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REVIEW

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A systematic review of empirical evidence for landscape-level fuel treatment effectiveness

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Abstract

Background: Adverse effects of wildfires can be mitigated within fuel treatments, but empirical evidence of their effectiveness across large areas is needed to guide design and implementation at the landscape level. We conducted a systematic literature review of empirically based studies that tested the influence of landscape-level fuel treatments on subsequent wildfires in North America over the past 30 years to evaluate how treatment type and configuration affect subsequent wildfire behavior or enable more effective wildfire response.

Results: We identified 2240 papers, but only 26 met our inclusion criteria. Wildfire sizes ranged from 96 to 186,874 ha and total treated area ranged from 8 to 53,423 ha. Total treated area within a wildfire perimeter was highly correlated with wildfire area ($r = 0.89$, $n = 93$ wildfires), and the average proportion of wildfire area that was treated was 22%. All studies demonstrated wildfire behavior changes within treatment boundaries (i.e., site-level effect), but only 12 studies provided evidence that treatments influence wildfires outside of treatment boundaries (i.e., landscape-level effect). These 12 landscape-level papers showed effects on fire severity, fire progression, and fire extent, but were dissimilar in design and analysis approaches, constraining the ability to generalize about the type and configuration of fuel treatments to maximize effectiveness.

Conclusions: It is clear that the state of knowledge based on empirical evidence is at its infancy. This is likely because of the vast challenges associated with designing and implementing sampling designs that account for combinations of spatial and temporal configurations prior to wildfire occurrence. We also suspect part of the reason empirical evidence is lacking is because the distinction between site-level and landscape-level effects is not well recognized in the literature. All papers used the term landscape, but rarely defined the landscape, and some specified identifying landscape-level effects that were truly site-level effects. Future research needs to develop innovative ways to interpret the role of fuel treatments at the landscape level to provide insight on strategic designs and approaches to maximize fuel treatment effectiveness.

Keywords: Empirical, Fire behavior, Fire extent, Fire management, Fire severity, Fuel treatment, Landscape, Spatial

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Resumen

Antecedentes: Loe efectos adversos de los incendios de vegetación pueden ser mitigados con tratamientos del material combustible, aunque evidencias empíricas sobre su efectividad a través de grandes áreas es necesaria para orientar su diseño e implementación a escala de paisaje. Condujimos una revisión sistemática de literatura de trabajos empíricos que probaron la influencia de los tratamientos de combustible a nivel de paisaje sobre los incendios posteriores en Norteamérica en los últimos 30 años, para evaluar cómo el tipo de tratamiento y su configuración, afectan el posterior comportamiento del fuego o permiten una repuesta más efectiva a los incendios.

Resultados: Identificamos 2.240 artículos científicos, aunque sólo 26 cumplieron con nuestro criterio de inclusión. El tamaño de los incendios varió entre 96 a 186.000 ha, y el área total tratada varió entre 8 y 53.423 ha. El área total tratada dentro de un perímetro se correlacionó altamente con el área de los incendios ($r = 0{,}89$, $n = 93$ incendios), y el porcentaje del área afectada por estos incendios dentro de las áreas tratadas fue del 22%. Todos los estudios mostraron cambios en el comportamiento del fuego dentro de los límites de los tratamientos (i.e. efectos de sitio), aunque sólo 12 mostraron evidencias de la influencia del tratamiento por fuera del límite de éstos (i.e. efectos del paisaje). Estos 12 estudios relacionados con consecuencias en el paisaje mostraron efectos en la severidad, progresión, y extensión de los incendios, pero al haber sido diferentes en el diseño y en los análisis efectuados, condicionó la posibilidad de generalizar el tipo y configuración de los tratamientos para maximizar su efectividad.

Conclusiones: Está claro que el estado del conocimiento basado en evidencias empíricas está en sus etapas iniciales. Esto es probablemente por los vastos desafíos asociados con la planificación e implementación de diseños de muestreos que tengan en cuenta las configuraciones espaciales temporales previo a la ocurrencia de incendios. Sospechamos asimismo que parte de la razón por la cual la evidencia empírica falta, es porque la distinción entre nivel de sitio y nivel de paisaje no está bien reconocida en la literatura. Todos los artículos relevados usaron el término paisaje, pero raramente lo definieron, y algunos efectos identificados como niveles de paisaje, son realmente efectos de niveles de sitio. Investigaciones futuras necesitan desarrollar caminos innovadores para interpretar el rol de los tratamientos de combustible a nivel de paisaje para proveer de una visión de diseños y enfoques estratégicos, para maximizar la efectividad de los tratamientos de combustibles.

Introduction

A fuel treatment is the manipulation or removal of vegetation to reduce the likelihood of wildfire ignition and spread, lessen potential damage from wildfire, or improve conditions for wildfire management, including suppression (Deal 2018). These treatments ultimately seek to create forest or rangeland conditions that manage the risks, costs, and benefits of wildfire in support of land management goals. Favorable conditions often include high canopy base heights, separated tree crowns, reduced and discontinuous surface fuels, and a species assemblage that is resistant or resilient to fire (Agee and Skinner 2005). To create these conditions, land managers use diverse silvicultural methods alone or in combination, including prescribed fire, mastication, slashing and piling, hand thinning, commercial and noncommercial thinning, regeneration harvests, and herbicides (e.g., Hunter et al. 2007; Jain et al. 2012). In some cases, artificial regeneration (e.g., direct seeding and planting) can be used to enhance fire resilience and reduce wildfire occurrence and size by altering species composition and age structure (Agee and Skinner 2005) or by establishing vegetative fuel breaks of fire resilient species (i.e., green-stripping, St John, Ogle 2008; Shinneman et al. 2018). In practice, each method treats a specific fuel matrix on a specific site. For example, commercial thinning to separate crowns and raise canopy base height can be combined with prescribed fire to reduce surface and ground fuels. When multiple treatments are implemented together, they can be spatially arranged in a fuel treatment design that reduces wildfire severity and rate of spread using a specific configuration or fuel breaks at specified locations (e.g., Finney 2001; Finney et al. 2007).

Through experiments, observation, and modeling under a wide range of conditions, researchers and land managers have repeatedly demonstrated the ability of various fuel treatments and fuel treatment designs to modify wildfire behavior, provide wildfire suppression opportunities, and reduce negative effects compared to untreated controls within a treatment area. However, the conditions under which such treatments are effective in reducing the short- and long-term risks of undesirable wildfire across broad spatial extents (e.g., watersheds, basins, and large areas spanning thousands of hectares) is highly variable, less certain, and difficult to quantify because the number of factors that influence wildfire behavior and effects increase with increasing spatial extent. In addition, the process used to design and schedule fuel treatments often requires land managers to balance other ecological and social goals in addition to altering fire behavior (Bahro et al. 2007). Heterogeneity in fuels, topography, weather, spatial patterns, treatment design, and other variables further complicate the evaluation of fuel treatment effectiveness over broad spatial areas.

Wildfire is a disturbance process that generally operates on a spatial scale of 10^2 to 10^8 m^2 and is considered a landscape-level process because wildfire responds to and creates heterogeneous patterns (Turner and Gardner 2015) and spreads across diverse landforms, ecosystems, and administrative boundaries. Therefore, if the management goal is to create a large spatial area where wildfire behavior is altered to reduce risk and negative effects, fuel management strategies must link site-specific, project-scale fuel treatments to the broader area at which wildfires occur. Indeed, a true indication of a 'landscape-level effect' is the ability of treatments to affect wildfire metrics (e.g., severity, spread rate, extent, etc.) outside of treatment footprints (Lydersen et al. 2017). Quantifying a landscape-level effect is needed to evaluate landscape-level fuel treatment effectiveness and is contrasted with measuring the effects of fuel treatments solely within treatment boundaries (i.e., site-level effects) (Fig. 1). Site-level effects of fuels treatments are well-documented, and a thorough review exists in Kalies and Yocom Kent (2016).

Primary research focused on the effectiveness of fuel treatment at broad spatial extents generally falls into

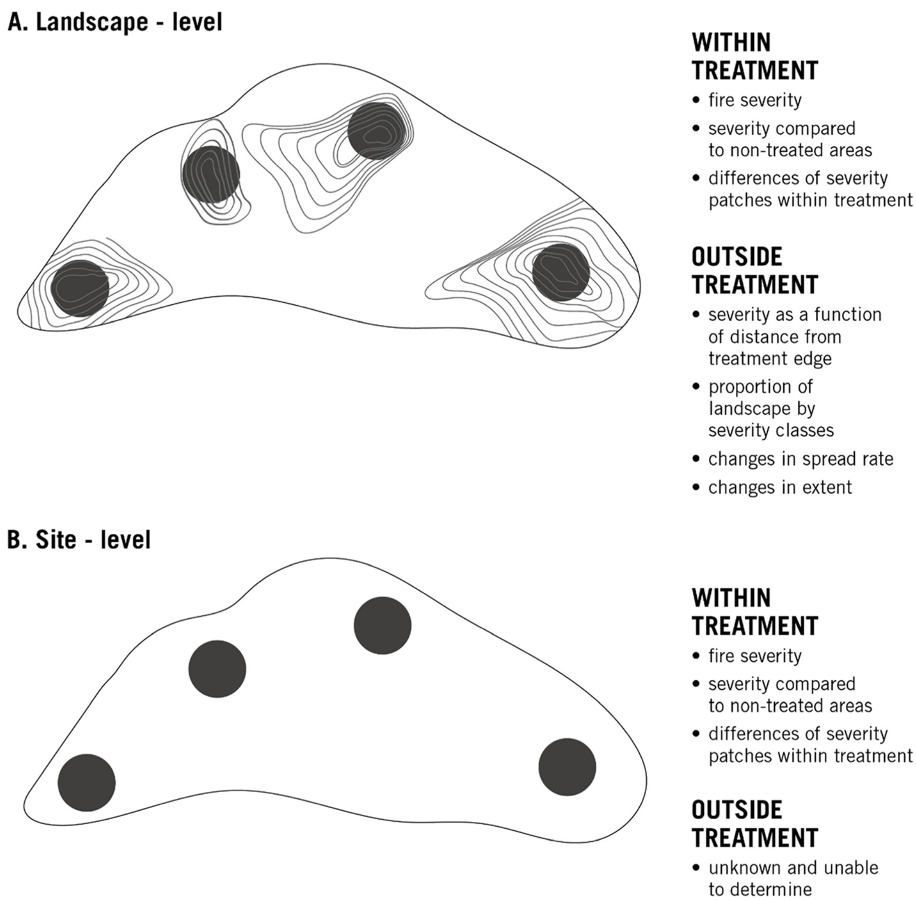

Fig. 1 The landscape-level effect hypothesis posits that fuel treatments can affect wildfire behavior outside of their footprint (i.e., in untreated areas). To test this hypothesis, a study must quantify a link between conditions within fuel treatments and some metric of fire behavior or effect outside of the treatment footprint. In both **A** and **B**, the dark line represents the perimeter of a wildfire and the dark circles within each perimeter represent treatment locations. In scenario **A**, the lighter lines represent contours of influence where the effect of the treatment permeates into untreated areas and decays with distance from treatment boundary. Asymmetric contour shapes reflect the notion that fire behavior outside of treatment boundaries will also be influenced by spatial heterogeneity in biological and physiographic characteristics. White areas represent untreated areas that are unaffected by conditions within the treatments. Scenario **A** can be interpreted as a prediction of the landscape-level effect hypothesis, that if true, then a spatial relationship exists between within treatment and outside of treatment conditions during a wildfire. Scenario **B** would not provide the necessary information to test the landscape-level effect hypothesis and is instead site-level; inference of treatment effect is restricted to within treatment boundaries. Text in the right-hand column provides examples of information that can be obtained for both scenarios **A** and **B**

three categories: (1) research that uses planned experiments or post-fire observations paired with statistical or model-based inference, referred to here as "empirical studies"; (2) research that uses a variety of simulation, statistical and computer modeling techniques to evaluate effectiveness primarily through model-based inference; and (3) case studies of past wildfires that provide anecdotal evidence, analysis, and insight into fuel treatment effectiveness at the landscape level, but do not make statistical or model-based inferences. Though their underlying methods are different, these approaches interact to quantify treatment effects and evaluate whether fuel treatments meet their stated objectives at the landscape level, with the common goal of improving fuel management and wildfire outcomes.

In this systematic literature review, we focus on empirical research of fuel treatments and actual wildfires to evaluate various metrics of effectiveness at the landscape level. The research reviewed here includes planned vegetation management that has fuels reduction as a primary objective, even if it was not explicitly called a "fuel treatment". In some cases, previous wildfire and the conditions following it are considered a fuel treatment. Most papers evaluated fuel treatment effectiveness at the landscape level following a wildfire that interacted with multiple fuel treatments or contiguous treatment over a large area. In all cases, the research reviewed here examines the effectiveness of fuels treatments in natural environments (i.e., empirical studies), rather than simulated or modeled fires over simulated or modeled landscapes.

Our primary objectives in this systematic literature review are to (1) provide a literature synopsis of the state of knowledge on landscape-level fuel treatments and (2) generalize results with a focus on evaluating landscape-level fuel treatment effectiveness across diverse metrics including wildfire characteristics, suppression opportunities, and ecosystem response. Our goal is to synthesize research findings to answer the question: How does treatment type and configuration affect intensity, rate of spread, and patterns of severity for subsequent wildfires or enable more effective wildfire response?

Empirical studies carried out at the landscape-level are relatively few compared to simulation and modeling projects, or studies focused on the operational, organizational, and public policy aspects of wildfire and fuels management. In large part, this is due to the difficult logistics, high expense, and potential risks of carrying out wildfire experiments over large areas. However, this concentrated body of research provides a critical scientific underpinning for improving the design, implementation, and use of fuel treatments in ways that accomplish land management objectives over large landscapes, addressing a critical need in fire-prone regions subject to intensifying wildfire activity under climate change. The goal of this review is to leverage and synthesize previous research to help improve landscape-level fuel management in practice and guide new research forward as land managers race to expand the pace and scale of fuel treatment. To date, a comprehensive synthesis of the available literature on empirically based landscape-level fuel treatment effectiveness with a systematic assessment of research gaps does not exist.

Methods

We conducted the literature search in October and November 2019 in collaboration with staff from the United States Department of Agriculture (USDA) Forest Service Library. Our search considered any literature published between 1990 and 2019 (inclusive) and was geographically limited to research conducted wholly in the USA and Canada. Using a wide range of key words and search terms (Table 1) with their truncated forms and Boolean operators developed for database search algorithms (Appendix), Forest Service Library personnel searched the Web of Science (Clarivate Analytics 2021), Scopus (Elsevier 2021), and the National Agricultural Library (NAL) Navigator databases. The search was focused on research conducted in ecosystems associated with fuel treatment as identified by expert

Table 1 Search terms used in the systematic review of landscape-level fuel treatment effectiveness. All variants of these terms were captured in the truncated terms used in the search (see Appendix)

Ecosystem terms	Methods	Wildfire terms	Other terms
Badland	biocontrol	behavior	configure
Barren	biological harvest	burn	cost
Chaparral	biological control	fire	deploy
Desert	brownstrip	flame	design
Dryland	brush control	frequency	effective
Forest	chain	fuel	efficacy
Glade	chemical control	hazard	landscape
Grassland	cut/cutting	intensity	leverage
Heathland	grazing	load	longevity
Outcrop	greenstrip	reduce	mitigate
Prairie	herbicide	risk	resilience
Rangeland	mastication	severity	resistance
Savanna	mechanical	suppression	scale
Scrub	mow	threat	spatial
Shrubland	pile	wildfire	
Steppe	prescribed		
Tall forb	seeding		
Tundra	slashing		
Woodland	thinning		

opinion and broadly defined by a variety of search terms (Table 1). Additional terms were used to identify relevant silvicultural methods, fuel and wildfire attributes, spatial scales, treatment outcomes, and other aspects of landscape fuel treatment (Table 1).

In addition to these searches, the Fire Research and Management Exchange System (FRAMES; University of Idaho 2021), FS/Info, and Treesearch database (USDA Forest Service 2021a) were searched using the search terms "landscape," "fuel," and "treatment." The Forest Service Citation Retrieval System (CRS; USDA Forest Service 2021b) was searched using the keywords "landscape," with "fire" and truncated forms of "hazard," "reduce," "reduction," and "fuel management." These additional searches in government databases were conducted to target government publications and primary research papers that were potentially absent from Web of Science, Scopus, and NAL databases. Identical search terms were not used in these searches to accommodate constraints on the native search functions in these systems.

The above searches resulted in 2240 unique citations from the seven search engines of multiple citation databases. We employed a multi-step review process to select papers from this large pool and applied a set of a priori inclusion/exclusion criteria to select papers to be included in this review. Papers had to address some aspect of a fuel treatment project at a landscape level. We defined a fuel treatment as the manipulation of live or dead vegetation that has the potential to influence fire behavior. We defined landscape level as an area that is larger than the treated area and has the potential to be influenced by the treated area. Furthermore, since the term landscape is typically applied to areas larger than the stand or patch, but smaller than the region, we applied a rough guide of 40 km^2 as the minimum study area size, with no minimum treatment area size.

A subgroup of five team members tested our selection process (i.e., application of the inclusion/exclusion criteria) on a subset of randomly chosen papers before applying it to all 2240 citations. During this process, we identified redundancy in which the same study was published multiple times in different forms, such as in a report, proceedings, or other non-peer reviewed medium and also as a peer-reviewed journal article. In these situations, we selected the peer-reviewed journal version of the research for inclusion in the literature review, thereby avoiding duplication of results.

The selection process identified 120 papers of the 2240 citations that met our criteria and were examined more thoroughly (Fig. 2). The primary reason for the large reduction in the number of selected papers relative to the original search results of 2240 citations was study area size. Many excluded studies were not conducted at a size or scale that met our criteria for landscape. For example, many papers included the term "landscape" in the title, abstract, or keywords, but were not landscape-level studies according to our definition because the study area was too small (e.g., plot). Another leading reason for papers being excluded was that they were off topic. Because the initial keyword search was quite broad (Table 1, Appendix), our results included many papers where vegetation was manipulated but for purposes other than fuel management to reduce the likelihood of wildfire ignition, lessen potential damage from wildfire, or improve conditions for wildfire management. Papers on biofuels from naturally occurring woody and herbaceous biomass were a prominent example of this literature group that was excluded.

In the next phase of selection, we reviewed each of the 120 papers and determined whether it was an empirically based study (Fig. 2). Empirical studies examined effectiveness of fuels treatments in natural environments, as opposed to computer-generated environments and simulated fires, and applied statistical methods to derive inference of effects and effectiveness. We identified 26 papers as empirical studies and then searched the bibliographies of these 26 papers to identify additional related papers that were not found in the original search. This

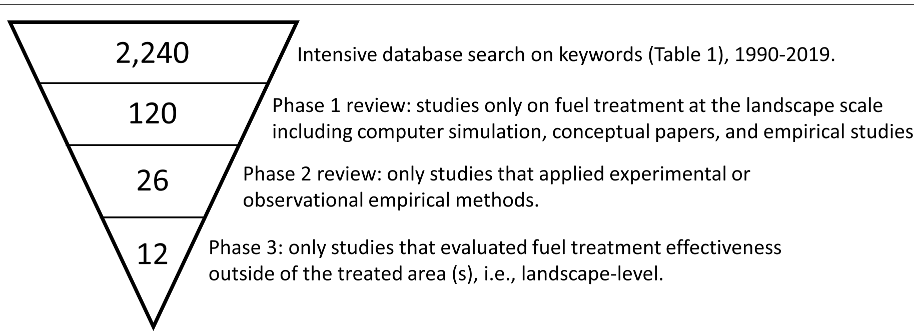

Fig. 2 Literature evaluation and phases used to identify publications that met selection criteria for the systematic review of landscape-level fuel treatment effectiveness. Numbers are polygons that represent the number of papers identified in each phase

subsequent search process concluded in May 2020. None of the candidate papers identified in the bibliography search applied to the selected papers met the inclusion criteria for this literature review.

Of the 2240 unique citations identified in the initial literature search, 26 are reviewed here based on their use of an empirical design to evaluate fuel treatment effectiveness at the landscape level. To guide the review, we identified 39 distinct elements that characterize these papers and directly address our study objectives. Specific elements are discussed in detail below with associated results, but in general, they concisely describe the study location, design, treatment objectives, variables, outcomes, results, and conclusions of these studies. This information was systematically extracted from each paper and entered into a database to form the foundation of the subsequent analyses and synthesis.

Results

Our systematic review of the literature found 26 empirical studies that used observational or experimental methods to evaluate the effects of one or more fuel treatments at what was considered to be the landscape level (Table 2).

Landscape-level effect analysis

The landscape-level effect hypothesis posits that fuel treatments that are strategically deployed in space and time can affect wildfire outcome in areas outside of the treatment boundaries (or footprint). Studies that met the strict definition for analyzing landscape-level treatment effectiveness are ones that evaluated the ability of fuel treatments to affect wildfire behavior or fire effects outside of the treatment footprint (Fig. 1). It is difficult to implement a rigorous study design that tests this landscape-level effect hypothesis because doing so requires that multiple wildfires burn through different areas containing fuel treatments that were strategically placed in a variety of designs on the landscape while accounting for other sources of variation. It is not surprising, then, that the subset of papers that provided results for treatment effects at the landscape-level was small ($n = 12$), their approaches were diverse and often were based on opportunistic or serendipitous wildfire events. Indeed, landscape-level analysis represented a small part of the overall study results in each of the 12 papers, which instead largely focused on site-level effects of fuel treatments within the treatment footprint (Fig. 1). The remaining 14 studies discussed treatment effectiveness at the landscape level (i.e., they met the inclusion criteria), but we classified them as site-level studies (despite some studies with large wildfire and/or treatment sizes), because they did not assess how treatments affected subsequent fires outside of the treated footprint.

Literature synopsis (objective 1)

Twenty-four of the 26 studies identified in our search and selection procedures were published in peer-reviewed journals, one was a report (Joint Fire Sciences Report), and one was a Forest Service Research Paper (Research Station). The 26 selected studies evaluated landscapes distributed in the Western and Southeastern United States (Fig. 3) and Canadian Rockies (Stevens-Rumann et al. 2016), and many of these studies evaluated multiple study sites. The most studied ecoregions (Level III, US Environmental Protection Agency 2013) included the Arizona/New Mexico Mountains (11 sites); Sierra Nevada, Idaho Batholith, Northern Rockies, Cascades, and Southern Rockies (5 sites each); and Southern California Mountains (3 sites). Six study sites in the Southeast included the Southeastern Plains, Mississippi Valley Loess Plain, Southern Coastal Plain, Southern Florida Coastal Plain, South Central Plains, and Ozark Highlands ecoregions, and there were two study sites in the Northern Lakes and Forests ecoregion. In the Western United States, 74% of the studies occurred on ponderosa pine dominated ecosystems and 52% of the studies occurred on Douglas-fir forests, and some studies included both ecosystems. The remaining studies focused on pinyon-juniper, fir-spruce, chaparral, and lodgepole pine. Ecosystems in the South and Southeast included longleaf-slash pine, oak-gum-cypress, loblolly-shortleaf pine, oak-pine, and oak-hickory.

Studies of landscape-level fuel treatment effectiveness examined many treatment methods (e.g., prescribed fire, commercial thin, fuel break) including individual and combined treatments (Fig. 4). However, some studies that included multiple treatment methods did not evaluate effects of the different treatments independently, but rather lumped different methods into a single class for analysis. Individual treatment methods were studied more often than combined treatments, and prescribed fire was the most studied treatment method (Fig. 4). Thinning treatment methods varied among studies and included treatments that reduce tree density using equipment and by hand under various silvicultural prescriptions (e.g., thinning from below, shelterwood) and product removals (e.g., noncommercial harvest, commercial harvest). The effectiveness of fuel breaks, defined as wide blocks or strips on which vegetation was manipulated to create lower fuel volume and reduced flammability, was also studied, and often entailed a combination of treatment methods. Wildland fires as fuel treatments were also studied. These included wildfires that were actively suppressed and wildfires that were intentionally managed so they could meet resource objectives. We did not find any landscape-level studies that assessed grazing, herbicide, or seeding/planting as fuel treatments.

Table 2 Empirical studies ($n = 26$ papers) identified in the systematic review of landscape-level fuel treatment effectiveness and organized by evaluation method. Landscape-level fuel treatment effectiveness is the ability of fuel treatments to affect wildfire outside of the treated footprint. Site-level studies address large wildfires and treatments within them, but only evaluate the effectiveness within the treated footprint. Other includes landscape-level studies, but that were not spatially explicit (Addington et al. 2015; Brewer and Rogers 2006), or a broad evaluation of fuel treatment effects when wildfires encountered these fuel treatments (Barnett et al. 2016)

Citation	Title
Landscape-level fuel treatment effectiveness	
Arkle et al. 2012	Pattern and process of prescribe fires influence effectiveness at reducing wildfire severity in dry coniferous forests
Cochrane et al. 2012	Estimation of wildfire size and risk changes due to fuels treatments
Cochrane et al. 2013	Fuel treatment effectiveness in the United States
Finney et al. 2005	Stand- and landscape-level effects of prescribed burning on two Arizona wildfires
Lydersen et al. 2017	Evidence of fuels management and fire weather influencing fire severity in an extreme fire event
Parks et al. 2015	Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression
Prichard and Kennedy 2014	Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event
Syphard et al. 2011a	Comparing the role of fuel breaks across southern California national forests
Syphard et al. 2011b	Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California
Tubbesing et al. 2019	Strategically placed landscape fuel treatments decrease fire severity and promote recovery in the northern Sierra Nevada
Wimberly et al. 2009	Assessing fuel treatment effectiveness using satellite imagery and spatial statistics
Yocom et al. 2019	Previous fires and roads limit wildfire growth in Arizona and New Mexico, U.S.A.
Site-level fuel treatment effectiveness	
Briggs et al. 2017	Short-term ecological consequences of collaborative restoration treatments in ponderosa pine forests of Colorado
Cannon et al. 2018	Collaborative restoration effects on forest structure in ponderosa pine-dominated forests of Colorado
Huffman et al. 2017	Efficacy of resource objective wildfires for restoration of ponderosa pine (*Pinus ponderosa*) forests in northern Arizona
Hunter et al. 2011	Short- and long-term effects on fuels, forest structure, and wildfire potential from prescribed fire and resource benefit fire iin southwestern forests, USA
Jain et al. 2007	Vegetation and soil effects from prescribed, wild, and combined fire events along a ponderosa pine grassland mosaic
Kennedy and Johnson 2014	Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland-urban interface during the Wallow Fire, Arizona, USA
Parks et al. 2016	Wildland fire limits subsequent fire occurrence
Safford et al. 2012	Fuel treatment effectiveness in California yellow pine and mixed conifer forests
Stevens-Rumann et al. 2013	Pre-wildfire fuel reduction treatments result in more resilient forest structure a decade after wildfire
Waltz et al. 2014	Effectiveness of fuel reduction treatments: assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ
Stevens-Rumann et al. 2016	Prior wildfires influence burn severity of subsequent large fires
Other	
Addington et al. 2015	Relationships among wildfire, prescribe fire, and drought in a fire-prone landscape in the south-eastern United States
Barnett et al. 2016	Beyond fuel treatment effectiveness: Characterizing interactions between fire and treatments in the US
Brewer and Rogers 2006	Relationships between prescribed burning and wildfire occurrence and intensity in pine-hardwood forests in norther Mississippi, USA

There was a broad distribution of wildfire size (Fig. 5) and total treatment size (Fig. 6) studied among the 26 papers. Wildfire and total treatment size distributions were both characterized by right skewness stemming from a few large size values with a wildfire size range of 186,778 ha and a total treatment size range of 53,415 ha (Table 3). Despite the broad range in values, wildfire size and total treatment size were highly correlated among the studies (Pearson's correlation $r = 0.89$, $n = 93$, $df = 91$, $p < 0.05$) (Fig. 7), suggesting that there was a consistent and positive relationship between the total area treated and wildfire size. The proportion of wildfire area that was treated

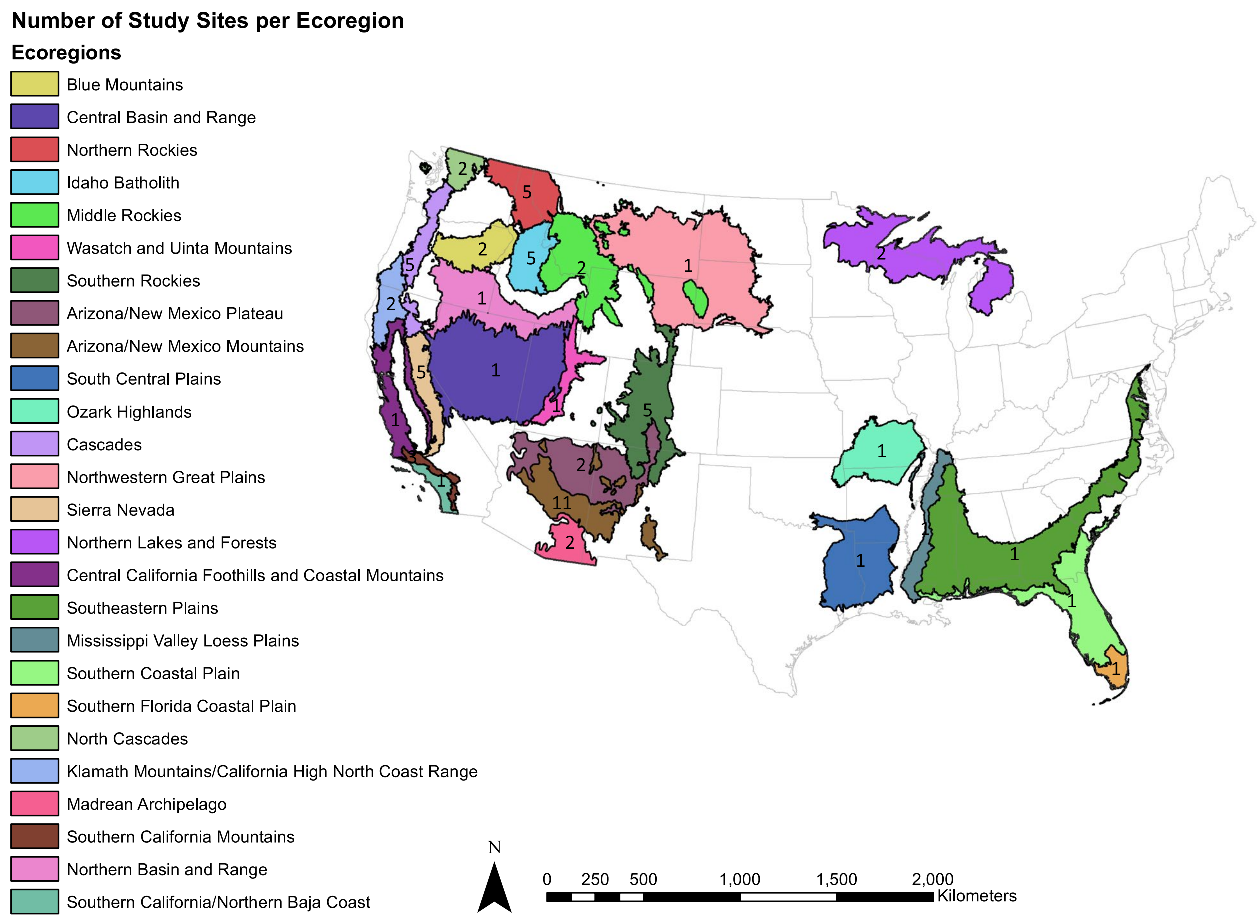

Fig. 3 Number of study sites within level III EPA Ecoregions in the USA (US Environmental Protection Agency 2013) from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness. This figure does not include study sites in Barnett et al. (2016), which evaluated all fuel treatments on federal lands in all ecoregions

was less variable (lower %SE) than either wildfire size or total treatment size (Table 3). On average, 22% of wildfire areas had received fuel treatments, but this ranged by 94% among all wildfires (Table 3).

The most common research objectives examined the effects of fuel treatments on wildland fire characteristics (e.g., fire severity, fire size, fire behavior), or on ecosystem response (e.g., stand structure, or creating disturbance-resilient conditions). Study objectives that focused on fuel treatment effects included fire severity (13 studies), fire size (8 studies), fire intensity (1 study), and ecosystem response (9 studies). Some studies also included how the spatial design (9 studies) and deployment (3 studies) of fuel treatments affect wildland fire characteristics. All the studies were concerned with fire management or ecological characteristics or both. Fire management considerations were addressed in 78% of the papers, while 59% addressed ecological considerations. Economic (3 studies), social (3 studies), and political (2 studies) considerations were addressed, but these were not explicitly quantified or compared statistically in any paper.

We identified numerous independent variables among the 26 studies in addition to treatment methods, implementation methods, and fire types (e.g., prescribed, past wildfire, resource objective). They included comparisons between treated and nontreated (or control) areas. Physical setting and weather prior to or during a wildfire event (e.g., drought indices, energy release component). Treatment related variables included time since treatment, distance from treatments, location of treatment (ecoregion or physical setting), treatment size, treatment frequency (number of times prescribed fire was implemented), treatment intensity, and fuel break length. Wildland fire-related variables included time since last disturbance (wildfire), prescribed fire or wildfire size, and suppression capabilities (i.e., firefighter access).

Response variables encompassed fire-related variables, forest structure characteristics, fuel metrics, and ecological responses that were measured and expressed in a multitude

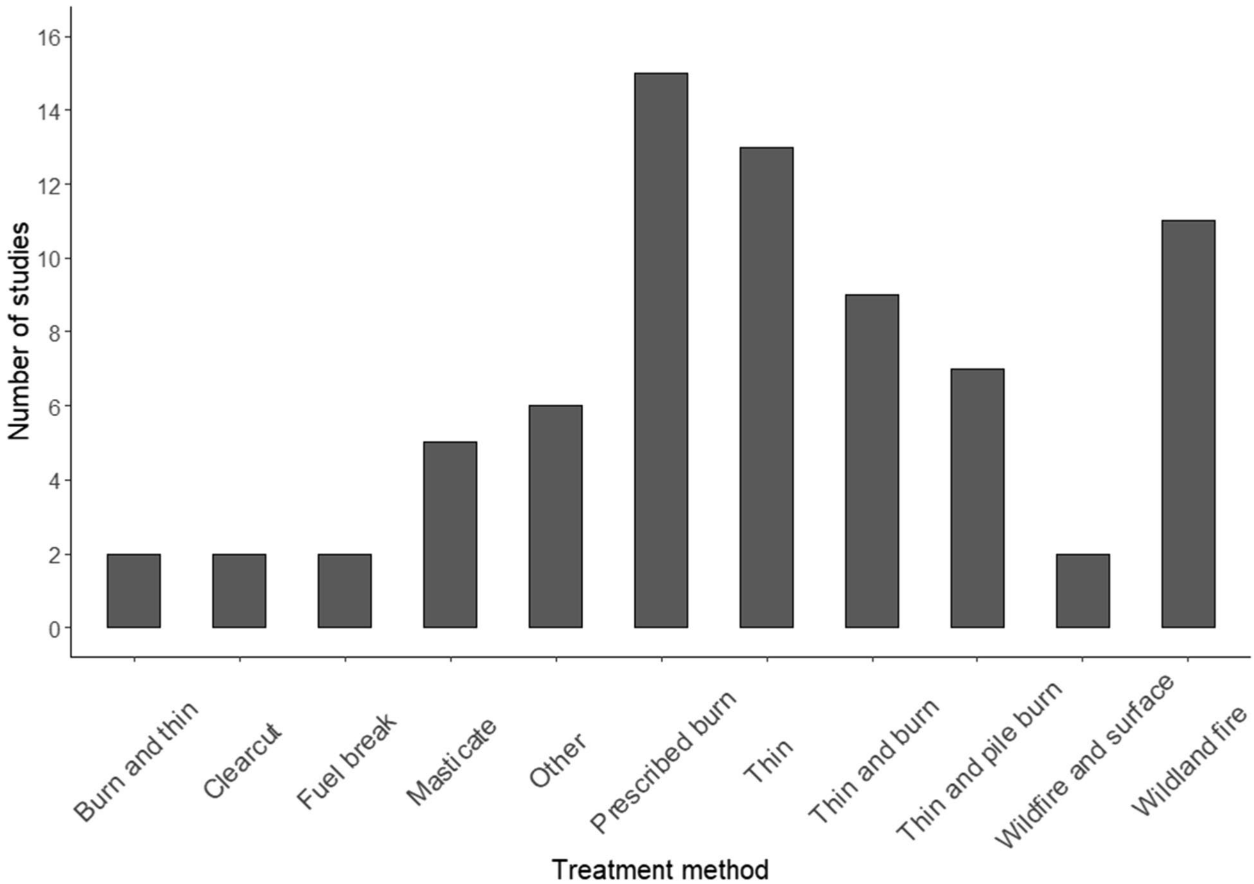

Fig. 4 Number of studies that evaluated each treatment method from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness. Note that some studies evaluated more than one treatment method

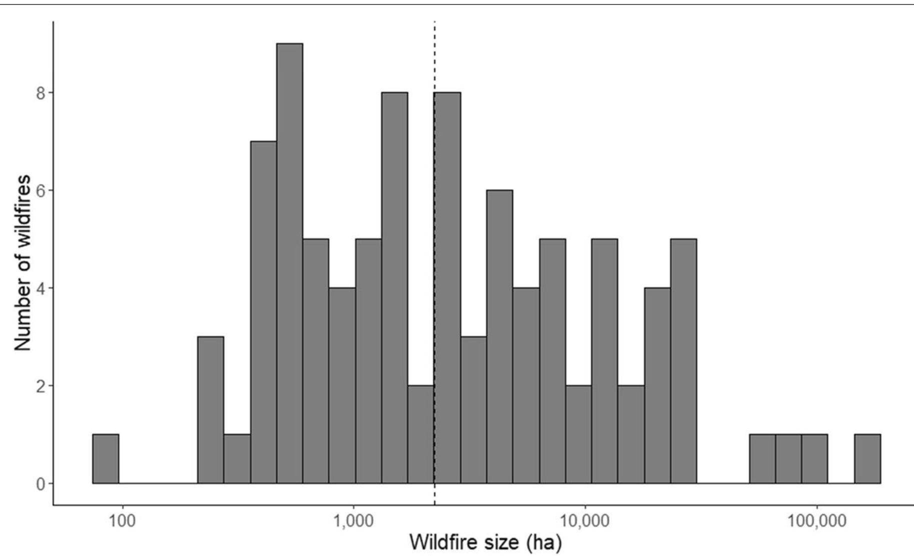

Fig. 5 The distribution of wildfire sizes ($n = 93$ wildfires) from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness. Dashed vertical line indicates the median value. Note that the *x*-axis is on a log10 scale

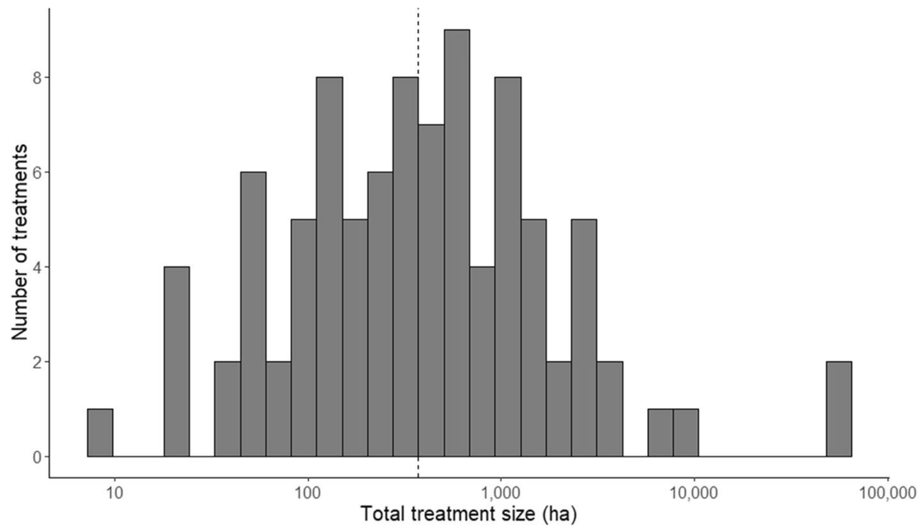

Fig. 6 The distribution of total treatment sizes within 93 wildfire perimeters from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness. Total treatment size is the sum of all the treated areas occurring within a wildfire perimeter. Dashed vertical line indicates the median value. Note that the *x*-axis is on a log10 scale

of ways and derived from field- and satellite-based observations. Fire-related variables included severity, incidence, extent, intensity, probability of occurrence, rate and/or probability of spread, ignition, growth, pattern, and encounter rate. Ecological and structural factors were also measured as the response to fuel treatments. For example, exotic understory plants, tree basal area, tree density, canopy cover, gap cover, gap frequency, species composition, coarse woody debris, snag density, patch density, patch size, canopy base height, canopy fuel load, and canopy bulk density were all represented as response variables among the studies.

Design-based and model-based sampling strategies were both employed among the studies. Design-based approaches included a variety of factorial designs or Before-After-Control-Impact (BACI) designs, while model-based approaches used post-wildfire field and/or remotely sensed data to build statistical or machine learning models to evaluate fuel treatment effectiveness.

Table 3 Summary statistics of variables extracted or derived from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness ($n = 93$ wildfires). Proportion is the proportion of wildfire area that was treated

Variable	Mean	Median	Min	Max	%SE
Wildfire size (ha)	9468	2235	96	186,874	26.1
Treatment size (ha)	1892	372	8	53,423	40.7
Proportion	0.22	0.17	0.01	0.95	9.1

Landscape fuel treatment effectiveness (objective 2)

We searched each paper for how the authors defined or implied what they meant by fuel treatment effectiveness and more importantly how they defined or implied landscape-level fuel treatment effectiveness. In general, fuel treatment effectiveness was interpreted as changing a particular factor or set of factors in a desirable direction. Eleven factors were identified among the 26 studies (with the number of studies addressing the factor shown in parentheses): severity (12), behavior (8), spread (5), ecological function and resilience (4), forest structure (3), hazard (3), resistance (3), crown fire potential (2), wildland fires as fuel breaks (2), allow for management (1), and returning landscapes to the historical range of variation (HRV, 1). Similarly, we assessed how studies measured landscape-level fuel treatment effectiveness and grouped responses into the following 13 factors (with the number of studies addressing each factor shown in parentheses): severity (13), spread (9), structure (7), biodiversity (3), fuels (3), size (2), spatial heterogeneity (2), incidence (1), encounter rate (1), intensity (1), crown fire (1), flammability (1), and large tree survival (1).

We were unable to answer the key research question—How does treatment type and configuration affect intensity, rate of spread, and patterns of severity for subsequent wildfires or enable more effective wildfire response? Studies rarely evaluated the effects of individual or combined treatment types and spatial configuration was not assessed explicitly due to the extreme challenges of implementing an appropriate study design at this broad spatial level. Hence, strong conclusions that

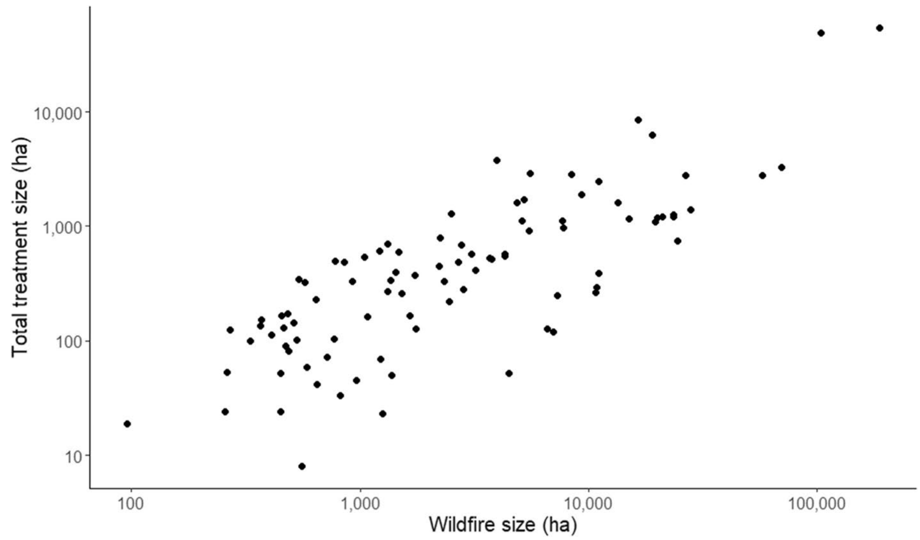

Fig. 7 The relationship between wildfire size and treatment size (Pearson's correlation $r = 0.89$, $n = 93$, df $= 91$, $p < 0.05$) from 26 papers identified in the systematic review of landscape-level fuel treatment effectiveness. Total treatment size is the sum of all the treated areas occurring within a wildfire area. Note that both axes are log10 scale

would inform operational decisions, such as the size, shape, pattern, and type of treatments to deploy, are not possible based on current published information. Below we outline the landscape-level findings for the three wildfire parameters addressed in these 12 papers that we found to estimate landscape-level effects (Table 2).

Wildfire severity There is evidence that fuel treatments can reduce the amount of area experiencing high severity fire outside of treatment boundaries. The area of high severity declined with increasing proportion of area treated at three spatial extents (202 ha, 1012 ha, 2023 ha) in the Rim Fire, California (Lydersen et al. 2017). The authors found that across all three spatial extents there was a negative relationship between the proportion of the landscape treated and the proportion of the landscape that burned at high severity. At the largest spatial extent (2,033 ha), 10–40% of the landscape needed to be treated for the proportion of high fire severity to decline precipitously compared to the need to treat 50–75% of the area at the smallest spatial extent (202 ha) to decrease the proportion of high severity. However, at both 202 ha and 1012 ha spatial extents, fire weather (defined by burn index or energy release) played a more important role in fire severity than the amount of the area treated.

A lower proportion of high severity fire was also observed in an area where Strategically Placed Landscape Area Treatments (SPLATS) were implemented compared to an adjacent untreated landscape following the American Fire in California (Tubbesing et al. 2019). The SPLAT area had 18% of its landscape treated prior to the fire and this resulted in a 15% lower proportion of the area experiencing a high severity outcome relative to the control landscape (SPLAT = 11%, control = 26% high severity). Finney et al. (2005) noted that in areas adjacent to and leeward of the three largest prescribed burn treatments analyzed within the Rodeo-Chediski Fire in Arizona, the proportion of high severity fire was lower (including some areas that were not burned at all) compared to untreated areas farther away from treatment boundaries. Recent treatments disrupted fire growth by burning more slowly than in untreated stands, which was consistent with model assumptions of landscape-level treatment effects where certain patterns of treated units efficiently retard fire growth across a landscape by causing repeated diversions. Within the Rodeo-Chediski Fire, the treatment units were not arranged to test or produce the modeled effect using SPLATS at a landscape level. Instead, the treatment's influence on wildfire outcomes created similar patterns to modeled random patterns that disrupt growth given large proportions of the landscape are treated (Finney et al. 2005). Prichard and Kennedy (2014) failed to observe the same phenomenon as Finney et al. (2005) in their study of the Tripod Complex Fires in Washington. There, the fires that burned through treated areas often burned at high severity in the surrounding untreated areas, with spotting distances of 0.5 to 1.0 km observed. However, these observations were given in the paper's discussion section and were not part of a formal analysis, making it difficult to compare directly with the results of Finney et al. (2005).

Inference from spatial modeling analyses also suggests that fuel treatments can reduce burn severity outside of treated areas. Spatial modeling techniques can be used to estimate the influence of unmeasured factors on a process outcome, for example, fire severity (Ver Hoef et al. 2018). Following the School fire in Washington, a large area of low severity fire was observed (dNBR) in an area with a high density of fuel treatments (Wimberly et al. 2009). Spatial modeling results led to the conclusion that burn severity patterns were not due to confounding effects of vegetation, fuels, and topography, but rather reflected a landscape-level effect of fuel treatments reducing fire severity in areas adjacent to and outside of their footprint (Wimberly et al. 2009). Arkle et al. (2012) evaluated 1-km buffers of untreated areas that surrounded prescribed fire treatments in four Idaho wildfires that burned in 2007. Using spatial modeling techniques, they found that fire severity decreased close to the prescribed fire edges. Fire severity increased with increasing distance from prescribed fire patches, with measurable treatment effects terminating approximately 200 m from the treatment edge.

Wildfire extent Fuel treatments can both increase and decrease wildfire extent; however, the limited evidence leans heavily toward fuel treatments having a decreasing effect on wildfire extent. Cochrane et al. (2012) used a hybrid approach by investigating 14 wildfires from nine states that contained treatments and using data (e.g., fire behavior, progression, weather) to mimic wildfire behavior using FarSite simulations. Using this approach, they were able to simulate the wildfire event with and without the treatments to determine the effectiveness of treatments at reducing wildfire size. They found that when fuel treatments encompassed 5.3 to 57.1% of land area, the average wildfire size was reduced by 7.2% (Cochrane et al. 2012). This study showed that on some wildfires, decrease in wildfire extent was strongly correlated with the proportion of area treated (Spearman's correlation $\rho = 0.69$), although this was highly variable among the wildfires they evaluated. In 11 of 14 fires, fuel treatments reduced the net-extent by 13.2%; however, on three wildfires, the presence of fuel treatments resulted in an average increase of 24.1% in fire size. While fuel treatments did not decrease wildfire extent on some wildfires, they did conclude that, in general, when fuel treatments were present there was a 1 to 1.8 ha ratio in reduction of fire extent. For example, a wildfire that was 1000 ha in size would have burned 1800 ha without established treatments. Cochrane et al. (2013) used a similar approach on an expanded study that evaluated 85 wildfires that contained a total of 3489 treatments to predict the extent of the same wildfires without these installed treatments. On 54 wildfires, fire size decreased by 64% when fuel treatments were included in the simulation, with a mean reduction of 19% of area burned. However, in 19 wildfires, fire size increased by 34% when fuel treatments were included, with a mean increase of 22% of area burned. Extent did not change in two (2%) of the wildfires they evaluated (Cochrane et al. 2013).

Fire progression Research that investigates how fuel treatments affect fire progression at a landscape level evaluated two fundamentally different treatment methods—fuel breaks and previous wildfires. These two approaches differ in their treatment applications, locations, primary objectives, and mechanisms for changing fire behavior. Fuel breaks are made from the mechanical removal of vegetation and are typically implemented in the Wildland-Urban Interface (WUI), are intended to prevent fire from spreading into developed areas, and can affect fire behavior primarily by providing firefighter access for suppression activities. On the other hand, previous wildfires are not actively constructed with respect to human activity, they are generally located away from human settlement and can potentially slow or stop the spread of subsequent wildfires in wildland areas by altering the fuel structure relative to adjacent unburned areas.

A study focused on the effectiveness of fuel breaks was conducted on four national forests in Southern California (Syphard et al. 2011a). The authors found that 147 wildfires of the 641 wildfires evaluated intersected a proportion of the 4063 km of fuel breaks that had been installed in these national forests during a 28-year period (Syphard et al. 2011a). Of the wildfires that intersected fuel breaks, 22 to 47% of the wildfires were stopped by the fuel breaks when combined with fire suppression; in contrast, 29 to 65% crossed the fuel break. In addition, they found that fire suppression activities were critical for a fuel break to be effective, as less than 1% of the wildfires were stopped by the fire break alone. Moreover, an accessible fuel break to enable fire suppression activities was critical; without firefighter access, fuel breaks, in general, do not stop wildfires. Fuel break effectiveness when combined with fire suppression activities also influenced fire size but this attribute was strongly linked to fire weather and recency of the established fire break. More recently established fuel break treatments allowed for better access and better suppression outcomes. Seasonality was also important on the two national forests that typically experience Santa Ana winds during fall when fuel breaks were least effective in stopping fires.

The effectiveness of a fuel break is difficult to extrapolate to other areas because location of a fuel break is also linked to biophysical setting (vegetation, seasonal weather, topography) and fire regime. Predictions of a wildfire intersecting a fuel break were only locally relevant because biophysical conditions that influence fire regimes varied greatly among national forests; thus, there is no one approach to predicting fire-fuel break intersections (Syphard et al. 2011a). For example, on the Los Padres National Forest in Southern California, 46% (23/53) of fire-fuel break intersections constrained the fire, while 54% (30/53) spread across the fuel break (Syphard et al. 2011b). Fire progression was altered on only one fire without firefighter suppression. Of the 30 fires that crossed the fuel break, 11 were not suppressed by firefighters because they were inaccessible, and in the other 19 fires, crews had access to the fuel breaks, but the fires still spread across the breaks. Fire size, treatment condition, weather, and a lack of firefighting resources were contributing factors in this last group of unsuccessful fire-fuel break interactions. Fuel breaks changed fire behavior after the intersection such that fire crews could access and suppress the fire in seven of the 53 fire-fuel break intersections. Of all fires analyzed, 40% did not intersect a fuel break (Syphard et al. 2011b).

Previous wildfires can potentially influence subsequent wildfire progression. Parks et al. (2015) evaluated the role of wildfires as a potential fuel break in subsequent wildfire progression using data from 1038 wildfires that burned from 1972 to 2012 in four large wilderness areas (Frank Church, Selway-Bitterroot, Gila and Aldo Leopold, and Crown of the Continent Biosphere Reserve) in the Western US. Sixty percent of the wildfires evaluated intersected with a previous wildfire, providing an opportunity to evaluate the effectiveness of longevity or age of the previous wildfire when it was intersected by a subsequent wildfire. Prior wildfires limited fire progression, but this effect decayed with time and the decay rate varied geographically. For example, in warm and dry areas, the ability of a previous wildfire to alter a subsequent wildfire lasted only 6 years compared to 14 to 18 years in cool and wet areas. However, extreme fire weather diminished the ability of previous wildfires to limit fire progression regardless of time since last wildfire (Parks et al. 2015).

Roads and previous wildfires limited fire growth at regional scales in the Southwestern US where 40% of wildfires analyzed encountered the perimeter of a previous wildfire (Yocom et al. 2019). Fire perimeter alignment indicated a halting effect of prior fire on subsequent fire. Of the fires that encountered a prior fire, 8.7% of perimeters aligned compared to 6.4% when fire perimeters were randomly shifted. Of fires that encountered a road, 25.7% of perimeters aligned compared to 11.6% when fire perimeters were randomly shifted. Of fires that encountered both a prior fire and roads, 1.8% of the fire perimeter aligned compared to 0.2% when fire perimeters were randomly shifted. Therefore, fires were 1.6 times more likely to align with prior fires, 2.2 times more likely to align with roads, and 9.9 times more likely for both roads and fire than by chance alone. Time since previous fire played a large factor in limiting fire growth as 60% of fire-fire interactions occurred when the time since fire was 5 years or less.

Discussion

The continuing crisis of large and severe wildfires warrants efficient and effective management approaches. Fuel treatments that favorably alter wildfire outcomes (e.g., reduce severity and limit extent) can aid in confronting the wildfire crisis by mitigating negative impacts. However, because the geographic area potentially affected by wildfires is vast and treatments cannot be implemented in every location, significant mitigation requires that treatments are effective at promoting favorable outcomes beyond their boundaries. Understanding how to distribute treatments across space and time is therefore key to maximizing the effectiveness of fuel treatments at broad spatial scales. We found empirical evidence in the literature that fuel treatments can diminish fire effects outside of their treatment boundaries; however, the evidence is limited in both quantity, depth, and consistency of information to a relatively small number of twelve published studies. Few studies documented landscape-level treatment effects, especially relative to the large number of studies conducting this type of work, and information that would inform operational decisions is lacking. Indeed, based on the information in the literature, we are unable to answer if treatment type and configuration affect intensity, rate of spread, and patterns of severity for subsequent wildfires or enable more effective wildfire response.

It is unsurprising that detailed information necessary to answer such questions is currently lacking. Although the number of opportunities to perform natural experiments increases annually with each new wildfire, the requirements of implementing a robust a priori study design needed to obtain the necessary empirical evidence are immense. Hence, the empirical evidence of fuel treatment effectiveness at a landscape level can validate results and subsequent predictions from simulation studies (i.e., wildfire behavior can be altered outside of a treatment footprint), but studies that explicitly test a specific spatial configuration and size remain few. Each of the studies that demonstrated a landscape-level effect of fuel treatments did so in their own unique way making it difficult for us to infer patterns or generalize results. No two studies were similar in design and implementation, and some were serendipitous in their ability to acquire the necessary data, further demonstrating the difficulty of designing and implementing studies to test landscape-level fuel treatment effectiveness. Given these shortcomings, the results we were able to glean from the papers is encouraging (e.g., Lydersen et al. 2017; Tubbesing et al. 2019; Cochrane et al. 2012). For example, fire severity, extent, and progression were all shown to be mitigated outside of treatment footprints, laying the foundation for more detailed investigation on how to optimize spatial and temporal implementation.

A key realization made during this review is what precisely constitutes a landscape-level effect. The term landscape describes an area that is spatially heterogeneous in at least one factor of interest (Turner 2001), and the definition may depend on discipline or perspective, rather than size of area (Turner 2001). An appropriate definition of a landscape could be a spatially heterogeneous area relevant to the phenomenon or process under consideration (e.g., wildfire) (Turner 2001). Our literature search found the term landscape used in the context of large wildfires, large treatment areas, or both, but the range in actual sizes that accompanied the term landscape was broad and lacked any clear rationale. However, wildfire is a landscape-level *process* interweaved with topography, weather, and fuels resulting in a particular landscape mosaic and should not be dependent upon an aerial extent to evaluate fuel treatment effectiveness. A critical element is understanding how a fuel treatment affects a wildfire outside of the fuel treatment footprint. Promoting this more precise interpretation of landscape-level effectiveness could help guide future research in designing and testing approaches to maximize fuel treatment effectiveness. For example, 26 studies met our selection criteria and provided detailed analysis of the effects of fuel treatments on various measures of wildfire behavior, but the design and analysis of some studies constrained inference to within treatment effects (i.e., site-level), despite studying large areas (e.g., 100's of hectares) in some cases. There is strong evidence that treatments of all types alter wildfire behavior when fires enter treatment boundaries, but this does little to advance our understanding of how to implement and deploy treatments to maximize the mitigating effect on wildfire outcome at the landscape level. Some of this apparent deficit is likely due to the relative ease of obtaining results from within treatment boundaries compared to untreated areas, but we suspect that some of it is also due to a lack of clear, precise, and consistent dialogue distinguishing landscape-level from site-level in the literature; site-level measures effects within treatment boundaries and inference is therefore limited to within treatments, while landscape-level measures the effect of treatments outside of treatment boundaries and can be inferred to broader areas. It is also important to define landscape from a wildfire perspective. Defining a wildfire landscape, such as efforts associated with "firesheds" (Bahro et al. 2007; Ager et al. 2021) as a term used to refer to an assessment and planning framework that is designed to reduce the potential for large and severe wildfires, may better define the landscape elements associated with a wildfire landscape. Providing a clear definition or concepts associated with a wildfire landscape could lead to more rigorous discussion and planning on how to best test a landscape-level effect hypothesis empirically. The development of strategic designs, such as the SPLATs concept, is a promising research direction toward this end.

The strong correlation between wildfire size and treatment area size was somewhat surprising. The relationship may indicate that there is a rather consistent or stable density of treatments and that as wildfire size grows, the total size of treated area within the wildfire perimeter grows too as a linear function (Fig. 7), at least in the areas studied in these papers. The value of these established treatments to increasing our understanding of landscape-level fuel treatment effectiveness may be limited, however. Better understanding will come when spatial and temporal designs are implemented to specifically test what combinations and arrangements optimize treatment effectiveness, and how effectiveness varies with geographically linked variables (e.g., physiography, vegetation, and climate).

We found two other rather consistent findings in addition to the wildfire size and treatment size relationship that may be generalizable. First, treatment density is important in affecting wildfire outcome outside of treated areas, but the relationship is scale dependent. This implies that treatment density needs to be higher at smaller spatial scales in order to achieve similar effects at broader spatial scales (Wimberly et al. 2009). Second, extreme fire weather acts as a top-down regulator on wildfire outcome, often overriding fuel treatments effects. However, the effect of fire weather is more pronounced at finer spatial scales. These two points (treatment density and fire weather) are related in that they both are scale dependent and suggest a cautionary note that inferences gleaned from fuel treatment effectiveness research will be influenced by the spatial scale of analysis and investigation.

The only information we found that addressed how treatments interact with fire suppression activities was in the context of fuel breaks (Syphard et al. 2011a, b). Fuel breaks are usually constructed with specific objectives to help protect the WUI by reducing fire behavior and allowing firefighter access, so it is unsurprising that this literature addressed fire suppression. Although papers on fuel breaks did fall into the subset of landscape-level effect studies, their analyses on suppression effects were limited. No other research type addressed suppression. Therefore, there is even more work to do in understanding how landscape-level fuel treatments can be applied to reduce suppression costs and increase firefighter safety than in understanding how treatments affect wildfire as a process.

Conclusion

We conducted a comprehensive literature search using liberal inclusion criteria to identify the subset of empirical papers that could inform our efforts to understand landscape-level fuel treatment effectiveness. There is a small likelihood that this search missed key papers that may alter the conclusions of this review. However, given the large number of papers we identified and evaluated for this purpose (2240) and the relatively small number that met our inclusion criteria (26), it seems clear that the empirically based understanding of fuel treatment effectiveness at a landscape level is in its infancy. Significant logistical barriers constrain our ability to conduct experimental and observational field studies for hypothesis testing and model building, and more broadly for elevating our knowledge and decision making, but the barriers are not insurmountable. The potential benefits of managing landscapes for more favorable wildfire outcomes make overcoming logistical obstacles to landscape-level research worth the effort and investment.

Appendix

The keywords fell into two groups.

Group 1:
Ecosystem: (forest* or woodland or savanna or rangeland* or grassland* or shrubland* or prairie* or scrub* or steppe* or chaparral or tundra or desert* or dryland* or tall forb* or barren* or glade* or outcrop* or badland* or heathland*) and (fuel* and (treatment or prescribed or thin* or masticat* or cut* or pile* slash* or graz* or mow* or chain* or seeding* or herbicide* or greenstrip* or brownstrip* or green strip* or brown strip* or biocontrol* or biological control* or biological harvest or mechanical control* or chemical control* or brush control*) and (landscape or spatial* or scale or configure* or design* or deploy*).
Group 2:
Ecosystem: (forest* or woodland* or savanna* or rangeland* or grassland* or shrubland* or prairie* or scrub* or steppe* or chaparral or tundra or desert* or dryland* or tall forb* or barren* or glade* or outcrop* or badland* or heathland*) and fuel* and (fire* or wildfire* or burn*) and (prescribed or thin* or masticat* or cut* or pile* or slash* or graz* or mow* or chain* or seeding* or herbicide* or greenstrip* or brownstrip* or green_strip* or brown_strip* or biocontrol* or biological_control* or biological harvest or mechanical_control* or chemical_control* or brush_control*) and (landscape* or spatial* or scale or configur* or design* or deploy*) and (hazard* or load* or behavior* or reduc* or severit* or intensit* or frequenc* or flam* or suppress* or risk* or threat* or mitigat* or cost* or leverage* or longevit* or effective* or efficac* or resisten* or resilien*)

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Declarations

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Not applicable.

Consent for publication
Not applicable.

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

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