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REVIEW

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Fuel treatment effectiveness at the landscape scale: a systematic review of simulation studies comparing treatment scenarios in North America

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Abstract

Background The risk of destructive wildfire on fire-prone landscapes with excessive fuel buildup has prompted the use of fuel reduction treatments to protect valued resources from wildfire damage. The question of how to maximize the effectiveness of fuel reduction treatments at landscape scales is important because treating an entire landscape may be undesirable or unfeasible. We reviewed 86 simulation studies that examined landscape-scale fuel reduction treatment effectiveness for landscapes of the USA or Canada. Each of these studies tested effects of fuel reduction treatments on wildfire through comparisons of landscape scenarios differing by treatment design or other attributes. Results from these studies were summarized to assess what they reveal about factors determining fuel treatment effectiveness at landscape scales.

Results Qualifying studies focused primarily but not exclusively on forested landscapes of the western USA and ranged in size from 200 to 3,400,000 ha. Most studies showed that scenarios with fuel reduction treatments had lower levels of wildfire compared to untreated scenarios. Damaging wildfire types decreased while beneficial wildfire increased as a result of treatments in most cases where these were differentiated. Wildfire outcomes were influenced by five dimensions of treatment design (extent, placement, size, prescription, and timing) and other factors beyond the treatments (weather, climate, fire/fuel attributes, and other management inputs). Studies testing factorial combinations showed that the relative importance of these factors varied across landscapes and contexts.

Conclusions Simulation studies have highlighted general principles of effective fuel treatment design at landscape scales, including the desirability of treating extensive areas with appropriate prescriptions at sufficient frequency to reduce wildfire impacts even under extreme conditions that may be more prevalent in the future. More specific, context-dependent strategies have also been provided, such as a variety of placement schemes prioritizing the protection of different resources. Optimization algorithms were shown to be helpful for determining treatment placement and timing to achieve desired objectives under given constraints. Additional work is needed to expand the geographical scope of these studies, further examine the importance and interactions of driving factors, and assess longer-term effects of fuel reduction treatments under projected climate change.

Keywords Fuel treatment, Landscape, Simulation, Wildfire

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Resumen

Antecedentes El riesgo de incendios destructivos en paisajes propensos al fuego con excesiva acumulación de combustibles ha inducido al uso de tratamientos de reducción del combustible para proteger recursos valiosos del daño por fuegos. La pregunta sobre cómo maximizar la efectividad de los tratamientos de reducción del combustible a escala del paisaje es importante, pues el tratar un paisaje entero puede ser indeseable o impracticable. Revisamos 86 estudios de simulación que examinaron la reducción del combustible a escala del paisaje en paisajes de los EEUU o Canadá. Cada uno de esos estudios probaron los efectos de tratamientos de reducción de combustible sobre los incendios a través de comparaciones de escenarios de paisajes que difirieron en el diseño del tratamiento u otros atributos. Los resultados de estos estudios fueron resumidos para determinar lo que ellos revelaban sobre factores que determinaban la efectividad de cada tratamiento a escala de paisaje.

Resultados Los estudios calificados se enfocaron primariamente, aunque no exclusivamente, en paisajes forestales del oeste de los EEUU y variaron en tamaño, entre 200 y 3,4 millones de ha. La mayoría de los estudios mostró que los escenarios que tenían tratamientos de reducción del combustible tuvieron un menor nivel de incidencia de incendios comparado con escenarios no tratados. Los tipos de incendios dañinos disminuyeron mientras que los incendios beneficiosos se incrementaron como resultado de los tratamientos en la mayoría de los casos cuando ellos pudieron ser diferenciados. Los resultados de los incendios estuvieron influenciados por cinco dimensiones del diseño de los tratamientos (extensión, ubicación, tamaño, prescripción, y el tiempo en que fueron ejecutados) y otros factores más allá de los tratamientos (tiempo meteorológico, clima, atributos del fuego y del combustible y otras particularidades del manejo). Los estudios que probaron combinaciones factoriales mostraron que la importancia relativa de esos factores varió a través de paisajes y contextos.

Conclusiones Los estudios de simulación han esclarecido los principios generales de los diseños de tratamientos de combustibles efectivos a nivel de paisaje, incluyendo el deseo de tratar áreas extensas con la prescripción apropiada y con frecuencias suficientes como para reducir los impactos de los incendios aún bajo condiciones más extremas que puedan prevalecer en el futuro. Más específicamente, las estrategias contexto-dependientes también han sido provistas, como una variedad de esquemas de ubicación de los tratamientos priorizando la protección de diferentes recursos. Los algoritmos de optimización han mostrado ser útiles para determinar la ubicación de los tratamientos y el tiempo de aplicación para lograr determinados objetivos bajo ciertos condicionamientos. Trabajos adicionales son necesarios para expandir el alcance geográfico de estos estudios, examinar la importancia de los factores conducentes y determinar los efectos a largo plazo de los tratamientos bajo el proyectado cambio climático.

Introduction

Amid growing concern over destructive wildfire in many areas of the world, there is a need to synthesize scientific information on fuel management strategies. Vegetation treatments aimed at reducing fuel loads (hereafter "fuel treatments") have been promoted as a strategy for wildfire risk reduction (Elia et al. 2016; Pastor et al. 2020; Keenan et al. 2021; Prichard et al. 2021). Fuel treatments take a variety of forms, including tree thinning in overstocked forests, prescribed fire, mastication of woody material, and reductions of herbaceous fuels through grazing, herbicides, or mechanical means (Agee and Skinner 2005; Diamond et al. 2012; Jain et al. 2012; Brennan and Keeley 2015; Bernau et al. 2018; Shinneman et al. 2019). By modifying the amount and structure of fuel in vegetation at risk of burning, fuel treatments can potentially lead to lower fire spread, intensity, or severity in the event of fire (Agee and Skinner 2005; Fernandes 2015; Kalies and Kent 2016). Fuel treatments may serve to slow the spread of fire at strategic locations and facilitate fire suppression, thus reducing the likelihood of fire reaching places where its effects would be detrimental (Agee et al. 2000; Syphard et al. 2011a; Ager et al. 2013; Shinneman et al. 2019). Another common objective of fuel treatments is to adjust fuel structure in a way that will reduce undesirable fire impacts and enhance ecosystem resilience in areas that ultimately burn (Reinhardt et al. 2008; Ager et al. 2013; Prichard et al. 2021). The effectiveness of fuel treatments towards achieving desired objectives, whether reducing wildfire damage or increasing its beneficial effects, depends on a variety of factors related to both the treatments themselves and the setting where they are implemented (Collins et al. 2010; Thompson and Anderson 2015; Kalies and Kent 2016). An understanding of the factors determining fuel treatment effectiveness is critical for designing treatments that will meet their intended purposes.

In North America, particularly the western USA, implementing fuel treatments to the extent needed to manage extreme wildfires is a major challenge. The USDA Forest

Service recently announced a management strategy aiming to treat 20 million acres on National Forest Systems lands and up to an additional 30 million acres of other Federal, State, Tribal, and private lands (https://www.fs.usda.gov/managing-land/wildfire-crisis). Even with this large-scale commitment, it is not possible to treat all areas within the recommended timeframe, hence the need to schedule and prioritize treatments. At the national to regional level, efforts have been made to identify landscapes where the need for fuel treatments is especially acute (Ager et al. 2014a; USDOI and USDA 2014). Within such landscapes, further specification of fuel treatment placement is typically required and may be subject to competing ideas; for example, treatments can be placed in areas close to the wildland urban interface (WUI) where they might be most effective at protecting homes (Schoennagel et al. 2009), or alternatively at locations with the highest fire hazard as a way to reduce the potential for high-severity burns (Vaillant and Reinhardt 2017).

The question of how to maximize the effectiveness of limited fuel treatments at the landscape scale has received considerable attention from the fire science community in recent years (Finney 2001; Collins et al. 2010; Chung 2015; Tubbesing et al. 2019). This question is distinct from the issue of whether fuel treatments are effective at modifying fire behavior and reducing fire impacts at local scales, which has also been widely studied and reviewed (Carey and Schumann 2003; Fernandes and Botelho 2003; Fulé et al. 2012; Martinson and Omi 2013; Kalies and Kent 2016). Evaluating fuel treatments at landscape scales is inherently more difficult than studying local treatment effects, at least when relying on experimental or empirical approaches; thus, simulation modeling is an important element of this research agenda. Over the past several decades, a variety of techniques have been developed that can simulate the spread and behavior of fire on model landscapes, as well as landscape attributes and dynamics over time (e.g., Crookston and Dixon 2005; Scheller et al. 2007; Ager et al. 2018; Parisien et al. 2019). Among their many uses, these simulation modeling techniques have been applied in studies comparing hypothetical scenarios that differ in the way that fuel treatments are implemented on a landscape. Such studies were reviewed by Collins et al. (2010), who outlined strategies and constraints for implementing fuel treatments on forested landscapes of the western USA, and Chung (2015), who addressed the use of optimization methods to determine where, when, and how to implement fuel treatments to minimize fire hazard or risk. Hunter and Robles (2020) reviewed studies addressing treatment effects on spatial and temporal scales beyond the treatment scale, focusing on treatments involving prescribed fire. Landscape-scale studies reviewed by these authors have shown that fuel treatments applied to a portion of a landscape can have a beneficial effect across a broader area, but that maximizing this benefit requires consideration of factors influencing the spread and behavior of fire across patches with different fuel characteristics (Collins et al. 2010; Chung 2015; Hunter and Robles 2020).

To follow up and expand upon the findings of previous reviews dealing with landscape-scale fuel treatments, we have conducted a systematic review that incorporates a broad range of studies pertaining to landscapes of North America. This paper focuses on studies using simulation approaches, while companion papers focus on empirical studies (McKinney et al. 2022) and case studies (Urza et al. 2023) involving actual fires. Our aim is to summarize results of simulation studies testing landscape fuel treatment effects on wildfire, addressing the question of what determines fuel treatment effectiveness (or lack thereof) at the landscape scale. This paper is organized around a set of themes that emerged from these studies, dealing with five dimensions of landscape-scale fuel treatment design (extent, placement, size, prescription, timing) and factors beyond treatments that can influence their effectiveness, such as weather, climate, fire/fuel attributes, and suppression effort. We sought to characterize the variables that have been tested and evaluate their effects on wildfire, including damaging and beneficial fire types, based on the evidence presented in the scientific literature.

Methods

In collaboration with the USDA Forest Service Library, we conducted a series of literature searches beginning in October–November 2019. Searches were limited to literature published since 1990 and excluded studies of areas outside the USA and Canada. Library personnel searched the Web of Science, Scopus, National Agricultural Library, Fire Research and Management Exchange System, 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 (Additional file 1). The lead author examined these references and used information from titles, abstracts, and (as needed) other content to identify papers that qualified for this review based on selection criteria described below. The search was then expanded through iterative backward and forward citation checks of the initial set of qualifying papers and a set of review papers that were deemed relevant because of their focus on fuel treatments, landscape-scale fire simulation modeling, or both (Collins et al. 2010; Miller and Ager 2013; Chung 2015; Thompson et al. 2015; Hessburg et al. 2016; Kalies and Kent 2016; Parisien et al. 2019; Hunter and Robles 2020). Forward citations were obtained via the Web of Science (www.webofscience.com) core collection from February 2021. The content of qualifying papers was examined, and if duplicate publications were encountered, only one was kept. Attempts were made to locate peer-reviewed versions of theses, dissertations, and government documents, but these were used if they contained material not presented elsewhere.

Papers were selected if they (1) examined fire outcomes of fuel treatments at the landscape scale, (2) used simulation modeling to compare two or more treatment scenarios, and (3) carried out modeling using data from actual landscapes in the USA or Canada or artificial landscapes modeled after locations in these countries. Landscape scale was defined as an area larger than the treatment area at a given point in time, so that the influence of treatments could be evaluated within a broader spatial context. Studies meeting selection criteria generally portrayed treated and untreated areas as contiguous patches within a defined area divided into pixels or polygons. Selected studies provided numerical results for response variables that were either actual fire attributes (e.g., burned area, fire severity) or measures of resource loss directly related to fire.

Some papers did not meet selection criteria in full and were thus excluded. Many studies addressed fuel treatment effects at the treatment scale, typically by comparing treated and untreated plots or stands. Because these studies did not address treatments in a landscape context, they were excluded from our synthesis even if the treatments were extensive or were sampled across a broad area. We also omitted studies that identified priority areas for implementing fuel treatments but did not test the effectiveness of their proposed strategy through comparison with an untreated or alternative scenario. Studies focusing on methodological aspects of fire simulation models, optimization algorithms, or prioritization schemes were also excluded unless accompanied by a tangible application meeting selection criteria. We omitted simulations where fuel reduction was not a stated objective of vegetation treatments (though it did not need to be the only objective) or where the measured response variables were not directly related to fire. Studies examining wildfire in the absence of planned vegetation treatments were also omitted.

Information from each qualifying study was extracted and summarized, including location, landscape size, simulation modeling method, simulation timeframe, scenario descriptors, wildfire metrics, and outcomes. Scenario descriptors (variables related to fuel treatments or landscape conditions) were equivalent to factors of an experiment defined by two or more levels each. Wildfire metrics (response variables) were selected and grouped according to whether they measured the net effect of all types of wildfire versus “damaging” or “beneficial” wildfires specifically. Damaging wildfires included those that were identified as high-severity, high-intensity, stand-replacing, uncharacteristic, or problem fires. Direct measures of fire severity, flame length, and resource loss were assigned to the damaging wildfire group, while low-severity and surface fires were labeled as beneficial wildfire. If a study presented more than one metric for a given wildfire type, one representative metric was selected. Outcomes of each tested scenario, typically presented as mean values of the wildfire metrics, were extracted either directly from tables or indirectly from figures using the online tool WebPlotDigitizer (Rohatgi 2021). In a few instances, the average of the median, 25th quantile, and 75th quantile was used as an estimate of the mean, and in other instances, means were calculated from histograms. For multi-year simulations, values were averaged across time steps. Most wildfire metrics displayed increasing values at increasing levels of fire, and those that did not were converted to this form, e.g., fire rotation period and fire arrival time were converted to fire frequency and fire spread rate, respectively, by taking their inverse.

Because of the broad range of simulation strategies, response variables, and units of measurement, a cohesive meta-analysis of results from the selected studies was not feasible. Instead, we focused on relative differences between reported scenario outcomes, especially differences between treated and untreated scenarios, as a common currency for comparisons across studies. We assembled a series of charts using the ggplot2 package in R (Wickham 2016; R Core Team 2019) to illustrate treatment differences as a backdrop for summarizing results. Additionally, results from studies with factorial designs (testing multiple levels of more than one factor) were analyzed to ascertain the relative importance of each factor in determining scenario outcomes. We used random forest modeling as a heuristic tool to quantify variable importance in these instances. Variable importance values measured as the increase in node purity were obtained from random forest models built using the randomForest package in R (Liaw and Wiener 2002; R Core Team 2019) where scenario descriptors were the predictors and scenario outcomes (mean values extracted for each scenario) were the responses.

Results

A total of 86 papers met the selection criteria. These included 73 journal articles, 6 General Technical Reports or proceedings published by the US Forest Service, 2 papers from other conference proceedings, 4 theses/dissertations, and 1 report prepared by a partnership of government agencies and non-governmental organizations (Table 1). Some papers reported on more than

Table 1 Landscapes of the USA and Canada represented by simulation studies testing landscape-scale fuel treatment effectiveness

State/province	Location	Landscape area (ha)	Fire modeling technique	Timeframe (yr)	Citation
AB	Bob Creek Provincial Park	20,775	Burn-P3	1	Stockdale et al. 2019b
AB	Edson[a]	250,000	SEM-LAND	1	Cary et al. 2009
AB	West-central Alberta	20,790	WILDFIRE, FPV	80	Acuna et al. 2010
AB/SK	Cold Lake Caribou Range	2,100,000	Burn-P3	1	Stockdale et al. 2019a
AZ	Camp Navajo	11,610	LANDIS-II	100	Hurteau 2017
AZ	Coconino NF	23,204	FFE-FVS	45	Bagdon et al. 2016
AZ	Coconino NF	168,853	MTT	1	Finney 2007
AZ	Coconino NF	63,298	FlamMap	1	Fitch et al. 2018
AZ	Coconino/Kaibab NF	386,100	LANDIS-II	90	McCauley et al. 2019
AZ	Grand Canyon NP/Kaibab NF	155,439	LANDIS-II	100	Loehman et al. 2018
AZ	Grand Canyon NP/Kaibab NF	335,000	LANDIS-II	100	O'Donnell et al. 2018
BC	Premier/Diorite forest	44,000	custom model	100	Ohlson et al. 2006
CA	Angeles NF	191,012	SIMPPLLE	50	Jones et al. 2008
CA	Angeles NF	234,061	FETM	100	Schaaf et al. 2008
CA	Eldorado/Stanislaus NF	149,869	FSim, FlamMap	1	Buckley et al. 2014
CA	Klamath NF	42,000	FlamMap	1	Osborne 2011
CA	Klamath NF	28,000	FARSITE	1	Schmidt et al. 2008
CA	Lake Tahoe Basin	7820	FlamMap, FARSITE	1	Stevens et al. 2016
CA/OR	Klamath-Siskiyou region	3,200,000	LANDIS-II	85	Maxwell et al. 2020
CA/NV	Lake Tahoe Basin	85,000	LANDIS-II	100	Loudermilk et al. 2014
CA	Lassen/Plumas NF	1,092,700	FlamMap	30	Ganz et al. 2007
CA	Plumas NF	19,236	FlamMap	40	Collins et al. 2013
CA	Plumas NF	19,236	FlamMap	1	Dow et al. 2016
CA	Plumas NF	18,623	FlamMap, FARSITE	1	Moghaddas et al. 2010
CA	Sequoia/Kings Canyon NP	324	MTT	1	Wei 2012
CA	Sequoia/Kings Canyon NP	15,552	FlamMap	1	Wei et al. 2008
CA	Sierra Nevada Range	2,200,000	LANDIS-II	50	Syphard et al. 2011b
CA/NV	Sierra Nevada Range	3,400,000	LANDIS-II	90	Liang et al. 2018
CA	Sierra NF	87,500	LANDIS-II	100	Krofcheck et al. 2018
CA	Sierra NF	1,430,000	Fsim	1	Scott et al. 2016
CA	Sierra NF	525,000	FSim	1	Thompson et al. 2017
CA	Stanislaus NF	40,500	FFE-FVS	50	Finney et al. 2007
CA	Tahoe NF	4300	FlamMap	40	Collins et al. 2011
CA	Tahoe NF	13,482	FARSITE	1	Tempel et al. 2015
CA	Tahoe NF	4594	FlamMap, FARSITE	1	Vaillant 2008
CA	Tahoe/Eldorado NF	55,398	FlamMap	1	Chiono et al. 2017
CO	Arapaho-Roosevelt NF	4000	WFDS-LS	50	Ex et al. 2019
CO	Pike-San Isabel NF	21,800	FlamMap	1	Jones et al. 2017
CO	Pike-San Isabel NF	40,000	FlamMap	1	Rideout et al. 2014
FL	Merritt Island NWR[a]	8000	FARSITE	1	Duncan et al. 2015
FL	Osceola NF	90,000	LANDIS-II	100	Krofcheck et al. 2019b
ID	Idaho Panhandle NF	271	FlamMap, FARSITE	1	Jain et al. 2008
MO	Mark Twain NF	71,142	LANDIS	200	Shang et al. 2004
MT	Bitterroot NF	23,487	SIMPPLLE	30	Chew et al. 2003
MT	Bitterroot NF	14,000	FlamMap	20	Chung et al. 2013
MT	Bitterroot NF	23,505	SIMPPLLE	50	Jones et al. 1999
MT	Bitterroot NF	161,874	VDDT, SIMPPLLE	50	Merzenich et al. 2003
MT	Bitterroot NF	9364	FARSITE, FFE-FVS	1	Stockmann et al. 2010
MT	Flathead NF	334,675	FIRECLIM, FireBGCv2	50	Prato and Paveglio 2018

Table 1 (continued)

State/province	Location	Landscape area (ha)	Fire modeling technique	Timeframe (yr)	Citation
MT	Glacier NP[a]	250,000	LANDSUM	1	Cary et al. 2009
MT	Lolo/Kootenai NF (Baldy)	not given	FFE-FVS	50	Finney et al. 2007
MT	Lolo/Kootenai NF (Prospect)	not given	FFE-FVS	50	Finney et al. 2007
MT	West Yellowstone[a]	10,000	iLand	120	Braziunas et al. 2021
NM	Santa Fe NF	45,000	LANDIS-II	50	Krofcheck et al. 2019a
NM	Santa Fe NF	77,489	FireBGCv2	100	Loehman et al. 2018
OK	Tallgrass prairie[a]	15,552	FARSITE	1	Kerby et al. 2007
ON	Pickle Lake area	127,548	FastFire	1	Rytwinski and Crowe 2010
ON	Quetico Provincial Park	202,500	Prometheus	1	Suffling et al. 2008
OR	Central Oregon	1,023,808	MC1	90	Halofsky et al. 2017
OR	Deschutes NF	70,245	FlamMap	1	Ager et al. 2007a
OR	Deschutes NF	756,634	Randig	1	Ager et al. 2014b
OR	Deschutes NF	1,250,000	Envision	50	Ager et al. 2018
OR	Deschutes NF	1,336,176	LSim	50	Ager et al. 2020
OR	Deschutes NF	1,200,000	Envision, FFE-FVS	50	Barros et al. 2017
OR	Deschutes NF	160,930	FlamMap	1	Kreitler et al. 2020
OR	Deschutes NF	1,252,900	Envision	50	Spies et al. 2017
OR	Deschutes NF	209,207	FSim	1	Thompson et al. 2013
OR	Deschutes NF[a]	2000	custom model	80	Campbell and Ager 2013
OR	Fremont-Winema NF	68,474	FlamMap	1	Ager et al. 2010a
OR	Malheur/Wallowa-Whitman NF	938,786	LANDIS-II	90	Cassell 2018
OR	Southwest Oregon[a]	1036	FFE-FVS, BEHAVE	150	Lauer et al. 2017
OR	Southwest Oregon[a]	1036	FFE-FVS, BEHAVE	not given	Lauer et al. 2020
OR	Umatilla/Wallowa-Whitman NF	16,336	FFE-FVS	60	Ager et al. 2005
OR	Umatilla/Wallowa-Whitman NF	16,343	FFE-FVS	60	Ager et al. 2007b
OR	Umatilla/Wallowa-Whitman NF	16,343	FFE-FVS, FlamMap	1	Ager et al. 2010b
OR	Umpqua NF	325,000	FlamMap, FARSITE	40	Roloff et al. 2005
OR	Umpqua NF	336,000	FlamMap	75	Roloff et al. 2012
OR	Wallowa-Whitman NF	178,000	VDDT, TELSA	200	Hemstrom et al. 2007
OR	Wallowa-Whitman NF	178,000	FARSITE	100	Kim et al. 2009
OR/WA	Blue Mountains	2,500,000	FlamMap, Fsim	1	Ager et al. 2016
SK	Prince Albert NP	165,3467	Burn-P3	1	Parisien et al. 2007
UT	Ash Creek area	809	FlamMap, FARSITE	1	Stratton 2004
UT	Bryce Canyon NP	216	FlamMap	1	Sidman et al. 2016
UT	Camp Williams	11,130	FlamMap	1	Frost 2015
UT	Zion NP	2297	FlamMap	1	Sidman et al. 2016
WA	Cascade Range	1000	BEHAVE, custom	50	Wilson and Baker 1998
WA	Gifford Pinchot NF	6070	custom model	30	Calkin et al. 2005
WA	Gifford Pinchot NF	6070	FFE-FVS	30	Hummel and Calkin, 2005
WA	Umatilla NF	54,600	FFE-FVS	50	Finney et al. 2007
WI	Chequamegon-Nicolet NF	6586	FARSITE	1	Ryu et al. 2007
WI	Chequamegon-Nicolet NF	78,000	LANDIS	250	Sturtevant et al. 2009
None	Unspecified location[a]	not given	MTT	1	Finney 2007
None	Unspecified location[a]	2500	Custom model	1	Loehle 2004

[a] Artificial landscape representing the location

one landscape (Finney 2007; Finney et al. 2007; Cary et al. 2009; Sidman et al. 2016; Loehman et al. 2018), resulting in a total of 93 landscape-scale simulation studies, although not all of these are unique landscapes because some locations were repeatedly studied by multiple papers (Table 1). Most of the studies focused on mountainous forested areas of the western USA, particularly in California, Oregon, and Montana (Table 1, Fig. 1). Among the selected studies were ten artificial landscapes that exemplified conditions in Oregon (Campbell and Ager 2013; Lauer et al. 2017, 2020), Florida (Duncan et al. 2015), Oklahoma (Kerby et al. 2007), Montana/Alberta (Cary et al. 2009; Braziunas et al. 2021), and western forests in general (Finney et al. 2007; Loehle 2004) (Table 1). Landscape size ranged from ca. 200 to 3,400,000 ha, with a median of 54,999 ha (Table 1). Models used for fire simulation included FARSITE, FlamMap, FFE-FVS, LANDIS, FSim, LANDSUM, SIMPPLLE, Burn-P3, and Envision (Table 1). Many studies applied fire simulation modeling for a single fire season (42 studies), but others tracked trends over a period of up to 250 years using landscape succession models (51 studies; Table 1). Models were calibrated using weather and fire data from recent historical periods, or less frequently, conditions projected to accompany future climate changes (8 studies).

Scenarios tested by these studies were differentiated by the way in which fuel treatments were implemented and sometimes also by factors beyond the treatments. Foremost among the tests were comparisons of treated and untreated scenarios. Factors distinguishing treatment scenarios were broken down into five categories that we refer to as dimensions of landscape-scale treatment design: extent (total treated area), placement (location and arrangement of treatments), size (of individual treatment units), prescription (type and intensity of treatment), and timing (Fig. 2). Some studies included additional non-treatment distinctions of climate, weather, fire attributes, fuel attributes, suppression effort, ignition management, or elevation zone. The following sections summarize findings related to each of these categories. Where applicable, the terms "effective" and "effectiveness" are used to indicate favorable outcomes of fuel treatments, and "fire impacts" to indicate unfavorable outcomes, noting that favorability is tied to lower values of the response variables for overall wildfire and damaging wildfire but higher values for beneficial wildfire. Outcomes measured at the full landscape scale are emphasized, with occasional mention of more localized outcomes, including from a study that only reported fire impacts within 2 km of treatments (Parisien et al. 2007).

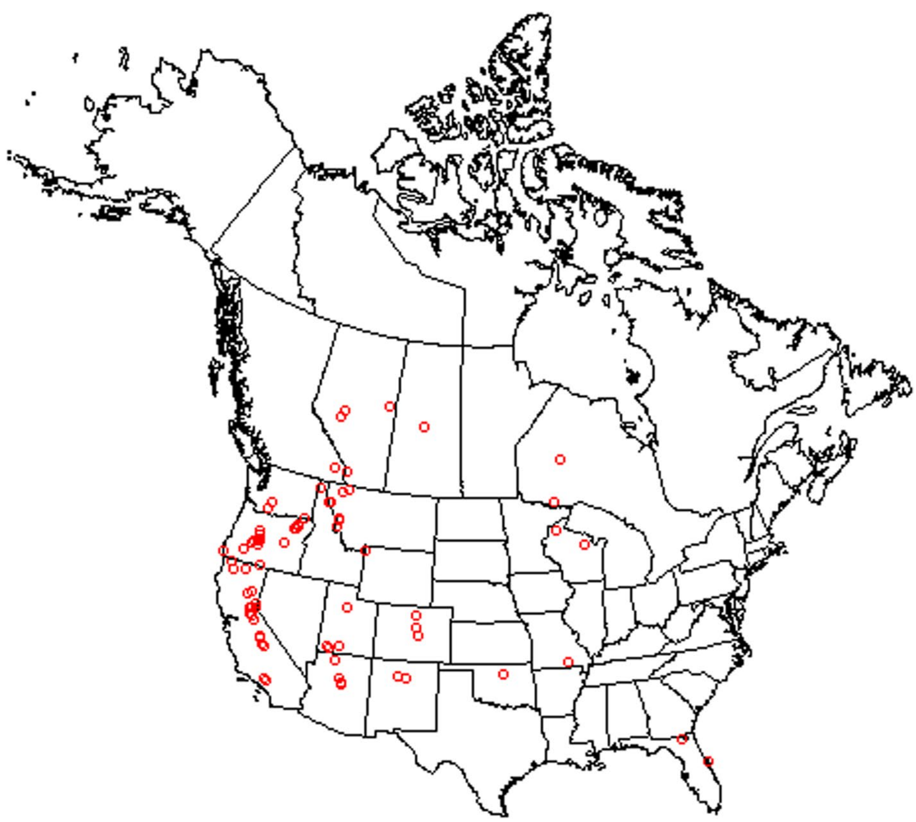

Fig. 1 Location of landscapes modeled using fire simulation to test landscape-scale fuel treatment effectiveness in the USA and Canada. Circles indicate approximate centers of landscapes varying in size from 200 to 3,400,000 ha

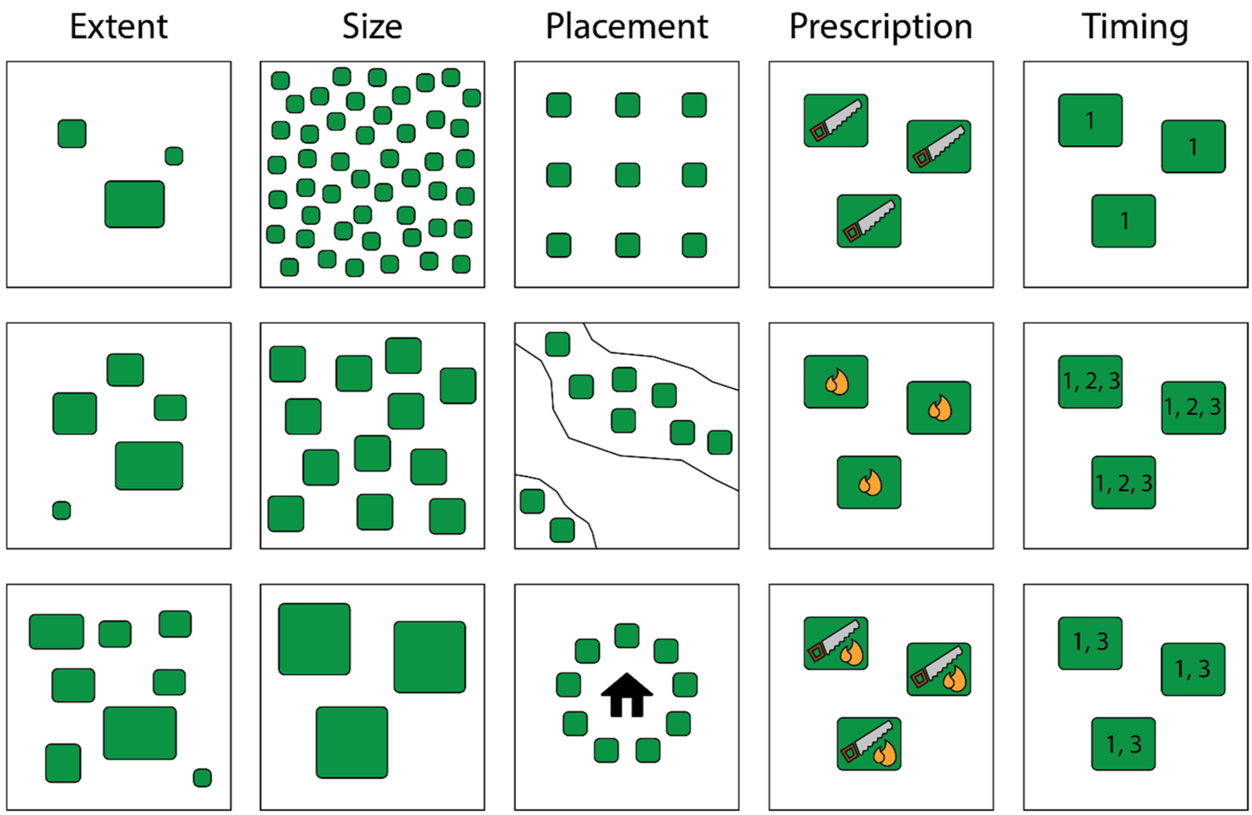

Fig. 2 Representation of dimensions of landscape-scale fuel treatment design. Green shapes depict treated areas within landscapes. Squares in vertical columns illustrate landscape scenarios that differ for the dimension listed above them. Extent: total treated area increases from top to bottom. Size: area of individual treated units increases from top to bottom. Placement: treatments arranged in a regular pattern (top), within specific zones (middle), or surrounding developed areas (bottom). Prescription: mechanical treatments (top), prescribed fire (middle), and mechanical treatments plus prescribed fire (bottom). Timing: first decade only (top), decades 1–3 (middle), and decades 1 and 3 only (bottom)

Figures 3 and 4 depict the range of wildfire outcomes in treatment scenarios from 76 core studies that had an untreated control scenario for relativizing treatment responses. These included studies that compared a single treatment scenario with a control (Roloff et al. 2005, 2012; Jain et al. 2008; Ager et al. 2010a, 2014b, 2018; Collins et al. 2013; Thompson et al. 2013; Buckley et al. 2014; Tempel et al. 2015; Sidman et al. 2016; Hurteau 2017; Stockdale et al. 2019b) and studies where a treatment/control comparison was tested under differing levels of non-treatment variables (Stratton 2004; Stockdale et al. 2019a; Halofsky et al. 2017). Studies that lacked a control scenario or presented results as a reduction from the control are shown in Fig. 5. Figures in Additional file 2 expand on Figs. 3, 4, and 5 by showing the factor levels that differentiated treatment scenarios, organized by the five dimensions of landscape-scale fuel treatment design. Figures 6, 7, 9, 10, 11, and 12 highlight tests that were readily comparable across studies because they met the following criteria: (1) treatment scenarios differed methodically within a given dimension (not covarying with levels of other dimensions), (2) wildfire outcomes were expressed as the absolute value of a fire metric, and (3) an untreated control scenario served as a point of reference. Tests involving factorial combinations appear in Fig. 13, which portrays the relative importance of factors as quantified through random forest models.

Treated vs. untreated

Studies comparing one or more treatment scenarios with untreated controls demonstrated that, in general, treatments were effective in leading to lower levels of overall wildfire and damaging wildfire and higher levels of beneficial wildfire (Figs. 3 and 4). For overall wildfire, 92% (438 of 475 scenarios) corresponded to less fire or diminished fire impacts on the landscape compared to the control. In studies that evaluated damaging wildfires, 94% (360 of 380 scenarios) of the outcomes were lower than controls. Although there were only 16 studies in which beneficial wildfire metrics were measured and compared to a control scenario, in 80% of the cases (39 of 49 scenarios), the treatments resulted in higher values of beneficial

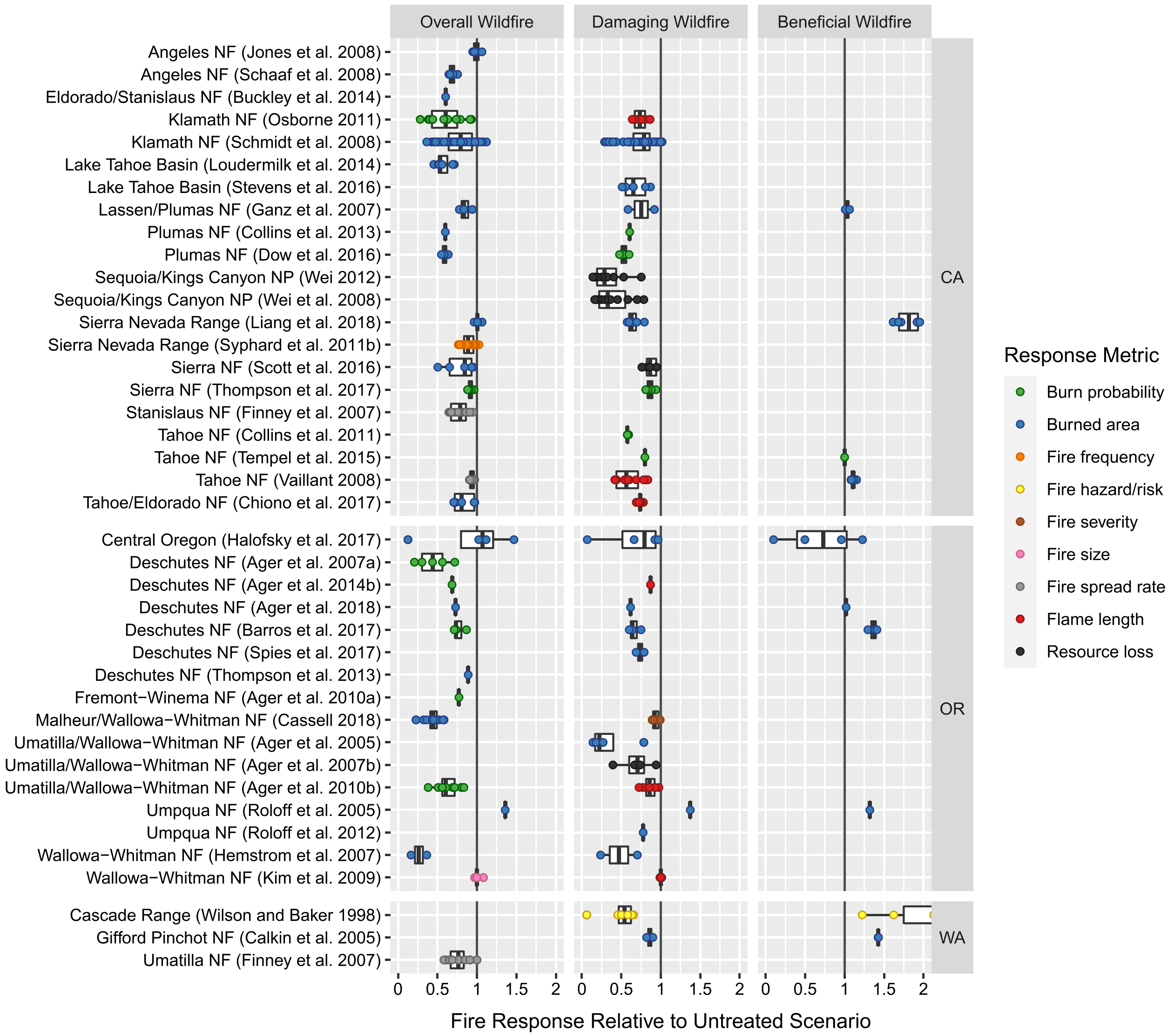

Fig. 3 Standardized values of wildfire response metrics across treatment scenarios of simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada (showing west-coast states; see Fig. 4 for other states and provinces). Each point is the average value for a specific treatment scenario tested for a given landscape/study and wildfire type (overall, damaging, beneficial), color-coded by metric and accompanied by boxplots. Landscapes are organized by their primary state as shown by abbreviations to the right of panels

fire. Putative reasons for cases where treatments failed to reduce overall/damaging wildfire or increase beneficial include the following: (1) treatments resulted in less damaging wildfire at the expense of more overall fire (Schmidt et al. 2008; Sidman et al. 2016; Halofsky et al. 2017; Liang et al. 2018; McCauley et al. 2019; Stockdale et al. 2019b); (2) treatments were geared primarily toward timber harvest, restoration, or habitat protection rather than fuel reduction (Roloff et al. 2005; Merzenich et al. 2003; Cassell 2018); (3) treatments were effective initially but resulted in changes in fuel structure through vegetation succession that increased burn susceptibility over the longer term (Loehman et al. 2018; Ex et al. 2019); (4) treated area was too small to have an effect under a given fire regime (Kim et al. 2009; Syphard et al. 2011b); or (5) stochastic variation of simulations with few replicates led to unexpected results (Jones et al. 2008).

Treatment extent

Studies included in this review generally indicated that fuel treatment effectiveness at the landscape scale is positively related to the amount of area treated, although the relationship was not necessarily linear and was affected by other dimensions of treatment design. A pattern of

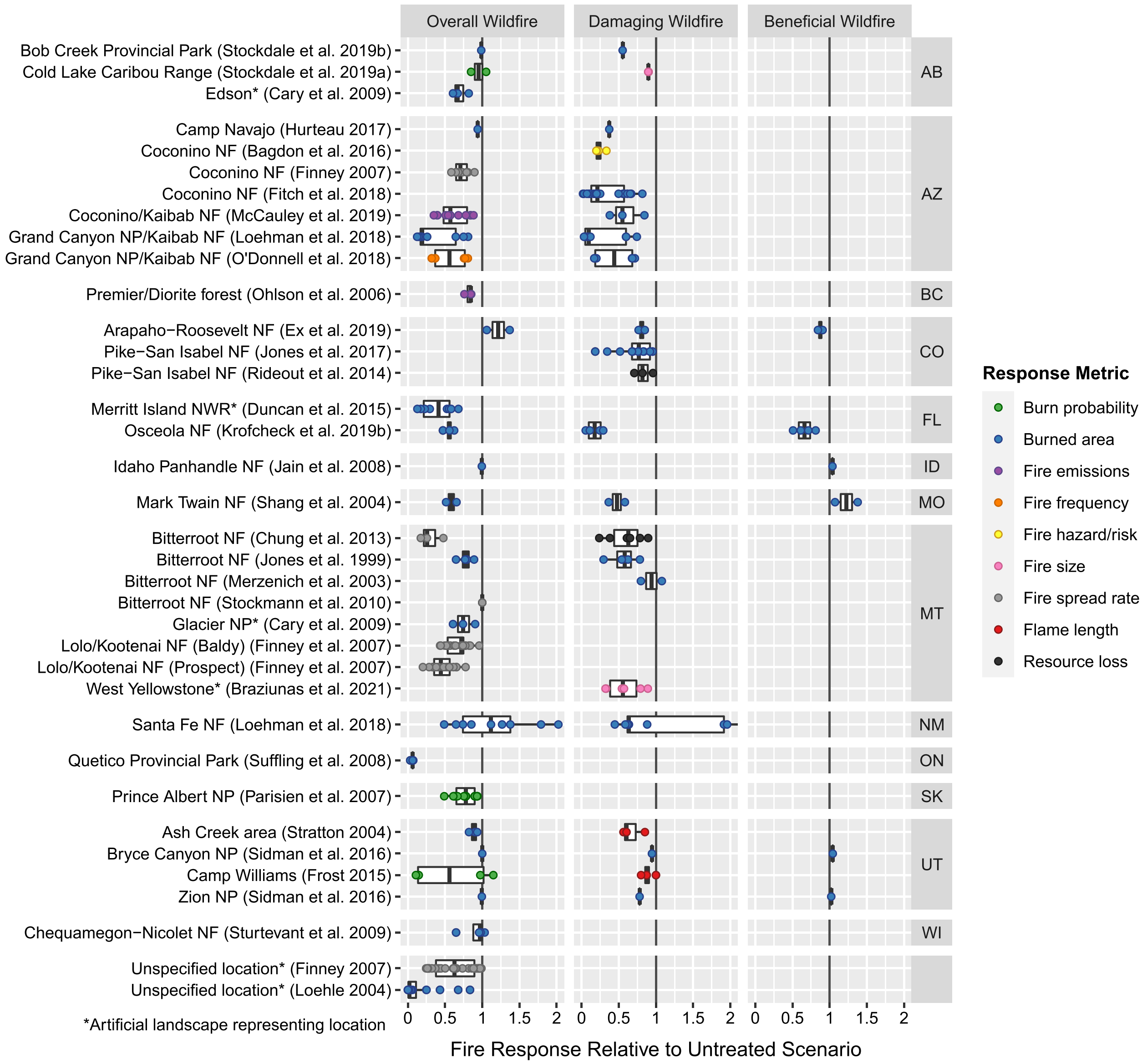

Fig. 4 Standardized values of wildfire response metrics across treatment scenarios of simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada (excluding west-coast states shown in Fig. 3). Each point is the average value for a specific treatment scenario tested for a given landscape/study and wildfire type (overall, damaging, beneficial), color-coded by metric and accompanied by boxplots. Landscapes are organized by their primary state/province as shown by abbreviations to the right of panels

monotonically increasing effectiveness with progressively higher treated area was especially consistent among single-year studies (Fig. 6) that measured treatment effects as if they happened all at once (Loehle 2004; Ager et al. 2007a; Finney 2007; Parisien et al. 2007; Schmidt et al. 2008; Wei et al. 2008; Cary et al. 2009; Ager et al. 2010b; Moghaddas et al. 2010; Osborne 2011; Wei 2012; Rideout et al. 2014; Ager et al. 2016; Scott et al. 2016; Stevens et al. 2016; Jones et al. 2017; Thompson et al. 2017; Fitch et al. 2018; Kreitler et al. 2020). The monotonically increasing pattern was also discernable for most multi-year simulations (Fig. 7) where the extent was measured as a treatment rate per unit time (Jones et al. 1999; Ager et al. 2005; Calkin et al. 2005; Ohlson et al. 2006; Ager et al. 2007b; Finney et al. 2007; Hemstrom et al. 2007; Syphard et al. 2011b; Campbell and Ager 2013; Chung et al. 2013; Loudermilk et al. 2014; Cassell 2018; O'Donnell et al. 2018; Loehman et al. 2018; McCauley et al. 2019; Braziunas et al. 2021), although there were a few cases where effectiveness decreased as treated area increased (Jones

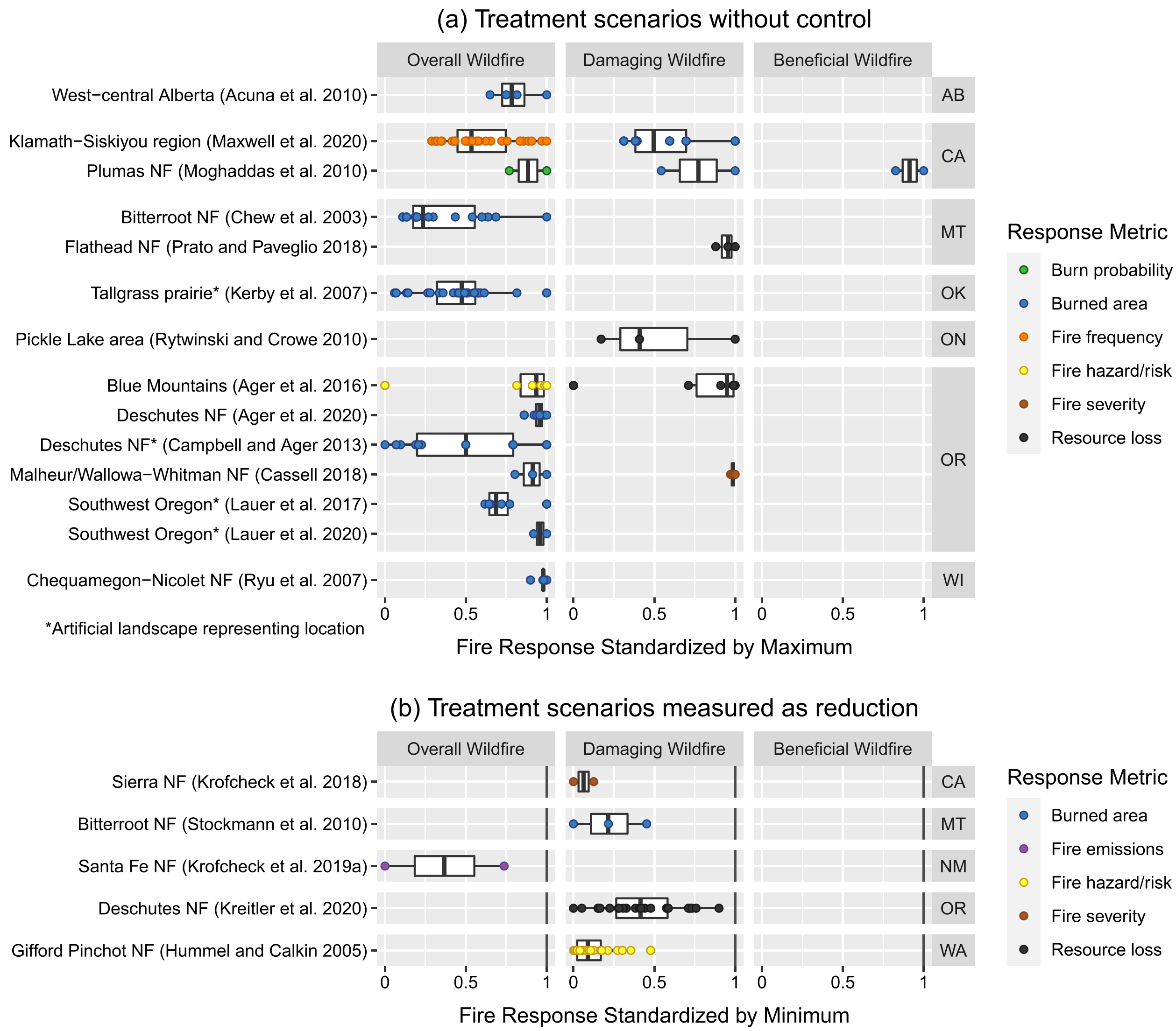

Fig. 5 Standardized values of wildfire response metrics across treatment scenarios of simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada, showing **a** cases lacking a control scenario, standardized by the scenario with the largest value, and **b** cases in which responses were presented as a reduction from the control, standardized by setting the smallest value to zero. Each point is the average value for a specific treatment scenario tested for a given landscape/study and wildfire type (overall, damaging, beneficial), color-coded by metric and accompanied by boxplots. Landscapes are organized by their primary state/province as shown by abbreviations to the right of panels

et al. 2008; Schaaf et al. 2008; Cassell 2018; Loehman et al. 2018). In some cases, the added benefits tended to become smaller as the treated proportion of the landscape became progressively larger (Figs. 6 and 7), due to a nonlinear relationship between treatment extent and landscape-scale fire effects (Loehle 2004; Finney et al. 2007; Wei et al. 2008; Wei 2012), but in other cases, benefits continued to accrue in a more linear fashion (Ager et al. 2007a; Scott et al. 2016; Jones et al. 2017; O'Donnell et al. 2018) (Figs. 6 and 7).

The larger treated area of some scenarios was due to the inclusion of areas that normally would not be treated, such as protected habitat or terrain with limited access. Hypothetically allowing these areas to be treated generally increased treatment effectiveness (Wilson and Baker 1998; Jones et al. 1999; Scott et al. 2016; Maxwell et al. 2020) although not always (Jones et al. 2008). Some studies found that effectiveness was increased when treatments were expanded from a single ownership category (public or private lands only) to a larger or broader ownership (Ager et al. 2005; Ager et al. 2007b; Hemstrom et al. 2007; Ganz et al. 2007), or from the defensible space around structures to the broader WUI (Loudermilk et al. 2014). These studies did not address whether placement

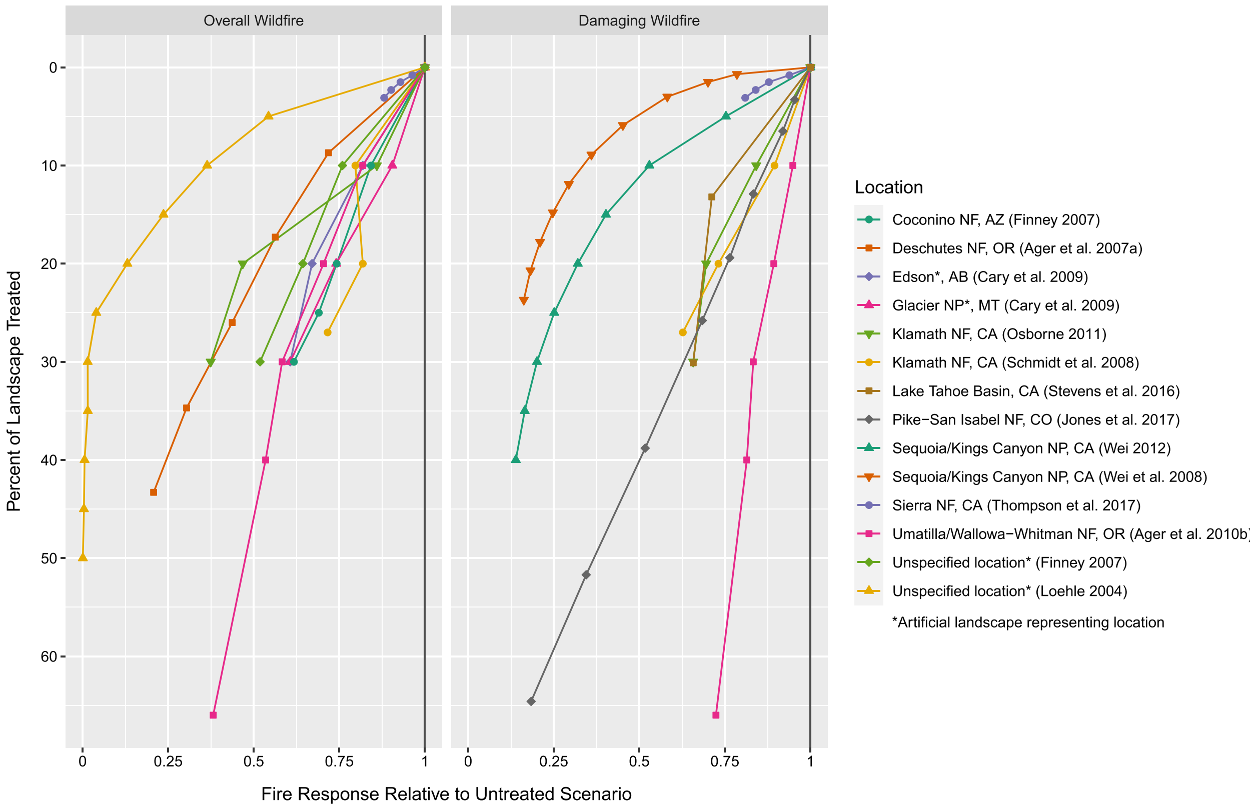

Fig. 6 Standardized values of wildfire response metrics plotted by treatment extent (percent of landscape treated) from selected single-year simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed by extent while other variables were kept consistent. Vertical panels indicate wildfire type (overall and damaging but not beneficial wildfire because of lack of data). Points connected by lines are mean values at different levels of treatment extent for a given landscape/study, color-coded by landscape

in the broadened areas had an effect beyond what could have been achieved by a comparable increase of treated area elsewhere, but other studies mentioned below (see placement constraint) examined this question.

Treatment placement

The studies selected for review tested a variety of schemes for determining where to place fuel treatments on a landscape (Fig. 8). We have organized these schemes along three descriptive axes labeled constraint, arrangement, and prioritization. Constraint refers to how much or which part of a landscape is eligible versus ineligible for treatment. Arrangement describes the way in which treatments are positioned relative to each other, and prioritization denotes the preferred basis for selecting treatment locations. Placement schemes can also be differentiated by whether they invoke simple rules for assigning treatments or use more complex criteria embedded in expert opinion or optimization algorithms. Expert-determined and optimized placement schemes are treated here as arrangement categories but are also recognized as forms of prioritization operating under a set of constraints.

Placement constraint

Many studies noted that placement options were constrained by legal or managerial restrictions in areas such as wilderness, private holdings, riparian zones, sensitive wildlife habitat, or locations with limited accessibility (Fig. 8A, B). Studies that examined the effect of broadening the land base eligible for treatment while keeping the treated area constant (Fig. 9) generally noted reduced fire impacts in the less restricted scenarios (Hummel and Calkin 2005; Finney et al. 2007; Chiono et al. 2017), but Dow et al. (2016) attained a better outcome by avoiding restricted areas, which they attributed to greater aggregation and continuity of treatments.

Arrangement

The arrangement of treatments in relation to one another formed the basis of many fuel treatment placement schemes (Fig. 8C–G). Random placement (Fig. 8D)

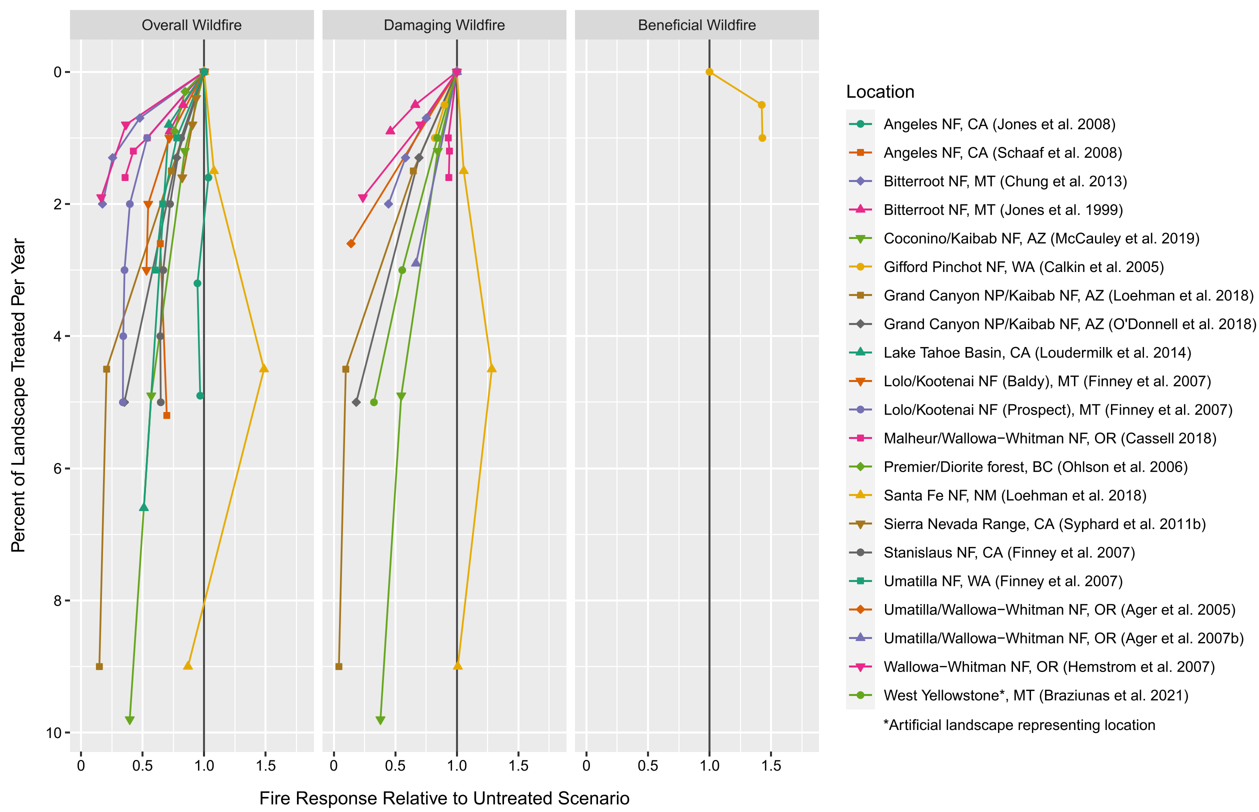

Fig. 7 Standardized values of wildfire response metrics plotted by treatment extent (percent of landscape treated per year) for selected multi-year simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed by extent while other variables were kept consistent. Vertical panels indicate wildfire type (overall, damaging, beneficial). Points connected by lines are mean values at different levels of treatment extent for a given landscape/study, color-coded landscape

was often used as a null model for comparison and in most cases was found to be less effective than other tested alternatives (Fig. 9; Loehle 2004; Finney 2007; Finney et al. 2007; Schmidt et al. 2008; Rytwinski and Crowe 2010; Chung et al. 2013; Braziunas et al. 2021). Schmidt et al. (2008) and Prato and Paveglio (2018) found that expert placement schemes (defensible fuel profile zones and a community wildfire protection plan, respectively) were sometimes but not always preferable to random placement. Kim et al. (2009) found only minor differences between random (Fig. 8D), dispersed (Fig. 8E), clumped (Fig. 8F), and regular (Fig. 8C) patterns of fuel treatment dispersion. Braziunas et al. (2021) examined scenarios where defensible space treatments were dictated by the arrangement of housing developments and found that clumped arrangements led to lower fire impacts compared to random arrangements (more so closer to homes than at the broader landscape scale). Loehle (2004) demonstrated that a grid of linear treatments delimiting compartments within an artificial landscape was more effective at reducing area burned than randomly placed treatments, especially when the total treated area was low.

An influential approach for fuel treatment placement, commonly referred to as "strategically placed area treatments" (SPLATs), builds on the idea that a regularly spaced array of fuel treatments will reduce fire spread on a landscape (Finney 2001; Schmidt et al. 2008). Finney (2001) demonstrated through theory and simulation that fire spread across a landscape could be reduced by partially overlapping rectangular fuel treatment units arranged in alternating rows offset by 30° (Fig. 8G). Two of the selected simulation studies compared landscape-wide SPLAT arrangements with other placement schemes (Fig. 9; Schmidt et al. 2008; Vaillant 2008) and two others implemented SPLATs within fuel breaks (Ganz et al. 2007; Parisien et al. 2007; see placement prioritization). SPLATs tested by Schmidt et al. (2008) were in most cases more effective than either random or expert-determined placement for reducing high-intensity fire on the landscape as a whole, but less effective than the expert-determined scheme for protecting a

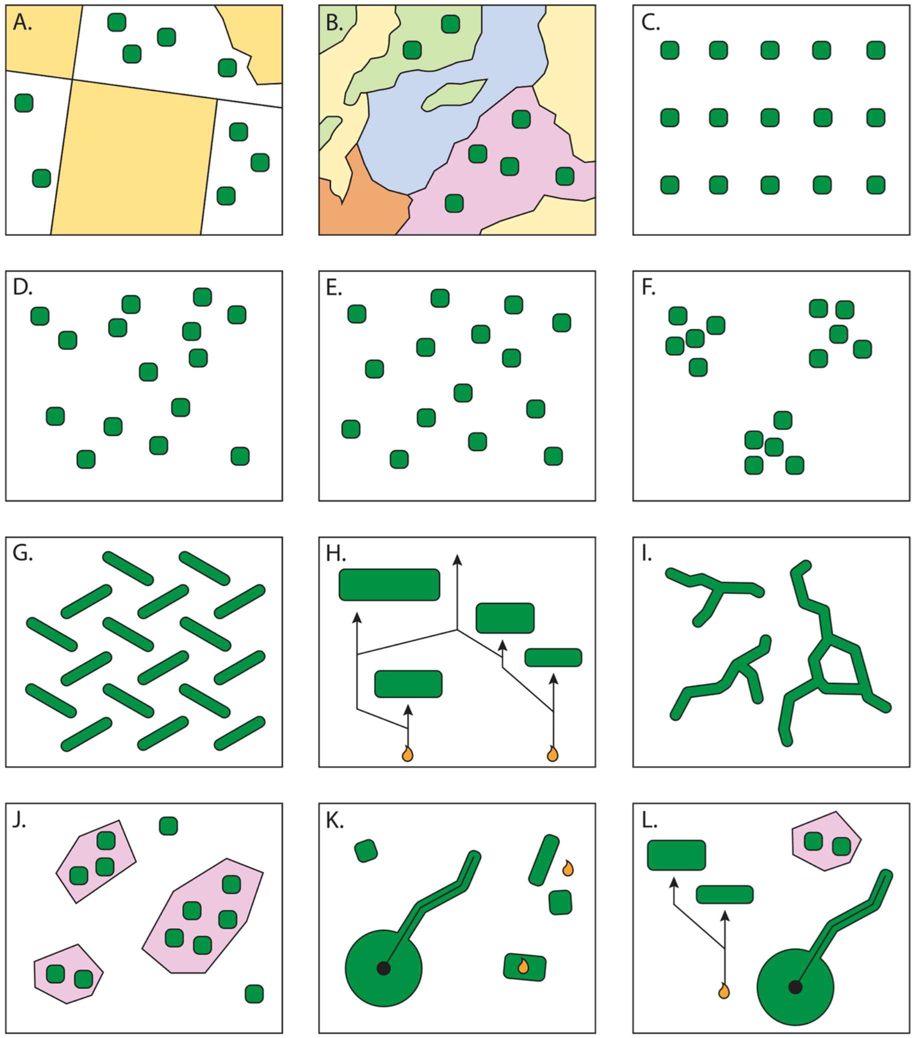

Fig. 8 Representation of fuel treatment placements used in fuel management and simulation studies. Fuel treatment types represented: constrained by property boundaries (**A**) or by vegetation type (**B**); placed in regular (**C**), random (**D**), dispersed (**E**), and clumped (**F**) patterns; strategically placed area treatment array (SPLAT; Finney 2001) (**G**); treatment optimization model (TOM; Finney et al. 2007) (**H**); prioritization with linear fuel breaks to protect defined resources (**I**) and by other landscape features, such as slope and aspect (**J**); defensible fuel profile zone (DFPZ; Schmidt et al. 2008) with defensible space around communities and roads or near locations with potential for ignition events (**K**); expert placement utilizing various strategies based on expert opinion (**L**)

residential area embedded in the landscape. Vaillant (2008) found that SPLAT placement was generally less effective than an optimized placement scheme with an equivalent treated area.

Treatment placement based on optimization algorithms generally outperformed alternative placement strategies with which they were compared (Fig. 9). The treatment optimization model (TOM), which places treatments at strategic locations predicted to intercept and slow the spread of large fires (Fig. 8H; Finney et al. 2007), was the most commonly tested optimization approach. Optimization using TOM was found to be more effective than random placement (Finney 2007, Finney et al. 2007) and expert-determined placement (Dow et al. 2016) when the treated area was kept constant (Fig. 9). A placement scheme developed using TOM and other optimization tools was more effective at reducing high-severity burned area than either a fuel treatment plan developed by managers with input from the public or a combination of the latter with the former, despite the smaller treated area of the TOM scenario (Stockmann et al. 2010). On the other hand, Vaillant (2008) and Osborne (2011) noted instances where TOM optimization was less effective than expert placement schemes, although differences in treatment extent or prescription could have also contributed to this result. The OptFuels

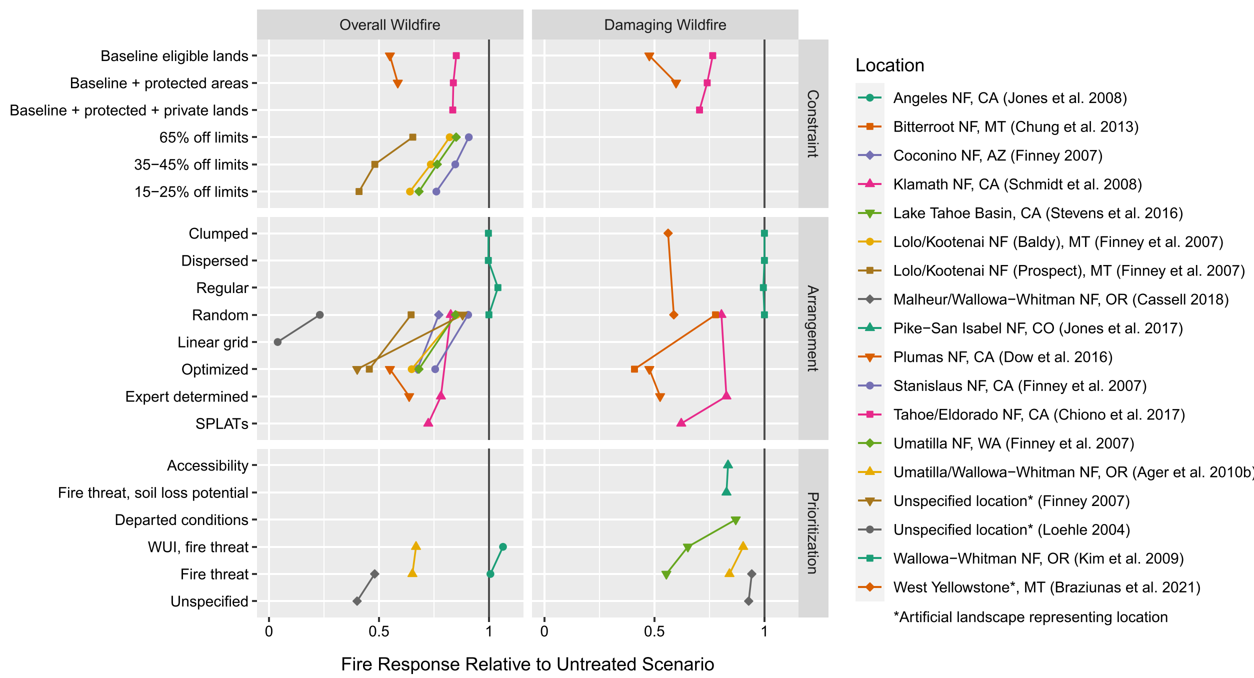

Fig. 9 Standardized values of wildfire response metrics plotted by treatment placement for selected simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed by placement scheme while other variables were kept consistent. Vertical panels indicate wildfire type (overall and damaging but not beneficial wildfire because of lack of data); horizontal panels indicate placement subcategory (constraint, arrangement, prioritization). Points connected by lines are mean values at different levels of treatment placement for a given landscape/study, omitting untreated scenarios, color-coded by landscape

optimization approach, which is similar to TOM but takes into account successional dynamics over time, was shown to result in lower resource loss from fire compared to random placement (Chung et al. 2013). The Opquest algorithm of Rytwinski and Crowe (2010) integrated fire simulation based on the Canadian Fire Behavior Prediction System with an optimization to minimize the risk of fire damage, which led to lower resource loss than either random placement or placement targeting high-risk stands on a forested landscape in Ontario. Kreitler et al. (2020) used the Land Treatment Designer (LTD) to minimize resource loss with the option of aggregating treated stands to make treatment implementation more feasible in practice. They found that spatially aggregated treatments were generally more effective than non-aggregated and that the inclusion of monetary cost effectiveness as an optimization parameter also made treatments more effective, in part because it led to solutions with greater treated area under a given budget constraint (Kreitler et al. 2020).

Studies comparing different expert-determined schemes sometimes revealed differences in effectiveness that could be traced to placement criteria or other variables (Suffling et al. 2008; Vaillant 2008; Osborne 2011; Maxwell et al. 2020). For example, Suffling et al. (2008) compared multiple fuel treatment placements designed by different experts with the aim of reducing fire spread from a park to surrounding timberlands. A post hoc assessment of these treatment alternatives showed that they differed by position relative to the park boundary, which appeared to influence effectiveness more than other varying attributes such as treatment extent, number, size, shape, and timing.

Prioritization

Placement prioritization schemes (Fig. 8H–L) ranged from those based on a single variable of local scope (e.g., stand density), those based on position in relation to landscape features of interest (e.g., proximity to the WUI), and those incorporating multiple criteria, sometimes intuitively as part of expert-determined placement. The threat of local undesirable fire, quantified using measures such as stand density, fuel load, or burn probability obtained from pre-treatment simulations, was a common prioritization criterion across many studies. Prioritized placement based on fire threat was nearly always more effective at reducing fire impacts than prioritization based on departed conditions (Krofcheck et al. 2018; Stevens et al. 2016), accessibility (Jones et al. 2017), or unspecified criteria embedded in expert schemes

(Krofcheck et al. 2019a), with some exceptions (Cassell 2018) (Fig. 9). However, placement schemes that prioritized the creation of breaks (Fig. 8I), by either linking or enhancing existing break-like features such as roads, lakes, ridges, or outcrops, were generally more effective than prioritization solely on the basis of fire threat (Chew et al. 2003; Parisien et al. 2007). Combining breaks with other types of fuel treatments tended to increase effectiveness compared to breaks alone (Osborne 2011; Frost 2015; Maxwell et al. 2020). Other comparisons involving breaks highlighted advantages of creating new breaks as opposed to enhancing existing ones along roadsides (Sturtevant et al. 2009) or linking lakes rather than placing breaks around the boundaries of a park in a boreal landscape (Parisien et al. 2007).

Treatment placement on or adjacent to areas with specific resources, such as residential developments or timber, tended to reduce losses to those resources, but generally underperformed placement schemes based on fire threat when considering fire impacts as a whole at the landscape scale (Jones et al. 2008; Ager et al. 2010b; Stevens et al. 2016; Prato and Paveglio 2018). Scott et al. (2016) found that treatments placed closer to homes were more effective at reducing the number of homes exposed to wildfire, compared to treatments placed farther away within the WUI, but the farther treatments led to lower landscape-scale burned area. In contrast, Ager et al. (2020) found that prioritizing the WUI led to lower fire impacts in both the WUI and the broader landscape compared to placement schemes that prioritized areas with high fire threat or high commercial timber volume. Some studies utilized optimization algorithms to minimize damage and maximize benefits where mitigating fire threat was one of the multiple ecosystem services examined. They showed that optimizing fire threat reduction alone predictably led to the best outcomes from a wildfire protection perspective, or alternatively found ways to balance wildfire protection with other ecosystem services under given budget constraints (Hummel and Calkin 2005; Ager et al. 2016; Bagdon et al. 2016).

Ex et al. (2019) addressed a question that is applicable to many montane landscapes in western North America that contain a patchwork of cover types associated with different topographic settings. They asked whether it would be more effective to treat more mesic north-facing slopes dominated by Douglas fir versus more xeric south-facing slopes dominated by ponderosa pine, given a one-time treatment opportunity at the start of a 50-year simulation. The south-facing slope strategy was initially more effective, but after the first decade, effects of the two strategies became more similar, and both strategies were ultimately less effective than the untreated control at reducing the ratio of crown fire to surface fire (Ex et al. 2019).

Treatment unit size

Studies testing effects of treatment unit size expressed size in various ways: area of square units (Duncan et al. 2015; Kerby et al. 2007; Lauer et al. 2020), width of rectangular SPLAT units (Schmidt et al. 2008), length of elongated treatment patches (Finney 2007; Finney et al. 2007), or mean area of patches of variable shape (Ryu et al. 2007). When a larger unit size was accompanied by a larger total treated area, there was a clear positive relationship between size and effectiveness (Schmidt et al. 2008), but when size was varied while keeping the treated area constant, results were more variable (Fig. 10). Finney et al. (2007) noted small but measurable decreases in fire spread rate with increasing treatment size in three of the four landscapes they modeled. However, Ryu et al. (2007) found that mean treatment size was positively correlated with burned area in scenarios where the larger treatments had progressively more heterogeneous shapes and less heterogeneous fuel loads. Duncan et al. (2015) noted that larger treatment sizes led to lower burned areas in a scenario where treated areas were of uniform age (single-age fuel mosaic), but if treated areas had varying fuel levels because of differing ages (multiple-age fuel mosaic), smaller treatment sizes were more effective at reducing burned area. Kerby et al. (2007) found that the effect of treatment size on burned area varied depending on the fuel load at the point where fire ignited; larger treatment sizes generally resulted in lower burned area when ignition point fuel loads were low (<4000 kg/ha) and higher burned area when ignition point fuel loads were high (>5000 kg/ha).

Looking at treatment unit size from the angle of spatially fragmented land ownership, Lauer et al. (2020) carried out simulations on a landscape representing timber management areas where ownership tends to be fragmented in blocks. They simulated harvest, fuel treatments, and wildfires on single ownership and fragmented ownership scenarios, under the assumption that owners would operate in a way to minimize risks and optimize revenue on lands they own, but cannot control what happens on other's lands. The single ownership scenario was found to lead to lower fire size, as well as increased realized timber value, compared to the fragmented ownership scenario (Lauer et al. 2020).

Prescription

Fuel treatments modeled by simulation studies were intended to imitate modifications of fuels that could result from real-world treatment prescriptions. Most studies modeled treatments in terms of specific prescriptions, although some merely described generic fuel reduction that might result from any number of prescription types. Treatments sometimes involved multiple prescription types applied to different portions of

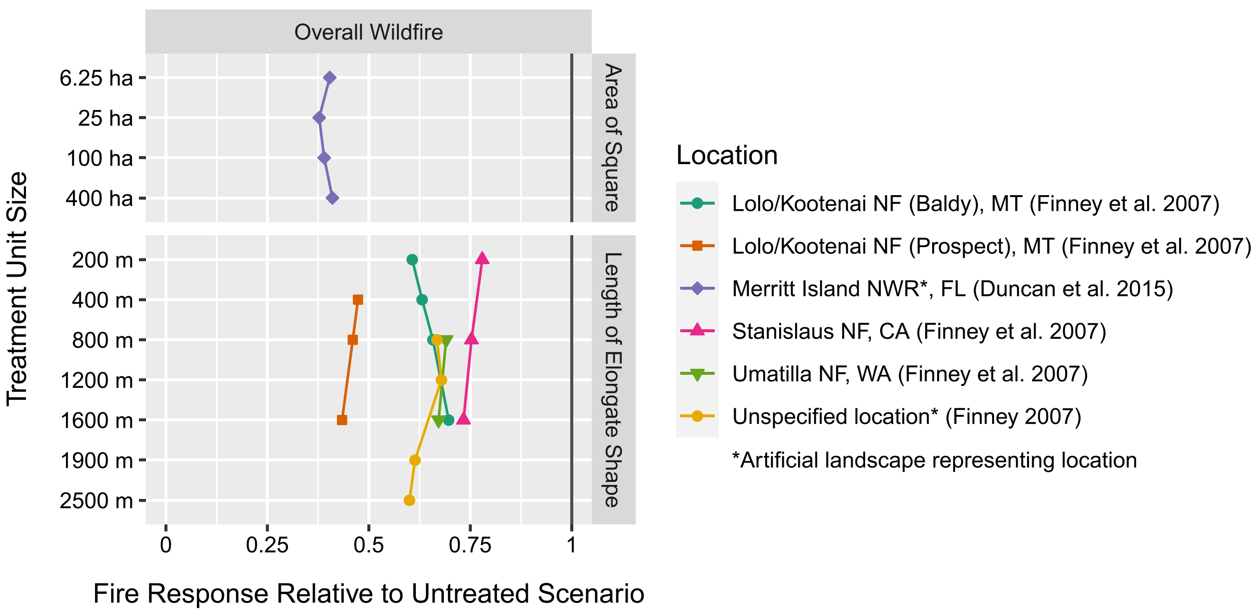

Fig. 10 Standardized values of wildfire response metrics plotted by treatment unit size for selected simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed by size while other variables were kept consistent. Vertical panels indicate wildfire type (overall wildfire only; no data for damaging or beneficial wildfire); horizontal panels indicate size measure (area, length). Points connected by lines are mean values at different levels of treatment unit size for a given landscape/study, omitting untreated scenarios, color-coded by landscape

the landscape as deemed appropriate, but not always in ways that differed among scenarios. Rather than accounting for the myriad ways in which treatment prescriptions differed, we focus on broad differences in three general categories: prescription type, intensity, and the main purpose of treatment.

Prescription type

Prescribed fire and mechanical fuel reduction were the two primary prescription types that were applied singly or in combination on simulated landscapes. On forested landscapes, tree thinning and mastication were common categories of mechanical treatment. Tree thinning entails the removal of ladder fuels to reduce surface fire intensity, separating crowns to reduce independent crown fire, or both. Mastication is intended to shift the location of the fuel from standing fuel (saplings and shrubs) to chunks or chips that decompose over time. Prescribed fire reduces ground fuel and surface fuel, depending on fire duration and intensity. Simulation studies showed the combination of prescribed fire and mechanical treatment was generally more effective than either one alone (Wilson and Baker 1998; Shang et al. 2004; Ager et al. 2007b), although not in all cases (Schmidt et al. 2008; Osborne 2011) (Fig. 11). Schmidt et al. (2008) found that thinning combined with burning, while more effective than thinning alone, was generally less effective than burning alone. They attributed this result to residual fuels left from thinning treatments that were not fully consumed by the subsequent prescribed fire, but also suggested that, beyond the timeframe of their simulation, fuel reductions from thinning would be longer lasting than those from prescribed fire (Schmidt et al. 2008). Perhaps for similar reasons, Osborne (2011) found that mechanical treatments (thinning with or without mastication) plus burning sometimes resulted in higher fire impacts than burning alone.

Prescription intensity

Intensification of prescriptions resulting in greater removal of fuel per unit area can be expected to reduce fire impacts, as demonstrated by Kerby et al. (2007) for a tallgrass prairie landscape. This was also true on forested landscapes modeled by Wilson and Baker (1998) and Ager et al. (2005), although treatment extent and placement had confounding effects in these examples. Wilson and Baker (1998) found that the proportion of the landscape in high fire risk classes decreased as the thinning intensity increased from light (30% of trees thinned from below) to heavy (70% thinned from below). These treatments were variously positioned within, adjacent to, or non-adjacent to reserves, and the most effective scenario was the one with both the highest intensity and largest treatment extent (Wilson and Baker 1998). Ager et al. (2005) reported lower area burned with active crown fire in a scenario that had higher thinning intensity (35% as

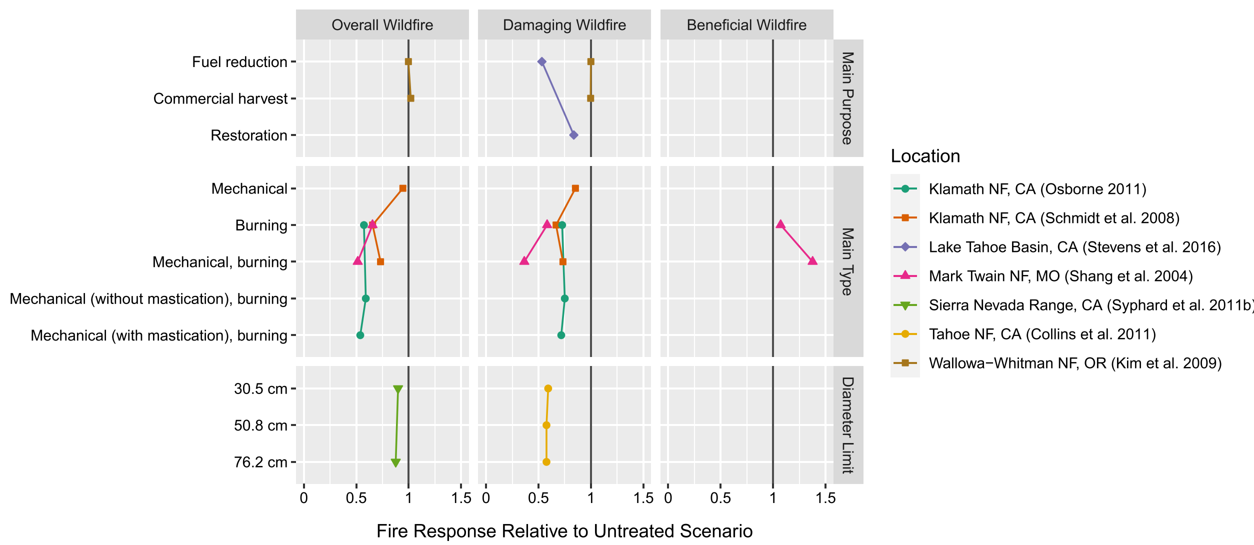

Fig. 11 Standardized values of wildfire response metrics plotted by treatment prescription for selected simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed by prescription type while other variables were kept consistent. Vertical panels indicate wildfire type (overall, damaging, beneficial); horizontal panels indicate prescription subcategory (main purpose, main type, diameter limit). Points connected by lines are mean values at different levels of treatment prescription for a given landscape/study, omitting untreated scenarios, color-coded by landscape

opposed to 45% of maximum stand density) as well as larger treated area. Other studies measured prescription intensity in terms of diameter limits (Fig. 11) which signify the amount of canopy fuel removed. Collins et al. (2011) found that diameter limits of 50.8 cm and 76.2 cm were slightly more effective than 30.5 cm at reducing high-intensity fire when applied to ca. 1% of a forested landscape. Syphard et al. (2011b) found that the frequency of wildfire was generally lower when the diameter limit was 76.2 cm compared to 30.5 cm, though they noted variation in this pattern at different elevations and treatment extents.

Main purpose of treatment prescriptions

Whether or not the primary objective of treatment prescriptions was fuel reduction had a bearing on their effectiveness. Prescriptions with different management objectives focus on different fuel strata; for example, if the objective is to manage for wildlife habitat that requires hiding cover, some ladder fuels will be left behind to provide that habitat attribute. As noted previously, the ineffectiveness of treatments modeled by Roloff et al. (2005) was likely due to the minor amount of fuel reduction (removal of ladder fuels and surface fuels) compared to habitat-enhancing treatments. Studies that compared fuel treatment scenarios with scenarios where the main objective was commercial timber harvest (or a combination of harvest and fuel reduction) showed that harvest-oriented scenarios tended to be less effective at reducing fire impacts (Fig. 11; Merzenich et al. 2003; Ganz et al. 2007; Kim et al. 2009; Cassell 2018; Krofcheck et al. 2019b) and sometimes even resulted in increased fire impacts compared to untreated scenarios (Merzenich et al. 2003), although covarying levels of treatment extent, placement, or timing likely also contributed to these differences. Prescriptions aimed at restoring historical forest structure also tended to be less effective for reducing fire impacts than those with a fuel reduction focus (Stevens et al. 2016; Maxwell et al. 2020). However, Loudermilk et al. (2014) found that continuous fuel treatment prescriptions were not consistently better at reducing fire impacts than prescriptions that transitioned to a forest restoration emphasis during the second half of a 100-year simulation.

Timing of treatment

All multi-year studies had a temporal dimension to their fuel treatment design, but not all of them tested differences in timing for their scenario comparisons. Where comparisons were made, they primarily tested differences in the sequence of treatment rates and prescription types. We categorized these timing schemes according to their main prescription type (mechanical, prescribed fire, or both) and the relative degree to which they were applied in earlier versus later periods of their simulation timeframes. In other cases, timing schemes were differentiated by optimization algorithms that were used to schedule treatments. In this section, we report and compare the outcomes of timing schemes when viewed across the full duration of each simulation, noting that this approach masks shorter-term perspectives in favor of a longer-term view of treatment effectiveness.

Several studies compared one or more scenarios involving an early treatment pulse against scenarios where treatment intensity remained steady. The transition from the early pulse was sometimes accompanied by a shift in prescription from mechanical treatments (with or without prescribed fire) to prescribed fire only (Ager et al. 2007b; Liang et al. 2018). In instances where the early pulse was more extensive per unit time than the steady treatment, the early pulse was generally more effective (Fig. 12; Spies et al. 2017; Barros et al. 2017; Liang et al. 2018; Ager et al. 2020). However, when the early pulse began at the same rate as the steady treatment and subsequently dropped to a lower rate (sometimes to zero), it was less effective than when the rate remained steady (Fig. 12; Ager et al. 2007b; Loudermilk et al. 2014; Spies et al. 2017; Schaaf et al. 2008). Scenarios where the pulse was delayed until later in the simulation were likewise less effective than early pulse scenarios (Jones et al. 1999), but a scenario with a later pulse was slightly more effective than a steady treatment scenario when both scenarios had the same rate early on (Ager et al. 2005). Ohlson et al. (2006) compared a steady mechanical treatment scenario with a scenario where mechanical treatment transitioned to prescribed fire (applied to a more extensive area) and found that the latter was only slightly more effective. Chew et al. (2003) found that treating stands with higher fire risk in a single decade, followed by treatment of lower-risk stands, was not necessarily more effective than treating higher- and lower-risk stands concurrently over three decades.

Duncan et al. (2015) approached treatment timing from a different angle, by comparing single-age and multiple-age fuel mosaics during a single fire season on a landscape representing conditions in east-central Florida. The single-age scenario tested the immediate effects of a one-time intensive fuel reduction effort, while the multiple-age scenario tested the longer-term effects of staggered timing, with gradual recovery of pre-treatment fuel levels over time. The multiple-age mosaic was found to be more effective at reducing burned area.

Some studies varied the timing of treatments to achieve pre-determined ecological or economic objectives and used optimization algorithms to determine how to schedule treatments for maximal effectiveness (Calkin et al. 2005; Hummel and Calkin 2005; Lauer et al. 2017, 2020; Acuna et al. 2010). Acuna et al. (2010) introduced an algorithm for optimizing the placement and timing of “fire smart” fuel break treatments in areas managed for ongoing timber harvest and demonstrated its effectiveness for reducing burned area and increasing net present value of timber resources. Fire-smart placement incorporating effects of fire spread as well as effects of previous harvests had a more favorable outcome than placement schemes ignoring these effects. Lauer et al. (2017) developed an optimization procedure for coordinating the timing and placement of timber harvest and

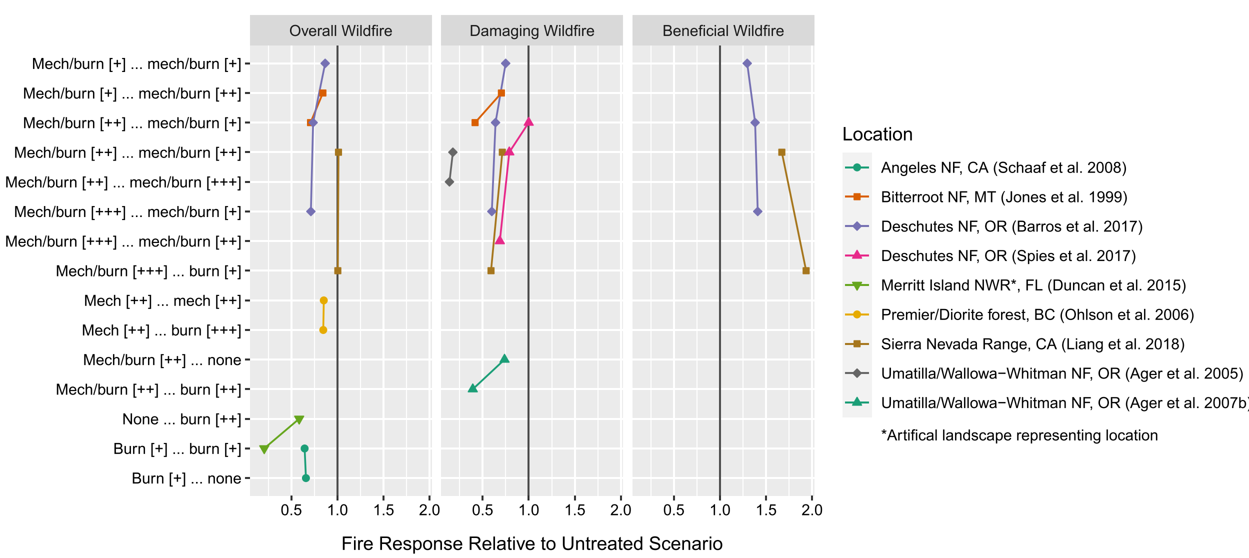

Fig. 12 Standardized values of wildfire response metrics plotted by treatment timing for selected multi-year simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada. Each study had an untreated scenario and two or more treatment scenarios that differed in how treatments were applied over time while other variables were kept consistent. *Y* axis labels denote prescription type (mech=mechanical, burn=prescribed burning) and relative treatment extent (number of + symbols) during early and later phases of a simulation (left and right of ellipsis, respectively). Vertical panels indicate wildfire type (overall, damaging, beneficial). Points connected by lines are multi-year mean values of different timing schemes for a given landscape/study, omitting untreated scenarios, color-coded by landscape

fuel treatments which they compared with other schemes (Faustmann rotation without fuel treatment and Reed rotation with and without fuel treatments) on an artificial landscape representative of southwestern Oregon. The optimization approach led to fewer large fires, more smaller fires, and greater net present value of timber compared to the alternatives (Lauer et al. 2017).

Factors beyond treatments

Many simulation studies examined the effects of non-treatment factors including weather, climate, fire and fuel attributes, and management inputs. As would be expected, the burned area was higher when modeling parameters were set to represent higher fuel loads across the landscape (Chew et al. 2003; Chiono et al. 2017) or to allow larger, more frequent, or longer-burning fires (Finney 2007; Syphard et al. 2011b; Loudermilk et al. 2014; Chiono et al. 2017). Long-term wildfire impacts were higher when the treatment lifespan was shorter (Campbell and Ager 2013) or ingrowth was higher (Collins et al. 2013). Higher levels of fire suppression predictably reduced the extent and severity of wildfire (Merzenich et al. 2003; Schaaf et al. 2008; Rideout et al. 2014; Stockdale et al. 2019a). Greater ignition management effort also resulted in less extensive wildfires (Cary et al. 2009). Sturtevant et al. (2009) found that eliminating ignitions caused by debris burning had a greater effect than fuel treatments on reducing area burned by wildfire on a forested landscape in northern Wisconsin.

Tests of different fire weather percentiles (ranging from 75th to 97.5th) generally showed greater wildfire impacts at higher percentiles (Stratton 2004; Finney et al. 2007; Schmidt et al. 2008; Vaillant 2008; Cary et al. 2009). Wildfire impacts were also higher for simulations utilizing historical fire weather from more extreme fire weather conditions compared to conditions that were less extreme (Frost 2015; Cassell 2018; Krofcheck et al. 2019b). For a forested landscape in Arizona, Fitch et al. (2018) found that burned area and suppression costs were higher at higher wind speeds and under weather conditions earlier in the fire season (May > June > July).

Scenarios comparing future trends with and without climate change sometimes showed greater wildfire impacts under projected future climates (Halofsky et al. 2017; Loehman et al. 2018; Maxwell et al. 2020), but not always (Loehman et al. 2018; O'Donnell et al. 2018). For a landscape in northern Arizona, Loehman et al. (2018) found that, in comparison to contemporary climate, wildfire levels were lower in an RCP 4.5 emissions scenario and even lower at RCP 8.5. Modeling of this same Arizona landscape by O'Donnell et al. (2018) revealed a similar pattern of lower wildfire at RCP 4.5 but a reversal of this pattern towards more wildfire at RCP 8.5. A second landscape modeled by Loehman et al. (2018) in New Mexico showed an interaction between climate change parameters and treatment extent, in which burned area (total and high-severity) decreased with increasing treated area under the hot-arid, RCP 8.5 HadGEM2-ES climate model, but increased under the warm-dry, RCP 4.5 CCSM4 model as treated area increased from 0 to 1.5% to 4.5% $year^{-1}$, followed at a decrease in burned area as treated area was raised to 9% $year^{-1}$. The authors attributed the pattern of the warm-dry scenario in part to conditions favoring regrowth following fuel treatments, leading to fuel buildup as treatments were expanded, up until the point where treatments were of sufficient frequency and extent to maintain lower fuel levels on the landscape. Under the hot-arid scenario, in contrast, fuel buildup was not sufficient to negate treatment effects even at the lowest treatment rates. Loehman et al. (2018) also noted that the FireBGCv2 simulation model they used for the New Mexico landscape allowed them to calculate the direct effects of climate changes on fire ignitions, unlike the LANDIS-II model used for the Arizona landscape.

Relative importance of factors

Factorial combinations of factors were tested for one or more fire types by 38 studies, and four of the studies (all from Finney et al. 2007) tested more than one combination, leading to a total of 63 cases (37 for overall wildfire, 22 for damaging wildfire, and 4 for beneficial fire) where we were able to assess the relative importance of factors (Fig. 13). Treatment extent was the most frequently tested factor and ranked as the most important in approximately half of the 46 cases where it was tested (Fig. 13). Placement arrangement and prioritization were also frequently tested and relatively important variables (Fig. 13). Among non-treatment factors, weather was the most commonly tested and was the most important factor in 11 of 17 cases (Fig. 13).

Discussion

The findings presented in this review were drawn from studies that employed simulation techniques to test landscape-scale effects of fuel treatments on wildfire in North America. We pinpointed a body of research pertaining to fuel treatment effectiveness which represents the best available substitute for landscape-scale experiments that typically cannot be implemented in the real world. Without the use of simulation modeling to compare scenarios, landscape-scale fuel treatment effectiveness can generally only be assessed on a post hoc basis after an actual wildfire encounters an existing fuel treatment network. The simulation studies summarized in this review complement a smaller set of empirical and observational studies

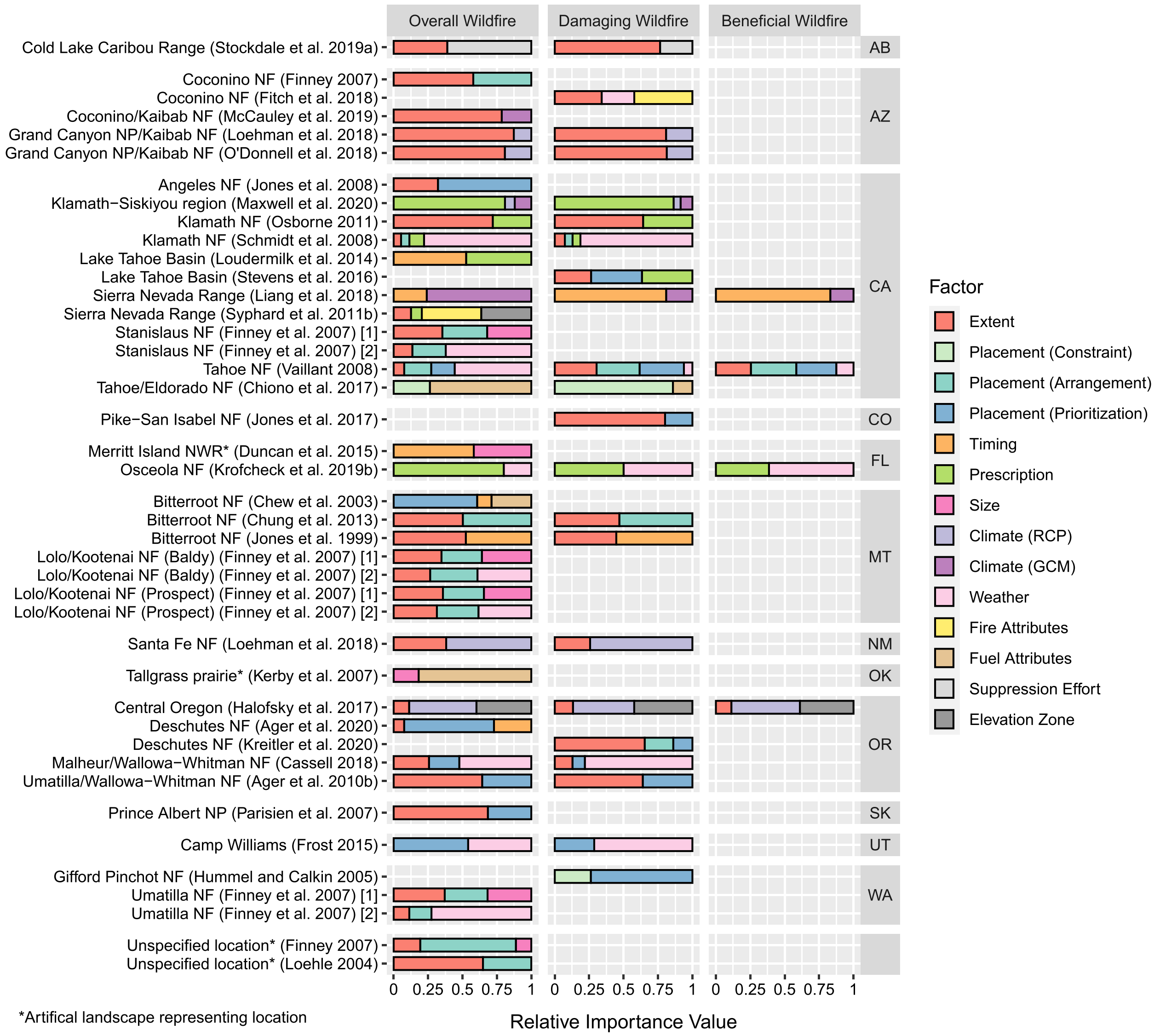

Fig. 13 Relative importance of factors influencing landscape-scale fuel treatment effectiveness for simulation studies that used a factorial testing framework. Each stacked bar shows the relative importance, measured as the increase in node purity from a random forest model, of factors that were tested for the indicated landscapes and wildfire types. Landscapes are organized by their primary state/province as shown by abbreviations to the right of panels

from North America (McKinney et al. 2022; Urza et al. 2023) and similar research from other continents (e.g., Bradstock et al. 2012; Wu et al. 2013; Salis et al. 2016).

Most studies that qualified for this review focused on forest-dominated landscapes of western North America, which can be attributed in part to the outsized importance of western forest ecosystems from the standpoint of fire management. Most western forests are naturally fire-prone, and in many places, they currently have heightened potential for damaging fire due to recent episodes of drought, disease, and fuel buildup (Hessburg et al. 2005, Hessburg et al. 2016; Keeley et al. 2009). In contrast, fuel reduction is of lesser importance in some ecosystems such as eastern deciduous forests where successional processes have led to vegetation that is less, rather than more, susceptible to wildfire (Alexander et al. 2021). Although our initial literature search revealed many studies dealing with restoration treatments of various types in ecosystems beyond western forests, few of these studies emphasized fuel reduction in a way that qualified them for inclusion. In other cases, studies did not qualify because they were not carried out at the landscape scale or did not compare wildfire metrics across landscape scenarios. We had anticipated finding more qualifying studies from other ecosystems where fuel reduction is an important component of fire management, such as annual-invaded drylands, southeastern savannahs, California chaparral, and boreal forests (Keeley et al. 2009). There is a need for additional research on landscape-scale fuel treatment effects in these ecosystems as well as underrepresented locations in the western forest zones.

The simulation studies we reviewed support the idea that fuel treatments imbedded in a landscape can have an effect on wildfire at the landscape scale. Fuel treatments were generally found to be effective at reducing the overall amount of wildfire and even more effective at reducing damaging higher-severity wildfire while also boosting beneficial wildfires of lower severity. These results are not entirely unexpected since the simulation modeling techniques rely on the understanding that treatments will affect fuel structure and fire behavior in specific ways at local scales (Parisien et al. 2019). To a certain degree, landscape-scale fuel treatment effects are simply the additive result of local treatment-induced modifications to fuels and fire that are programmed into the models. However, the way in which local fuel treatments translate to wildfire outcomes at broader landscape scales also depends on fire behavior and spread as influenced by spatial context, including the layout of treated and untreated patches (Finney 2001). A full understanding of fuel treatment effects on wildfire cannot be attained without examining this broader scale, and simulation modeling is the simplest approach for this task (Collins et al. 2010; Chung 2015). The caveat is that fire simulation models are imperfect predictors of real-world wildfire (Cruz and Alexander 2013; Omi 2015; Benali et al. 2016; Parisien et al. 2019) and the modeling techniques of the reviewed studies varied in their level of sophistication. Some studies did not fully integrate effects of fire spread into their modeling, such as those that reported fire hazard in terms of fuel load without an accompanying indication of burn probability. Furthermore, not all of the reported differences in wildfire outcomes are necessarily significant from a statistical or practical standpoint. Although some studies presented statistical analyses of scenario differences, we have not emphasized these results because the value of statistical significance in simulation contexts is questionable (White et al. 2014).

The reviewed studies employed a variety of modeling techniques and wildfire metrics to address a diverse set of questions, but they were united by a common approach in which wildfire outcomes were compared across two or more landscape scenarios. Scenario comparisons demonstrated the relevance of five key dimensions of landscape-scale treatment design (treatment extent, placement, size, prescription, and timing) and showed that other factors, notably weather and climate, are also important for determining fuel treatment effectiveness. Some studies focused on a single factor, others tested multiple factors in a factorial framework, and yet others tested treatment alternatives with covarying combinations of factor levels. The latter group included many studies where the intent was to evaluate treatment options "as a package" rather than isolate the effects of individual factors. This type of evaluation is common in environmental assessments such as those required by the US National Environmental Policy Act (NEPA), as referenced by one of the studies (Stockmann et al. 2010). In contrast, studies evaluating the influence of specific factors, even testing factor levels that would not normally be considered, are valuable for understanding the driving forces behind treatment effects. Factorial tests indicated that factor importance varies across different contexts, suggesting that further work is needed to better understand which factors or dimensions of treatment design require the most attention under given circumstances.

Three of the dimensions of fuel treatment design (extent, size, placement) are exclusively landscape-scale concepts describing treated patches within a non-treated matrix, whereas the other two (prescription, timing) are applicable to both local and landscape scales. Accordingly, landscape-scale effects of prescription and timing might be expected to be similar to their local-scale effects, unless their interaction with treatment extent, size, and placement alters the expected outcome. The studies we reviewed generally reported landscape-scale prescription and timing effects that were in line with what would be expected locally. For example, the expectation that accelerated mechanical fuel reduction followed by periodic prescribed fire will reduce local wildfire severity in dry western forests (Jain et al. 2012) was supported at the landscape scale (Ager et al. 2007b; Liang et al. 2018).

The extent was the treatment dimension most frequently tested, and these tests largely confirmed that greater treated area can lead to reduced wildfire impacts. Fuel treatments are only effective to the degree that wildfires actually encounter them, and the greater the treated area, the greater the probability of such encounters (Barnett et al. 2016; Thompson et al. 2017; Hunter and Robles 2020). The relationship between treatment extent and wildfire extent (or other measures of wildfire impact), commonly referred to as leverage (Loehle 2004; Thompson et al. 2017), is likely to become more attenuated as treated area increases, and some authors have identified a treatment threshold of ca. 20–30% of a landscape beyond which further treatments are characterized by diminishing returns (Ager et al. 2007a; Finney et al. 2007; Loehle 2004). However, some studies of this review showed continuing effects beyond this threshold, suggesting that the expectation of diminishing returns may not be valid in all situations.

In contrast to treatment extent, there were few studies looking at the size of individual treatment units, and most of these studies were from artificial landscapes with simplified characteristics. This may reflect in part the more theoretical nature of the size question, since unit size will rarely be uniform across actual treated landscapes, except in certain cases such as SPLAT arrangements (Schmidt et al. 2008), timber management areas with checkerboard ownership (Lauer et al. 2020), and possibly grazing units (Kerby et al. 2007). The theoretical implications of studies examining size are consequential for understanding how large a treatment unit needs to be to have an effect on reducing fire spread (Finney et al. 2007; Kerby et al. 2007). Finney et al. (2007) suggested that unit size is especially important in situations where spotting allows smaller units to be more easily breached. Strategies fostering heterogeneity in treatment size and shape may ultimately prove more effective than those focused on uniformity (Ryu et al. 2007).

Treatment placement is relevant in practice because some treatment locations may be more effective at modifying fire behavior and spread than others and because there are typically limitations on where treatments can be done (North et al. 2015). Although several studies of this review showed that relaxing these limitations may lead to better wildfire outcomes, there was limited evidence that this would be helpful on its own without an accompanying increase of treated area. Because of placement constraints, some of the tested placement schemes, such as purely dispersion-based arrangements, are potentially impractical in real-world settings. However, dispersion-based arrangements (e.g., random, regular, clumped) may be applicable to certain situations where the landscape features being targeted for treatment are dispersed in such ways (Braziunas et al. 2021). The SPLAT arrangement is appealing from a theoretical perspective but challenging to implement in practice (Finney 2001; Schmidt et al. 2008; Tubbesing et al. 2019). TOM optimization is based on the same principles as SPLATs, with the objective of using fuel treatments as barriers to fire spread, but is more flexible in finding locations that will have this effect given the heterogeneity and constraints of real landscapes (Finney et al. 2006). Our review clearly shows that TOM and other optimization techniques can improve treatment placement, while not discounting the merit of expert opinion or simple strategies such as placing treatments in areas of highest calculated fire threat or closest to areas needing protection. Understanding existing barriers to fire spread (Povak et al. 2018) and utilizing that information in fuel treatment design can make fuel treatment networks more effective.

An important point highlighted by this review is that the optimal placement of fuel treatments depends on management objectives. Ager et al. (2013) outlined six spatial strategies for fuel management defined by the spatial pattern of values requiring protection, the role of fuel treatments in modifying wildfire spread on the landscape, the performance measure, and the treatment goal. Treatment scenarios of the reviewed studies included examples of each of these strategies. Some scenarios demonstrated the strategy labeled "restoration of low severity fire regime" and placed treatments in areas with high fuel buildup. Other scenarios prioritized treatment locations that would reduce fire spread or facilitate suppression, and thus demonstrated other strategies presented by Ager et al. (2013): "broad landscape protection," "localized protection," "protection of dispersed values," "restoration of mixed severity fire regime," and "strategic containment." The dichotomy between strategies aimed at protecting valued resources from fire damage versus promoting low-severity fire has been a topic of ongoing discussion in the fuel treatment literature (Reinhardt et al. 2008; Schoennagel et al. 2009; Omi 2015; Vaillant and Reinhardt 2017; Prichard et al. 2021). Studies of this review largely emphasized resource protection strategies, as indicated by the greater number of reports for damaging wildfire than beneficial wildfire, suggesting a research gap that could be addressed in future studies.

In most management contexts, fuel reduction is not the only purpose or type of vegetation treatment and wildfire is not the only management concern. Although this review has focused on treatments geared toward fuel reduction, it also captured other types of treatments and management actions whenever they were presented in conjunction with or as an alternative to fuel treatments. Our focus on response variables directly measuring wildfire was sometimes broadened to include resource loss as a proxy for damaging wildfire, and some studies' optimization techniques incorporated variables beyond fire. That these additional treatments and variables entered into our review illustrates the interlocking and multifaceted concerns of land management in North America. Tradeoffs between wildfire protection and other management objectives such as commercial harvest, forest restoration, habitat protection, and carbon sequestration may need to be addressed on many managed landscapes (Stockmann et al. 2010; Ager et al. 2016, 2019; Stevens et al. 2016; James et al. 2018). Potential strategies for dealing with these tradeoffs include adjustments to harvesting procedures or restoration prescriptions to make them better aligned with fuel reduction goals (Acuna et al. 2010; Stephens et al. 2021) or the use of optimization algorithms to identify management solutions that could maximize a set of competing benefits (Hummel and Calkin 2005; Bagdon et al. 2016; Kreitler et al. 2020).

The performance of fuel treatments under extreme fire weather is a critical issue given recent trends toward more extreme conditions that are projected to continue under climate change (Prichard et al. 2021; Hawkins et al. 2022; Jain et al. 2022). The studies we reviewed affirmed that more extreme conditions lead to greater amounts and impacts of wildfire, making wildfire outcomes less favorable overall, but that the relative effect of fuel treatments can also increase making them more important for mitigating unfavorable outcomes than under less extreme conditions. Extreme fire weather was in most cases simulated using previous fires at or near the tested landscapes, so there is uncertainty over whether these conditions are representative of what will be the extreme in the future.

Simulation models that track landscape dynamics over time are necessary for understanding longer-term implications of fuel treatments including effects of climate change (Loehman et al. 2020). The influence of time was addressed by multi-year studies but was side-stepped by studies that modeled treatment effects for a single year. Single-year studies sometimes tested treatments that had been implemented in stages, and sometimes ran high numbers of replicate simulation "years" to generate wildfire outputs, but they did not track landscape dynamics beyond one fire season. Consequently, single-year studies did not capture feedbacks between fuel treatments, wildfire, and vegetation succession, such as the possibility that short-term reductions in wildfire due to treatments allow greater fuel buildup leading to more damaging subsequent wildfires (Calkin et al. 2015; Parks et al. 2016; McKenzie and Littell 2017). The multi-year studies contain considerable detail that we have glossed over by focusing on overall effects across simulation timeframes. The small number of studies that applied climate change projections to multi-year simulations indicated that wildfire impacts may vary depending on how climate affects fuel buildup on one hand and fire weather conditions on the other. Further studies modeling fuel treatments under different climate change scenarios are needed to clarify the circumstances under which treatment effects are likely to be fuel-driven or weather-driven.

By providing an overview of landscape-scale fuel treatment simulations, this review can help in both management prioritization and in the identification of potential research gaps. These studies highlight several findings relevant to fuel management, including the potential for nonlinear effects of treatment extent, the effectiveness of optimization algorithms and other prioritization methods, and the importance of environmental context and management goals in formulating fuel treatment strategies. Some issues remain less well understood at a landscape level, including the effects of treatment size and the large set of potential interactions between factors. It will remain important to frame research questions that anticipate future environmental contexts and management needs. For example, in addition to affecting landscape and environmental contexts, continued global change is likely to have societal impacts that shift policy and management priorities with regard to wildfire and its impacts. The ability of simulation studies to rapidly explore these dynamics, especially with continued technical advances in modeling, will provide land managers with flexibility and room-to-maneuver in the face of global change.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-022-00163-2.

Additional file 1. Search terms used by the USDA Forest Service Library to identify scientific literature on landscape-scale fuel treatments.

Additional file 2. Standardized values of wildfire response metrics across treatment scenarios of simulation studies testing landscape-scale fuel treatment effectiveness in the USA and Canada.

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Authors' contributions
TBJ directed the project and developed the research synthesis approach with assistance from JEO and FFK. JEO identified qualifying studies for review, carried out supplemental literature searches, summarized the data, and organized the content of the paper. Figures were created by JEO and FFK. All authors contributed to the writing process. The authors read and approved the final manuscript.

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Declarations

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