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REVIEW

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Landscape-scale fuel treatment effectiveness: lessons learned from wildland fire case studies in forests of the western United States and Great Lakes region

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Abstract

Background: Maximizing the effectiveness of fuel treatments at landscape scales is a key research and management need given the inability to treat all areas at risk from wildfire. We synthesized information from case studies that documented the influence of fuel treatments on wildfire events. We used a systematic review to identify relevant case studies and extracted information through a series of targeted questions to summarize experiential knowledge of landscape fuel treatment effectiveness. Within a larger literature search, we identified 18 case study reports that included (1) manager assessment of fuel treatment effectiveness during specific wildfire events; (2) fuel treatment effects on fire size, severity, and behavior outside of the treatment boundaries; and (3) the influence of fuel treatments on fire suppression tactics.

Results: Seventeen of the 18 case studies occurred in the western United States, and all were primarily focused on forested ecosystems. Surface fire behavior was more commonly observed in areas treated for fuel reduction than in untreated areas, which managers described as evidence of treatment effectiveness. Reduced fire intensity diminished fire effects and supported fire suppression efforts, while offering the potential to use wildfires as a fuel treatment surrogate.

Conclusions: Managers considered treatments to be most effective at landscape scales when fuels were reduced in multiple fuel layers (crown, ladder, and surface fuels), across larger portions of the landscape. Treatment effectiveness was improved by strategic placement of treatments adjacent to prior treatments or past wildfires, in alignment with prevailing winds, and adjacent to natural fire breaks (e.g., ridgetops), efforts that effectively expanded the treatment area. Placement in relation to suppression needs to protect infrastructure also can take advantage of continuity with unvegetated land cover (e.g., parking lots, streets). Older treatments were considered less effective due to the regrowth of surface fuels. Treatment effectiveness was limited during periods of extreme fire weather, underscoring the need for treatment designs to incorporate the increasing occurrence of extreme burning conditions. Overall, fuel treatment effectiveness would be improved by the increased use of landscape-scale treatment designs that integrate fuels, topography, prevailing winds, fire or treatment history, and available infrastructure.

Keywords: Case study, Fire behavior, Fire effects, Fire suppression, Fuel treatment, Landscape, Topography, Treatment design, Treatment placement, Wind

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Resumen

Antecedentes: Maximizar la efectividad de los tratamientos de combustibles a escala de paisaje es una necesidad clave en investigación y manejo, dada la imposibilidad de tratar todas las áreas con riesgo de incendio. Sintetizamos la información de estudios de caso que documentaron la influencia de tratamientos de combustibles en eventos de incendio. Usamos una revisión sistemática para identificar los casos de estudio relevantes y extrajimos la información mediante una serie de preguntas orientadas, para sintetizar el conocimiento de experiencias sobre la efectividad de tratamientos de combustibles a nivel de paisaje. Dentro de una amplia revisión de literatura, identificamos 18 reportes de estudios de caso que incluyeron: 1) Determinación de la efectividad del tratamiento durante eventos de fuego, 2) el efecto de los tratamientos sobre el tamaño de los incendios, severidad y comportamiento, por fuera de los límites de los tratamientos, y 3) la influencia de los tratamientos de combustible sobre las tácticas de supresión del fuego.

Resultados: Diecisiete de los 18 estudios de caso ocurrieron en el oeste de los EEUU y todos estuvieron enfocados en ecosistemas forestales. El comportamiento de fuegos de superficie fue más comúnmente observado en áreas tratadas para reducir la carga de combustibles en relación a áreas no tratadas, que los gestores describen como evidencia de la efectividad de los tratamientos. Una reducción en la intensidad del fuego disminuyó los efectos de los incendios y permitió apoyar los esfuerzos de supresión, mientras que ofreció asimismo el potencial para usar a los incendios como un sustituto del tratamiento de combustibles.

Conclusiones: Los gestores del territorio consideran que los tratamientos de combustibles son más efectivos a escala de paisaje cuando los combustibles son reducidos en estratos de combustibles múltiples (en la corona, en las escaleras de combustibles, y en el combustible superficial) a través de grandes porciones del paisaje. La efectividad de los tratamientos fue mejorada mediante la ubicación estratégica de los mismos de manera adyacente a tratamientos previos o a incendios pasados, en línea con los vientos prevalentes, y cercanos a barreras naturales del fuego (i. e. crestas rocosas), esfuerzos que efectivamente expanden el área tratada. La ubicación en relación a las necesidades de supresión para proteger las infraestructuras puede también beneficiarse de la continuidad de tierras no vegetadas (i.e. calles, lugares de estacionamiento de vehículos). Los tratamientos antiguos fueron considerados menos efectivos debido al recrecimiento de combustibles superficiales. La efectividad de los tratamientos fue limitada durante períodos con clima de fuego extremo, subrayando la necesidad de contar con diseños de tratamientos que tengan en cuenta el incremento en la ocurrencia de fuegos cuando se dan condiciones propicias. Por sobre todo, la efectividad de los tratamientos puede ser mejorado mediante el incremento en el uso, a escala de paisaje, de diseños de tratamientos que integren combustibles, topografía, vientos predominantes, historia del fuego o de los tratamientos, e infraestructura disponible.

Background

Fuel treatments manipulate live and dead vegetation to alter forest and rangeland structure and composition to create fire-resistant and fire-resilient ecosystems (Agee and Skinner 2005; Hoffman et al. 2018). A primary management objective is the use of fuel treatments to reduce future wildfire severity and increase the effectiveness of fire suppression (Snider et al. 2006), leading to widespread interest among natural resource managers in the effectiveness of fuel treatments for mitigating fire behavior, bolstering suppression efforts, and reducing fire effects. The need for action in both fuel management and fire suppression has vastly outpaced our ability to cope, and identified targets of treatment area and retreatment frequency are not being met (North et al. 2015b; Schoennagel et al. 2017; Thompson et al. 2018). Thus, strategic designs are necessary to prioritize fuel reduction treatments in configurations most likely to mitigate wildfire behavior and severity over large areas (e.g., Collins et al. 2010, Finney 2007, Ott et al. in review). Designing and implementing cost-effective fuel treatment strategies requires understanding treatment effectiveness in a landscape context, considering treatment size, placement, and proximity to other treatments or landscape features.

Because fuel treatments are often constrained to relatively small portions of the landscape, there is increasing interest in the potential for treated areas to modify wildfire at the "landscape scale" (i.e., treatment effects outside of treatment boundaries), as compared to evaluating treatment effects solely within treatment boundaries. Evaluating the effectiveness of fuel treatments at the landscape scale is challenging because many factors influence wildfire and post-wildfire outcomes, including climate and weather-driven components (fuel moisture, fire weather, vegetation type), topography, fuel dynamics, ignitions, and suppression efforts (Parks et al. 2018). Given that these factors vary through space and time at multiple scales, it is challenging to evaluate the effects of fuel treatments on large wildfire events using a rigorous statistical design (but see examples in McKinney et al. 2022). For example, fires naturally exhibit variable fire behavior and result in a mosaic of fire effects on the ecosystem (i.e., fire severity), and this variability can hinder comparisons between treated and untreated stands (e.g., Prichard et al. 2020). Treated areas are usually implemented in non-random locations based on various considerations including operational constraints (North et al. 2015a), and resulting differences in topography, fuel load, or fire weather can confound observations of treatment effects.

In the absence of statistically rigorous studies, on-the-ground experiences can provide unique information about how wildfire interacts with fuel treatments to affect fire behavior, suppression opportunities, and outcomes. Fire management requires balancing competing resources and human safety, often in politically charged situations or emergency response crises (Thompson et al. 2017). Fire managers' experiential knowledge integrates across many unmeasurable factors, providing perspectives on treatment effectiveness that cannot always be measured in empirical post-fire assessments. Specifically, managers involved in fuel treatment planning and implementation, fire suppression, or post-fire rehabilitation (e.g., erosion assessments) can provide important insights from their observations before, during, and after fire events to inform fuel treatment prioritization at landscape scales.

Syntheses that provide the current state of knowledge associated with fuel treatments from manager experience supply relevant information that can inform fire management practices, identify science gaps and research needs, and inform policy (Hood et al. 2010, Jain et al. 2012). In addition to in-depth interviews, focus groups, and content analysis, another approach is to synthesize published case studies. A case study is "an empirical enquiry that investigates a contemporary phenomenon within its real-life context" (Yin 2009). After high-profile wildfires, fire managers often document how fuel treatments influenced fire behavior and severity, using direct observations from a wildfire event and post-fire assessments. These assessments are increasingly required, such as through the Fuel Treatment Effectiveness Monitoring (FTEM) program (https://iftdss.firenet.gov/firenetHelp/help/pageHelp/content/10-ftem/ftemabout.htm). The data are often qualitative, consisting of lessons learned, tools, barriers, and other components that may inform managers about implementation and longevity efforts associated with these large landscape fuel treatments.

In this paper, we extracted information from 18 manager case studies that evaluated fuel treatment effectiveness for wildfire events at landscape scales to generate emergent information beyond the unique content of each report. We conducted a formal literature review to identify relevant case studies that evaluated the effectiveness of fuel treatments at the landscape level during an actual wildfire event. We then posed a series of structured questions to extract information from each study and synthesized the results of the combined case studies. Our objective was to examine how fuel treatments may have affected wildfires at the landscape scale, considering metrics such as wildfire behavior, suppression decisions, and subsequent post-fire outcomes, in addition to identifying broader lessons learned through experiences. For each case study, we summarized manager perspectives on the following questions: (1) How did fuel treatments mitigate adverse effects of wildfire, i.e., fire behavior and fire effects, beyond the treatment boundaries; (2) did the fuel treatments influence fire suppression strategies and firefighter safety; (3) what factors influenced fuel treatment effectiveness; (4) are there barriers to the development, implementation, and maintenance of fuel treatments; and (5) are there identified research needs for enhancing the effectiveness of fuel treatments at the landscape scale? Synthesizing case studies can be challenging because each is unique, but when combined, these papers provide a synopsis of the current approaches and general outcomes specific to landscape fuel treatment planning, implementation, and effectiveness.

Methods

This paper is part of a collection of related review papers (concepts, simulations, empirical evidence) aimed at synthesizing knowledge of fuel treatment effects at the landscape scale (Jain et al. 2022). In collaboration with USDA National Forest Service Library personnel who had extensive literature search experience and the necessary computer infrastructure, we performed a systematic literature search that returned 2240 citations during October and November 2019. Our search included literature published since 1990 and was geographically limited to research conducted in the USA and Canada that occurred in forest, rangeland, or shrubland ecosystems. Using a wide range of keywords and search terms (see McKinney et al. 2022), the Library personnel searched Treesearch; Web of Science; Scopus; FS/Info (National Forest Service Library catalog); Navigator (National Agriculture Library catalog, CAB [Commonwealth Agricultural Bureaux] Abstracts, Agricola, AGRIS [International System for Agricultural Science and Technology], Biosis, Environment Complete, Geobase, GeoRef, Medline, Zoological Record); Google Scholar; FRAMES (Fire Research and Management Exchange System); FEIS (Fire Effects Information System); JFSP (Joint Fire Science Program); and AMSET (Adaptive Management Services Enterprise

Team). Because we used databases such as FRAMES, FEIS, JFSP, and AMSET, unpublished reports and locally published reports were identified which typically are difficult to find using traditional literature searches.

From the wide distribution of papers identified in the search, we identified papers that addressed our landscape fuel treatment effectiveness objectives by applying a set of a priori criteria. First, papers had to describe the effects of a fuel treatment, defined as the alteration of live or dead vegetation that has the potential to influence fire behavior. The most common treatment types were prescribed fire and mechanical thinning, but we also included wildland fire use, timber stand improvement, commercial timber harvest, and other vegetation management actions that target fuels among a suite of objectives (see McKinney 2022). Second, papers had to consider treatment effects at the landscape scale. We defined "landscape scale" as an area that is larger than the treated area but with the potential to be influenced by the treated area, allowing for the evaluation of treatment effects beyond treatment boundaries. We used 40 km^2 as the minimum study area size, with no minimum treatment area size. We then performed a forward and backward citation search, searching the literature cited in the selected papers, and literature that cited the selected papers, to identify additional resources not found in the original search. The overall literature search process concluded during May 2020 and resulted in a total sample of 127 papers. We classified the papers into three categories: empirical studies, simulation studies, and case studies. The categories were synthesized separately, given broad differences in methodology, topical focal areas, and scope of inference (described in Jain et al. 2022).

This paper focuses on all 18 case studies identified during the search (Table 1, Fig. 1), eight of which were located by the formal literature review and ten from the subsequent citation search. Case studies reported on actual wildfires using a narrative approach and were primarily from "grey literature" publications by land management agencies rather than from peer-reviewed scientific journals or conference proceedings. The selected case studies investigated fuel treatment effectiveness during wildfire events, considering fire behavior, suppression tactics, and fire effects, and generally did not include statistical analysis. Case studies either had a forest manager as an author or had been requested by forest managers to meet the need for a post-fire assessment. We used a structured series of questions to systematically extract specific information from each case study (Table 2). This produced a structured summary of each case study, which we used to determine consistencies, identify differences, and compile key themes to inform future post-fire and fuel treatment effectiveness assessments.

Results and discussion

Description of case studies

The available case studies were predominantly located in forest ecosystems of the western U.S. (Fig. 1). All of the case studies were focused primarily on forest vegetation types, although some included areas of shrubland or grassland (Table 1). We found no case studies from ecosystems in the eastern or southeastern U.S. Six case studies took place in forests of the Sierra Nevada Mountains, two were in forests of the southern Rocky Mountains, three were in a mix of chaparral shrublands and conifer forests in southern California, two were in the Arizona/New Mexico Mountains, two were in the Cascade Mountains, and one was in the Idaho Batholith. Additionally, the case studies included one study in the Superior National Forest in northern Minnesota and one in the northwestern Great Plains; these two studies are clearly identified in the following description of findings, given their different environmental contexts, ecology, and management history as compared to the studies in the western U.S.

The wildfires described in the case study reports burned between 1999 and 2013 and ranged in size from approximately 1000 to more than 500,000 acres (400 to 200,000 ha; Table 1). Each case study described a unique combination of a wildfire event and previous fuel treatments or fires, and given the large size of most of the wildfires, the reports described the varied effects of many units within multiple treatment types. Several types of fuel treatments were evaluated, including mechanical thinning, prescribed fire, mastication, and lop and scatter, as well as previous wildfires, timber stand improvement, commercial timber harvest, and tree plantations. Although not all of these "treatment types" were intentionally implemented to modify fuels and fire behavior, the manager case studies commonly considered the effects of a broad range of previous events that had the potential to alter the fuel profile and subsequent wildfire. The treatments varied widely in their timing (i.e., how recently they were completed before the wildfire), size, and location in relation to other treatments or landscape features (e.g., ridges). While many of the case studies discussed the influence of these factors on treatment effectiveness, the reports were descriptive and did not analyze trends or produce specific criteria determining effective treatments.

Fuel treatment effects on fire behavior, suppression tactics, and fire effects

The case studies evaluated multiple indicators of fuel treatment effectiveness, including various measures of fire behavior, suppression tactics, and fire effects. It is important to note that fuel treatment effects were

Table 1 Description of fuel treatment and wildfire case studies

Ecoregion(s) EPA level III	Case study reference	Wildfire name and year	Acres burned	Treatment type(s)	Dominant vegetation type(s)
Arizona/New Mexico Mtns	Jackson et al. 2011	Wallow 2011	538,049	Prescribed fire, managed wildfire, commercial harvest	Subalpine forest
Arizona/New Mexico Mtns	Keller et al. 2011	Wallow 2011	538,049	Thinning	Dry mixed conifer
Cascades; Blue Mtns	Harbert et al. 2007	Monument 2007 GW 2007 Egley Complex 2007	53,556 1461 140,360	Thinning, pile burning, prescribed fire, previous wildfire	Dry mixed conifer, grass, and shrubs
Idaho Batholith	Graham et al. 2009	Cascade Complex 2007	500,000	Thinning, pruning, mastication, prescribed fire	Subalpine forest, dry mixed conifer
North Cascades	Gray and Prichard 2015	Tripod 2006 Octopus Mtn 2012	175,184 3048	Previous wildfire	Subalpine forest
Northern Lakes and Forests	Fites et al. 2007b	Ham Lake 2007 Cavity Lake 2006	75,000 31,500	Thinning, prescribed fire	Mixed conifer
Sierra Nevada	Crook et al. 2015	Rim 2013	257,314	Thinning, mastication, pile burning, managed wildfire, prescribed fire	Shrubs, woodland, mixed conifer
Sierra Nevada	Dailey et al. 2008	Moonlight 2007	64,997	Thinning, salvage harvest, mastication, prescribed fire	Mixed conifer
Sierra Nevada	Ewell et al. 2012	Lion 2011	20,674	Previous wildfire	Mixed conifer
Sierra Nevada	Fites et al. 2007a	Antelope Complex 2007	23,420	Thinning, mastication, prescribed fire	Mixed conifer
Sierra Nevada	Murphy et al. 2007	Angora 2007	3100	Thinning, pile burning, prescribed fire	Mixed conifer
Sierra Nevada; Cascades	Murphy et al. 2010	20 wildfires 1999–2009[a]	Varied	Thinning, mastication, pile burning, prescribed fire, lop/scatter	Dry mixed conifer, shrubs
Northwestern Great Plains	Jain et al. 2007	Germain 2003 Indian 2003	66,496 33,594	Prescribed fire	Dry mixed conifer, grass
S. California Mtns	Henson 2007	Day 2006 Zaca 2007	159,713 241,846	Thinning, pile burning, prescribed fire	Shrubs, dry mixed conifer
S. California Mtns	Rogers et al. 2008	Grass Valley 2007	1242	Thinning, chipping, pruning, prescribed fire	Shrubs, dry mixed conifer
S. California Mtns	Reiner et al. 2014	Mountain 2013	27,531	Thinning, mastication, pruning, pile burning, prescribed fire	Shrubs, mixed conifer
S. Rockies	Graham et al. 2012	Fourmile Canyon 2010	6,181	Thinning, chipping, pile burning	Dry mixed conifer
S. Rockies	Graham et al. 2003	Hayman 2002	138,000	Thinning, prescribed fire, previous wildfire	Dry mixed conifer

[a] Twenty wildfires were evaluated that occurred from 1999 to 2009: Dow (1999), Treasure (2001), Stream (2001), Cone (2002), Boulder (2006), Antelope Complex (2007), Davis (2007), Calpine (2007), Moonlight (2007), Franks (2007), Irish (2007), Peterson Complex (2008), Rich (2008), Butte (2009), Silver (2009), Milford Grade (2009), Brown (2009), Sugarloaf (2009), Friend-Darnell (2008), Ponderosa (2009)

different across all the case studies because each set of fuel treatments was exposed to a unique fire event. The manager perspectives generally reflected an understanding that treatment effectiveness depended on the resulting distribution and abundance of fuels in various fuel strata, effects that can differ within a specific treatment type based on treatment intensity, recency, and design criteria (Jain et al. 2012).

Multiple studies documented that wildfire exhibited less extreme fire behavior in treated stands than in untreated stands. Although fuel treatments are not necessarily intended to stop a wildfire without accompanying fire suppression (Prichard et al. 2021), there was some evidence that very recent prior fire (prescribed and wildfire occurring within 1 year or less) could stop fire progression locally (Graham et al. 2003). Multiple case studies reported slower rates of fire spread in treated

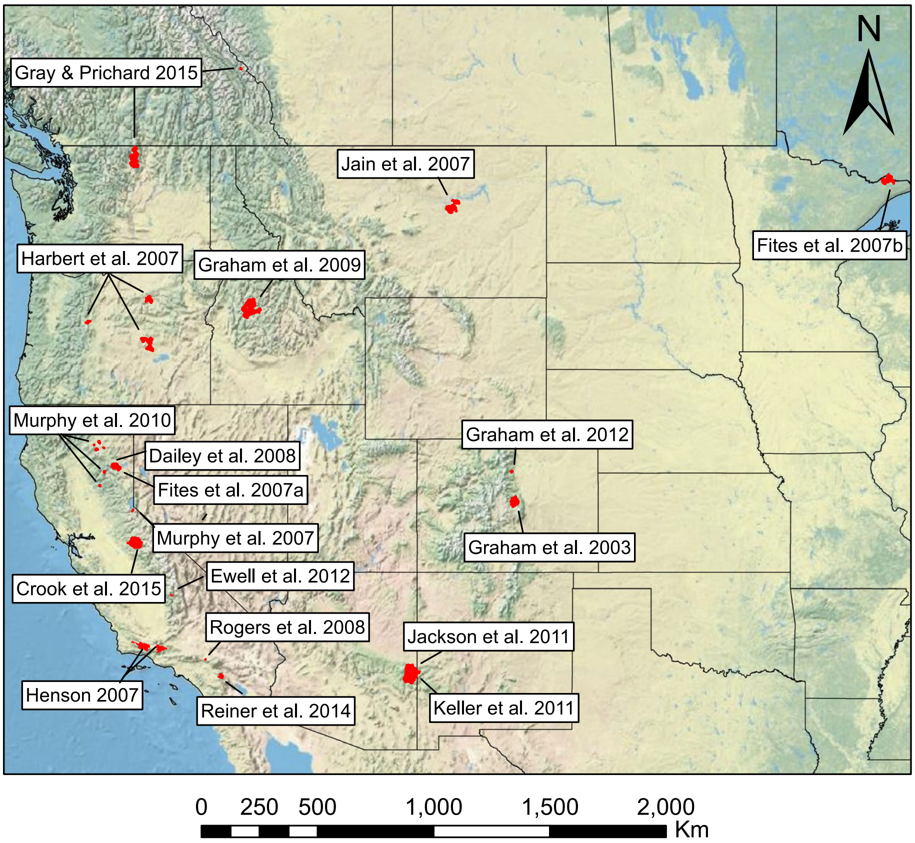

Fig. 1 Locations of wildfires (red polygons) evaluated in the 18 case studies

Table 2 Themes and list of questions used to summarize managers' perspectives from each case study

Theme	Question
Setting	Where was the case study located? What are defining characteristics of the affected landscapes? What are the dominant vegetation types?
Treatment types	Which types of treatments were implemented? What is the range of sizes for the treatment units? What was the stated rationale behind treatment placement/design?
Indicators	Which indicators were evaluated to assess treatment effectiveness?
Effectiveness	How effective were fuel treatments (fire spread, fire intensity, fire effects, and suppression tactics)? What was the time period between treatment implementation and wildfire?
Interacting factors	What factors influenced treatment effectiveness?
Management	What barriers exist when implementing fuel treatments? What were identified as lessons learned?
Inference	What research needs were identified? What limitations might affect inference from case studies?

stands (Murphy et al. 2007; Rogers et al. 2008) or within recent fire perimeters (Ewell et al. 2012). Other studies stated that treated areas ignited easily and did not inhibit fire progression, particularly where treatments were small or narrow, did not reduce surface fuels sufficiently, or where implementation was not complete (Graham et al. 2009, 2012). Managers generally considered fuel treatments successful at changing fire behavior, reducing spotting distances (distance between the main fire and new fires started by wind-transported sparks or embers), and reducing convective and radiant heat. In several reports (Fites et al. 2007a; Keller et al. 2011; Murphy et al. 2007), fire transitioned from very high intensity in untreated stands to low or moderate intensity as it entered stands where fuel reduction work had occurred. Treated stands were more likely to experience surface fire behavior rather than crown fire (Graham et al. 2009; Murphy et al. 2007). Treated areas also were reported as experiencing less torching (ignition of a tree or group of trees) and spotting than outside treatment areas (Murphy et al. 2010).

Several case studies focused on the potential for fuel treatments to facilitate fire suppression efforts, and in many cases, fuel treatments were considered to have made suppression resources more effective. For example, reduced rate of spread and shorter flame lengths in treatment areas provided opportunities for fire line construction, anchor points (barriers to fire spread from which to start building a fire line), safety zones (cleared areas used for firefighter escape if the line becomes unsafe), structure protection, and spot fire suppression (Fites et al. 2007b; Graham et al. 2009; Harbert et al. 2007; Reiner et al. 2014; Rogers et al. 2008). There were reports from fireline personnel stating that burnout operations (setting fire to consume fuel between the edge of the fire and the control line) were more successful where stand density and fuel load had been reduced (Fites et al. 2007b; Keller et al. 2011; Murphy et al. 2010), and previously treated areas along roads and trails greatly reduced the time needed to prepare for burn operations (Fites et al. 2007a; Henson 2007). Although fireline decisions are dynamic and are thus difficult to evaluate empirically, multiple studies reported that the presence of large fuel treatments contributed to firefighters' perception of safety and presented suppression opportunities that otherwise may not have been available.

Fire effects, or the impacts of fire on the environment, were less severe in treated than in untreated areas in many, though not all, of the case studies. Several case studies included quantitative analyses comparing at least one metric of fire severity in treated and untreated stands based on post-fire severity assessments, but high variability made statistical comparisons challenging, and many of the effects were interpreted qualitatively (see McKinney et al. for a review of empirical fuel treatment studies). Treated areas were reported to have lower tree crown consumption (Dailey et al. 2008; Fites et al. 2007b) and higher survival of large diameter trees (Jain et al. 2007), presumably due to treatment-related changes in tree canopy base height and consequent reductions in fire intensity. Similarly, in shrub-dominated ecosystems, treatments that reduced surface fuel load and shrub heights resulted in lower severity of fire effects on soils and vegetation (Reiner et al. 2014). However, reduced fire intensity did not always translate to reduced tree mortality: even where thinning treatments were credited with restricting fire behavior to a surface fire, extreme burning conditions and the presence of surface fuels sometimes resulted in near-total tree mortality (Graham et al. 2003). Managers also reported that treatments that were smaller, poorly maintained, or designed to modify only a single fuel layer were less effective at reducing fire severity than larger, recent treatments designed to modify multiple fuel layers (Crook et al. 2015; Graham et al. 2003).

Factors influencing fuel treatment effectiveness

Fuel treatments include a wide range of management approaches intended to alter fuels, each with its own effect on the distribution and abundance of fuels across multiple strata. Treatments also interact with the heterogeneous landscapes on which they are implemented, and outcomes are affected by temporal variability in fuels and weather at annual, seasonal, and daily scales. These complex interactions were consistently recognized in the manager case studies as influencing the effectiveness of fuel treatments and the outcomes of wildfire. The primary factors identified by the case studies included treatment effects on fuel layers, treatment recency, treatment size and placement in relation to topography and adjacent features, and weather conditions. Overall, the managers' perspectives of the factors influencing treatment effectiveness agreed with accepted fuel layer principles of forest fuel reduction treatments (Agee and Skinner 2005): reduction of surface fuels, increased height of the live crown, and decreasing crown density.

In the case studies, the effectiveness of treatments in mitigating wildfire outcomes was strongly related to the extent to which the treatments reduced surface, ladder, and crown fuels. Specifically, fuel treatments that reduced the load in multiple fuel layers were considered more effective in reducing fire intensity and severity than those designed to modify only a single layer. For example, several case studies reported that thinning and prescribed fire combined were most effective in combination compared to thinning or prescribed fire alone (Crook et al. 2015; Dailey et al. 2008; Fites et al. 2007a; Jackson et al. 2011; Murphy et al. 2010), consistent with a prior data-driven review of site-level treatment effects (Kalies & Kent 2016). Treated areas with abundant surface fuels, including incomplete treatment implementation (e.g., piles not burned), lop and scatter, or mastication without prescribed fire, did not result in adequate fuel reductions and often experienced severe fire effects on soil and vegetation (Fites et al. 2007a; Graham et al. 2003, 2012; Murphy et al. 2007, 2010). In other words, treatments that redistributed fuels were generally considered less effective than treatments that reduced fuels, consistent with common principles of fire science (e.g., Agee & Skinner 2005).

Although previous wildfires are not intentionally designed treatments, many managers considered their presence on the landscape to be an important driver of large wildfire events, and decisions around suppression tactics often considered previous fire boundaries within a mosaic of treated areas. Wildfires can be intentionally managed as a way to remove fuels (or achieve other resource benefits) when burning under conditions where low to moderate fire severity and intensity can be expected, and this approach can simultaneously accomplish fuel reductions and restore fire as an ecological process (Crook et al. 2015; Ewell et al. 2012). Previous wildfires, along with treatments such as higher-severity prescribed fires that experienced intensive reductions in surface fuels, had less severe fire effects than lower-intensity treatments. For example, Crook et al. (2015), Fites et al. (2007b), and Graham et al. (2003) found that recent wildfires appeared to be more effective at reducing fire severity than mechanical treatments. Previous wildfires and prescribed fires that created heterogeneous forest structures and composition tended to produce mosaics of fire severity following subsequent fires (Crook et al. 2015; Graham et al. 2009), an outcome that may meet both fuel reduction and forest restoration objectives simultaneously (Prichard et al. 2021; Stephens et al. 2021).

The abundance and distribution of fuels within treated areas are known to be directly related to time since treatment or past fire (Cochrane et al. 2013), and many of the case studies described a decline in the effectiveness of older treatments. Treatments are only effective for a finite time because fuels accumulate over time as vegetation regrows. Recent treatments, if completed, were consistently more effective at mitigating fire behavior and reducing fire severity than older treatments that had experienced vegetation regrowth (Crook et al. 2015; Graham et al. 2003, 2009; Harbert et al. 2007; Reiner et al. 2014). The case studies indicated that the length of time needed before retreatment depended on site productivity, plant species traits, and initial fuel removal, consistent with a broad-scale analysis of reburning potential after wildfires (Buma et al. 2020). More intensive fuel reductions within stands typically last longer than less intensive treatments, particularly after reductions in multiple fuel layers (Agee and Skinner 2005). For all treatment types, the long-term reduction of wildfire hazard requires maintenance of fuel treatments as they age (Agee and Skinner 2005; Reinhardt et al. 2008).

Thinning to low overstory densities can promote the regeneration and growth of young trees and shrubs, particularly if this regeneration is not controlled through the intermittent use of prescribed fire (Jain et al. 2020). This effect was documented in some of the case studies, where prior timber harvests without surface fuel removal resulted in relatively high mortality of the residual trees (Dailey et al. 2008; Graham et al. 2003). Recent tree plantations, which are often characterized by young forests and spatially homogenized fuels (e.g., Zald and Dunn 2018), were described as burning with greater fire severity than nearby unmodified fuels, while older plantations experienced lower fire severity (Graham et al. 2003). Treatments designed to introduce fire-resistant species rather than to control surface fuels, such as shelterwoods followed by overstory removal, may create ladder fuels in the short-term but more fire-resilient conditions in the long term (Agee and Skinner 2005).

Fuel treatments interact with spatial heterogeneity in topography, landscape features, and existing vegetation to influence post-fire outcomes. In many of the case studies, fuel treatment effectiveness was influenced by prevailing winds and how they interacted with topography. Fuel treatments on steep slopes were less effective in changing fire behavior or reducing fire severity than those on flatter ground, especially under high wind conditions (Harbert et al. 2007; Murphy et al. 2007). One case study (Henson 2007) found that areas previously treated with thinning and prescribed fire successfully slowed fire as it was backing downhill but did not impede rapid uphill runs. Fuel treatments strategically located along ridge tops, in which fuel reduction impacts coincide with topography-related reductions in the rate of spread, were considered particularly useful in facilitating fire suppression efforts (Harbert et al. 2007; Murphy et al. 2010) or reducing the probability that past fires reburned (Gray & Prichard 2015).

Large treatments were consistently considered more effective than smaller treatments. At landscape scales, networks of larger treated areas were more effective than smaller, disconnected treated areas at reducing fire effects (Jackson et al. 2011). Many of the case studies described how the momentum produced by large fires overwhelmed small fuel treatments (Crook et al. 2015; Dailey et al. 2008; Fites et al. 2007a; Murphy et al. 2010) and produced spots that easily breached narrow fuel breaks (Graham et al. 2012). Thus, treatment placement adjacent to previous treatments, wildfires, land uses that reduce vegetation, or natural firebreaks of nonflammable features (e.g., wetlands, rock outcrops) can increase the footprint of the treated area and amplify effectiveness. Alignment with prevailing winds places treatments in the path of where fires are most likely to occur, and orienting treatments to maximize the distance a fire travels through the treated landscape can increase the effect of the treatment on fire progression. Managers described the strategic placement of fuel treatments on the windward side of resource values such as housing developments and discussed the importance of aligning linear treatments parallel with prevailing winds to inhibit spotting across the treatment (Graham et al. 2009; Reiner et al. 2014). Placement in relation to suppression needs is critical in wildland-urban interface areas, taking into consideration access, egress, and communities at risk (Rogers et al. 2008). Overall, landscape-scale treatment designs that integrate fuels, topography, prevailing winds, fire or treatment history, and available infrastructure are more effective than opportunistically implementing small, disconnected treatments.

A common theme of the case studies was that, during periods of extreme fire weather, fuel treatment effectiveness declined regardless of other factors. Short-term fire weather is often the primary driver of fire activity (e.g., Hart & Preston 2020), making quantitative inferences about fuel treatment effectiveness challenging in large fires that span a range of fire weather conditions. Under more moderate burning conditions, treatments were generally considered effective at mitigating fire behavior and supporting suppression efforts; however, half of the case studies reported that at least some fuel treatments were less effective or ineffective because they were overwhelmed by extreme fire behavior during periods of extreme fire weather conditions (Crook et al. 2015; Dailey et al. 2008; Fites et al. 2007a; Graham et al. 2003, 2009, 2012; Harbert et al. 2007; Henson 2007; Rogers et al. 2008). Fuel treatments are typically designed for moderate weather conditions, yet to maintain effectiveness into the future, fuel treatment designs may need to incorporate the increasing probability of extreme fire weather conditions (Stavros et al. 2014, Abatzoglou & Williams 2016).

At shorter temporal scales, seasonal variation in vegetation phenology can have important effects on fire outcomes, especially in ecosystems with an important component of shrubs and other deciduous species. For example, the case study from the Great Lakes Region (Fites et al. 2007b) reported that treatments were more effective at moderating fire behavior in a summer-season wildfire compared to a spring-season wildfire, presumably because the summer fire occurred after understory plants had leafed out, helping to reduce fire behavior in treated areas. Although we had only one study from the Great Lakes Region, this observation suggests an important role of understory phenology that could inform fuel treatment effectiveness monitoring in similar vegetation types.

Barriers to implementation and research needs

Many barriers to implementing effective treatments were identified, including limited resources and competing objectives. Declining or variable funding levels for fuel treatments have impeded consistent long-term planning, implementation, and maintenance of fuel treatments (Reiner et al. 2014). Because resources for fuel treatments are limited, small treatments targeting high-value resources are often prioritized over landscape-scale treatment designs, despite evidence that strategic treatment designs that include adjacent wildlands increase protection opportunities in the wildland-urban interface (Jackson et al. 2011; Rogers et al. 2008). Targets for accomplishing treatments across large areas can also compete with retreatment needs, leading to the deterioration of fuelbreaks and other investments (Henson 2007). In some cases, fuel reduction goals directly conflict with other resource management objectives (Reinhardt et al. 2008). For example, in northern California, the protection of dense forest habitat for species such as spotted owl (*Strix occidentalis* Xántus de Vésey, 1860) is sometimes viewed as in conflict with fire risk reduction efforts (Fites et al. 2007a). Lastly, managers identified the need for increased communication with community cooperators and agency partners about the risks and gains of completing fuel treatments to improve engagement and coordinate planning efforts (Reiner et al. 2014).

Although these case studies cumulatively advance our understanding of landscape fuel treatment effectiveness, critical knowledge gaps remain, and several opportunities for future research were identified by the case study authors. Specific research needs included assessing the relationship between treatment scale and fire size (e.g., the potential for fuel treatments to prevent small fires from increasing in size), evaluating fire effects across forest and rangeland mosaics in complex topography, and the need for site-specific pre- and post-treatment data. Given the finding that higher-intensity treatments (e.g., combination of thinning and prescribed burning) were generally found to be most effective, there was an expressed need to quantify the cost and benefits of different landscape strategies, such as the tradeoff between treating more acres with less intense, low-cost treatments versus targeting fewer acres with more intense, high-cost treatments. Research is also needed to determine the environmental factors that drive the longevity of treatment effectiveness to inform the development of appropriate maintenance schedules. Finally, there is a need to better understand the interaction of topography and winds with treatment effectiveness, which would inform the placement of treatments across large landscapes.

Conclusions

Our thematic synthesis of wildfire case studies found that fire managers generally considered fuel treatments to be effective at landscape scales, mitigating adverse effects of wildfire by reducing flame lengths, changing fire behavior from crown to surface fire, limiting torching and spotting, and reducing fire effects compared to untreated areas. Fuel treatments generated opportunities for effective fire suppression, thereby minimizing costs and increasing safety, while also offering the prospect of intentionally managing fire to treat fuels and restore fire as an ecological process in fire-adapted ecosystems. However, fuel treatment effectiveness was influenced by several external factors. More intensive fuel reduction treatments that modified multiple fuel layers were considered more effective in reducing fire intensity and severity than those designed to modify only a single layer. Treatments are only effective for a finite length of time, and recent treatments were consistently more effective at mitigating fire behavior and reducing fire severity than older treatments that had experienced vegetation regrowth. Fuel treatment effectiveness was also influenced by landscape heterogeneity, and landscape-scale treatment designs that integrate fuels, topography, prevailing winds, fire or treatment history, and available infrastructure were more effective than small, opportunistic treatments. Actionable information for managers about treatment design at landscape scales to increase effectiveness included strategic treatment placement adjacent to prior treatments or fires and alignment with prevailing winds and topographic features. Treatment placement in relation to suppression needs is critical in wildland-urban interface areas. Importantly, treatment effectiveness was often limited during periods of extreme fire weather, highlighting the need for treatment designs to incorporate the increasing occurrence of extreme burning conditions.

Abbreviations

AGRIS: International System for Agricultural Science and Technology; CAB: Commonwealth Agricultural Bureaux; FEIS: Fire Effects Information System; FRAMES: Fire Research and Management Exchange System; JFSP: Joint Fire Science Program; U.S.: United States of America; USDA: United States Department of Agriculture.

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Authors' contributions

TBJ conceived of the study idea, and all authors designed the study approach. AKU and TBJ developed structured summaries of the case studies and used thematic synthesis to develop results. All authors contributed substantially to the writing and approved the final manuscript.

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Availability of data and materials

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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.

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