02431. https://doi.org/10.1002/eap.2431.
Hardy, C.C. 2005. Wildland fire hazard and risk: Problems, definitions, and context. *Forest Ecology and Management* 211: 73–82.
Hessburg, P.F., J.K. Agee, and J.F. Franklin. 2005. Dry forests and wildland fires of the inland Northwest USA: Contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* 211.
Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Pova, and F.K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*: e02432. https://doi.org/10.1002/eap.2432.
Huffman, D.W., A.J. Sánchez Meador, M.T. Stoddard, J.E. Crouse, and J.P. Roccaforte. 2017. Efficacy of resource objective wildfires for restoration of ponderosa pine (*Pinus ponderosa*) forests in northern Arizona. *Forest Ecology and Management* 389: 395–403. https://doi.org/10.1016/j.foreco.2016.12.036.
Hunter, M.E., and M.D. Robles. 2020. Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. *Forest Ecology and Management* 475: 118435. https://doi.org/10.1016/j.foreco.2020.118435.
Jain, T.B., I. Abrahamson, N. Anderson, S. Hood, B. Hanberry, F. Kilkenny, S. McKinney, J. Ott, A. Urza, J. Chambers, M. Battaglia, J.M. Varner, and J.J. O'Brien. 2021. *Effectiveness of fuel treatments at the landscape scale: State of understanding and key research gaps. JFSP PROJECT ID: 19-S-01-2*, 65. Boise: Joint Fire Sciences Program.
Jolly, W.M., M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G.J. Williamson, and D.M.J.S. Bowman. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 6: 7537.
Kalies, E.L., L.L. Yocom, and Kent. 2016. Tamm review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management* 375: 84–95. https://doi.org/10.1016/j.foreco.2016.05.021.
Keane, R.E. 2015. *Wildland fuel fundamentals and applications*. Switzerland: Springer.
Kennedy, M.C., M.C. Johnson, K. Fallon, and D. Mayer. 2019. How big is enough? Vegetation structure impacts effective fuel treatment width and forest resiliency. *Ecosphere* 10: e02573.
Koontz, M.J., M.P. North, C.M. Werner, S.E. Fick, and A.M. Latimer. 2020. Local forest structure variability increases resilience to wildfire in dry western US coniferous forests. *Ecology Letters* 23: 483–494.
Martinson, E.J., and P.N. Omi. 2013. *Fuel treatments and fire severity: A meta-analysis. Res Pap RMRS-RP-103WWW*, 39. Fort Collins: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.
McKenzie, D., C. Miller, and D.A. Falk. 2011. *The landscape ecology of fire*. Springer Science & Business Media.
McKinney, S.T., I. Abrahamson, T. Jain, and N. Anderson. 2022. A systematic review of empirical evidence for landscape-level fuel treatment effectiveness. *Fire Ecology* 18(1): 1–6. https://doi.org/10.1186/s42408-022-00146-3.
Moreira, F., D. Ascoli, H. Safford, M.A. Adams, J.M. Moreno, J.M.C. Pereira, F.X. Catry, J. Armesto, W. Bond, M.E. González, T. Curt, N. Koutsias, L. McCaw, O. Price, J.G. Pausas, E. Rigolot, S. Stephens, C. Tavsanoglu, V.R. Vallejo, B.W. Van Wilgen, G. Xanthopoulos, and P.M. Fernandes. 2020. Wildfire management in Mediterranean-type regions: Paradigm change needed. *Environmental Research Letters* 15: 011001. https://doi.org/10.1088/1748-9326/ab541e.
North, M., A. Brough, J. Long, B. Collins, P. Bowden, D. Yasuda, J. Miller, and N. Sugihara. 2015. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. *Journal of Forestry* 113: 40–48.
North, M., R. York, B. Collins, M. Hurteau, G. Jones, E. Knapp, L. Kobziar, H. McCann, M. Meyer, and S. Stephens. 2021. Pyrosilviculture needed for landscape resilience of dry western United States forests. *Journal of Forestry*. https://doi.org/10.1093/jofore/fvab026.
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.
NWCG. 2014. *National Wildfire Coordinating Group Glossary of Wildland Fire Terminology PMS*, 205.
Ottmar, R.D., D.V. Sandberg, C.L. Riccardi, and S.J. Prichard. 2007. An overview of the fuel characteristic classification system—Quantifying, classifying, and creating fuelbeds for resource planning. *Canadian Journal of Forest Research* 37: 2383–2393.
Palmer, M.A., J.B. Zedler, and D.A. Falk. 2016. *Foundations of restoration ecology*. Springer.
Parks, S.A., L.M. Holsinger, C. Miller, and C.R. Nelson. 2015. Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. *Ecological Applications* 25: 1478–1492.
Parks, S.A., C. Miller, C.R. Nelson, and Z.A. Holden. 2014. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems* 17: 29–42.
Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: Ten common questions. *Ecological Applications*: e02433. https://doi.org/10.1002/eap.2433.
Prichard, S.J., N.A. Povak, M.C. Kennedy, and D.W. Peterson. 2020. Fuel treatment effectiveness in the context of landform, vegetation, and large, wind-driven wildfires. *Ecological Applications* 30: e02104. https://doi.org/10.1002/eap.2104.
Prichard, S.J., C.S. Stevens-Rumann, and P.F. Hessburg. 2017. Tamm review: Shifting global fire regimes: Lessons from reburns and research needs. *Forest Ecology and Management* 396: 217–233.
Robichaud, P.R., S.A. Lewis, R.E. Brown, and L.E. Ashmun. 2009. Emergency post-fire rehabilitation treatment effects on burned area ecology and long-term restoration. *Fire Ecology* 5: 115–128. https://doi.org/10.4996/fireecology.0501115.
Safford, H.D., J. Stevens, K. Merriam, M. Meyer, and A. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management* 274: 17–28.
Sánchez, J.J., J. Loomis, A. González-Cabán, D. Rideout, and R. Reich. 2019. Do fuel treatments in U.S. National Forests reduce wildfire suppression costs and property damage? *Journal of Natural Resource Policy Research* 9: 42–73.

Scott, J.H., M.P. Thompson, and D.E. Calkin. 2013. *A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315*. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Scott, J.H., M.P. Thompson, and J.W. Gilbertson-Day. 2017. Exploring how alternative mapping approaches influence fireshed assessment and human community exposure to wildfire. *GeoJournal* 82: 201–215.
Shinneman, D.J., M.J. Germino, D.S. Pilliod, C.L. Aldridge, N.M. Vaillant, and P.S. Coates. 2019. The ecological uncertainty of wildfire fuel breaks: Examples from the sagebrush steppe. *Frontiers in Ecology and the Environment* 17: 279–288. https://doi.org/10.1002/fee.2045.
Spies, T. A., R. M. Scheller, and J. P. Bolte. 2018. Adaptation in fire-prone landscapes: interactions of policies, management, wildfire, and social networks in Oregon, USA. Ecology and Society 23.
State of California. 2021. *California's Wildfire and Forest Resilience Action Plan: A comprehensive strategy of the Governor's Forest Management Task Force*, 46.
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. Parsons, S.M. Ritter, and J.T. Stevens. 2020. Forest restoration and fuels reduction: Convergent or divergent? *Bioscience*. https://doi.org/10.1093/biosci/biaa134.
Stephens, S.L., N. Burrows, A. Buyantuyev, R.W. Gray, R.E. Keane, R. Kubian, S. Liu, F. Seijo, L. Shu, and K.G. Tolhurst. 2014. Temperate and boreal forest mega-fires: Characteristics and challenges. *Frontiers in Ecology and the Environment* 12: 115–122.
Stephens, S.L., B.M. Collins, E. Biber, and P.Z. Fulé. 2016. US federal fire and forest policy: Emphasizing resilience in dry forests. *Ecosphere* 7.
Stephens, S.L., J.D. McIver, R.E.J. Boerner, C.J. Fettig, J.B. Fontaine, B.R. Hartsough, P.L. Kennedy, and D.W. Schwilk. 2012. The effects of forest fuel-reduction treatments in the United States. *Bioscience* 62: 549–560. https://doi.org/10.1525/bio.2012.62.6.6.
Stephens, S.L., C.I. Millar, and B.M. Collins. 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. *Environmental Research Letters* 5: 024003.
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. https://doi.org/10.1002/ecs2.1445.
Tedim, F., V. Leone, and G. Xanthopoulos. 2016. A wildfire risk management concept based on a social-ecological approach in the European Union: Fire Smart Territory. *International Journal of Disaster Risk Reduction* 18: 138–153. https://doi.org/10.1016/j.ijdrr.2016.06.005.
Thompson, M., K. Riley, D. Loeffler, and J. Haas. 2017. Modeling fuel treatment leverage: Encounter rates, risk reduction, and suppression cost impacts. *Forests* 8: 469.
Thompson, M.P., and D.E. Calkin. 2011. Uncertainty and risk in wildland fire management: A review. *Journal of Environmental Management* 92. https://doi.org/10.1016/j.jenvman.2011.03.015.
Thompson, M.P., B.M. Gannon, M.D. Caggiano, C.D. O'Connor, A. Brough, J.W. Gilbertson-Day, and J.H. Scott. 2020. Prototyping a geospatial atlas for wildfire planning and management. *Forests* 11: 909.
Thompson, M.P., D.G. MacGregor, C.J. Dunn, D.E. Calkin, and J. Phipps. 2018. Rethinking the wildland fire management system. *Journal of Forestry* 116: 382–390. https://doi.org/10.1093/jofore/fvy020.
Thompson, M.P., C.D. O'Connor, B.M. Gannon, M.D. Caggiano, C.J. Dunn, C.A. Schultz, D.E. Calkin, B. Pietruszka, S.M. Greiner, R. Stratton, and J.T. Morisette. 2022. Potential operational delineations: New horizons for proactive, risk-informed strategic land and fire management. *Fire Ecology* 18: 17. https://doi.org/10.1186/s42408-022-00139-2.
Thompson, M.P., N.M. Vaillant, J.R. Haas, K.M. Gebert, and K.D. Stockmann. 2013. Quantifying the potential impacts of fuel treatments on wildfire suppression costs. *Journal of Forestry* 111: 49–58. https://doi.org/10.5849/jof.12-027.
Tubbesing, C.L., D.L. Fry, G.B. Roller, B.M. Collins, V.A. Fedorova, S.L. Stephens, and J.J. Battles. 2019. Strategically placed landscape fuel treatments decrease fire severity and promote recovery in the northern Sierra Nevada. *Forest Ecology and Management* 436: 45–55.
Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology* 91: 2833–2849. https://doi.org/10.1890/10-0097.1.
Urgenson, L.S., C.M. Ryan, C.B. Halpern, J.D. Bakker, R.T. Belote, J.F. Franklin, R.D. Haugo, C.R. Nelson, and A.E. Waltz. 2017. Visions of restoration in fire-adapted forest landscapes: Lessons from the Collaborative Forest Landscape Restoration Program. *Environmental Management* 59: 338–353.
Urza, A.K., B.B. Hanberry, and T.B. Jain. In Press. A thematic synthesis of case studies of landscape fuel treatment effectiveness: Lessons learned from fire managers. *Fire Ecology*.
USDOI, USDA. 2014. The national strategy: The final phase in the development of the national cohesive wildland fire management strategy.
USFS. 2012. National forest system land management planning.
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.
Wimberly, M.C., M.A. Cochrane, A.D. Baer, and K. Pabst. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. *Ecological Applications* 19: 1377–1384. https://doi.org/10.1890/08-1685.1.

Publisher's Note