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Research article

Stakeholder perceptions and scientific evidence linking wildfire mitigation treatments to societal outcomes

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ABSTRACT

A number of watershed partnerships have emerged in the western US to address the impacts of wildfire through investing in wildfire mitigation activities. To motivate collective action and design effective risk mitigation programs, these stakeholders draw on evidence linking wildfire mitigation to outcomes of interest. To advance knowledge in this area, we 1) assessed the strength of existing scientific evidence linking wildfire mitigation treatments with societal outcomes and 2) measured the importance of this evidence to watershed partnerships in the western US. To address objective one, we created a systematic evidence map to identify the most common wildfire mitigation treatment and societal outcome relationships reported. From the more than 100 studies examined, we found that the most commonly studied linkages were related to the impacts of thinning on infrastructure and timber. To answer objective two, we surveyed 38 professionals affiliated with organizations involved in eight watershed partnerships in the western US. We asked about the relative importance and strength of evidence linking wildfire treatments to societal outcomes for their watershed partnership, and used this information to create an importance-strength analysis and gap analysis. We found that most linkages were considered important to these organizations, and that the biggest gap identified was for evidence linking mulching to water quality or quantity outcomes. Forest and wildfire specialists perceived a larger need for additional evidence generation than other professional groups. Jointly, the results from this study point to areas of evidence generation important for watershed partnerships and other organizations involved in wildfire mitigation, and suggest a need to more thoroughly disseminate information about existing evidence to this new group of stakeholders investing in wildfire risk mitigation.

1. Introduction

The frequency and severity of wildfire globally is estimated to increase due to climatic changes (Goldammer, 2008; Rocca et al., 2014; Westerling et al., 2006). Although many ecosystems are adapted for natural and human-induced wildfires (Goldammer, 2008), the increase in fire prevalence, coupled with increasing housing density in the wildland urban interface, historic land management practices, and ongoing wildfire suppression strategies, have led to a rise in societal impacts. Societal impacts of wildfire include loss of life and property, negative effects on mental and physical health, and impaired drinking water (Thomas et al., 2017). Expenditures to fight fires in the US have required federal agencies to spend over $27 billion since 2000 (National Interagency Fire Center, 2018). In the US, the financial costs of wildfire mitigation treatments are largely born by society through government funding; however, the anticipated future costs of mitigation treatments are projected to vastly outpace these appropriations (Blue Forest Conservation, 2017). In response, governmental and non-governmental entities have been developing innovative funding mechanisms to expand non-governmental funding sources to increase the pace and scale of wildfire mitigation treatments.

One example of a novel funding mechanism is the creation of watershed investment partnerships, also sometimes called water funds, comprised of public and private organizations that pool funding to invest in entities that carry out watershed protection activities. To date, there are more than 400 watershed partnerships operating in 62

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Table 1
Definitions of wildfire mitigation treatments (adapted from Nunamaker et al., 2007 and Rummer, 2010).

Term	Definition
(Pre-wildfire)	
Prescribed burning	The intentional planned ignition of a fire by managers to reduce fuel buildup and decrease the chances of a severe wildfire
Defensible space	An area around a structure where flammable vegetation and non-vegetation materials have been altered or removed to slow the encroachment and reduce the intensity of wildfire approaching the structure
Thinning	The use of hand tools or machinery to reduce vegetation density
Fuel breaks	Strips of altered or eliminated vegetation to control the spread of wildfire
(During wildfire)	
Suppression	The use of diverse techniques, equipment, and training to minimize wildfire events or to completely prevent wildfires from occurring
(Post-wildfire)	
Mulching	The addition of natural and/or artificial materials to mitigate post-wildfire increases in runoff and erosion from precipitation events and assist with the establishment of plants to stabilize post-fire hillslopes
Rehabilitation	The use of various techniques to recover an area back to pre-fire conditions and reduce the likelihood of irreversible undesirable changes caused by a fire
Salvage logging	The removal of trees in forested areas damaged by wildfire to recover the timber's economic value

countries globally and covering over 1.2 billion acres of land (Bennett and Ruef, 2016). In fire-prone areas of the western US, partnership investments are being applied toward wildfire mitigation efforts with the ultimate goal of avoiding downstream watershed degradation post-wildfire. However, many of these watershed partnerships also have additional environmental or social goals for investing in wildfire risk mitigation (Goldman-Benner et al., 2012; Bremer et al., 2016). Understanding which societal outcomes are important to watershed partnerships and their views on the strength of the existing evidence base can direct future efforts to generate new evidence on the impact of wildfire mitigation activities, which will help motivate collective action in investing in watershed protection and evaluation of watershed partnership impacts (Jones et al., 2017).

From a purely biophysical standpoint, wildfire mitigation treatments alter the physical processes and effects of fire (Reinhardt et al., 2008). However, there is less evidence concerning the expected *societal* outcomes—defined here as both social and economic outcomes—resulting from wildfire mitigation; questions regarding societal outcomes of wildfire mitigation treatments are growing due to increasing human movement into fire-prone areas (McCaffrey et al., 2012). A systematic review conducted by Kalies and Yocom Kent (2016) examined the ecological and social effects of two mitigation treatment types (thinning and prescribed burning) but did not include information on other types of wildfire mitigation treatments. Milne et al. (2014) conduct a review of the costs and benefits of wildland fires. They develop a framework highlighting literature that exists on costs/benefits of wildfires and the methods used in those studies. Neither of the aforementioned papers broadly summarized the existing evidence between wildfire mitigation strategies and their impacts on social and economic outcomes. Assessing the state of knowledge on societal outcomes from investing in wildfire mitigation treatments could aid in justifying future funding decisions, prioritizing mitigation activities, and evaluating return on investments (Pullin and Knight, 2001; Sutherland et al., 2004) for any organization involved in wildfire mitigation activities.

The overall goal of this study was to advance knowledge about the existing evidence linking wildfire mitigation treatments to societal outcomes and the importance of this evidence to watershed partnerships in the western US. The specific objectives were to: 1) assess the strength of existing scientific evidence linking wildfire mitigation treatments to societal outcomes through a systematic evidence map, and 2) measure the perceptions of representatives of watershed partnerships regarding the importance and strength of this evidence through a survey. Combined, the information generated in this study highlights where there is sufficient information on wildfire mitigation and societal outcomes, and where there are gaps, allowing us to identify where future research efforts are needed. It also identifies which treatment-outcome linkages are of most importance for watershed partnerships.

2. Defining wildfire mitigation treatments and outcomes

Until recently, fire suppression has been the most widely used management approach to tackle wildfire (Hurteau et al., 2014). While mitigating short-term risk, fire suppression actually increases future risk in many ecosystems by facilitating the ongoing growth of fuel loads (Calkin et al., 2015). Today, fire management in the western US is shifting toward pre-fire mitigation treatments, which are more pro-active approaches that aim to restore forests to their historic density to decrease the risk of future wildfires. The most common of these include reducing flammable fuels through mechanical or manual vegetation thinning or removal, and prescribed burning (Pollet and Omi, 2002). During a wildfire event, suppression is often employed to decrease the fire's severity. Post-fire restoration treatments are also widely used but costlier, with the general goal of repairing a region already damaged by wildfires. Post-fire restoration typically involves erosion minimization projects, such as mulching or seeding of burned areas to encourage vegetation recovery (Agee and Skinner, 2005; Rocca et al., 2014).

Table 1 provides definitions for wildfire suppression as well as four pre- and three post-wildfire mitigation treatments examined in this study. We chose these eight mitigation treatments based on an initial scoping search of the literature (see Nunamaker et al., 2007; Rummer, 2010), followed by conversations with contacts from a wildfire and forestry science institute regarding treatments commonly applied to mitigate the frequency and severity of future wildfires in the western US.

Societal outcomes from wildfire mitigation treatments are not defined consistently in the literature, but typically include both the economic and social well-being outcomes that result due to a wildfire mitigation action. These outcomes go beyond the biophysical changes that occur due to wildfire treatments. Social outcomes can include a decrease in loss of human life, avoided physical or mental health issues (McCool et al., 2006), or improvements to public values and perceptions of forest management (Toman et al., 2014; Varela et al., 2014). The economic outcomes of mitigation treatments can include reduced expenditures on future fire suppression, evacuation, and post-fire restoration (Prestemon et al., 2012), avoided losses to property and other infrastructure (McCool et al., 2006), or the added value of intact forests for timber or recreation/tourism (Dombeck et al., 2004).

The societal outcomes listed in Table 2 represent changes to various economic and/or social attributes found in a scoping literature search conducted by the authors. The original list of societal outcomes was presented to the same wildfire and forestry specialists mentioned above and to representatives of watershed partnerships, and updated based on their feedback. This list of societal outcomes is not meant to be exhaustive, but to represent wildfire mitigation interests in the western US.

3. Methodology

We used two separate, but complementary, methods. First, we

Table 2
Definitions for societal outcomes that may change as a result of wildfire mitigation treatments (Δ = change).

Term	Definition
Employment	Δ in number of employment opportunities
Future suppression costs	Δ in costs or avoided costs of future wildfire suppression
Habitat/biodiversity	Δ in the amount of biodiversity and viable habitat in a region
Infrastructure/property	Δ in costs or avoided costs of impacts to property
Post-fire restoration costs	Δ in costs or avoided costs of future forest restoration
Public perceptions	Δ in public perceptions of wildfire treatments as a result of successful treatments
Recreation/tourism	Δ in the ability to recreate at a site
Timber/non-timber forest products	Δ in costs or avoided costs to value of forest products
Water quality/quantity	Δ in the water quality or quantity in a region

carried out a systematic evidence mapping exercise summarizing the societal outcomes of the most common wildfire mitigation treatments found in the peer-reviewed and gray literature. An evidence map is a technique used by researchers to compile available information on a topic, and to identify gaps and gluts (linkages being over studied) in information to enhance prioritization of future research (Haddaway et al., 2016). Evidence maps are increasingly recognized as an effective method to gather broad scale evidence on multiple interventions and outcomes, with the primary output being a visual representation displaying the occurrence or absence of these linkages found in the literature (McKinnon et al., 2016).

Second, we conducted a survey of representatives of organizations involved in eight watershed partnerships in the western US. The information from the survey was used to create an importance-strength analysis (ISA) and gap analysis— methods which help identify specific treatment-outcome linkages where evidence is perceived to be sufficient or missing from the perspective of stakeholder groups investing in these activities. ISA and gap analysis are adapted from importance-performance analysis which is used to determine satisfaction with a given service (Martilla and James, 1977; Tonge and Moore, 2007; Vaske et al., 2009).

3.1. Evidence map

3.1.1. Data collection

3.1.1.1. Literature searches. We searched for evidence following best practices outlined by Livoreil et al. (2017), which included steps for planning and conducting a literature search, as well as reporting results. All searches were conducted in English, and both peer and non-peer reviewed literature were considered for inclusion to minimize publication bias. To obtain as much evidence as possible, the dates of studies were not restricted and we did not restrict the search based on geographic area. For the peer-reviewed literature, we used Web of Science as a preliminary search engine, followed by relevant databases in EBSCO host. Both databases were explored using the full search string listed in Table 3, with searching limited to titles and abstracts.

We conducted an additional full-text search in Google Scholar. Due to differing Boolean Logic, we used a modified search string (Table 3), where the first 200 hits were screened as is recommended by the literature (see Haddaway et al., 2015). Science.gov, a search engine covering over 60 databases from 13 US government agencies, was searched with the same modified search string. To avoid publication bias we ran the same search in Google for gray, non-peer reviewed literature by screening the first 200 hits. This was complemented by follow-up searches for articles on specific websites used in previous studies with a similar topic. These included government sources (e.g., US Forest Service's 'treesearch' and USGS publications warehouse), non-governmental organizations (e.g., The Nature Conservancy) and other sources (e.g., Wildfire Today, Fire Management Today). The wildfire and forestry specialists whom were familiar with this study shared papers they deemed relevant, which were added to the list of citations along with relevant references from these studies (Kalies and Yocom Kent, 2016; Leverkus et al., 2015; Milne et al., 2014).

3.1.2. Data analysis

3.1.2.1. Study inclusion criteria. Following the Centre for Evidence Based Conservation guidelines, we set article inclusion criteria as follows: (1) *Title Screening*: The title had a clear focus on wildfire or a wildfire mitigation treatment (i.e., Table 1) and contained any relevant outcome or outcome adjacent terms (i.e., Table 2). (2) *Abstract Screening*: The abstract had a clear focus on a wildfire mitigation treatment and stated a clear link to a societal outcome. (3) *Full-Text Screening*: The article had a clear focus on a wildfire mitigation treatment, described the land area or human population being impacted by the treatment, and had a clear link to a societal outcome. Papers focused on biophysical outputs (i.e., biodiversity and water quality) were only included if they also contained evidence directly linking the outputs to outcomes that provided benefits for people or society (i.e., avoided costs of water remediation, wildlife habitat used for recreation purposes). Literature that reported on purely biophysical outcomes or wildfire risk reduction were removed during the screening process, as the focus of this paper was on linking wildfire mitigation activities to economic and social well-being.

3.1.2.2. Article screening. To minimize bias, we implemented a team-based approach to screen articles (James et al., 2016). The teams determined article relevancy in three steps: (1) *Titles*: The total set of citations were split between five teams of two researchers each. Both team members compared 20% of the same citations and discussed any discrepancies before screening the remaining 80% of titles individually (40% for each team member). Titles that were clearly irrelevant were discarded. When there was doubt to the relevancy, an article was included so relevancy could be determined in the following step. (2) *Abstracts*: The five research teams divided the remaining abstracts from Step 1, and each pair compared 20% of the same citations and discussed any discrepancies before screening the remaining abstracts individually. (3) *Full Article*: The five teams reviewed the remaining full-text articles from Step 2, each pair of whom compared 20% of the same citations and discussed any discrepancies before screening the remaining articles individually. Studies were discarded if they failed to fulfill the inclusion criteria for any of the steps above.

3.1.2.3. Data extraction strategy. We utilized Microsoft Excel to store all the meta-data derived from the relevant studies. This included the reviewer's initials, type of study, journal/source, author, year of publication, title, link to full-text paper, study I.D. number, data type, model information, when the data was collected, population type, location name, country, site ownership, scale and time of treatment(s), type of treatment(s), type of outcome, and measurement of outcome.

3.1.2.4. Creation of evidence map. Between the eight wildfire mitigation treatments in Table 1 and nine societal outcomes of interest in Table 2, 72 treatment-outcome linkages had the potential to be catalogued in the evidence map. We recorded the count of each linkage and symbolized the visual representation of each count using a heat map approach, where linkages reported in more case studies were listed using a darker shade, and those reported on fewer times were shaded

Table 3
Search strings used in evidence map.

Full search string	
Intervention Terms	(“fuel treatment” OR “reduction treatment” OR “mitigation treatment” OR “silviculture treatment” OR “forest treatment” OR “wildfire hazard reduction treatment” OR “fuel management practice*“)
AND	
Intervention Adjacent Terms	(“suppress*” OR “control* burn*” OR “prescribe* burn*” OR “mechanical thinning” OR “hand thinning” OR “defensible space” OR “erosion mitigat*” OR “seeding” OR “mulching” OR “salvage log*” OR “rehabilitat*” OR “pre wildfire” OR “post wildfire” OR “pre fire” OR “post fire” OR “forest”)
AND	
Outcome	(“economic” OR “social” OR “non-market” OR “market” OR “service*” OR “good*” OR “benefit” OR “avoid*” OR “externalit*” OR “suppress*” OR “restor*” OR “house*” OR “home*” OR “property” OR “infrastructure” OR “sale” OR “business” OR “work” OR “evacuat* OR “travel time” OR “timber” OR “non timber” OR “aesthetic” OR “scenic” OR “air” OR “water” OR “soil” OR “erosion” OR “sediment*” OR “carbon” OR “habitat” OR “biodiversity” OR “recreat*” OR “tourism” OR “education” OR “science” OR “food” OR “medicin*” OR “graz*” OR “health” OR “injury” OR “human” OR “value” OR “perception” OR “cultur*” OR “spiritual”)
AND	
Outcome Adjacent Terms	(“impact” OR “effect” OR “increase” OR “decrease” OR “ecosystem” OR “cost” OR “loss” OR “lost” OR “beauty*” OR “quality*” OR “quantity” OR “purif*” OR “retain” OR “retention” OR “deliver*” OR “stor*” OR “sequest* OR “provi*” OR “resource” OR “physical” OR “mental” OR “mortality” OR “fatal*” OR “death”)
Modified search string	
(“wildfire reduction treatment”) AND (“economic” OR “social” OR “non-market” OR “market” OR “service” OR “good” OR “benefit” OR “avoided cost”)	

lighter. The direction of the treatment-outcome relationships (positive, negative or neutral) was also assessed among the five most common linkages.

3.2. Stakeholder surveys

3.2.1. Data collection

We implemented a survey to collect data on stakeholder perceptions of the strength of existing evidence available linking wildfire mitigation treatments to societal outcomes and their perceptions of the importance of this evidence (Appendix 1). We included representatives of organizations currently investing human and/or financial resources in eight watershed partnerships throughout three western US states: five in Colorado, two in Arizona and one in Oregon. These partnerships were recommended by Carpe Diem West and Forest Trend's Ecosystem Marketplace, organizations with extensive knowledge on current watershed partnership initiatives. Partnerships were chosen based on their involvement in wildfire mitigation investment and willingness to participate in the study.

Contacts from the partnerships supplied us with a list of 61 potential survey takers who could represent their organizations' perceptions of scientific evidence. In October 2017 we sent an initial email to this list asking them to take part in the questionnaire. We sent follow-up emails to non-respondents of the first round of outreach once a week for two weeks before removing them from the participant list. In total, 38 respondents completed and returned the questionnaire over a four-month period, resulting in a 62% response rate. Participants represented organizations from each partnership, and a mix of public service groups (n = 11) (e.g., water utilities and local governments), non-governmental organizations (n = 9) (e.g., The Nature Conservancy), forest/fire specialists (n = 12) (e.g., US Forest Service, local fire departments and science institutes), and private businesses (n = 6) (e.g., breweries and ranches).

Participants ranked their perceived importance of having evidence on each wildfire treatment-outcome relationship analyzed in the systematic map on a Likert scale from 1 (not important) to 4 (very important). Participants then ranked their perceptions on how strong the available evidence is for these relationships, from 1 (doesn't exist) to 4 (is strong). The participants also had the option to list a 0 (I don't know) on either scale if they were not aware of the importance or strength of any given linkage. We removed 18.75% of responses to individual survey questions due to an ‘I don't know’ selection.

3.2.2. Data analysis

To create the ISA framework the information described above was graphed on an x/y axis. This created four quadrants labeled as follows: Quadrant 1: ‘Less Effort Needed’ (low importance/high strength), Quadrant 2: ‘Continue Good Work’ (high importance/high strength), Quadrant 3: ‘Low Priority’ (low importance/low strength), and Quadrant 4: ‘Future Prioritization’ (high importance/low strength). Gap analysis was then applied to these data to provide a quantifiable measure of the perceived disparity between the mean importance and strength values of each treatment-outcome linkage. For example, through gap analysis it is possible for a researcher to subtract a strength score from importance score to determine which linkages are thought to be the highest prioritization and which are less of a priority. A larger gap value signified a larger disparity between the importance of a linkage and the strength of that evidence. A positive gap value implied the perception that the linkage was being understudied (high importance/low strength) while a negative value signified treatments and outcomes were being over studied (low importance/high strength). The standard deviation of each mean value was calculated to determine the dispersion of the stakeholder perspectives relative to the average. This analysis was conducted across all 38 respondents, as well as spilt separately between the various organizational affiliations (forest/fire specialists, private businesses, etc.) to determine if these groups hold different perceptions on scientific evidence.

4. Results and discussion

4.1. Evidence map

The initial literature search resulted in 1211 documents. After duplicate and non-English documents were removed, 864 papers remained. Using the inclusion criteria in section 3.1, each document was screened by title, abstract, and finally full-text. This resulted in a final set of 103 papers for data extraction (Appendix 2). The majority (66%) of papers were peer-reviewed and the remaining (34%) were gray literature. Almost all studies analyzed (94%) were conducted between 2000 and 2018. Most studies focused on either one forest within one state (38%), or multiple forests spanning multiple states (33%). Almost half of the studies (47%) focused on wildland urban interface (WUI) areas. The majority of studies examined regions within the western US (77%), with California (n = 35), Oregon (n = 23), Montana (n = 16), Arizona (n = 13) Washington (n = 13), and Colorado (n = 12) representing the major study sites. Outside of the US, four papers originated from Australia, two from Spain, two from Italy and one from Portugal. This US focus may have resulted from our choice of terminology (i.e., Tables 1 and 2) and our use of federal agency websites.

Nearly 58% of the papers focused on one wildfire mitigation treatment type, while the remainder reported on multiple, which resulted in a sample size of 187 treatment-outcome linkages analyzed.

	Intervention								
	Thinning	Burns	Suppression	Defensible space	Rehabilitation	Fuel breaks	Mulching	Salvage logging	**Total**
Infrastructure/ property	19	14	5	7	2	2	2	0	51
Future suppression costs	9	11	10	4	1	2	0	1	38
Public perceptions	9	9	1	8	1	2	1	0	31
Timber/non-timber forest products	14	6	1	1	0	0	1	2	25
Water quality/ quantity	3	2	2	0	3	0	1	0	11
Restoration costs	3	3	2	1	0	0	0	1	10
Employment	3	3	1	0	1	1	0	0	9
Habitat/ biodiversity	2	1	1	1	2	0	1	0	8
Recreation/ tourism	1	2	1	0	0	0	0	0	4
Total	63	51	24	22	10	7	6	4	**187**

High number of studies → Low number of studies

Fig. 1. Evidence map of treatment-outcome linkages found in the literature.

Thinning was the most common mitigation treatment examined (n = 63), followed by prescribed burning (n = 51) and wildfire suppression (n = 24) (Fig. 1). The least cited mitigation treatments were fuel breaks (n = 7), mulching (n = 6), and salvage logging (n = 4). In terms of societal outcomes, changes in infrastructure/property was the most commonly reported result (n = 51), while future suppression costs (n = 38) and public perceptions of management (n = 31) were the second and third most commonly cited outcomes (Fig. 1). Impacts of mitigation treatments on habitat/biodiversity (n = 8) and tourism/recreation (n = 4) were the least reported. Water outcomes were assessed in 11 cases. Nearly 44% of outcomes reported were economic, 22% were social, and the remainder were a mix of both. Only 5 of the 72 potential treatment-outcome linkages were referenced in 10 or more case studies (7%) and only 13 out of the 72 potential treatment-outcome linkages (18%) were referenced in four or more. There were 22 possible linkages (31%) not referenced at all in the literature.

Impacts of thinning on infrastructure and property was the most common relationship reported (n = 19). Of these studies, 81% provided positive outcome data of thinning on infrastructure and property in the form of a reduction in burn probability of structures, the number of structures saved due to previous thinning projects, and the associated avoided costs to the owners of property and infrastructure. The remaining 19% of papers reported neutral findings of thinning, with no papers reporting negative societal impacts of thinning on infrastructure and property. The effects of thinning on timber/non-timber forest products was tied for second most commonly cited linkage (n = 14) (Fig. 1). Almost 89% of these papers reported positive outcomes as well, typically referring to the amount of biomass produced from thinning and the resulting revenue from biomass sales in US dollars. The other 11% of papers discussed neutral findings that could result in either positive or negative outcomes depending on the size of the thinning project. These studies mentioned that economies of scale are important to consider to make a thinning project profitable (e.g. Hunter et al., 2007).

The impact of prescribed burns on infrastructure and property was also the second most commonly reported relationship (n = 14) (Fig. 1). All of these papers reported positive societal outcomes. Similar to impacts of thinning, these outcomes included a reduction of burn probability of structures and reported the number of homes saved from previous burning projects, as well as avoided acres burned and resulting avoided costs in US and Australian dollars. Prescribed burns were also found to reduce costs of future suppression in 11 studies, all of which reported positive economic outcomes in the form of US dollars saved. Additionally, ten papers discussed fluctuations in future suppression costs due to employing fire suppression techniques (Fig. 1). Half of these studies reported reduced fire suppression costs as a positive economic outcome of implementing suppression sooner. The other four studies stated that positive results could potentially occur dependening on the type of ecosystem where the wildfire is being suppressed, or the magnitude of the suppression. One paper cited negative outcomes that could result in an economic strain on the federal budget due to surrounding WUI communities free riding from supression efforts on public lands (Busby and Albers, 2010).

The 187 references analyzed in Fig. 1 vary in evidence quality, with many studies being post-hoc observations versus experimental or quasi-experimental designs. This invokes an important caveat to interpreting the positive, negative, and neutral results from the systematic map. However, a full assessment of evidence quality was beyond the scope of this study.

4.2. Stakeholder survey

Fig. 2 shows the ISA framework as a complete grid of treatment-outcome linkages across all 38 survey respondents, with perceived importance mapped out on the x-axis and perceived strength on the y-axis. Of the 72 possible linkage combinations, 37 fell into Quadrant 2: 'Continue Good Work' and 19 in Quadrant 3: 'Low Priority'. Quadrant 4: 'Future Prioritization' contained 12 perceived linkages, while only four linkages were found to exist in Quadrant 1: 'Less Effort Needed'.

On average, gaps between the perceived importance and strength of treatment-outcome linkages vary greatly. When generalized across all 38 survey respondents, the treatment-outcome linkage with the largest

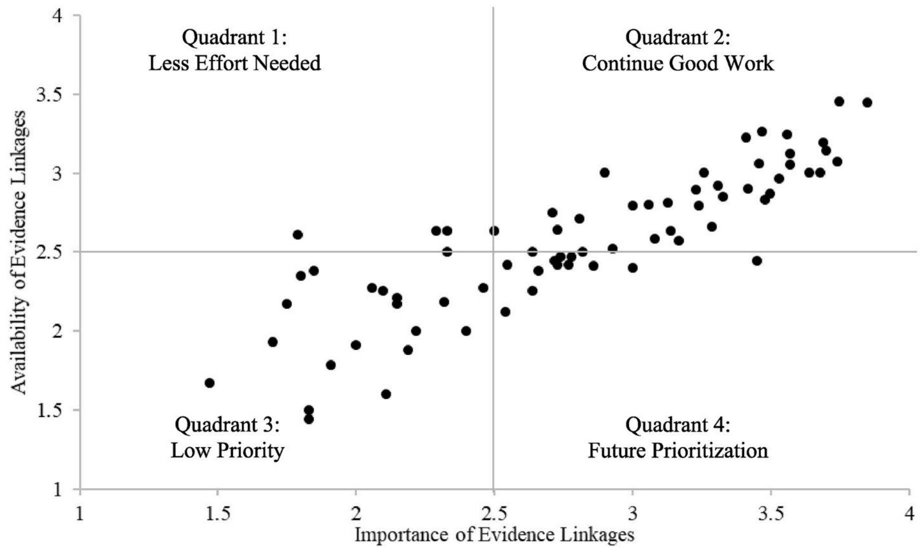

Fig. 2. Grid of perceived importance and strength of treatment-outcome linkages across organizations.

disparity between importance and strength was identified as the impact of post-wildfire mulching on water quality and quantity, which had the highest average gap value of 1.01 (Table 4). This value was positive and located in Quadrant 4, signifying that the relationship between mulching and water health was perceived to be understudied (very important [mean = 3.45] with weak evidence [mean = 2.44]). The other linkages in Quadrant 4 that were believed to be most important for future research prioritization included the impacts of: fuel breaks on public perceptions of the mitigation treatments (GV = 0.6), rehabilitation on recreation and tourism (GV = 0.45), defensible space on water quality/quantity (GV = 0.42) and mulching on habitat and biodiversity (GV = 0.39).

The largest negative gap value (GV = −0.82) indicating the linkage perceived to be most over studied was the relationship between impacts of post-fire rehabilitation on timber and non-timber forest products. This linkage had a slight importance (mean = 1.79) and moderate strength of evidence (mean = 2.61) linking the intervention to the outcome. The two linkages with the largest standard deviation (*SD* = 1.3) were the impacts of mulching on future suppression costs and the impacts of salvage logging on public perceptions, indicating the highest disparity of stakeholder viewpoints on these relationships. The most agreement occurred regarding the relationship between fuel breaks and employment (*SD* = 0.3).

When broken out by organizational affiliation, the perceptions of almost all subgroups followed similar trends, the exception being the forest and wildfire specialists (Table 5). These specialists indicated that 19 treatment-outcome relationships were currently being understudied and were necessary to prioritize in future wildfire science research. Of these linkages, the five with the highest gap values were: 1) the impact of defensible space on future suppression costs (GV = 1.56), 2) the impact of fuel breaks on public perceptions (GV = 1.4), 3) the impact of mulching on water quality/quantity (GV = 1.25), and 4) the impact of salvage logging on a) public perceptions (GV = 1.2) and b) timber/non-timber forest products (GV = 1.2). Forest/wildfire specialists also perceived just one linkage belonging in the 'Less Effort Needed' category: the impact of fire suppression on timber and non-timber forest products (GV = −0.67).

4.3. Comparing evidence map and stakeholder survey

The five most commonly reported treatment-outcome relationships found in the evidence map were impacts of: 1) thinning on a) infrastructure/property and b) timber/non-timber forest products; 2) prescribed burns on a) infrastructure/property and b) future suppression costs; and 3) current wildfire suppression on a) future suppression costs (Fig. 1). These five relationships were all located in Quadrant 2: 'Continue Good Work' when averaged across organizations surveyed (Fig. 2 and Table 4). They were almost all located in the same quadrant when broken down by each organizational sector as well, implying that organizations' perceptions of evidence on these linkages align with results found in the published literature. The evidence map reported overwhelmingly positive societal outcomes of implementing these mitigation treatments in the form of reducing economic costs and social losses.

The forest and fire specialists differed from other organizational sectors in the 'Future Prioritization' quadrant, where they deemed 19 linkages (seven above the average) as highly important but currently being understudied (Appendix 3). When compared to the results from the evidence map, eight of these relationships were not found in the literature, eight were only referenced once or twice, and only three had more than two references. The fact that there are few studies focusing on these linkages perceived to be important by specialists implies a research gap, even though the average survey participant believed the evidence to be adequate for many of these relationships. Specialists are likely to be more familiar with scientific literature than other stakeholder groups surveyed, and thus more aware of research needs in their given fields (Baatiema et al., 2017). Another study comparing group perceptions to the strength of scientific evidence found similar contrasting observations between stakeholders (Ntshotsho et al., 2015). They conclude that an observed disparity could lead to future challenges in advancing an evidence-based approach to management, including weaknesses in goal setting, establishing appropriate indicators, and the implementation of project monitoring grounded in science.

In terms of linkages perceived to be over studied in the survey, the average respondent listed four relationships with a low importance/high strength score: 1) prescribed burning on timber/non-timber forest products; 2) fire suppression on timber/non-timber forest products; and 3) post-fire rehabilitation on a) infrastructure/property and b) timber/non-timber forest products (Fig. 2). Forest and fire specialists also listed post-fire rehabilitation and its impacts on forest products as the one relationship where less research effort is needed. While the evidence map resulted in zero studies currently reporting on this relationship (Fig. 1), a lack of studies on any treatment-outcome relationship does not necessarily imply an evidence gap - it could be due to an absence of any theoretical connection, and thus lack of a need for empirical work on the given relationship (Cook et al., 2012). The gap values of post-fire

Table 4
Mean importance/strength and gap values of treatment-outcome linkages across all 38 respondents (sorted from largest positive to largest negative gap value).

Quadrants	Importance		Strength		Gap Value (I–S)
Quadrant 1: Less Effort Needed	Mean	SD	Mean	SD	GV
Prescribed burning x timber/non-timber forest products	2.33	1.24	2.5	0.96	−0.17
Rehabilitation x infrastructure/property loss	2.33	1.28	2.63	1.01	−0.3
Fire suppression x timber/non-timber forest products	2.29	1.01	2.63	0.83	−0.34
Rehabilitation x timber/non-timber forest products	1.79	0.92	2.61	0.92	−0.82
Quadrant 2: Continue Good Work	Mean	SD	Mean	SD	GV
Fire suppression x future suppression costs	3.68	0.57	3	1.08	0.68
Prescribed burning x water quality/quantity	3.74	0.56	3.07	0.84	0.67
Fire suppression x water quality/quantity	3.48	0.99	2.83	0.71	0.65
Thinning x future suppression costs	3.64	0.68	3	0.69	0.64
Fuel breaks x future suppression costs	3.5	0.78	2.87	0.81	0.63
Prescribed burning x public perceptions	3.29	0.94	2.66	0.72	0.63
Fuel breaks x water quality/quantity	3.17	1.04	2.57	0.93	0.6
Prescribed burning x future suppression costs	3.53	0.66	2.96	0.88	0.57
Rehabilitation x water quality/quantity	3.7	0.47	3.14	0.91	0.56
Rehabilitation x restoration costs	3.57	0.75	3.05	0.85	0.52
Defensible space x future suppression costs	3.42	0.81	2.9	0.97	0.52
Rehabilitation x public perceptions	3.14	0.94	2.63	0.9	0.51
Thinning x water quality/quantity	3.69	0.63	3.19	0.78	0.5
Salvage logging x restoration costs	3.08	0.86	2.58	0.79	0.5
Thinning x restoration costs	3.33	0.85	2.85	0.88	0.48
Fuel breaks x infrastructure/property loss	3.57	0.82	3.12	0.71	0.45
Thinning x public perceptions	3.24	0.94	2.79	0.83	0.45
Fuel breaks x restoration costs	2.93	0.98	2.52	0.9	0.41
Defensible space x infrastructure/property loss	3.85	0.53	3.45	0.8	0.4
Thinning x habitat/biodiversity	3.46	0.89	3.07	0.8	0.39
Salvage logging x timber/non-timber forest products	3.31	0.95	2.92	0.95	0.39
Fire suppression x public perceptions	3.23	0.92	2.89	0.88	0.34
Thinning x infrastructure/property loss	3.56	0.65	3.24	0.7	0.32
Rehabilitation x habitat/biodiversity	3.13	0.81	2.81	0.75	0.32
Mulching x restoration costs	2.82	1.17	2.5	1.07	0.32
Fire suppression x infrastructure/property loss	3.75	0.68	3.45	0.74	0.3
Fire suppression x restoration costs	3.26	0.96	3	0.77	0.26
Prescribed burning x restoration costs	3.06	0.9	2.8	0.91	0.26
Prescribed burning x infrastructure/property loss	3.47	0.79	3.26	0.73	0.21
Defensible space x public perceptions	3	1	2.79	.63	0.21
Prescribed burning x habitat/biodiversity	3.41	0.89	3.22	0.75	0.19
Salvage logging x water quality/quantity	2.64	1.01	2.5	0.71	0.14
Defensible space x restoration costs	2.81	1.08	2.71	0.85	0.1
Thinning x recreation/tourism	2.73	1.04	2.64	0.91	0.09
Salvage logging x habitat/biodiversity	2.71	1.2	2.75	0.89	−0.04
Thinning x timber/non-timber forest products	2.9	0.98	3	0.86	−0.1
Salvage logging x employment	2.5	0.97	2.63	0.92	−0.13
Quadrant 3: Low Priority	Mean	SD	Mean	SD	GV
Mulching x recreation/tourism	2.11	0.93	1.6	0.89	0.51
Mulching x public perceptions	2.4	1.07	2	0.63	0.4
Defensible space x employment	1.83	0.86	1.44	0.53	0.39
Mulching x employment	1.83	0.75	1.5	0.58	0.33
Prescribed burning x employment	2.19	1.11	1.88	0.72	0.31
Mulching x future suppression costs	2.22	1.3	2	0.82	0.22
Salvage logging x future suppression costs	2.46	1.12	2.27	0.79	0.19
Fire suppression x employment	2.32	1.16	2.18	0.4	0.14
Defensible space x habitat/biodiversity	1.91	0.97	1.78	1	0.13
Fuel breaks x employment	2	0.95	1.91	0.3	0.09
Salvage logging x recreation/tourism	2.15	1.07	2.17	0.98	−0.02
Fuel breaks x recreation/tourism	2.15	1.1	2.21	0.97	−0.06
Mulching x infrastructure/property loss	2.1	1.2	2.25	1.04	−0.15
Defensible space x timber/non-timber forest products	1.47	0.84	1.67	0.91	−0.2
Rehabilitation x employment	2.06	1.09	2.27	0.9	−0.21
Defensible space x recreation/tourism	1.7	0.82	1.93	0.83	−0.23
Mulching x timber/non-timber forest products	1.75	0.71	2.17	0.98	−0.42
Salvage logging x infrastructure/property loss	1.85	1.14	2.38	1.06	−0.53
Fuel breaks x timber/non-timber forest products	1.8	0.82	2.35	0.75	−0.55
Quadrant 4: Future Prioritization	Mean	SD	Mean	SD	GV
Mulching x water quality/quantity	3.45	0.82	2.44	1.13	1.01
Fuel breaks x public perceptions	3	0.96	2.4	0.68	0.6
Rehabilitation x recreation/tourism	2.86	1.11	2.41	1.06	0.45
Defensible space x water quality/quantity	2.54	1.22	2.12	0.99	0.42
Mulching x habitat/biodiversity	2.64	1.12	2.25	0.46	0.39
Salvage logging x public perceptions	2.77	1.3	2.42	0.79	0.35
Fire suppression x habitat/biodiversity	2.78	1.17	2.47	0.87	0.31

(*continued on next page*)

Table 4 (*continued*)

Quadrants	Importance		Strength		Gap Value (I–S)
Prescribed burning x recreation/tourism	2.73	1.18	2.42	1.06	0.31
Thinning x employment	2.72	1.03	2.44	0.7	0.28
Fuel breaks x habitat/biodiversity	2.66	1.08	2.38	0.77	0.28
Fire suppression x recreation/tourism	2.74	1.1	2.47	0.92	0.27
Rehabilitation x future suppression costs	2.55	1.05	2.42	1.02	0.13

*Positive gap values imply perceptions of treatment-outcome evidence linkage being understudied while negative values signify perceptions of linkage being over studied. The value of the gap (−4 to +4) indicates the magnitude of the perception. Values closer to 0 are weaker perceptions, while those closer to the extremes are stronger. A smaller standard deviation signifies convergence of greater agreement among the survey participants, while a larger standard deviation implies greater divergence or disagreement.

rehabilitation and its impacts on forests were −0.82 for the average respondent and −0.67 for the specialists (out of a −4 to +4 range), implying that they do not hold very strong perceptions on the need for additional evidence.

Likewise, the average respondent reported gap values close to zero for the impacts of 1) fire suppression on forest products (GV = −0.34), 2) post-wildfire rehabilitation on infrastructure and property (GV = −0.3), and 3) prescribed burns on forest products (GV = −0.17). These small negative gap values imply weak perceptions that these relationships are being over studied. The impact of prescribed burns on forest products was the only relationship perceived to be over studied that was reported on by more than two studies in the evidence map (n = 6). Again, little to no evidence regarding the other relationships may be due to appropriate reasons, i.e. there is no practical reason for a linkage between certain mitigation treatments and societal outcomes to exist. However, the fact that decision-makers *believe* these linkages are over studied suggests there might be a knowledge gap between their perceptions and the evidence that exists within the current literature.

4.4. Science and management implications

The results of the evidence map and stakeholder survey allow for several practical recommendations to be made for wildfire managers, researchers, and the watershed partnerships starting to invest in wildfire risk mitigation across the US and elsewhere. First, there was general consensus that the most commonly identified treatment-outcome linkages in the evidence map were highly important, and researchers in the field should continue producing evidence on these relationships. Only a few of the treatment-outcome relationships were found in more than five case studies (Fig. 1), signifying a lack of many gluts.

Second, there was a significant number of wildfire treatment-outcome relationships that were perceived to be understudied: 12 by the average survey participant and 19 by the forest and fire specialists (Table 5). Nearly all (83%) of the linkages the average participant believed to be understudied were found only once or not at all in the evidence map (Fig. 1). Interestingly, only two of these linkages were around water (Fig. 2), reflecting the fact that watershed partnerships have a diverse interest in societal outcomes from their investments. Similarly, 90% of linkages that forest and fire specialists perceived as being understudied were reported on once or not at all. The largest gap reported by all groups was on the impacts of mulching on water quality and quantity. Past studies have found the addition of mulch to be an erosion control best management practice for decreasing runoff flow rates and avoiding the influx of sediment into a watershed (Bakr et al., 2012, 2015; Faucette and Risse, 2002). Mulching could be a beneficial treatment for slopes with hydrophobic soils post-wildfire (Groen and Woods, 2008). The large gap value of this linkage implies the importance of this relationship for researchers to prioritize.

Third, organizations on average believed that only four relationships are being over studied (Fig. 2), one being the impacts of post-fire rehabilitation on forest products. Forest and fire specialists also perceived post-fire rehabilitation and forest products as being over studied, although the evidence map found zero studies reporting on this relationship. Similarly, only one study reported on the impact of fire suppression on forest products and two studies described impacts of post-fire rehabilitation on property and infrastructure. Small negative gap values resulting from these perceptions imply that forest/fire specialists and other survey participants did not hold strong beliefs about these relationships being over studied. The one linkage perceived to be over studied that was reported on by more than two case studies (n = 6) was the impact of controlled burns on forest products (Fig. 1). These results imply a gap exists between stakeholder perceptions that the relationships are being over studied and the actual lack of evidence regarding these linkages. It is recommended that scientists address this gap by increasing the dissemination of evidence to better align stakeholder perceptions with the current evidence base.

Finally, the views of forest and wildfire specialists differ substantially from other organizational sectors involved in watershed partnerships, especially regarding areas that need more research. This deviation could simply be due to the nature of being a specialist; these organizations are commonly the generators of science or implementors of fuel mitigation treatments, and as such may be more aware than other groups of the knowledge gaps that exist within the current literature and the limits of when science is or is not applicable. However, a reoccurring issue in natural resource management is a lack of consistency regarding the use of scientific data to inform policy prescriptions (Pullin and Knight, 2003). Integrating scientific evidence into wildfire mitigation treatment programs could result in better societal outcomes broadly, and could help ensure that investments by watershed partnerships result in their expected outcomes. The utility of evidence by watershed partnerships could be enhanced through co-production of new evidence and increasing efforts to disseminate existing evidence to these groups (Roux et al., 2006; Ntshotsho et al., 2015).

Table 5
The number of treatment-outcome linkages in each quadrant broken down by organizational sector.

	Quadrant			
Organizational Sector	'Less Effort Needed'	'Continue Good Work'	'Low Priority'	'Future Prioritization'
Utilities/local government (n = 11)	7	38	24	3
NGO (n = 9)	0	41	11	7
Forest/fire specialists (n = 12)	1	28	24	19
Private (n = 6)	7	49	2	2
AVERAGE (n = 38)	4	37	19	12

5. Conclusion

This study catalogued the evidence that exists regarding the impact of wildfire mitigation treatments on societal outcomes, and the perspectives of representatives of watershed partnerships regarding the importance and strength of these relationships. The results from the evidence map reveal that research on wildfire mitigation treatment effects target a small number of societal outcomes compared to the broad range of potential outcomes. This does not necessarily imply gaps in the evidence base for all linkages, as some treatment-outcome relationships should not be studied due to a lack of theoretical connections. However, according to stakeholders, there are several relationships not adequately covered in the current wildfire mitigation literature that deserve future research attention, e.g., the impact of mulching on water quality/quantity outcomes. Overall, this study illustrates that watershed partnerships have a broad interest in societal outcomes from wildfire mitigation treatments. Continuing to assess treatment-outcome relationships and disseminating that information to new actors involved in wildfire mitigation can aid in strengthening knowledge and lead to improvements in evidence-based wildfire mitigation investment programs moving forward.

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Appendix 1. Importance and strength of scientific evidence survey

This survey focuses on the strength and importance of scientific evidence regarding various societal outcomes of wildfire mitigation.

Part 1: *Importance* of Evidence

STEP 1: Using the list of wildfire treatments on the left-hand side of the table below, please check "Yes" under the Step 1 column for any treatments that you believe are important to the watershed partnership.

STEP 2: For each of the intervention types that you checked with a "Yes" in Step 1, please rate how important you feel having scientific information is (for the purpose of wildfire risk mitigation) linking that intervention to the outcomes listed across the top row. For example, if you checked "Yes" for "Defensible space", fill in a number between 0 and 4 (explained below) for every column to the right of "Defensible space". If you did not check "Yes" on "Defensible space", leave that intervention row blank.

Rate between 0 and 4 using the following definitions. Evidence linking this intervention to this outcome is:

0	1	2	3	4
I don't know	Not important	Slightly important	Moderately important	Very important

	STEP 1:	STEP 2: OUTCOMES								
	YES	Infrastructure/property	Suppression costs	Management perceptions	Forest products	Restoration costs	Water quality/quantity	Employment	Habitat/biodiversity	Recreation/tourism
INTERVENTIONS										
Controlled/prescribed burning										
Defensible space										
Thinning										
Fire suppression										
Fuel breaks										
Mulching										
Rehabilitation										
Salvage logging										

Part 2: *Strength* of Evidence

We are also interested in understanding your perception on the strength of scientific information for wildfire risk mitigation. **For each of the intervention types that you checked with a "Yes" in Step 1 above**, please rate how strong you feel the CURRENT scientific information is linking that intervention to the outcomes listed across the top row. For example, if you checked "Yes" for "Defensible space" above, fill in a number between 0 and 4 (explained below) for every column to the right of "Defensible space". If you did not check "Yes" on "Defensible space", leave that intervention row blank.

Rate between 0 and 4 using the following definitions. Evidence linking this intervention to this outcome is:

0	1	2	3	4
I don't know	Doesn't exist	Is weak	Is moderate	Is strong

	STEP 2: OUTCOMES								
	Infrastructure/property	Suppression costs	Management perceptions	Forest products	Restoration costs	Water quality/quantity	Employment	Habitat/biodiversity	Recreation/tourism
INTERVENTIONS									
Controlled/prescribed burning									
Defensible space									
Thinning									

Fire suppression
Fuel breaks
Mulching
Rehabilitation
Salvage logging

Appendix 2. Final list of papers included in systematic map

Author(s)	Year	Title
Ager, A.A., Vaillant, N.M., Finney, M.A.	2010	A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure
Ager, A.A., Parks, N.	2011	Seeking Common Ground: Protecting Homes From Wildfires While Making Forests More Resilient to Fire
Amacher, G.S., Malik, A.S., Haight, R.G.	2005	Forest landowner decisions and the value of information under fire risk
Amacher, G.S., Malik, A.S., Haight, R.G.	2005	Not Getting Burned: The Importance of Fire Prevention in Forest Management
Aronson, G., Kulakowski, D.	2013	Bark beetle outbreaks, wildfires and defensible space: how much area do we need to treat to protect homes and communities?
Barbour R. J., Zhou, X., Prestemon, J.P.	2008	Timber product implications of a program of mechanical fuel treatments applied on public timberland in the Western United States
Bennetton, J., Cashin, P., Jones, D., Soligo, J.	1998	An economic evaluation of bushfire prevention and suppression
Benoit, J.W., González-Cabán, A., Fujioka, F.M., Chen, S., Sanchez, J.J.	2013	Spatial allocation of market and nonmarket values in wildland fire management: A case study
Biesecker, R.L., Fight, R.D.	2006	My fuel treatment planner: a user guide
Bostwick, P., Menakis, J., Sexton, T.	2012	How Fuel Treatments Saved Homes from the 2011 Wallow Fire
Bradstock, R.A., Cary, G.J., Davies, I., Lindenmayer, D.B., Price, O.F., Williams, R. J.	2012	Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation
Busby, G., Albers, H.J.	2010	Wildfire Risk Management on a Landscape with Public and Private Ownership: Who Pays for Protection?
Bushy, G., Amacher, G., Haight, R.	2013	The social costs of homeowner decisions in fire-prone communities: information, insurance, and amenities
Calkin, D., Jones, G., Hyde, K.	2008	Nonmarket Resource Valuation in the Postfire Environment
Cohan D., Haas S., Roussopoulos P.J.	1983	Decision analysis of silvicultural prescriptions and fuel management practices on an intensively managed commercial forest
Cooper, J., Nechodom, M., Perrot, L.	N/A	Life Cycle Assessment of Energy Use and Air Emissions from Producing Electricity from California Forest Wildfire Fuels Treatments InLCA VIII
Daugherty, P.J., Fried, J.S.	2007	Jointly optimizing selection of fuel treatments and siting of forest biomass-based energy production facilities for landscape-scale fire hazard reduction
Elia, M., Lafortezza, R., Colangelo, G., Sanesi, G.	2014	A streamlined approach for the spatial allocation of fuel removals in wildland-urban interfaces
Eller, L.	2015	Fighting Fires With Funding
Fried, J., Christensen, G., Weyermann, D., Barbour, R. J., Fight, R., Hiserote, B., et al.	2005	Modeling opportunities and feasibility of siting wood-fired electrical generating facilities to facilitate landscape-scale fuel treatment with FIA BioSum
Fried, J.S., Winter, G.J., Gilless, K.J.	1999	Assessing the Benefits of Reducing Fire Risk in the Wildland-Urban Interface: A Contingent Valuation Approach
Gan, J., Jarrett, A., Johnson Gaither, C.	2013	Forest Fuel Reduction and Biomass Supply: Perspectives from Southern Private Landowners
Graham, R.	2003	Hayman Fire Case Study: Summary
Hjerpe, E., Kim, Y.	2008	Economic Impacts of Southwestern National Forest Fuels Reductions
Houtman, R.M., Montgomery, C.A., Gagnon, A.R., Calkin, D.E., Dietterich, T.G., McGregor, S., et al.	2013	Allowing a wildfire to burn: estimating the effect on future fire suppression costs
Huang, C., Finkral, A., Sorensen, C., Kolb, T.	2013	Toward full economic valuation of forest fuels-reduction treatments
Huggett, R.J., Abt, K.L., Shepperd, W.	2008	Efficacy of mechanical fuel treatments for reducing wildfire hazard
Hunter, M.E., Shepperd, W.D., Lentile, J.E., Lundquist, J.E., Andreu, M.G., Butler, J.L., et al.	2007	A comprehensive guide to fuels treatment practices for ponderosa pine in the Black Hills, Colorado Front Range, and Southwest
Ince, P.J., Spelter, H., Skog, K., Kramp, A., Dykstra, D.P.	2008	Market impacts of hypothetical fuel treatment thinning programs on federal lands in the western United States
Jakes, P.	2011	Chapter 6: A socioeconomic assessment of Forest Service Recovery Act Projects: Huron Fuels Treatment Project, Michigan
Jakes, P.	2007	Social science informing forest management-bringing new knowledge to fuels managers
Jones, G., Loeffler, D., Butler, E., Hummel, S., Chung, W.	2013	The financial feasibility of delivering forest treatment residues to bioenergy facilities over a range of diesel fuel and delivered biomass prices
Jones, J.G., Chew, J.D., Zuuring, H.R.	1999	Applying simulation and optimisation to plan fuel treatments at landscape scales
Kalies, E.L., Yocom Kent, L.L.	2016	Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review
Keegan, C.E., Fiedler, C.E., Morgan, T.A.	2004	Wildfire in Montana: Potential hazard reduction and economic effects of a strategic treatment program
Kennedy, M.C., Johnson, M.C.	2014	Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland-urban interface during the Wallow Fire, Arizona, USA
Kim, Y.	2012	The Efficacy of Hazardous Fuel Treatments: A Rapid Assessment of the Economic and Ecological Consequences of Alternative Hazardous Fuel Treatments
Kline, J.D.	2004	Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the Nation's forests
Knotek, K.	2006	Trends in public attitudes towards the use of wildland fire
Kwon, J., Vogt, C., Winter, G., McCaffrey, S.	2008	Forest fuels treatments for wildlife management: do local recreation users agree?
Lasaux, M.J., Spinelli, R., Hartsough, B.R., Magagnotti, N.	2009	Using a small-log mobile sawmill system to contain fuel reduction treatment cost on small parcels
Leverkus, A., Puerta-Piñero, C., Guzmán-Álvarez, J.R., Navarro, J., Castro, J.	2012	Post-fire salvage logging increases restoration costs in a Mediterranean mountain ecosystem
Loomis, J., Gonzalez-Caban, A.	2008	Contingent valuation of fuel hazard reduction treatments
Loomis, J., Le Trong, H., González-Cabán, A.	2009	Willingness-to-pay function for two fuel treatments to reduce wildfire acreage burned: A scope test and comparison of white and hispanic households
Loomis, J., Wohlgemuth, P., González-Cabán, A., English, D.	2003	Economic benefits of reducing fire-related sediment in southwestern fire-prone ecosystems
Los Alamos Area Office	2000	Environmental Assessment for the Wildfire Hazard Reduction and Forest Health Improvement Program at Los Alamos National Laboratory, Los Alamos, New Mexico
Lowell, E.C., Becker, D.R., Rummer, R., Larson, D., Wadleigh, L.	2008	An Integrated Approach to Evaluating the Economic Costs of Wildfire Hazard Reduction through Wood Utilization Opportunities in the Southwestern United States
Martin, A., Botequim, B., Oliveira, T.M., Ager, A., Pirotti, F.	2016	Temporal optimisation of fuel treatment design in blue gum (Eucalyptus globulus) plantations

Mason, C.L., Lippke, B.R., Zobrist, K.W., Bloxton, T.D., Ceder, K.R., Comnick, J.M., et al.	2006	Investments in Fuel Removals to Avoid Forest Fires Result in Substantial Benefits
Thompson, M.P., Anderson, N.M.	2015	Modeling fuel treatment impacts on fire suppression cost savings: A review
McCaffrey, S.M.	2006	The public and wildland fire management: social science findings for managers
McCool, S.F., Burchfield, J.A., Williams, D.R., Carroll, M.S.	2006	An event-based approach for examining the effects of wildland fire decisions on communities
Mell, W.E., Manzello, S.L., Maranghides, A., Butry, D., Rehm, R.G.	2010	The wildland–urban interface fire problem – current approaches and research needs
Mercer, D.E., Prestemon, J.P.	2012	Economic analysis of fuel treatments
Milne, M., Clayton, H., Dovers, S., Cary, G.J.	2014	Evaluating benefits and costs of wildland fires: critical review and future applications
Moghaddas, J.J., Craggs, L.	2007	A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest
Monroe, M.C., Nelson, K.C., Payton, M.	2006	Communicating with homeowners in the interface about defensible space
Murphy, K., Rich, T., Sexton, T.	2007	An Assessment of Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition on the Angora Fire
Nechodom, M.	2009	Biomass to energy: Forest management for wildfire reduction, energy production, and other benefits
North, M.P., Collins, B.M., Stephens, S.L.	2012	Using fire to increase the scale, benefits and future maintenance of fuels treatments
Nowicki, B.	2002	The Community Protection Zone: Defending Homes and Communities for the Threat of Forest Fires
O'Callaghan, J., Fischer, A. P., Charnley, S.	2013	Managing wildfire risk in fire-prone landscapes: how are private landowners contributing?
Omi, P.N., Joyce, L.A.	2003	Fire, fuel treatments, and ecological restoration, Fort Collins, Colorado, USA, 16–18 April 2002
Omi, P.N., Rideout, D.B., Botti, S.J.	1999	An analytical approach for assessing cost-effectiveness of landscape prescribed fires
Penman, T.D., Bradstock, R.A., Price, O.F.	2014	Reducing wildfire risk to urban developments: Simulation of cost-effective fuel treatment solutions in south eastern Australia
Penman, T.D., Collins, L., Syphard, A.D., Keeley, J.E., Bradstock, R.A.	2014	Influence of Fuels, Weather and the Built Environment on the Exposure of Property to Wildfire
Penman, T.D., Nicholson, A.E., Bradstock, R.A., Collins, L., Penman, S.H., Price, O.F.	2015	Reducing the risk of house loss due to wildfires
Podolak, K., Edelson, D.	2015	Estimating the Water Supply Benefits from Forest Restoration in the Northern Sierra Nevada. An unpublished report of The Nature Conservancy prepared with Ecosystem Economics
Price, O.F., Bradstock, R.A.	2012	The efficacy of fuel treatment in mitigating property loss during wildfires: Insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia
Rapp, V.	2004	Reducing fire hazard: balancing costs and outcomes
Reinhardt, E.D., Keane, R.E., Calkin, D.E., Cohen, J.D.	2008	Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States
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Appendix 3. Linkages perceived to be 'Future Prioritization' by forest and fire specialists (sorted from largest to smallest gap value)

Treatment-Outcome Linkages	Importance		Strength		Gap Value (I–S)
	Mean	SD	Mean	SD	GV
Defensible space x future suppression costs	3.56	0.73	2	0.63	1.56
Fuel breaks x public perceptions	3.5	0.67	2.1	0.74	1.4
Mulching x public perceptions	3.25	0.96	2	1	1.25
Mulching x water quality/quantity	3.25	0.96	2	1.15	1.25
Salvage logging x public perceptions	3.4	0.89	2.2	0.84	1.2
Rehabilitation x recreation/tourism	2.57	1.27	1.5	0.55	1.07
Mulching x restoration costs	3	1.15	2	1.15	1
Salvage logging x recreation/tourism	2.5	1.29	1.5	0.71	1
Fuel breaks x future suppression costs	3.42	0.9	2.44	0.73	0.97
Fuel breaks x water quality/quantity	2.91	1.22	2	0.5	0.91
Salvage logging x future suppression costs	2.6	0.89	1.75	0.5	0.85
Salvage logging x restoration costs	3	1	2.2	0.84	0.8
Salvage logging x water quality/quantity	3	0.71	2.25	0.5	0.75
Fuel breaks x restoration costs	2.91	0.94	2.18	0.87	0.73
Prescribed burning x recreation/tourism	2.64	1.12	2.13	0.99	0.51
Fuel breaks x habitat/biodiversity	2.75	1.06	2.27	0.65	0.48
Thinning x employment	2.78	0.97	2.33	0.52	0.45
Prescribed burning x restoration costs	2.75	0.87	2.45	1.04	0.3
Fire suppression x recreation/tourism	2.67	1.07	2.38	0.74	0.29

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