FINAL REPORT

Effectiveness of Fuel Treatments at the Landscape Scale: State of Understanding and Key Research Gaps

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Table of Contents

List of Tables

List of Figures

List of abbreviations/acronyms: The report does not repeatedly use the same abbreviation or acronym. Acronyms were used to refer to commonly published acronyms (e.g., FARSITE) and each one was clearly defined, and each acronym was used only one time in the document. Therefore, we did not include a list of acronyms.

Keywords: Model simulation, empirical studies, case studies, landscape, fuel treatment effectiveness, North America, wildfire

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Abstract

Maximizing the effectiveness of fuel treatments at the landscape scale is a key research and management need given the inability to treat all areas at risk from wildfire, and there is a growing body of scientific literature assessing this need. We synthesized existing scientific literature on landscape-scale fuel treatment effectiveness in North American ecosystems through a systematic literature review. We identified 127 studies that addressed this topic using one of three approaches: simulation modeling, empirical analysis, or case studies. Of these 127 studies, most focused on forested landscapes of the western United States. Together, they generally provided evidence that fuel treatments reduced negative outcomes of wildfire and in some cases promoted beneficial wildfire outcomes, although these effects diminished over time following treatment and were influenced by factors such as weather conditions at the time of fire. The simulation studies showed that fuel treatment extent, size, placement, timing, and prescription influenced the degree of effectiveness. Empirical studies, though limited in scope, provided evidence that fuel treatments were effective at reducing the rate of spread, progression, extent, or severity of actual wildfires both within and outside of treated areas. Case studies documented outcomes of specific wildfire events and contained managers' evaluations of fuel treatment effectiveness. These case studies shared certain characteristics associated with changing a wildfire outcome, such as recency of treatment implementation, or strategic placement in relation to previous treatments or wildfires, suppression needs/infrastructure, or prevailing winds and topographic firebreaks. Across the three study types, the importance of treating multiple strata to reduce fuels contributing to fire spread and severity was emphasized. Fuel treatments contributed to fire suppression efforts by reducing costs and facilitating suppression activities such as fireline construction. We conclude that existing literature contains useful information that can inform future fuel treatment planning, but that additional research is needed in underrepresented ecosystems and underdeveloped topics including cost-benefit analysis, fuel treatment longevity, and interactions among fuel, topography, and climate that contribute toward influencing fuel treatment effectiveness. There is a need for more empirical studies that evaluate fuel treatments beyond treatment boundaries, simulation studies that examine conditions expected under future climate scenarios, and case studies that document manager experiences and what they view are indicators of effective landscape-scale fuel treatments.

Objectives

This report provides key findings from four literature synthesis documents (concepts and fuel treatment effectiveness measurements, empirical, simulation, and case studies) that evaluate the extent to which landscape fuel treatments:

- Mitigate adverse effects of wildfire.
- Provide opportunities to manage fire for beneficial effects of wildfire.
- Provide opportunities for cost efficient fire suppression strategies and maximize firefighter safety.
- Provide results to inform future fuel treatment planning.
- Identify research gaps.

Background

Although there is evidence of some success, the challenges associated with fuels management and fire suppression have outpaced our ability to effectively manage wildfire (North et al. 2015, Schoennagel et al. 2017, Thompson et al. 2018). This is clearly demonstrated by indicators such as larger and more extreme wildfire behavior, copious amount of land area in need of treatment, human exposure to and risk from fire and smoke, property losses, and the escalation of funding devoted to fire suppression. A primary management strategy is to use fuel treatments to reduce future fire risk and future fire suppression costs, but the effectiveness of fuel treatments at the landscape scale is poorly understood. Syntheses that provide the state of knowledge associated with fuel treatments from both the scientific literature and manager experiences are valuable to both scientists and managers because they provide relevant information that can inform planning and implementation, identify science gaps, and research needs, and inform policy (e.g., Hood 2010, Jain et al. 2012). A synthesis of landscape scale fuel treatment effectiveness is needed to provide critical knowledge and guidance for fuel treatment planning at multiple scales, and for informing future research priorities. This knowledge when combined with current technology and local expertise, could inform design of less costly, more effective fuel treatments that lead to less costly and less risky fire suppression operations, less fire risk to highly valued resources, and improved ecological structure and function.

Evaluating the effectiveness of fuel treatments at the landscape scale is challenging because many interacting factors influence wildfire conditions and post-wildfire outcomes (Figure 1). Prior to a fire event, vegetation dynamics, previous disturbances, including past wildfires, and fuel management objectives all contribute to whether a particular fuel treatment will be effective at altering fire behavior, effects, and risks to human safety. In addition, factors such as physical setting and the condition of the fuels and proximity to communities or infrastructure that need protection can influence fire suppression tactics. Wildfire ignition is also influenced by the physical setting, climate, and weather− leading to an element of uncertainty as to where the next wildfire will occur. For these reasons, it makes sense that there is limited information available to inform future planning and deployment of fuel treatments that are effective across landscapes.

A team of scientists gathered and synthesized the existing scientific literature to provide the current state-of-knowledge on landscape fuel treatment effectiveness. We first conducted a comprehensive assessment of the literature using a systematic approach to determine the degree to which the literature has evaluated different metrics of fuel treatment effectiveness at the landscape scale. The diversity of the literature dictated a multiple synthesis approach focused on different types of studies. The first synthesis is titled "Quantifying fire hazard and fuel treatment effectiveness from stands to landscapes: Measurements and concepts of landscape-scale fuel treatments and effectiveness" (Hood et al., Appendix C.2). The goal of this product is to identify core concepts and provide a venue to stimulate discussion about how to measure fuel treatment effectiveness to improve fuel treatment, and ultimately improve the resilience of ecological and social systems to wildland fire. The second synthesis, titled "Empirical evidence for landscape-level fuel treatment effectiveness: A systematic review" (McKinney et al., Appendix C.2) synthesizes information on the influence of landscape-level fuel treatments on subsequent wildfires in North America through field-based, experimental, and observational studies.

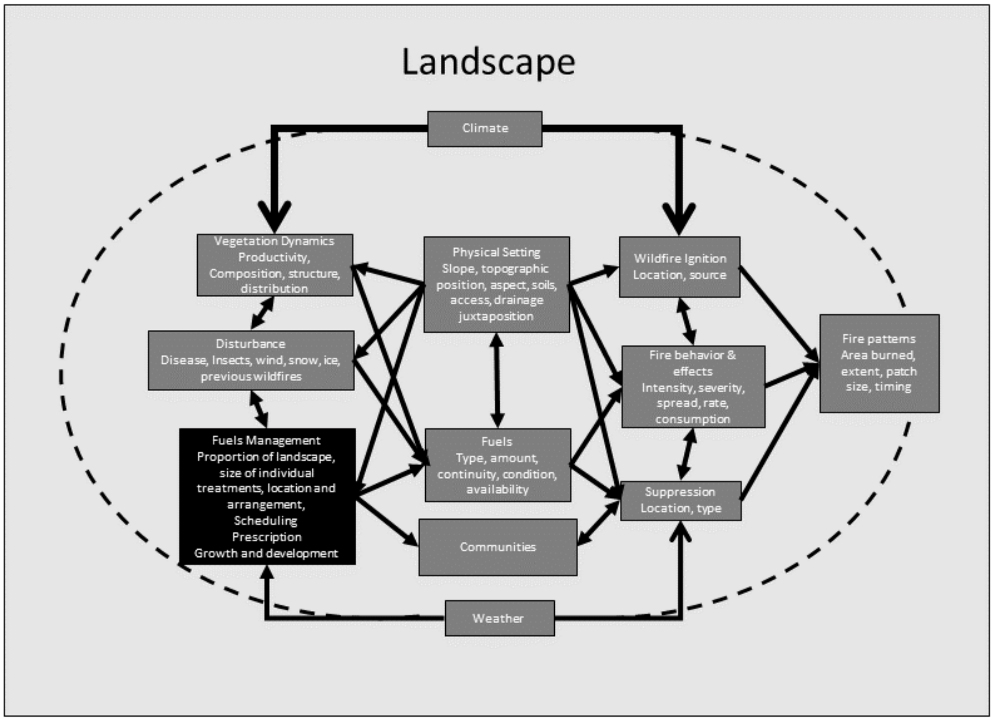

Figure 1. Conceptual model of factors that influence fuel treatment effectiveness. This model illustrates the interactions and complexities associated with quantifying fuel treatment effectiveness at the landscape scale.

The third synthesis, titled “Fuel treatment effectiveness at the landscape scale: A systematic review of simulation studies comparing treatment scenarios in North America” (Ott et al., Appendix C.2), provides information on studies where wildfire is simulated to evaluate landscape fuel treatment effectiveness. The fourth synthesis considers manager experience and is titled: “A thematic synthesis on Wildfire Case Studies: Lessons learned from fire managers” (Urza et al., Appendix C.2). It extracts manager experiences on the role of fuel treatments and their application during a wildfire event. This report pulls information from these four syntheses to provide a comprehensive view of the literature to provide the key findings that evaluate the extent to which landscape fuel treatments:

Mitigate adverse effects of wildfire.

- Provide opportunities to manage fire for beneficial effects of wildfire.
- Provide opportunities for cost efficient fire suppression strategies and maximize firefighter safety.
- Provide results to inform future fuel treatment planning.
- Identify research gaps.

Results will provide: 1) recommendations that could inform fuel treatment design, deployment, priorities, and effectiveness of fuel treatments at the landscape scale and 2) identify science gaps and research questions that provide a roadmap to address strategically important information concerning fuels management and policy. In addition, we refine concepts and provide recommendations based on what we learned to inform future research needs and applications, such as experimental designs and modeling methodologies.

Materials and Methods

Literature Search

In collaboration with the USDA Forest Service Library, we conducted a series of literature searches beginning in October 2019. Searches were limited to literature published since 1990 and excluded studies in areas outside the U.S. and Canada. Library personnel searched the Web of Science, Scopus, National Agricultural Library, Fire Research and Management Exchange System (FRAMES), FS/Info, and TreeSearch databases. Search terms included 'fuel', 'fire' and related synonyms, and for some searches, additional terms specifying ecosystems, treatment types, fire behavior/effects, and landscape-scale terminology (Table 1). The additional terms served to filter out off-topic papers when searching the larger databases. The search resulted in 2,240 unique citations. Individual syntheses (McKinney et al., in review, Ott et al., in review, Urza et al., in review) provide detailed descriptions of their literature search methodology, which is summarized here.

From the wide distribution of studies identified in the search, we used a multi-step review process to identify papers that addressed our landscape fuel treatment effectiveness objectives by using a set of *a priori* inclusion/exclusion criteria. The first step was to eliminate papers that did not meet the broadest definition of landscape scale fuel treatments. Papers had to address some aspect of a fuel treatment project at the landscape scale. Our broad definition of a fuel treatment was any alteration of live or dead vegetation that has the potential to influence fire behavior, including wildland fire use as well as prescribed fire, mechanical or chemical treatments. In our search, we defined landscape scale as either (1) an area larger than the treated area that has the potential to be influenced by the fuel treatment or (2) an area of at least 40 km^2. A subgroup of five team members tested this selection process on a subset of randomly chosen papers before applying it to all 2,240 citations.

Studies selected in the first step were grouped in one of four groups based on their thematic approach and methodology: basic concepts, empirical studies, simulation studies, and case studies. Studies in the basic concepts group did not present results of specific fuel treatment evaluations but provided background and foundational information. Empirical studies evaluated fuel treatments effectiveness using actual wildfires on treated landscapes, sometimes accompanied by simulated wildfire for comparison. Simulation studies evaluated fuel treatment effectiveness solely using fire simulation modeling on model landscapes patterned after real-world landscapes where fuel treatments have been or could be implemented. Case studies reported on actual wildfires using a narrative approach and were primarily from "gray literature" published by land management agencies, rather than from peer-reviewed scientific journals. Different team members examined studies in each group and conducted additional searches and refinements to the selection process, as described below. As a result, the final selection criteria for the fuel treatment evaluations differed among the studies within each group (Figure 2) and are described in more detail in literature synthesis and data extraction.

Table 1. Search terms used in literature search. All variants of these terms were captured in the truncated terms used in the search. See Appendix A for examples of literature search list.

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		

Separate teams of scientists synthesized the literature by the study type (basic concepts, empirical, simulation, case studies). Hood et al. (Appendix C.2) focused on the basic concepts and measurements needed to quantify landscape fuel treatment at the landscape scale. Mckinney et al. (Appendix C.2) synthesized the empirical studies. Ott et al. (Appendix C.2) synthesized the simulation studies. Urza et al. (Appendix C.2) summarized the case studies. This report identifies the commonalities and differences in these four synthesis studies to address the JFSP proposal research questions and research needs. The next section focuses on how each team approached their synthesis.

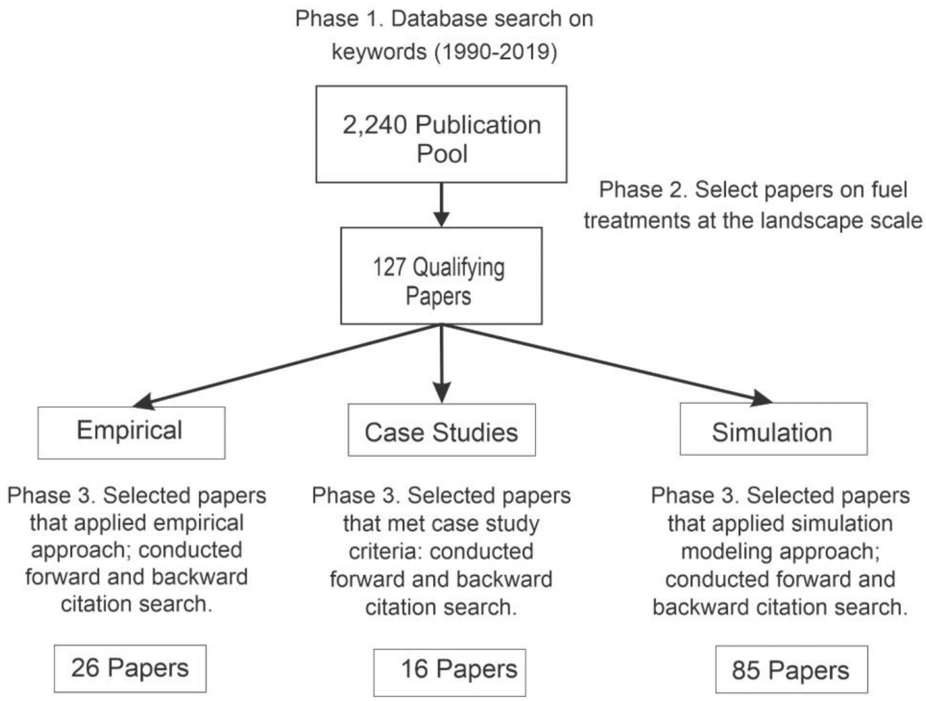

Figure 2. Literature search process that identified studies reviewed in each synthesis type (empirical, simulation, and case study).

Literature Synthesis and Data Extraction

Empirical

Empirical studies examined effectiveness of landscape-scale fuels treatments using data from actual fires and applied statistical methods to derive inference of treatment effectiveness. McKinney et al. (Appendix C.2) identified 26 papers as empirical studies, and then searched of all the citations included in these 26 papers to identify additional related papers that were not found in the original search. This subsequent search process concluded in May 2020. None of the candidate papers identified in the citation search met the inclusion criteria for this literature review. To guide the review, the identified 39 distinct elements that characterize these papers and directly address our study objectives. These elements describe the study location, design, treatment objectives, variables, outcomes, results, and conclusions of these studies. They systematically extracted the elements from each paper to form the foundation of the subsequent analyses and synthesis.

Simulation

Many of the papers identified through the initial literature search and selection process presented studies that used fire simulation modeling to evaluate landscape-scale fuel treatment effectiveness. Ott et al. (Appendix C.2) included additional selection criteria to pinpoint studies that were most useful for our synthesis. The selected studies compared wildfire outcomes across two or more landscape scenarios, where at least one scenario included treatments to address fuels reduction, and where the treated area was less than the total landscape area at a given point in time. Studies examining wildfire in the absence of treatments were also omitted, except in cases where previous wildfires were incorporated into a fuel treatment design. The set of studies was expanded using backward and forward citation searches, the latter through the Web of Science core collection as of February 2021 (e.g., Collins et al. 2011, Thompson and Calkin 2011, Chung et al. 2013, Hessburg et al. 2016, Kalies and Kent 2016, Hunter and Robles 2020). This process resulted in a total of 85 simulation papers meeting selection criteria. These included 73 journal articles, 4 General Technical Reports published by the U.S. Forest Service, 4 papers from conference proceedings, 2 theses and 2 dissertations. Information from each qualifying study was extracted and summarized, including location descriptors, landscape size, simulation modeling method, simulation timeframe, fuel treatment scenarios tested, response variables measured and treatment effects. Ott et al. (Appendix C.2) used the online tool WebPlotDigitizer (Rohatgi 2021) to extract data from charts.

Case Studies

Case studies were selected if the studies 1) discussed the effectiveness of fuel treatments during actual fire events, 2) had a forest manager as an author or it was requested by forest managers to meet the need for a post-fire assessment, and 3) investigated fuel treatment effectiveness during wildfire events but did not include any statistical analysis. Sixteen cases studies were identified and used to conduct the synthesis. Urza et al. (Appendix C.2) used a series of questions to systematically extract data and retrieve specific information from the case studies (Table 2). We summarized information among the studies to identify consistencies, themes, and key elements that all studies reported to inform future post-fire and fuel treatment effectiveness assessments.

Table 2. Themes and list of questions used to extract information from each case study.

Theme	Question
Location	Where was the case study located? What are defining characteristics of the affected landscapes?
Treatment types	Which types of treatments were implemented? 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?
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?

Results and Discussion

Locations of Landscapes by Synthesis Type

Most of the literature focused on fuel treatments and associated wildfires on landscapes of the western United States, with only a few studies located in the central or eastern U.S. or Canada (Figures 3, 4 and 5). Most of the empirical studies were in the western U.S. and predominantly in the southwest (Figure 3). Most of the case studies were also located in the western U.S., with only one (Fites et al. 2007b) located in the central United States (Figure 4). Simulation studies had the widest distribution, but were also concentrated in the western U.S., especially California, Oregon and Montana (Figure 5). Landscapes with ponderosa pine or dry mixed conifer forest vegetation were especially common for all three synthesis types.

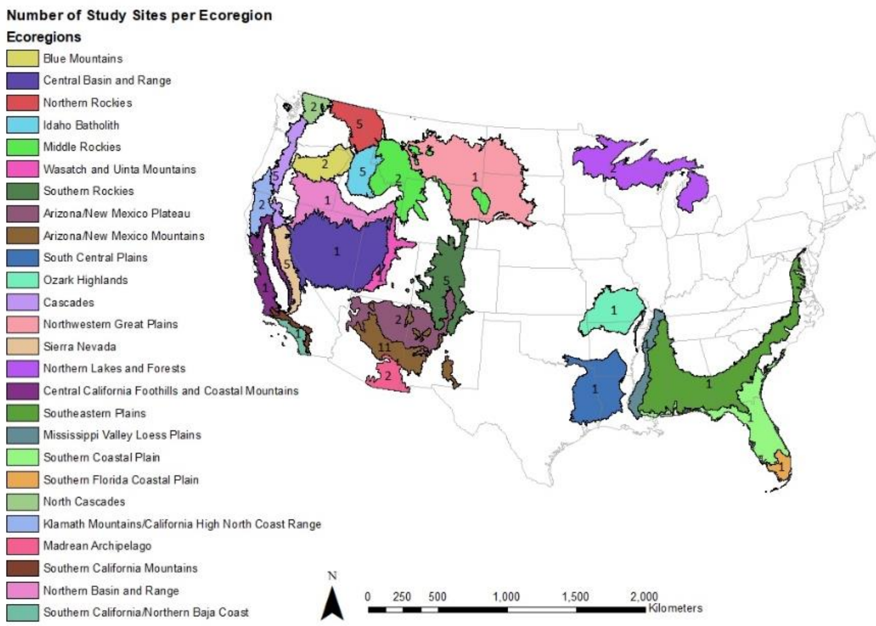

Figure 3. Ecoregions where landscape-scale empirical studies were conducted.

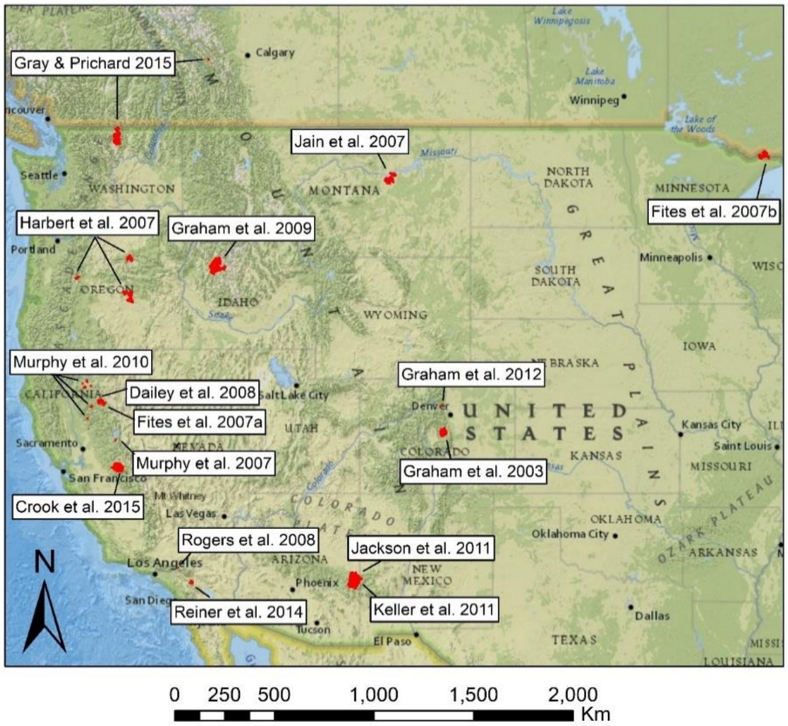

Figure 4. Locations of case studies by citation.

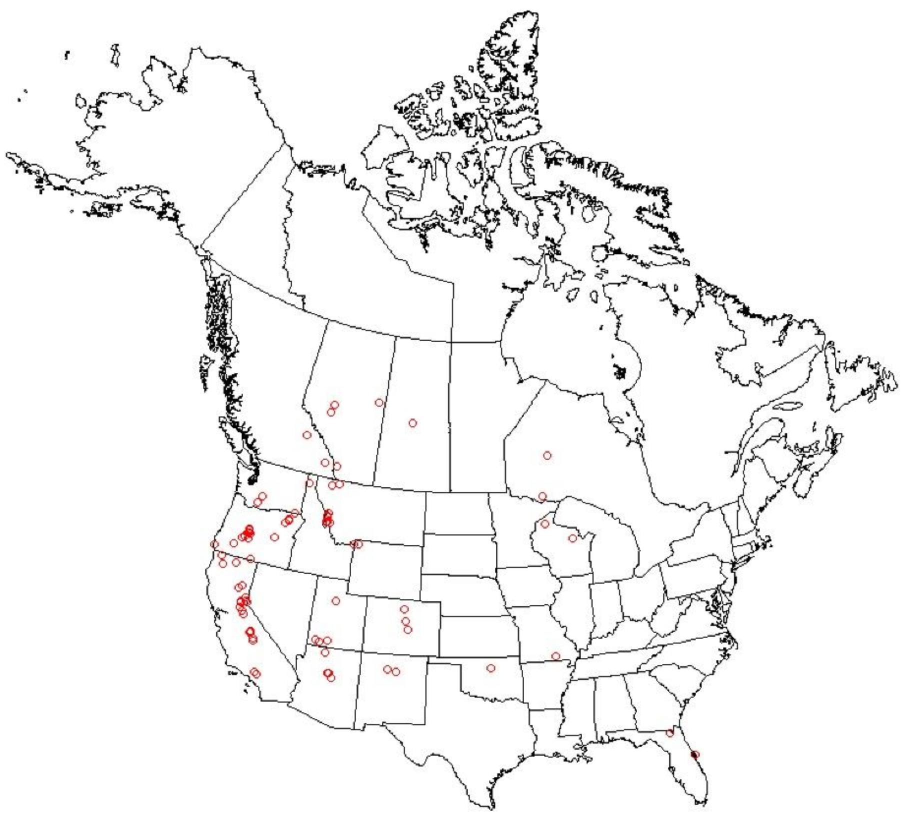

Figure 5. Location of model simulation studies.

Do Landscape Fuel Treatments Mitigate Wildfire Effects?

A major research question for this work was: Do fuel treatments mitigate adverse effects of wildfire at the landscape scale based on measures of intensity, severity and ecosystem response? In general, for all synthesis types fire behavior characteristics within fuel treatments were effective at creating more desirable conditions by slowing the rate of spread, shifting fire behavior from crown fire to surface fire, and decreasing fire severity (Table 3). Simulation and empirical studies provided evidence of fuel treatment effectiveness outside the treatments as measured by rate of fire spread or fire progression, fire extent and fire severity (Table 3).

Table 2. Treatment effectiveness on wildfire characteristics. A dash indicates that information was not provided and "Yes" indicates that there was some evidence in a portion of the studies that showed that fuel treatments were effective at addressing one of the wildfire characteristics (fire spread or progression, extent, and severity).

Synthesis Type	Rate of fire spread/progression		Fire behavior		Fire extent	Fire severity	
	Inside Treatment	Outside Treatment	Inside Treatment	Outside Treatment	Outside Treatment	Inside Treatment	Outside Treatment
Empirical	Yes	Yes	--	--	Yes	Yes	Yes
Simulation	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Case studies	Yes	--	Yes	--	--	Yes	--

Empirical

The empirical studies demonstrated that fuel treatments can mitigate undesirable characteristics associated with fire severity, behavior, or rate of spread. For example, Syphard et al. (2011a) 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. They also noted that predictions of a wildfire intersecting a fuel break were only locally relevant because biophysical conditions that influence fire regimes varied greatly among national forests (Syphard et al. 2011a). Therefore, 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.

In general, the proportion of high severity outcomes decreased in areas with more of the landscape was treated (Lydersen et al. 2017), had an abundance of fuel treatments (Wimberley et a. 2009), was within Strategically Placed Landscape Area Treatments ("SPLATs"; Tubbesing et al. 2019), or was adjacent to large, prescribed fires (Finney et al. 2005). Fire severity increased with increasing distance from prescribed fire patches (e.g., approximately 200 m from treatment edges was reported by Arkle et al. 2012).

Decrease in fire extent was positively correlated with the proportion of area treated. For example, Cochrane et al. 2012 show that treatments reduced the wildfire extent by 13.2% in 11 of the 14 wildfires they evaluated. Cochrane et al. 2013, who evaluated 53 wildfires, show that wildfire extent decreased by 64% when fuel treatments were present. However, in some wildfires (19), wildfire extent increased.

Simulation

Because of the large number of simulation studies measuring a wide range of variables, the scope of the simulation synthesis was narrowed to focus on direct wildfire effects. Ecosystem responses such as vegetation regeneration, wildlife occupancy, carbon storage, and soil condition were not included in the synthesis except in a few cases where they were embedded within resource loss indices. Wildfire effects were grouped according to whether they measured the net effect of all wildfire versus effects of 'damaging' wildfire specifically. Damaging wildfires included those that were identified as being high-severity, high-intensity, stand-replacing, uncharacteristic, or problem fires. Direct measures of fire severity, flame length and resource loss were also assigned to the damaging wildfire group. Some simulation studies measured multiple variables in one or both of these groups, and in these instances, a single representative variable was selected per group for semi-quantitative analyses that summarized wildfire effects across studies and simulation scenarios. The primary questions addressed by these analyses were: (1) Do fuel treatment scenarios reduce landscape-scale wildfire effects relative to control (untreated/no-action) scenarios? (2) Are certain types of fuel treatment scenarios more effective than others at reducing landscape-scale wildfire effects relative to untreated/no-action scenarios?

(1) Do fuel treatment scenarios reduce landscape-scale wildfire effects relative to control (untreated/no-action) scenarios?

Of the 94 simulation landscapes reviewed (note that some of the 85 simulation papers included more than one modeled landscape), 80 simulation landscapes compared one or more fuel treatment scenarios with a control scenario and measured effects of all wildfires (80 studies, 566 scenarios) and/or they measured the proportion of a simulated landscape that would lead to a damaging wildfire (59 studies, 331 scenarios). For all wildfires, 86% (489 out of 566 scenarios) compared to the control corresponded to less fire or diminished fire impacts on the landscape. In studies that evaluated damaging wildfires, 94% (311 of the 331 scenario) of the outcomes were lower than controls indicated that fuel treatments contributed to less damaging wildfires.

(2) Are certain types of fuel treatment scenarios more effective than others at reducing landscape-scale wildfire effects relative to untreated/no-action scenarios?

We identified 5 dimensions of fuel treatment design/deployment that were tested in the simulation studies: extent (total area treated per unit time), size of individual treatment units, placement (spatial location or arrangement of treatments), timing of treatment implementation, and prescription (technique used for fuel reduction). Several general patterns emerged from these tests.

Extent: Fuel treatment effectiveness generally increased with increasing treated area. In some studies, there was a pattern of diminishing returns as treated area got larger, with little change after about 30% of the landscape was treated. However, other studies showed continuing or even increasing returns for over 30% treated.

Size: A few studies tested effects of individual treatment size on fuel treatment effectiveness, generally by comparing treatment units that were similar in shape (e.g., square or rectangular) but differed in length and/or width. The effect of treatment size depended on other variables such as fire duration, fuel heterogeneity and fuel load, and appeared to be less important than other dimensions of fuel treatment design/deployment such as extent and placement.

Placement: Certain fuel treatment placement patterns were generally more effective than others. Optimized arrangements derived from optimization algorithms (e.g., Treatment Optimization Model, Optfuels) were nearly always more effective than random placement. The SPLATs arrangement, comprised of partially overlapping rectangular fuel treatment units, also performed relatively well, as did linear fuelbreaks and some placement schemes developed by panels of experts. Many studies tested fuel treatment placement schemes that prioritized areas with certain characteristics, especially areas with high fuel loads or high risk of damaging fire. These prioritization schemes were sometimes but not always more effective that non-prioritized (naïvely, uniformly, or randomly distributed) placement. Many authors noted the challenge of developing effective placement schemes under constraints posed by land management restrictions and feasibility of treatment implementation. Lifting such constraints in hypothetical scenarios often led to more effective treatments, although in many cases, this can be attributed to increases in treated area as well as the greater range of options for treatment placement.

Timing: Many simulation studies tested treatments that were effectively implemented all at once, but others examined various ways of implementing treatments over time. Studies that compared steady rates of treatment with accelerated treatment implementation generally found that the latter was more effective at reducing fire impacts on the short term, but that steady treatment applications could eventually have a similar effect. Treatment timing based on optimization algorithms such as Approximate Dynamic Programming (ADP) performed better than other timing schemes.

Prescription: A variety of fuel treatment prescriptions were modeled in the simulation studies, most commonly involving some form of mechanical fuel reduction, prescribed fire, or both. Studies that compared landscape-scale effects of different prescription types showed that a combination of mechanical and prescribed fire was generally more effective than mechanical treatment alone. Studies comparing different diameter limits for tree thinning treatment did not show significant differences in effectiveness at the landscape scale despite expected differences at the local scale of treated stands.

Case studies

Several common themes were reported in the case studies. Although fuel treatments are not necessarily intended to independently stop a wildfire without accompanying fire suppression, they were generally considered successful at changing fire behavior (e.g., from crown to surface fire), reducing spotting distances and convective and radiant heat. Reducing fire intensity makes suppression resources more effective and reduces fire effects. However, there was some evidence that very recent prior fire (including both prescribed fire and wildfire within 1 year) did appear to stop the fire locally. In several reports, fire transitioned from very high intensity in untreated stands to low or moderate intensity as it entered stands where fuels reduction work had occurred. Surface fire behavior was more common in treated stands. Treated areas also were generally reported as experiencing lower flame lengths, slower rate of spread, less transition to crown fire, and less spotting than outside treatment areas. Fire severity was generally lower in treated areas than in untreated areas, with the exception of periods when fire intensity and burning conditions were extreme due to weather. Tree survival and change in canopy base height were affected by previous treatments. In one case, smoke volume was said to have been reduced when the fire reached treated areas.

Do Fuel Treatments Provide Opportunities to Manage for the Beneficial Use of Wildfire?

Although many studies showed that fuel treatments were effective toward enhancing fire suppression opportunities, but primarily inside the fuel treatments is where this was evaluated. All synthesis types indicated that topography and weather were critical in determining fuel treatment effectiveness and only simulation studies evaluated how fuel treatments influenced long-term risk within and outside the treatment footprint (Table 4).

Table 3. Fuel treatment effectiveness on other wildfire related attributes. A dash indicates that information was not provided and "Yes" indicates that there was some evidence in a portion of the studies that showed that fuel treatments were effective at promoting beneficial wildfire and enhancing fire suppression. Only simulation studies illustrated the effectiveness of fuel treatments on long-term risk.

Synthesis type	Beneficial wildfire		Fire suppression		Topography	Weather	Long-term risk*	
	Inside treatment	Outside treatment	Inside treatment	Outside treatment	Context	Context	Inside treatment	Outside treatment
Empirical	Yes	Yes	Yes	Yes	Yes	Yes	--	--
Simulation	--	--	--	--	Yes	Yes	Yes	Yes
Case studies	No	No	Yes	--	Yes	Yes	--	--

Empirical

The papers in this synthesis provided limited evidence to address this question directly. Previous wildfires can influence subsequent wildfire progression. Parks et al. (2015) reported that 60% of wildfires they evaluated intersected a previous wildfire in four large wilderness areas. Although this outcome appeared to illustrate that the intersection of wildfires over time limited fire progression, the longevity and effectiveness diminished over time. However, this tended to vary based on the physical setting. For example, in dry and warm sites, effectiveness of a previous wildfire at stopping progression of a subsequent wildfire was only 6 years, while in cool and moist or wet areas, the effectiveness longevity increased from 14 to 16 years after the previous wildfire. Yocom et al. (2019) reported that previous wildfires combined with roads limited fire growth in the southwestern United States, but this effect was limited as time progressed and this positive fire-to-fire interaction seemed to occur when previous wildfires were 5 years-old or less.

Simulation

Most of the simulation studies were focused om detrimental wildfire effects and considered fuel treatments to reduce wildfire damage. However, some studies also reported wildfire outcomes that would likely be beneficial, including resulting in surface fire (rather than crown fire) and low-severity fire. There were 18 studies in which these beneficial wildfire metrics were compared to a control (untreated/no-action) scenario. A clear majority of cases (79%), fuel treatment promoted beneficial wildfire.

How are Fuel Treatments Integrated into Wildfire Management Operations?

There were no empirical studies that evaluated how fuel treatments were integrated into wildfire management, but there was evidence in the simulation and case studies.

Simulation

Only a few of the selected simulation studies addressed fire suppression operations directly, either as a treatment variable that differed between scenarios or as a response variable affected by wildfire. Fire suppression costs were examined by several studies as shown in tables 5 and 6. In most cases, fuel treatment scenarios had reduced suppression costs compared to untreated/no-action scenarios.

Table 4. Cost scenarios reported in simulation studies. Simulation studies that addressed an aspect of suppression operations. Dashes indicate lack of information.

Citation	Location (National Forest or Provincial Forest)	Note	Number of total treatment scenarios	Number of lower cost scenarios*	Number of higher cost scenarios*
Fitch et al. 2018	Coconino, AZ	High severity fire	18	18	0
Fitch et al. 2018	Coconino, AZ	Mixed severity fire	17	13	4
Ohlson et al. 2006	Premier/Diorite BC	--	3	3	0
Schaaf et al. 2008	Angeles, CA	--	4	4	0
Beck et al. 2014	Eldorado/Stanislaus CA	Includes rehabilitation	1	1	0
Thompson et al. 2017	Sierra, CA	Avoided costs	6	6	0
Chew et al. 2003	Bitterroot, MT	Total for 3 decades	16	10	6
Thompson et al. 2013	Deschutes, OR	Study area near treatments	1	1	0

*Cost of treatment scenarios compared to control (untreated/no-action) scenarios.

Table 5. Control and fuel treatment scenarios and related wildfire suppression costs. Simulation studies that addressed wildfire suppression costs in the context of landscape fuel treatment.

Citation	Location (National Forest or Provincial Forest)	Average control costs ($)	Average treatment costs ($)	Average cost savings ($)	Cost savings (%)
Fitch et al. 2018	Coconino, AZ	4,045,630	2,072,687	1,972,943	49%
Fitch et al. 2018	Coconino, AZ	10,136,022	7,240,714	2,895,308	29%
Ohlson et al. 2006	Premier/Diorite, BC	2,702,055	2,272,534	429,521	16%
Schaaf et al. 2008	Angeles, CA	7,089,000	5,588,250	1,500,750	21%
Beck et al. 2014	Eldorado/Stanislaus, CA	64,000,000	24,850,000	39,150,000	61%
Thompson et al. 2017	Sierra, CA	Not given	Not given	1,878,333	Not given
Chew et al. 2003	Bitterroot, MT	2,445,755	2,379,422	66,333	3%
Thompson et al. 2013	Deschutes, OR	5,093,335	4,432,626	660,709	13%
Thompson et al. 2013	Deschutes, OR	2,848,653	2,195,551	653,102	23%

Case Studies

The case studies emphasize the effectiveness of fuel treatments during fire suppression. Fuel treatments presented suppression opportunities that otherwise may not have been available. For example, the reduced rate of spread in treatments provided opportunities for fireline construction, safety zones, structure protection, and spot fire suppression. There were also anecdotal reports from fireline personnel stating that burnout operations were more successful where stand density and fuel loadings had been reduced. There was evidence that fuel treatments sometimes directly influenced the survivability of structures (Graham et al. 2009).

Did Fuel Treatments Provide Long-term Risk Reduction?

Simulation

Multi-year simulations ranging from 20 to 200 years were carried out for 57 simulation studies from 51 papers. Most of these multi-year studies tested scenarios where treatments were implemented on a recurring basis throughout the duration of the simulation, and these studies generally showed lasting treatment effects due to the continuous maintenance and/or expansion of treated areas. Only 4 studies examined multi-year effects of treatments that were implemented once at the start of the simulation, and these studies suggest that treatment benefits would wear off over the course of 20-40 years. Besides those studies mentioned above that tested how long treatment effects lasted, longevity and maintenance were not a primary focus of the selected simulation studies.

Case Studies

In the case studies, enhanced long-term wildfire risk was sustained only if ladder fuels and crown fuels were reduced. More importantly, the reduction of wildfire risk required maintenance of fuel treatments as they aged and several studies acknowledged several factors that need consideration when reducing fire risk: 1) treatments are effective for a finite length of time, 2) the length of time needed before retreatment depends on environment, fuels, rate of vegetation recovery, etc., 3) more recent treatments were more effective at mitigating fire behavior and reducing fire severity, 4) treated areas with high surface fuels (e.g., from recovery after an older treatment or mastication without prescribed fire) had more severe fire effects on soil and vegetation, and 5) incomplete treatment implementation (e.g., piles not burned) did not result in adequate fuel reductions.

Were Past and Future Wildfires Integrated into Fuel Treatment Effectiveness?

Empirical

As mentioned earlier, Parks et al. (2015) noted that past wildfires do alter subsequent wildfire progression, but only for 6 years in warm and dry forests and 14 to 16 years in cool and moist forests. Yocom et al. (2019) reported that 40% of wildfires encountered the perimeter of a previous wildfire, and progression was limited in about 9% of these encounters. Cochrane et al. (2012 and 2013) included previous wildfires, along with prescribed fires and thinning, in their assessment of fuel treatment effectiveness on subsequent wildfires. Treatments were estimated to decrease wildfire extent in 79% and 74% of the wildfires they evaluated, respectively.

Simulation

Fuel load reductions caused by past wildfires were incorporated into simulation studies that used spatial patterns of fuels to determine where to place fuel treatments on modeled landscapes. Many of the simulation studies relied on placement schemes that prioritized areas with high fire hazard or risk, and thus would have generally avoided treating areas that recently burned. Other studies took this a step further and used optimization algorithms to determine where to place treatments to disrupt fire paths. Some studies optimized both placement and timing of fuel treatments over multi-year simulations.

Case Studies

Several case studies reported that past wildfires altered the effects of subsequent fires. For example, Cook et al. (2015) found that prior managed wildfires (wildfires intentionally managed for resource benefit objectives) appeared to be more effective at reducing fire severity than mechanical treatments. Wildfires can be used to treat fuels 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. Graham (2003) reported that a recent fire (occurring within one year or less) had significant but isolated effects on fire growth, and in some cases appeared to stop fire progression locally. Multiple case studies emphasized that the potential for past wildfires to mitigate wildfire behavior and effects will decrease over time. Managers expected and allowed a mosaic of severity types, especially where past wildfire resulted in heterogenous forest structure and composition.

Questions Specific to Simulation Studies

The simulation synthesis focused exclusively on direct effects of fire that can be quantified at the landscape scale using simulation methods. Fuel treatment effectiveness was thus inferred from metrics that included area burned, size of individual fires, number of fires, burn probability, fire spread rate, fire frequency, fire risk, fire hazard, fire severity, fire intensity (including flame length and fireline intensity), smoke emissions, and resource loss due to fire. These metrics were generally obtained by running one or more fire simulations on a model landscape and averaging or summing across simulations and landscape subunits (e.g., stands, pixels, polygons).

What were the modeling strategies?

Most of the selected simulation studies used spatially explicit models of fire spread rate across landscapes comprised of pixels or polygons, although some used models that relied on burn probabilities that did not explicitly depend on fire spread from their surroundings. Fire simulation modeling platforms included FlamMap, FFE-FVS, FARSITE, BEHAVE, LANDIS, FireBGCv2, VDDT, SIMPPLE, SEM-LAND, LANDSUM, Prometheus, Burn-P3, FSim, iLand, and Envision. Some of these platforms use closely related techniques and build on each other. Some of them also model vegetation and fuels over time and are thus helpful for multi-year simulations. Additionally, some studies employed optimization algorithms to determine where and/or when to apply fuel treatments, especially minimum travel-time (MTT) algorithms such as the Treatment Optimization Model (TOM). Other optimization algorithms used included MAGIS, STARFire, Optfuels, OptQuest, and Approximate Dynamic Programming (ADP).

Was the evaluation robust concerning the degree of model evaluation?

Some of the selected simulation papers introduced and evaluated new modeling techniques as part of their study, while most papers applied existing techniques without formal evaluation. Most papers presented details regarding the calibration and application of models to their study areas. However, some of the papers presented few details and/or stated that their results are preliminary, diminishing confidence in their robustness.

Did the syntheses demonstrate robust findings and insights and impetus for future studies?

There was variation in the quality of the studies related to the number of times a given simulation was run (analogous to experimental replicates), the use of statistical tests, and the completeness of presented results. The various simulation modeling techniques used by different studies also differ in robustness, as some are more advanced than others. Simulation modeling is recognized to have shortcomings regardless of the technique employed. Given these caveats, most of the simulation papers appeared to be of adequate quality to provide useful insights into the questions they each addressed. Collectively, they provide a general view of fuel treatment effectiveness in a variety of settings and illustrate gaps where future research would be beneficial.

Did the Synthesis Inform Future Fuel Treatment Planning?

In the three synthesis studies (empirical, simulation and case studies) fuel treatments can diminish fire effects inside the treatment boundary by altering fire severity and providing fire suppression opportunities. However, scientific (rather than anecdotal) information on how fuel treatments are effective over space and time, especially outside of treatment boundaries, and how we can use fuel treatments to maximize effectiveness at broad scales is much more limited. In the empirical synthesis type, we identified 12 papers that showed evidence that fuel treatments can diminish fire effects outside of their treatment boundaries; but the information from these 12 papers had limited depth and consistency. The simulation papers were the main source of available scientific information for informing future fuel treatment planning.

Landscapes

In all three synthesis types, factors such as topography, fire weather, climate, fire duration, fire regime, fire timing, fuel load, and suppression effort all contributed to the effectiveness of fuel treatments at the landscape scale. However, in empirical papers, the term “landscape” was rarely clearly characterized or defined. In case studies, landscapes were defined by the extent of specific wildfires. The landscapes of simulation studies were demarcated prior to simulation modeling and often corresponded to ownership or management boundaries. We think that it is critical that landscapes be clearly defined, similar to the strategies used in defining firesheds or PODs, with the following questions in mind: What is the size and intensity of the fire event that is expected? What is the desired post-wildfire severity (distribution of fire severity in trees; surface, and soils)? How are fires likely to spread within the context of topography, wind direction, and spatial distribution of fuels? What is the most appropriate scale for planning and implementing fuel treatments and possible suppression tactics that will protect valued resources and otherwise meet treatment objectives? Similarly, how is historical fire regime integrated and used to inform treatment and future wildfire regimes? Methods for predicting the probability, location and severity of future wildfires are essential for addressing these questions.

Integrated management

Clearly defined, quantifiable objectives are needed that are related across spatial and temporal scales from the individual stand, local, regional, and national levels to evaluate whether a fuel treatment or fuels management program is effective. The definitions of fuel treatments present potentially conflicting goals of, on one hand, management to suppress fires, and on the other hand, the concurrently recognized value of fire as an essential process in many ecosystems, such that suppressing or excluding fire can degrade ecosystem resilience, perpetuate high fuel hazard, and increase risk to ecological and social resources. The ambiguity around fuel treatment definitions, with potentially opposing goals, creates confusion about what an effective fuel treatment really is (Prichard et al. 2021).

Management objectives do not need to be considered in isolation but can be integrated toward creating disturbance-resilient landscapes. Reed et al. (2015) define an integrated landscape approach as:

> "A framework to integrate policy and practice for multiple land uses, within a given area, to ensure equitable and sustainable use of land while strengthening measures to mitigate and adapt to climate change. It also aims to balance competing demands on land through the implementation of adaptive and integrated management systems. These include not only the physical characteristic features of the landscape itself, but all of the internal and external socio-economic and socio-political drivers that affect land use, particularly related to conservation, forestry and agriculture. In short, landscape approaches seek to address the increasingly complex and widespread environmental, social and political challenges that transcend traditional management boundaries."

Shared Stewardship meets most of the characteristics of an integrated landscape approach. Shared Stewardship is an outcome-based strategy that has three core elements: determine management needs by state, emphasize management in the right places and at the right landscape scale, and use all the available authorities and tools to implement on-the-ground management, including carefully managed fire, across boundaries by working with partners and stakeholders to help identify the best tools (USDA 2018).

Assessing Landscape Fuel Treatments

We suggest a method to evaluate fuel treatment effectiveness in the context of a fuel management program, composed of three, linked components: changing fuels, changing fire behavior under specified weather and topographic conditions, and changing fire effects (Figure 6). The advantage of the fuel management triangle is that it places the emphasis on how to achieve desirable fire effects by proactively changing fuels and subsequent fire behavior. Land management agencies' and organizations' goals are centered on creating resilient ecosystems that provide multiple environmental and social services that can withstand stress and disturbance (USDOI and USDA 2014, Stephens et al. 2016, Urgenson et al. 2017, California Forest Management Taskforce 2021). Therefore, a fuel management program that links fuels, fire behavior, and fire effects explicitly should be more successful in attaining goals than a program that focuses primarily or solely on altering fire behavior. We think of this as an adaptive cycle, where fuel treatment prescriptions and placement change over time and areas are prioritized for social resource protection and ecological resource management (North et al. 2021).

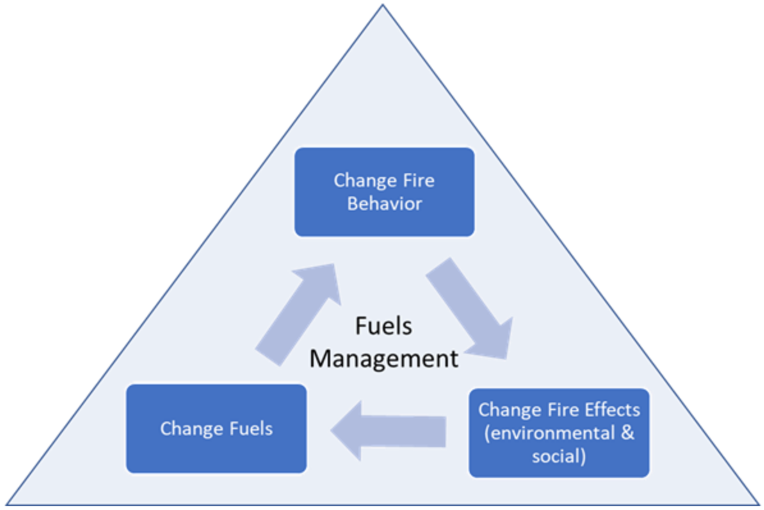

Figure 6. Fuel management triangle. The fuel management triangle illustrates the relation of fire behavior and fire effects when fuels are manipulated. These outcomes, if quantified, can identify whether a fuel treatment followed by wildfire met the desired environmental and social fire effects.

We argue that the success of a fuel treatment and a larger fuels management program must be evaluated at two levels: fire hazard/risk states and actual fuel treatment outcomes (Table 7). Doing so will help resolve confusion about how to evaluate fuel treatments by separately quantifying hazard and risk state attributes of vegetation and then quantifying fire effects outcomes of actual fires. Importantly, these levels can be evaluated at multiple scales (e.g., for a stand, a single fire, multiple fires, or across a landscape) over time based on preidentified objectives to determine effectiveness of fuel treatments and fuels management programs. By separating the components of a fuel treatment into how the fuels were altered versus how the potential or actual fire behavior and effects were altered relative to untreated areas, it becomes easier to evaluate the impacts of the treatments on resulting effects (Hood et al. Appendix C.2).

Hazard and Risk State Evaluations and measuring effectiveness

Reducing fuels and altering fuel arrangement affects fire hazard, or the potential fire intensity. Hazard is characterized by the amount, type, arrangement, and location of fuels that, together with weather and topography, determine fire behavior. Fuels are the one component of the fire behavior triangle that can be managed. Implementing fuel treatments to reduce fire hazard is a proactive management action to alter fire behavior to mitigate fire severity in the event of a fire. Hazard describes the condition of fuels from objective quantification of actual vegetation and fuels, as well as the subjective prediction of potential fire behavior and effects (i.e., severity) based on best-available modeled output (Table 7). Numerous quantifiable stand-level attributes exist to characterize the fire hazard state. Managers can measure stand characteristics and analysts can use these values in fire behavior and effects models to calculate attributes of potential fire behavior (e.g., potential flame length, rate of spread) and potential fire effects (e.g., severity, exposure) for given weather scenarios (Ottmar et al. 2007; Scott et al. 2013).

Fire hazard affects how a fire may burn through an area, but it does not address the likelihood of a fire burning a specific area – that is quantified by fire risk. Fire risk is the probability of expected loss given the likelihood of a fire at a given intensity and has three components: likelihood of ignition, expected fire intensity, and fire effects of the expected fire intensity (Scott et al. 2013, Ager et al. 2019). Fire hazard is therefore a component of fire risk, as hazard is composed of fire intensity and fire effects. An area may have high fire hazard but a very low probability of ignition, reducing the overall fire risk. It is important to realize that fire effects may be both positive and negative, such that a fire of a given intensity could have either or both desirable and undesirable outcomes. The likelihood of fire of a certain intensity dictates an area's exposure and susceptibility to fire effects. Risk state attributes are modeled outputs that consider hazard attributes coupled with likelihood of fire occurrence.

Fuel treatment effectiveness is evaluated based on the clearly articulated management objectives and desired conditions and measurement methods such as box plots to compare fuel treatment effectiveness. For example, Jain et al. (2007) conducted a study along the breaks of the Missouri River in a ponderosa pine savanna to determine if prescribed fire followed by wildfire achieved management objectives. The management objectives included increasing forage area, decreasing tree density, and promoting herbaceous and forb abundance. They found that prescribed fire alone did not meet the the management objectives and wildfire alone killed too many trees and exceeded the management objectives; however, prescribed fire followed by wildfire tended to meet the conditions articulated in the management objectives. The analysis used a series of box plots to illustrate the shift in trees/acre, canopy base height, shrub cover, forb cover, and grass cover. Figure 7 illustrates an example of forb, grass, and shrub cover for one area burned by the HCross prescribed fire that was later burned by a wildfire.

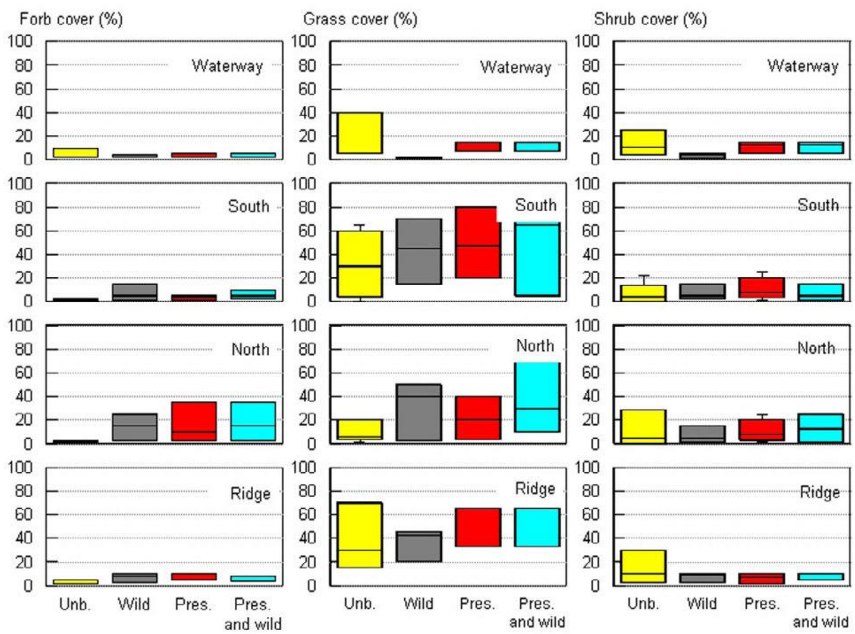

Figure 7. Example from Jain et al. (2007) illustrating how fuel treatment effectiveness was evaluated. Box plots show the variation among the different fire events. Unburned sites were used as a frame of reference. Unb. = unburned, Pres. = prescribed fire, wild=wildfire, Pres. and wild = prescribed fire followed by wildfire. Top graph are sites in draws and riparian areas, south are south facing aspects, north are north facing aspects and ridge are ridgetops.

Table 6. Metrics to quantify stand and landscape fuel treatment effectiveness. Attributes of interest are dictated by pre-identified objectives and landscape boundaries. Hazard state attributes describe the condition of fuels from objective quantification of actual vegetation and fuels and the subjective prediction of potential fire behavior and effects (i.e., severity) based on best-available modeled output. Risk state attributes are modeled output that consider hazard coupled with likelihood of fire occurrence. Fuel treatment effectiveness attributes are based on actual fire behavior and effects and should be compared against no-treatment alternatives.

Planning Phase – Pre-fire states (conditions): Evaluation of hazard and risk			
Condition	**Stand Attributes that can be altered**	**Landscape Attributes that can be altered**	**Stand and landscape Attributes that cannot be altered**
Hazard state	• Data-derived, objective: Surface fuel load, canopy base height, canopy bulk density, fire-resistant species • Modeled output, subjective: Fire behavior fuel model, potential flame length, potential rate of spread, potential fire type (surface, torching, crowning), potential severity	• Fire Return Interval Departure • Structural stage/Age class • Fire Regime Condition Class • Fuel treatment configuration • Proportion of identified landscape treated • Potential Flame Length • Potential fire type (surface, torching, crowning) • Potential severity	Species composition – moist mixed conifer Topographic complexity (slope %) Treatment limitations Social acceptance Economic viability Laws (i.e., endangered species act)
Risk state	Likelihood of ignition Exposure Susceptibility	Exposure, susceptibility, safety zones, suppression opportunities, natural fire breaks	Location of towns and wildland urban interface

Evaluation Phase – post-fire outcomes: Evaluation of fuel treatment effectiveness			
Evaluation criteria	**Individual fire attributes**	**Landscape fire attributes over time**	**Stand and landscape resilience**
Environmental attributes	Fire severity, fire size, strategic point protection ability, fire extent, fire progression/rate of spread	Total area burned, characteristic fire severity (% or trees/acre killed), characteristic patch size (%)	Ability to recover after the fire (regeneration and survival)
Social attributes	Fire fighter safety, safety zones, structures lost, evacuations (# days and people), suppression costs	Fire suppression opportunities, structures lost Evacuations (# days and people), suppression costs, smoke production, smoke exposure	Maintain wildlife habitat, recreation opportunities, safety

Innovation in Landscape Fuel Treatment

The syntheses identified five areas that may inform future fuel planning:

- Despite the broad range in values, wildfire size and total treatment size were highly correlated among the empirical studies (Pearson's correlation $r = 0.89$, $n = 93$, $df = 91$, $p < 0.05$) (Figure 8), suggesting that there was a consistent and positive relationship between the total treatment size and wildfire size.
- Using optimization algorithms to determine placement and/or timing of treatments led to greater effectiveness compared to other schemes.
- Prioritizing treatments in stands with greatest fire hazard/risk generally led to greater reduction of damaging wildfire at landscape scale compared to prioritizing stands near WUI, but the latter was generally more effective for protecting WUI.
- More extreme fire weather led to greater wildfire extent but not necessarily less treatment effectiveness relative to untreated scenarios.
- Effectiveness varied across climate change scenarios due to effects of climate on both fire weather and vegetation/fuel dynamics.

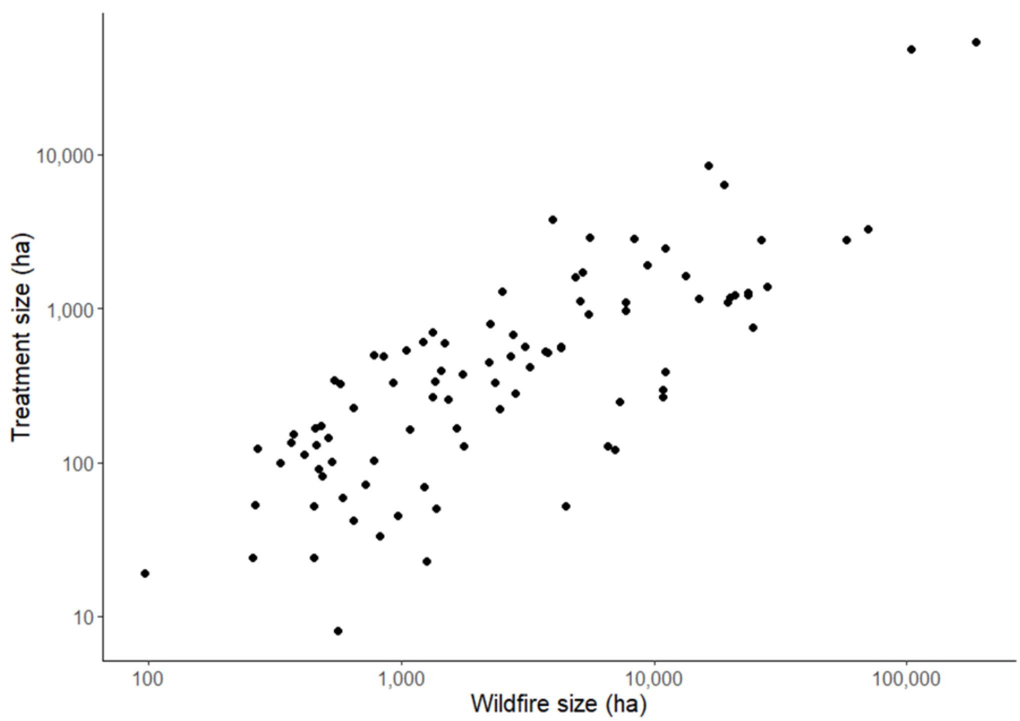

Figure 8. The relationship between wildfire size and total treatment size taken from empirical studies. The relationship between wildfire size and total treatment size (Pearson's correlation $r = 0.89$, $n = 93$, $df = 91$, $p < 0.05$) from 26 papers evaluating landscape-scale fuel treatment effectiveness. Total treatment size is the sum of all the treated area occurring within a wildfire area. Note that both axes are log10 scale.

Fuel Treatments and How they Alter Fuel Strata

Across the landscape fuel treatment effectiveness literature, treatment comparisons were very generalized and rarely did they link any single treatment or treatment combination to the primary fuel strata that a treatment is designed to alter. This makes accurate interpretation of results and comparison of studies difficult in some cases because it is unclear exactly how the treatments altered fuels. Here is a short synopsis of different treatments in relation to the strata that are affected by a particular silviculture method, which, ideally, would be systematically incorporated into landscape fuel treatment studies. Table 8 provides a general relation between the treatment and its focus on manipulating specific fuel strata.

Fuel Strata

There are three broad fuel bed types: crown (also referred to as aerial), surface, and ground fuels. These broad categories can be further described into six layers: 1) canopy, 2) shrub and small trees, 3) low, nonwoody vegetation, 4) woody fuels, 5) moss and lichens, and 6) ground fuels (Sandberg et al. 2001, Riccardi et al. 2008, Jain et al. 2012). Modification of any of these fuels has implications for fire behavior, fire suppression, and fire severity.

Crown fuels (also referred to as canopy fuels or aerial fuels) are those higher than 6 feet above the ground, such as trees, snags, and ladder fuels.

Ladder fuels were described by Jain et al. (2012) as those fuels that provide access for flames to transition from a surface fire to torching/crowning fire in taller fuel layers and tree crowns. Ladder fuels can include lichens and moss, climbing ferns or other epiphytes that live on the trees, dead branches, vines, leaning snags, and stringy or fuzzy bark. Understory and midstory trees that reach the lower crown of the dominant crown classes can provide a “ladder” to the upper crown during a wildfire. Ladder fuels bridge the vertical gap between the surface and canopy layers.

Surface fuels include grasses, forbs, shrubs, litter, and woody material lying on, or in contact with the ground surface below 6 feet (Sandberg et al. 2001, Jain et al. 2012). The fuel depth, continuity of surface fuel, and the chemistry all influence surface fire behavior.

Ground fuels include humus, the fermentation layer, surface and partially buried rotten wood. Ground fuels tend to smolder and may burn for hours, days, and even weeks. Long duration smoldering can lead to soil damage, tree mortality, and smoke impacts.

Treatments and relation to fuel strata

Prescribed fire

Fuel strata focus: Surface and ground fuels

Prescribed fire is a common tool used to meet a variety of management objectives. It can be used to reduce hazardous fuels but also is used to dispose of logging debris, prepare sites for natural or artificial regeneration, improve wildlife habitat, manage competing vegetation, and improve forage. From a fuel hazard perspective, prescribed fire can reduce loading of fine fuels, duff, large woody fuels, rotten material, small shrubs, and other live surface fuels. In addition, it can also diminish horizontal fuel continuity. However, the effectiveness of a prescribed fire is dependent on several factors that we do not cover and the specific prescribed fire prescription which varies depending on the management objectives, risk, potential consequences, and technical difficulty (Graham et al. 2004, Jain et al. 2012).

Mechanical Treatments

Fuel strata focus: Surface, ladder, and canopy fuels

A mechanical treatment includes all treatments regardless of the type of treatment that uses handsaws or machinery where specific trees and other vegetation are selected for removal or retention. A mechanical treatment can manipulate surface, ladder, canopy fuels and ground fuels; some manuscripts refer to treatments as being mechanical with no additional details, therefore when "mechanical treatment" is used to indicate a treated area, the reader knows that some mechanical method was used, but not which fuel stratum(-a) was manipulated or removed.

Noncommercial mechanical treatments are treatments that manipulate vegetation with no commercial value (i.e., treat biomass without product removals) that uses handsaws to slash small material, masticators that crush, compact, or mulch material, or a machine that can cut and pile slash such as with a grapple piler that is used to pile logging slash or slash created by handsaws. The type of machinery used in mechanical thinning dictates what vegetation is manipulated. Depending on machine and operation type, this type of mechanical treatment by itself does not directly alter ground fuels except by ground disturbance from machine movement, which can crush slash and vegetation and scarify or compact the soil. In some cases, such as a masticator, a compacted slash bed and can increase the amount of fine wood material on the site. When it comes to treating surface and ladder fuels, the effectiveness of noncommercial mechanical treatments is highly variable because effectiveness depends on the biomass that is treated and the machine that is used. There are several papers that focus on mastication and its effect on surface fuels; some recent examples include Keane et al. (2018), Jain et al. (2018), Sikkink et al. (2017), Kreye et al. (2014), Heinsch et al. (2018), Smidt et al. (2019). Noncommercial treatments can be used in different types of thinning, as treatment following a regeneration harvest, to remove heavy shrubs in a woodland or shrubland ecosystem, or to control rapid understory vegetation growth on very productive sites.

Table 7. Relation of treatment type and fuel strata. Each treatment type specifically manipulates an identified fuel stratum.

Treatment	Fuel Stratum			
	Ground fuels	Surface fuels	Ladder fuels	Crown fuels
Prescribed fire	X	X		
Mechanical				
Commercial				X
Noncommercial		X	X	
Mastication		X	X	
Thinning Types (commercial valued commodities only)				
Thin from below			X	X
Crown thin				X
Selection thinning			X	X

Commercial mechanical treatments are focused on trees that have a commercial value and, depending on the presence of commercial sized trees and noncommercial sized trees and shrubs, it is sometimes used in conjunction with a noncommercial mechanical treatment and a prescribed fire that can be used to treat surface and ground fuels creating a three-treatment type sequence: commercial mechanical treatment, noncommercial mechanical treatment, and prescribed fire. A specified tree size, species and quality that is of commercial value is dependent on the location and local markets. For example, a particular species may be commercially viable at 5" diameter breast height (DBH) in one location but not commercially viable until 8" DBH in another location. Typically, the merchantable portion of a treatment focuses on altering crown fuels by separating crowns and decreasing canopy bulk density, which typically removes larger diameter trees than thinning ladder fuels. However, there are numerous ways to implement these treatments depending on the current condition of the stand (species, tree size, tree density) and the desired outcome (Graham et al. 1999). A commercial mechanical treatment alone may be used successfully when a dense understory has prevented light from reach the ground, resulting in low levels of surface fuels.

Identified management and policy considerations and research gaps

Many barriers to implementing effective treatments were identified in the case studies, including limited resources and competing objectives, given uncertainty where the next damaging wildfire will occur. Declining or variable funding levels for fuel treatments make consistent planning, implementation, and maintenance of fuel treatments difficult. Treatments may not be finished before the wildfire occurs. One example of competing resource objectives and values at risk is the need to balance the protection of dense forest habitat for species such as spotted owl (*Strix occidentalis*) with fire risk reduction efforts. Lastly, another challenge was the need for increased communication and planning with community cooperators and agency partners about the risks and gains of completing fuel treatments.

Not all ecosystems are represented in the literature. We selected members of our team that were experts in a wide breath of ecosystems so that we could tap into their knowledge when understanding the literature focused on shrublands, savannas and grasslands. We also had team members from throughout the United States. However, over 95% of the papers that qualified for our synthesis studied forested ecosystems, primarily in the western United States. This can be attributed in part to the outsized importance of western forest ecosystems from the standpoint of wildfire management and fuels reduction. Even so, we had hoped to find more qualifying studies from other ecosystems where fuels reduction is an important component of fire management, such as nonnative annual species-invaded drylands of the interior west and southeastern pine savannas, where the most prescribed fire occurs. We suggest that future research should include underrepresented forest and non-forest ecosystems from across the continent.

Another area lacking in the literature was information on cost-benefit analysis or providing ways for managers to identify a balance that meets multiple resource management objectives while also creating disturbance resilient ecosystems. There were very few studies that discussed trade-offs between intense small-scale treatments versus extensive broad scale treatments. Other cost-benefits could focus on the effectiveness of fuel treatments in decreasing suppression costs or facilitating the use of beneficial wildfire. Although not necessarily economic, another issue concerns liability trade-offs and risks associated with using more beneficial wildfire when ignitions begin in fuel treatments that are landscape scale. Another example would be for science to identify a fuel treatment strategy to coordinate and integrate treatments planned at the landscape scale with targeted treatments designed to protect the wildland urban interface.

Our synthesis focused primarily on how fuel treatments performed in the event of large wildfires, rather than the effect of fuel treatments at keeping wildfires small. Treatments offer suppression opportunities and subsequently influence how many fires are being extinguished in fuel treatments. In the case studies, there were comments that the wildfires ignited outside the fuel treatments and therefore when fuel treatments were burned by wildfires, the wildfires were already large. If fuel treatments allow for effective wildfire management, including successful full suppression compared to untreated areas, our focus may have undervalued their suppression benefit.

Longevity of fuel treatments was mentioned in all three synthesis types. In most cases fuel treatments were short-lived from 1 year to 20 years; however, in most cases the longevity of fuels was focused on surface fuels. Future studies should focus on the longevity of treatment effects in each relevant fuel stratum to test the following hypotheses: 1) surface fuels have the shortest fuel treatment longevity; 2) crown fuels have the longest fuel treatment longevity; 3) ladder fuels longevity decreases when crown fuels are separated creating growing space for latter fuels to flourish. Studies that focus on fuel strata longevity can inform managers when is it necessary to conduct maintenance treatments and choose a method of treatment that extends treatment longevity.

A discussion of research gaps in empirically based studies is premature given the current state of knowledge. Empirical approaches to understanding landscape-level fuel treatment effectiveness are in their infancy. Indeed, the field is at a point where clear and precise terms and concepts are not broadly recognized. The fundamental issue is the varied and imprecise use of the term 'landscape.' Wildfire is a landscape-level process. Fuel treatment effectiveness should be evaluated by how it affects that process, functionally, from a landscape perspective. The terms landscape scale and landscape size have little generalizable meaning. Large wildfires and or large treatments may be called 'landscape', but our inference on treatment effectiveness will remain constrained to within-site (i.e., within treatment) effects if the sampling design and analysis are site-level and not also measuring effects outside the treatment footprint. Therefore, instead of identifying gaps in understanding, there should be 1) broad recognition of what is meant by landscape-level fuel treatment effectiveness and how the characteristics of fuel treatments affect wildfire activity outside of treatment boundaries, and 2) long-term commitment to designing and implementing research projects at the landscape level over large areas that can inform questions and test hypotheses about the type, size, density, and configuration of fuel treatments that best affect subsequent wildfire in desirable directions.

There is a need for more simulation modeling studies that focus on potential future weather and fuel conditions rather than conditions of the recent past. Managers should consider and integrate vegetative shifts due to climate change. Another question within the context of future climate is how fire weather will differ, including whether fires will tend to burn at different times of year than they have in the past. The case studies also pointed out that fuel treatments need to be designed reflect the fire behavior and suppression efforts they will experience in the future.

Each of the simulation studies selected for this synthesis compared scenarios that differed by at least one the dimensions of fuel treatment design/deployment (e.g., extent, size, placement, timing, prescription), and some also tested effects of other factors (e.g., weather percentiles, climate scenarios, fire suppression levels, etc.). Relatively few studies tested multiple dimensions and/or other factors in ways that revealed their relative importance and potential interactions. Additional studies along these lines will likely be valuable. Simulation studies and empirical studies need to report interactions and combinations of driving factors. This could inform the placement and deployment of fuel treatments on the landscape. As presented in Figure 1, there are several factors that together create a particular outcome.

For maximum value, simulation studies comparing treatment scenarios should include an untreated control scenario. In addition, analysis should also contain statistically valid comparisons among treatments and control scenarios including plausible interactions. Metadata standards should be developed for these studies so that they can be more easily categorized and compared. We recommend that burned area be included as a standard metric for these types of simulation studies in addition to any other metrics of interest. This is because burned area is already the most used metric and it can be easily rescaled as a percentage of total landscape area or as the reduction in burned area per unit area treated (also known as leverage). Breaking apart the amount of area burned with different levels of severity or intensity makes this metric even more useful.

Each synthesis type (empirical, simulation, or case study) provided a unique set of results. A major contribution to future research is to integrate these three types of information in individual studies. Cochrane et al. (2013) used both model simulation and empirical data, illustrating how both approaches when blended can provide broader and more comprehensive insights; however, their research did not include important manager insight that were voiced in the case studies. Another approach would be to organize information from different synthesis types geographically or by the specific wildfires that have been studied, leading to a more comprehensive story that provide different perspectives and tools.

Conclusions

We identified hundreds of papers that evaluate fuel treatments but relatively few did so at the landscape scale. We found 179 papers out of 2240 (approximately 8%) of the research associated with fuel treatment that were classified as landscape scale. Most of this literature is in simulation modeling (85 papers) and very few are empirical studies (12) that looked at the effectiveness of fuel treatments outside of the treatment boundary. There needs to be more focus on linking fuel treatments to changes in fuel strata, which should be the focus of fuel treatment effectiveness. There are numerous ways to implement fuel treatments, but the resulting fuel strata and their condition, not the type of treatment, influence fire behavior. This is an area for significant improvement in future research. We are far from the stage where we could estimate thresholds of any type. An important recommendation is to implement well-designed and controlled field experiments over large areas that can produce empirical data to confront the higher-level questions on effectiveness over large landscapes. Long-term investment of resources and a recognition that information may take years or decades to acquire due to uncontrolled factors, primarily where, when, and how a wildfire will run through an experimental area, will be needed to advance the field on landscape fuel treatment effectiveness.

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Appendix B: Product Listing

Our project consisted of literature syntheses on landscape fuel treatments. We presented the results of these syntheses in a special session for the 9th International Fire Ecology and Management Congress on November 30, 2021. This session provided the unique opportunity to also include manuscripts in a Special Collection of the journal *Fire Ecology*. Submission to the Journal will be prior to February 234, 2022.

Below are the titles, authors, of the oral presentations and the four syntheses will also be part of the manuscript submissions to Fire Ecology.

What we know about landscape fuel treatment effectiveness: Special Session for the 9th International Fire Ecology and Management Congress

Co-organizers: Theresa B. Jain, Sharon M. Hood, Jeffrey Ott, Shawn T. McKinney, and Brice Hanberry work for the Rocky Mountain Research Station.

Special Session Abstract

A team of scientists from throughout the United States were funded by the Joint Fire Science Program to produce the state-of-knowledge on landscape fuel-treatment effectiveness. We will present a synthesis on the current literature using five presentations and a summary of what we have learned in this session. Five papers will be presented quantifying fire hazard and fuel treatment effectiveness. The first presentation discusses a way to quantify fire hazard and fuel treatment effectiveness from stands to landscapes, which providing the foundation of the session. Three presentations will follow that focus on specific results from a broad literature synthesis separated on our current knowledge from empirical studies, simulation studies, and management/wildland fire case studies. We conclude the session focusing on what we clearly understand, what we find to be ambiguous and that needs additional research, and what proposed strategies would move our understanding forward. Key takeaways from this synthesis are that there is little information available in the literature that specifically focuses on landscape fuel treatment effectiveness, that there are inconsistent definitions of what is meant by “landscape fuel treatment effectiveness”, and that there is a broad range of methods and approaches diminishing our ability to make inferences and quantify specific effectiveness attributes to guide future implementation of fuel treatments intended to alter fire behavior within and outside fuel treatment boundaries.

Presentation 1: Quantifying fire hazard and fuel treatment effectiveness from stands to landscapes

Authors: Sharon M. Hood, USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory; J. Morgan Varner, Tall Timbers Research Station; Theresa Jain, USDA Forest Service, Rocky Mountain Research Station

US federal policies recognize the important role of wildland fire in fire-adapted ecosystems and need for landscape-scale restoration, balanced with the need to effectively manage fire to mitigate detrimental social and ecological effects. Towards these goals, treating fuels is a primary strategy used to modify fire behavior by manipulating vegetation. Wildland fire is a landscape-scale process, and the scale at which national strategic goals are evaluated, making it imperative to evaluate fuel treatment effectiveness at larger spatial and temporal scales. We posit that the successfulness of a fuel treatment and a larger fuels management program must be evaluated at two levels: fire hazard and risk states and actual fuel treatment outcomes. To assess trends in fuel treatment effectiveness, we propose a method to examining vegetation, environmental, and social attributes across large spatial scales and time. This method allows visualization of the data distribution of attributes of interest and naturally incorporates the range of variation that will invariably exist within ecosystems and landscapes. Our proposed method of quantifying fire hazard and risk states, followed by outcomes of fire on environmental and social attributes, allows assessment of how individual fuel treatments and fuels management programs are effective based on predetermined objectives.

Presentation 2: A systematic review of empirical evidence for landscape-level fuel treatment effectiveness

Authors: Shawn T. McKinney, Ilana Abrahamson, Theresa Jain, Nathaniel Anderson, USDA Forest Service, Rocky Mountain Research Station

Fuel treatments can mitigate negative effects of wildfire, but empirical evidence of effectiveness across landscapes is needed for implementation at the landscape-level. We conducted a systematic review of empirically-based studies that tested landscape-level fuel treatment effects on North American wildfires over the past 30 years. Twenty-six papers met our inclusion criteria. Wildfire size ranged from 96 to 186,874 ha and total treated area from 8 to 53,423 ha. Treated and wildfire area were highly correlated ($r = 0.89$), and 22% of wildfire area was treated on average. All studies demonstrated site-level effects, but only 12 studies provided evidence of landscape-level effects. Landscape-level effects included fire severity, progression, and extent, but studies were dissimilar in design and analysis, constraining generalization about the type and configuration of treatments to maximize effectiveness. The empirically-based state of knowledge is underdeveloped because of challenges in implementing appropriate sampling designs prior to wildfire occurrence, and because the distinction between site-level and landscape-level effects is not broadly recognized. All papers used the term landscape and some claimed landscape-level effects that were truly site-level. Research should develop ways to interpret the role of fuel treatments at the landscape-level to provide insight on designs and approaches that maximize effectiveness.

Presentation 3: Landscape-scale Fuel Reduction Treatment Effectiveness Inferred from Simulation Studies

Authors: Jeffrey Ott, Francis Kilkenny, Theresa Jain, USDA Forest Service Rocky Mountain Research Station.

The question of how to maximize the effectiveness of fuel reduction treatments at landscape scales is important, given that in most instances, it is not feasible or desirable to treat an entire landscape at risk. Managers may want to know how to leverage treatments under existing resources and constraints so that they will have maximum effect beyond treated areas. Simulation modeling has been widely used to address this question. We reviewed 80+ simulation studies that evaluated landscape-scale fuel reduction treatment effectiveness for landscapes in the United States and Canada. These studies have generally shown that localized treatments are effective at reducing fire impacts on the broader landscape, but that effectiveness depends on the amount of treated area, size of individual treatments, location and arrangement of treatments, type of treatment, timing of treatment, and other factors beyond the treatments themselves. We conclude that simulation modeling is a valuable tool for research and decision-making related to fuel reduction treatments and will become even more useful as models incorporate increasing realism of fuel structure and fire behavior under conditions likely to exist in the near future.

Presentation 4: Lessons learned about landscape fuel treatment effectiveness from wildland case studies

Authors: Brice Hanberry USDA Forest Service; Alexandra Urza USDA Forest Service; Theresa Jain USDA Forest Service

Opportunities for quantitative assessment of landscape-scale fuel treatment effectiveness are rare, given scale, uniqueness of fires, and lack of replication. We performed a formal literature search to identify case studies that evaluated the effectiveness of fuel treatments at the landscape level during an actual wildfire event. Eleven case studies provide an in-depth look at the outcomes of high-profile wildfire events and qualitative descriptions of the impact of fuel treatments on fire behavior, fire effects, and suppression efforts. We will share common themes and lessons learned from case studies, including the factors that influence fuel treatment effectiveness and areas in need of further research

Presentation 5: Effectiveness of fuel treatments at the landscape scale: State of understanding and key research gaps (this presentation may not be submitted to Fire Ecology, but the report based on this presentation was submitted to Joint Fire Sciences as the final report).

Authors: Theresa Jain, Ilana Abrahamson, Nathaniel Anderson, Mike Battaglia, Brice Hanberry, Sharon Hood, Francis Kilkenny, Shawn McKinney, Jeffrey Ott, Alexandra Urza, Rocky Mountain Research Station, Joseph O'Brien, Southern Research Station, and Morgan Varner, Tall Timbers Research station, Jeanne Chambers, Rocky Mountain Research Station

Syntheses that provide both the current state of knowledge associated with fuel treatments from the literature and manager experience have proved valuable to both scientists and managers in the past because they provide relevant information that can inform planning and implementation, identify science gaps and research needs, and inform policy. No up-to-date review and synthesis of landscape fuel treatment effectiveness exists. Joint Fire Science Program funded a team to conduct a systematic review of the current knowledge concerning landscape fuel treatment effectiveness. Four synthesis were conducted: 1) landscape-scale fuel treatment effectiveness: exploring concepts and measurements, 2) empirical evidence for landscape-level fuel treatment effectiveness: A systematic review, 3) fuel treatment effectiveness at the landscape scale: a systematic review of simulation studies comparing treatment scenarios in North America, 4) lessons learned about landscape fuel treatment effectiveness from wildland fire case studies. Using a "weight of evidence" approach, this abstract will synthesize the findings from the four separate reviews and provide recommendations that could inform manager and policy-maker decisions on how to design, deploy, prioritize, and measure effectiveness of fuel treatments at the landscape scale and identify the shortcomings of the literature and where to focus future research.

Appendix C: Metadata

Appendix C.1. Literature Search Criteria

In collaboration with the USDA Forest Service Library, we conducted a series of literature searches beginning in October –and November 2019. Searches were limited to literature published since 1990 and excluded studies in areas outside the U.S. and Canada. Library personnel searched the Web of Science, Scopus, National Agricultural Library, Fire Research and Management Exchange System (FRAMES), FS/Info, and TreeSearch databases. Search terms included ‘fuel’, ‘fire’ and related synonyms, and for some searches, additional terms specifying ecosystems, treatment types, fire behavior/effects, and landscape-scale terminology. The following strings of keywords were separated into two search groups (Refer to table 1, final report for a table of the keywords).

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*)

Appendix C.2. Literature Synthesis

This project did not collect data per se; but did identify several publications that we used in each literature synthesis. Therefore, as far as metadata and information useful to Joint Fire Science we provide summary of each study followed by the literature cited for four synthesis types:

1) General concepts and discussion on ways to quantify fuel treatment effectiveness from stands to landscape.
2) A systematic review of empirical evidence for landscape-level fuel treatment effectiveness
3) Landscape-scale Fuel Reduction Treatment Effectiveness Inferred from Simulation Studies
4) Lessons learned about landscape fuel treatment effectiveness from wildland case studies

Quantifying fire hazard and fuel treatment effectiveness from stands to landscapes

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US federal policies recognize the important role of wildland fire in fire-adapted ecosystems and need for landscape-scale restoration, balanced with the need to effectively manage fire to mitigate detrimental social and ecological effects. Towards these goals, treating fuels is a primary strategy used to modify fire behavior by manipulating vegetation. Wildland fire is a landscape-scale process, and the scale at which national strategic goals are evaluated, making it imperative to evaluate fuel treatment effectiveness at larger spatial and temporal scales. We posit that the successfulness of a fuel treatment and a larger fuels management program must be evaluated at two levels: fire hazard and risk states and actual fuel treatment outcomes. To assess trends in fuel treatment effectiveness, we propose a method to examining vegetation, environmental, and social attributes across large spatial scales and time. This method allows visualization of the data distribution of attributes of interest and naturally incorporates the range of variation that will invariably exist within ecosystems and landscapes. Our proposed method of quantifying fire hazard and risk states, followed by outcomes of fire on environmental and social attributes, allows assessment of how individual fuel treatments and fuels management programs are effective based on predetermined objectives.

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

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Fuel treatments can mitigate negative effects of wildfire, but empirical evidence of effectiveness across landscapes is needed for implementation at the landscape-level. We conducted a systematic review of empirically-based studies that tested landscape-level fuel treatment effects on North American wildfires over the past 30 years. Twenty-six papers met our inclusion criteria. Wildfire size ranged from 96 to 186,874 ha and total treated area from 8 to 53,423 ha. Treated and wildfire area were highly correlated (r = 0.89), and 22% of wildfire area was treated on average. All studies demonstrated site-level effects, but only 12 studies provided evidence of landscape-level effects. Landscape-level effects included fire severity, progression, and extent, but studies were dissimilar in design and analysis, constraining generalization about the type and configuration of treatments to maximize effectiveness. The empirically-based state of knowledge is underdeveloped because of challenges in implementing appropriate sampling designs prior to wildfire occurrence, and because the distinction between site-level and landscape-level effects is not broadly recognized. All papers used the term landscape and some claimed landscape-level effects that were truly site-level. Research should develop ways to interpret the role of fuel treatments at the landscape-level to provide insight on designs and approaches that maximize effectiveness.

Table C.2.1. Empirical studies identified through literature evaluation, organized by evaluation method. Landscape-scale fuel treatment effectiveness is the ability of fuel treatments to affect wildfire outside of their footprint. Site-level studies address large wildfires and treatments within them but only evaluate the effectiveness within the fuel treatment boundaries.

Citation	Title
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. 2011 (a)	Comparing the role of fuel breaks across southern California national forests
Syphard et al. 2011 (b)	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.
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

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Landscape-scale Fuel Reduction Treatment Effectiveness Inferred from Simulation Studies

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The question of how to maximize the effectiveness of fuel treatments at landscape scales is important, given that in most instances, it is not feasible or desirable to treat an entire landscape at risk. Managers may want to know how to leverage treatments under existing resources and constraints so that they will have maximum effect beyond treated areas. Fire simulation modeling has been widely used to address this question. As part of a literature synthesis, we identified 85 studies that used fire simulation modeling to evaluate landscape-scale fuel reduction treatment effectiveness for landscapes in the United States and Canada. Most of these studies were focused on western montane forests. Each study compared burned area, intensity, severity, or some other metric of wildfire response under contrasting landscape scenarios, generally including an untreated/no-action scenario in addition to one or more treatment scenarios. We extracted average wildfire response values for each scenario and summarized results across studies through a series of boxplots and tables (see example figure C.1), differentiating results relating to all wildfire, damaging wildfire, and beneficial wildfire. The majority of the studies showed that localized fuel treatments had their intended effect of reducing all/damaging wildfire and/or increasing beneficial fire at the landscape scale (see figure C.1 below). However, effectiveness differed widely depending on the amount of treated area, size of individual treatments, location and arrangement of treatments, type of treatment, timing of treatment, and other factors beyond the treatments themselves, such as weather conditions, climate scenarios and fire suppression effort. We conclude that simulation modeling is a valuable tool for research and decision-making related to fuel reduction treatments and will become even more useful as models incorporate increasing realism of fuel structure and fire behavior under conditions likely to exist in the near future.

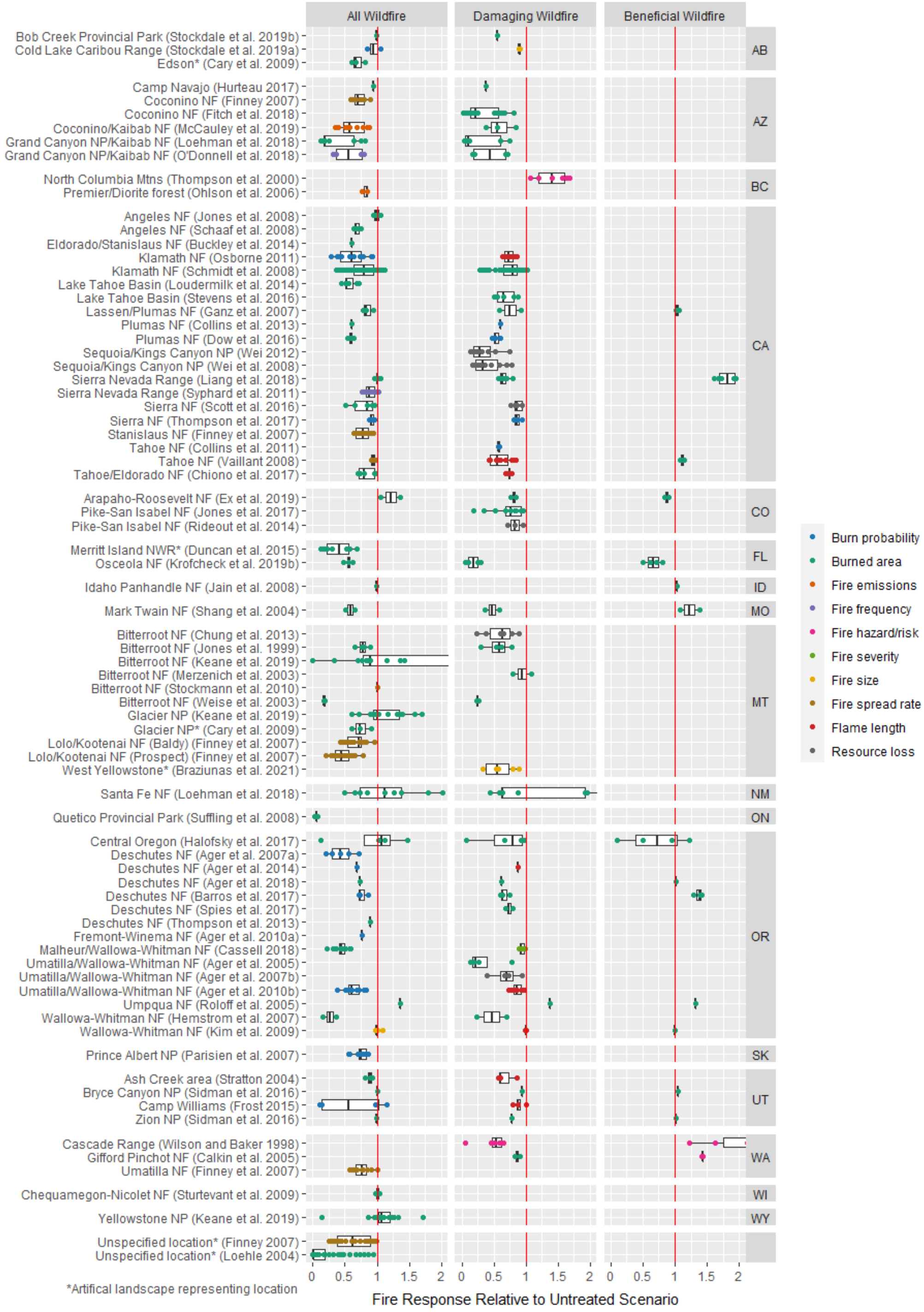

Figure C.2.1. Values of wildfire response metrics across treatment scenarios, standardized relative to untreated scenarios, of landscape simulation studies. Each point is the average value for a specific treatment scenario tested for a given landscape/study and wildfire type (all, damaging, beneficial), color-coded by metric. Landscapes are organized by state/province as shown by abbreviations to the right of panels. Values < 0 and > 0 are lower and higher, respectively, than the untreated scenarios indicated by vertical red lines.

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Lessons learned about landscape fuel treatment effectiveness from wildland case studies

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Maximizing the effectiveness of fuel treatments at a landscape scale is a key research and management need given the inability to treat all areas at risk from wildfire. To better understand effectiveness of fuel treatments at the landscape scale, 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. We located 2,240 publications, which we filtered to 16 case study papers that met three criteria: manager evaluation of the effectiveness of a fuel treatment, for specific wildfire events, at landscape scales. Fifteen of the sixteen case studies were located in the western United States, and most 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 intentionally manage fire as a fuel treatment. Primary factors that influenced treatment effectiveness were treatment effects on fuel layers, treatment recency, treatment size and placement in relation to topography and adjacent features, and weather. Treatments that decreased canopy fuel continuity while reducing surface fuels were consistently considered more effective at mitigating fire effects than treatments that modified a single fuel layer. At landscape scales, treatment effectiveness was improved by strategic placement of treatments adjacent to prior treatments or fires and alignment with prevailing winds and topographic fire breaks to expand the effective area. Placement in relation to suppression needs to protect infrastructure also can take advantage of continuity with land uses that lack vegetation. Treatment effectiveness was often 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.

Table C.2.2. Fuel treatment and wildfire case studies by EPA Level III ecoregion, reference, wildfire name, month and year fire started, and acres burned.

Ecoregion	Reference	Wildfire Name	Month/Year	Acres
Arizona/New Mexico Mtns	Jackson et al. 2011	Wallow	05/2011	538,049
Arizona/New Mexico	Keller et al. 2011	Wallow	05/2011	538,049
Cascades, Blue Mtns	Harbert et al. 2007	Monument, GW, Egley Complex	07/2007 08/2007 07/2007	53,556 1,461 140,360
Idaho Batholith	Graham et al. 2009	Cascade Complex	08/2007	500,000
North Cascades	Gray & Prichard 2015	Tripod Octopus Mtn	07/2006 08/2012	175,184 3,048
Northern Lakes & Forests	Fites et al. 2007b	Ham Lake Cavity Lake	05/2007 07/2006	75,000 31,500
Sierra Nevada	Crook et al. 2015	Rim	08/2013	257,314
Sierra Nevada	Dailey et al. 2008	Moonlight	09/2007	64,997
Sierra Nevada	Fites et al. 2007a	Antelope Complex	07/2007	23,420
Sierra Nevada	Murphy et al. 2007	Angora	06/2007	3,100
Sierra Nevada, Cascades	Murphy et al. 2010	20 wildfires*	1999-2009	varied
Northwestern Great Plains	Jain et al. 2007	Germain Indian	08/2003 08/2003	66,496 33,594
Southern California	Rogers et al. 2008	Grass Valley	10/2007	1,242
Southern California	Reiner et al. 2014	Mountain	07/2013	27,531
Southern Rockies	Graham et al. 2012	Fourmile Canyon	08/2010	6,181
Southern Rockies	Graham et al. 2003	Hayman	06/2002	138,000

**Twenty wildfires were evaluated that occurred from 1999 through 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).*

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