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Review and synthesis

Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison

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ABSTRACT

Prescribed fire can result in significant benefits to ecosystems and society. Examples include improved wildlife habitat, enhanced biodiversity, reduced threat of destructive wildfire, and enhanced ecosystem resilience. Prescribed fire can also come with costs, such as reduced air quality and impacts to fire sensitive species. To plan for appropriate use of prescribed fire, managers need information on the tradeoffs between prescribed fire and wildfire regimes. In this study, we argue that information on tradeoffs should be presented at spatial and temporal scales commensurate with the scales at which these processes occur and that simulation modeling exercises should include some realistic measure of wildfire probability. To that end, we synthesized available scientific literature on relationships between prescribed fire and wildfire regimes, and their associated ecological and societal effects, focusing specifically on simulation modeling studies that consider wildfire probability and empirical and modeling studies that consider prescribed fire and wildfire regimes at spatial and temporal scales beyond individual events. Both empirical and modeling studies overwhelmingly show that increasing use of prescribed fire can result in wildfire regimes of lower extent and intensity. In some studies, a consequence associated with increased use of prescribed fire is an increase in the total, cumulative amount of fire on a landscape over time. Presumably this has implications for emissions and ecosystem carbon, however, effects on ecosystem carbon dynamics are much less clear as results vary considerably across studies. Results likely vary because studies use various landscape models with different parameter settings for processes (e.g., vegetation succession) and use different methodologies, time frames, and fire management and climate change scenarios. Future syntheses and meta-analyses would benefit from researchers providing more comprehensive and transparent documentation of model parameters, assumptions, and limitations. The literature review also revealed that studies on the implications of prescribed fire and wildfire regimes with regard to values other than carbon and emissions are scant and this represents a critical research need. Empirical studies are needed to calibrate and provide magnitude of order comparisons with simulation models and address tradeoffs with respect to other values (e.g., wildland urban interface, wildlife habitat). Such studies should be conducted with consideration for our framework, which includes the implications of prescribed fire and wildfire across broad spatial and temporal scales.

1. Introduction

Land managers utilize prescribed fire globally for a variety of purposes (Ryan et al., 2013). Many benefits to ecosystems and society from prescribed fire have been documented, including improved wildlife habitat (Fontaine and Kennedy, 2012), rangeland production (Hunt et al., 2014), and reduced hazardous fuels that may otherwise promote high intensity wildfire which can threaten communities (Fernandes and Botelho, 2003). Prescribed fire however, also comes with costs to ecosystems and society. Examples include impacts to fire-sensitive species (Pilliod et al., 2003) and reductions in air quality from smoke production which can impact human health (Hu et al., 2008). Wildfires are associated with the same costs (and benefits) and often with greater magnitude, as the effects of fire are amplified with increasing size and intensity. Prescribed fire is implemented with the assumption that it will mitigate the effects of wildfire to ecosystems and society because it has been shown to reduce the intensity of subsequent wildfire (Fernandes and Botelho, 2003). The actual tradeoffs between

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prescribed fire and wildfire, however, have rarely been examined at appropriate spatial and temporal scales.

There have been several evaluations of wildfire and prescribed fire tradeoffs in the scientific literature, but most have been conducted at relatively narrow spatial and temporal scales. Many studies for example, compare fire behavior and fire effects for individual wildfire and prescribed fire events. Other studies focus on examinations of the behavior and effects (e.g., on carbon, wildlife habitat, vegetation, air quality) of wildfires burning through areas previously treated with prescribed fire. These studies generally show that that under specified conditions, prescribed fire can mitigate the intensity and effects of subsequent wildfire within the footprint of the area treated with prescribed fire (Kailes and Yocom Kent, 2016). Such studies also demonstrate that prescribed fire can result in benefits to ecosystems and society and associated costs can be minimal, especially when compared to wildfire (McIver et al., 2012). These types of studies, however, are inadequate for fully evaluating tradeoffs between prescribed fire and wildfire regimes because they do not evaluate the temporal or spatial scales at which prescribed fire is needed to effectively impact wildfire probability, behavior, extent, or effects to valued resources.

Many have argued for a more robust framework for comparing prescribed fire and wildfire regimes that incorporates broader spatial and temporal scales (Abt et al., 2008; Pennman et al., 2011; Williamson et al., 2016). A simplified illustration of a possible framework for evaluating prescribed fire and wildfire at different scales, given in Fig. 1, includes the cumulative effects of multiple prescribed fires and wildfires in a landscape over time. Ultimately, managers need a greater understanding of the relationship between prescribed fire and wildfire regimes over broad temporal and spatial scales in order to determine how much, how often, and where prescribed fire should be applied on a landscape to maximize the benefits and minimize the social and ecological costs associated with both prescribed fire and wildfire. While there are several factors that could be considered in the evaluation of the relationship between wildfire and prescribed fire regimes, we propose that there are two of particular importance: (1) scale (temporal and spatial) and (2) wildfire probability.

1.1. Scale

Wildfire and prescribed fires and their effects operate at different spatial and temporal scales. A small percentage of wildfires result in significant, costly, and long-lasting impacts to ecosystems and society (Attiwill and Binkley, 2013; Strauss et al., 1989). Such wildfires tend to cover large spatial scales and are relatively infrequent. Individual prescribed fires tend to cover smaller spatial scales and result in less severe effects (and ample benefits) to ecosystems and society that are relatively short-lived. Relative to the most costly wildfires, prescribed fires also tend to occur with much greater frequency. Cumulative area burned in prescribed fire over time could equal or surpass the area burned in wildfire, and often does in some regions (Melvin, 2015). Many have argued that the frequency of prescribed fire should increase drastically to reduce the probability of the most costly and destructive wildfires (Ingalsbee and Raja, 2015). To evaluate the appropriate amount of prescribed fire, relationships between wildfire and prescribed fire regimes need to be evaluated over areas and time frames commensurate with the scales at which these events occur. Fig. 1 shows a framework for comparisons of prescribed fire and wildfire regimes that incorporates spatial and temporal scales that are much larger and longer than individual prescribed fire or wildfire events. To that end, it includes multiple prescribed fires across a landscape, their maintenance treatments, and the degree to which they interact with wildfires over multiple years. Fig. 1 also shows example scales, but the appropriate spatial and temporal scale will vary by region and ecosystem depending on the scale of management and the fire regime.

1.2. Wildfire probability

As vegetation grows and fuels accumulate, prescribed fires become less effective in mitigating wildfire intensity and effects over time. There is also great uncertainty as to when and where the wildfires that are likely to cause the most economic hardships will occur. For these reasons, one cannot always assume that prescribed fire will be effective in mitigating the effects of wildfire because there is uncertainty as to whether a wildfire will encounter an area managed with prescribed fire within the lifespan of its effectiveness. Indeed, some have found that

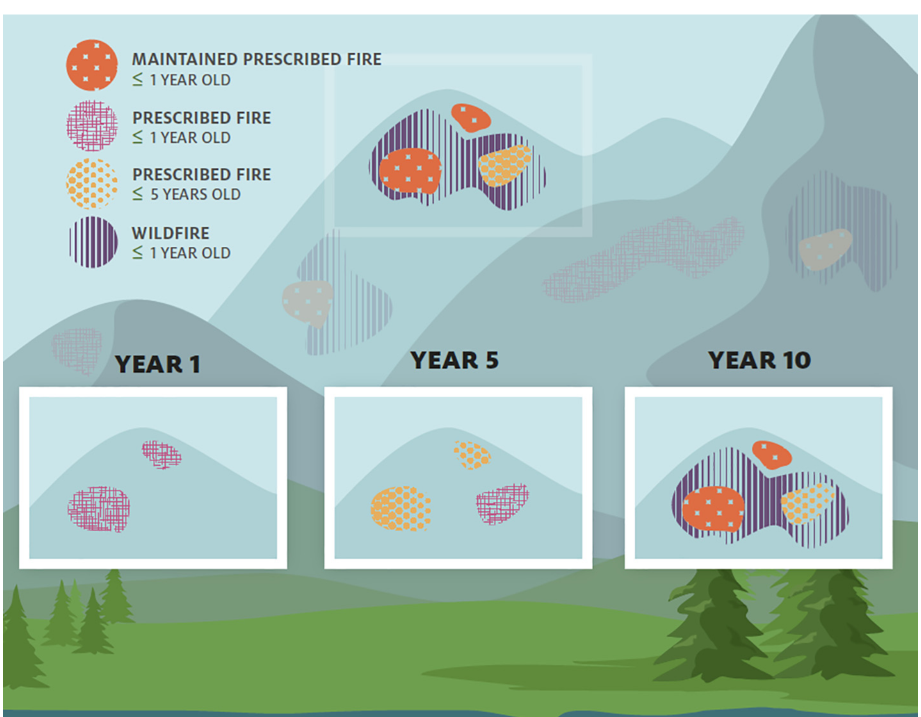

Fig. 1. Illustration of a conceptual framework examining the relationships between prescribed fire and wildfire regimes. Any evaluation of prescribed fire and wildfire regimes should be conducted at spatial and temporal scales that adequately characterize the regimes by including multiple prescribed fires over a landscape, their maintenance treatments, and the degree to which they interact with wildfires over multiple years. Evaluations should include common metrics that describe fire regimes (e.g., fire frequency, fire area, fire behavior) and fire effects (e.g., fire severity, air quality) summarized over relevant scales.

the encounter rate between wildfire and prescribed fire is relatively rare (Barnett et al., 2016; Rhodes and Baker, 2008), although many areas (e.g., Southeast, wildland urban interface) have been excluded from such analyses and investigators tend to find increasing encounter rates as the scale of prescribed fire increases. For this reason, it is important that any evaluation of tradeoffs between wildfire and prescribed fire regimes, especially those studies using simulation modeling, consider the probability of wildfire occurrence and spread in space and time.

There are significant challenges associated with examining tradeoffs between prescribed fire and wildfire regimes at larger spatial and temporal scales. Notably, accurate data on fuels, wildfire, and prescribed fire are often not available at such scales, making empirical studies difficult if not impossible. This necessitates the reliance on simulation modeling to examine interactions between prescribed fire and wildfire regimes. The use of simulation modeling is where the incorporation of wildfire probability is of particular importance, because it is an important variable that can determine outcomes in most modelling exercises.

The purpose of this literature review is to synthesize information from studies that address tradeoffs between wildfire and prescribed fire regimes utilizing our framework (Fig. 1), whereby studies considers the cumulative effects of multiple prescribed fires and wildfires over space and time. This review includes empirical and simulation modeling studies that describe any metric of prescribed fire regimes (e.g., probability, frequency, extent) and the implications for similar metrics of wildfire regimes over spatial and temporal scales beyond individual prescribed fire or wildfire events. The review also includes any studies that extend such analyses to examine the implications of altered wildfire regimes for wildfire effects on ecosystem services (e.g., air quality, carbon storage, infrastructure exposure).

For the purposes of this review, we define prescribed fire as the intentional use of wildland fire to meet resource management objectives. This can take the form of manager ignited fires used to reduce fuel hazard, enhance wildlife habitat, or improve rangeland condition. In many forested systems, prescribed fire is commonly preceded by mechanical treatments to reduce fuels to levels that allow for the safe and effective application of prescribed fire as a maintenance treatment (McIver et al., 2012). We also define prescribed fire as the use of lightning-ignited fire to meet resource objectives under appropriate conditions. Such practices have been shown to be effective in reducing fuels and changing forest structure over large areas (Huffman et al., 2017; Hunter et al., 2011) and influencing behavior and spread patterns of subsequent wildfires (Parks et al., 2014, 2015). We acknowledge that these definitions differ from those used by U.S. federal land management agencies, which define prescribed fire as a planned fire intentionally ignited to meet management objectives and wildfire as unplanned fire caused by lightning or humans (Fire Executive Council, 2009). However, we felt it important that our analysis include both prescribed fire and wildfire used to meet resource management objectives because both tools are used to increase the scale of beneficial fire effects on a landscape (Ingalsbee and Raja, 2015; North et al., 2012).

2. Methods

In order to focus on studies that examine prescribed fire and wildfire regimes, this literature review excluded studies that compared effects from individual prescribed fire and wildfire events, or that examine the implications of an individual wildfire burning through a previously treated area. Such studies were not included because other syntheses have been devoted to this topic (Kailes and Yocom Kent, 2016; Omi and Martinson, 2010) and they do not address the relative impacts of prescribed fire and wildfire regimes over long time frames and broad spatial scales. Studies were included that examined prescribed fire regimes alone or in conjunction with other fuel treatments (e.g., thinning). To account for the potential beneficial use of wildfire, for the purpose of this literature review, the term prescribed fire includes management-ignited fire as well as wildfire burning under conditions such that it results in benefits to ecosystems or society. It should be noted, however, that we only considered these types of wildfires as prescribed fires when study authors distinguished wildfires that burned under favorable conditions and were used to meet management objectives. Otherwise, we classified non-management-ignited fires as wildfires.

In compiling a set of relevant studies, we followed the guidance of Jahangirian et al. (2011) for searching large bodies of literature for applicable papers, which encompasses screening results from database searches and 'chasing' articles for references and citations forward and backward in time. We relied on our own expertise and knowledge of key papers to include in the study to identify appropriate key words in Google Scholar. After several pilot searches, we found that the key words "prescribed fire and wildfire tradeoff" yielded the most relevant studies and resulted in 3350 references. Utilizing the sampling screening method described in Jahangirian et al. (2011), we examined the first 1000 references. For each relevant study, we 'chased' articles forward and backward in time by examining their references cited and using the 'cite by' feature in Google Scholar (Jahangirian et al., 2011). This resulted in 71 relevant studies published before 2020, which we incorporated into the literature review. This included studies that addressed prescribed fire and wildfire regimes and their effects empirically or with simulation modelling.

The studies included in the literature review often evaluated prescribed fire and wildfire regimes by examining the effects of increasing prescribed fire extent or frequency on subsequent wildfire occurrence, extent, behavior, or effects (compared to prescribed fire effects). Since many studies utilized different metrics for wildfire regimes and associated effects, for ease of study comparison, we grouped different metrics related to wildfire regimes into the following categories: wildfire frequency, wildfire behavior, wildfire area burned, and total area burned. Wildfire frequency metrics describe the frequency of wildfire ignitions or probability of wildfire occurrence irrespective of their size or behavior. This included, for example, the number of ignitions that reach a certain size threshold (e.g., 200 ha) and burn probability, a metric commonly used in wildfire risk assessments that describes the probability of fire reaching a certain area (Miller and Ager, 2013). Wildfire behavior/severity metrics describe some aspect of fire behavior (e.g., fire intensity, flame length, rate of spread) or the immediate fire severity, often as measured as consumption of dominant vegetation (Keeley, 2009). Wildfire area burned metrics describe wildfires in terms of their size or extent of spread on a landscape, regardless of fire behavior. This includes "leverage," which is defined as the slope of the relationship between wildfire area and past prescribed fire area and is a measure of the level of impact past fire has on subsequent wildfire extent (Price and Bradstock, 2011). Total fire area metrics described the size or extent of both prescribed fire and wildfire either annually or cumulatively over a period of time. The different metrics used in studies included in this review to describe wildfire regimes are listed in Table 1 along with their assigned category.

It is important to distinguish wildfire area burned versus total fire area burned (prescribed fire plus wildfire) over time because one cannot always assume that an increase in prescribed fire acreage will result in the same decrease acreage in wildfire (i.e. 100 acres in prescribed fire results in 100 fewer acres in wildfire for a given period). Some have suggested that, in certain ecosystems, disproportionately large amounts of prescribed fire are needed to impact wildfire extent (i.e. 300 acres in prescribed fire results in 100 fewer acres in wildfire) (Price and Bradstock, 2011). Others have suggested that prescribed fire implemented on a small portion of a landscape (e.g., 1–2% annually) can have significant impacts on wildfire extent (Finney et al., 2007). The level of impact prescribed fire has on wildfire area burned, which some have termed "leverage" (Loehle, 2004; Price and Bradstock, 2011), should have a significant impact on total fire area over time, which might also have implications for the cumulative costs and

Table 1
Categories of wildfire behavior metrics used in the literature review. The ‘category’ column gives the name of the category for which we assigned metrics. The ‘description’ column describes our interpretation of the category of metrics. The ‘metric included’ column lists the actual metrics used in the literature compiled for this study that we assigned to specific categories.

Category	Description	Metrics included
Wildfire frequency	Describes how often wildfire occurs in a given area regardless of wildfire size or behavior	Wildfire incidence/number Wildfire occurrence rate Proportion of burn blocks with wildfire Burn probability Conditional burn probability Probability of wildfire Fire potential Wildfire rotation interval Mean inter-fire interval Wildfire return interval
Wildfire extent	Describes wildfire in terms of size or extent of spread across a landscape, regardless of fire intensity.	Wildfire extent/area Probability of large wildfire Fire size distribution Percent landscape burned Wildfire area relative to forest area Average wildfire size Reduction in area burned Leverage
Total area burned	Describes the size or extent of area burned in both prescribed fire and wildfire either annually or cumulatively over period.	Total burned area (prescribed and wildfire)
Wildfire behavior/severity	Describes some aspect of wildfire behavior in terms of intensity or rate of spread.	Wildfire intensity-weighted acres Area burned by fire severity class Probability of high severity burn Proportion of burn blocks with intense wildfire Area burned by flame length class Potential flame length Potential rate of spread Percent of landscape in stand-replacement fire Conditional flame length Area in stand-replacement fire Fire severity patch size Fire intensity Fire travel time Mean wildfire severity

benefits associated with both prescribed fire and wildfire to ecosystems and society (e.g., emissions, wildlife habitat).

The studies included in this literature review also used different metrics to describe wildfire and prescribed fire effects on ecosystem services and social values. For ease of analysis, we grouped metrics for the fire effects into the following categories: ecosystem carbon pools, ecosystem carbon fluxes, wildfire emissions, total emissions, watershed, wildland urban interface, suppression, economics, wildlife, and resilience. We distinguished wildfire emissions from carbon fluxes because wildfire emissions have particular implications for air quality and human health. While many metrics can be indicators of ecosystem resilience, or the ability of a system to recover from disturbance without fundamental change to ecosystem processes or structure, we only considered potential metrics of ecosystem resilience when investigators explicitly address ecosystem resilience as a research question or hypotheses. The different metrics used in studies included in this review to describe relationships between altered wildfire regimes and wildfire effects are listed in Table 2 along with their assigned category.

Within each category for wildfire regimes and wildfire effects described in Tables 1 and 2, we summarized the number of studies that addressed each category and their primary finding. Three categories were used to define primary study findings: treatment effect – decrease, no treatment effect, and treatment effect – increase. Studies labeled treatment effect – decrease reported a decrease in wildfire regime or effect metric as a result of implementing a prescribed fire regime. An example would include a study that reported incidence of prescribed fire leading to a decrease in area burned by wildfire and a subsequent decrease in sensitive wildlife habitat impacted by wildfire. Studies labeled no treatment effect reported no impact of prescribed fire regime on metrics for wildfire regimes or effects. Studies labeled treatment effect – increase reported an increase in wildfire regime or effect metric as a result of prescribed fire regime. An example could include a study that found increasing incidence of prescribed fire leading to an increase in total area burned (prescribed fire plus wildfire) and an increase in total carbon emissions (from prescribed fire and wildfire) over a given time period. In each case, the comparators were scenarios, time frames, or other landscapes with no to limited prescribed fire. It is important to note that the labels ‘increase’ and ‘decrease’ do not necessarily equate to positive or negative impacts of wildfire. They simply note the direction of change in the metric. An exception to this rule was the treatment of some carbon flux terms, which can be negative or positive depending on different conventions. For studies related to carbon fluxes, results were labeled treatment effect-decrease when they found that prescribed fire regime resulted in a system operating as a carbon source (e.g. carbon from ecosystem to atmosphere) relative to a no management scenario. Results were labeled treatment-effect increase when a prescribed fire regime resulted in system operating as a carbon sink relative to a no management scenario. Results from studies that relied primarily on empirical analyses were presented separately from those that relied primarily on simulation modeling. Some studies included analyses from multiple countries or regions within a country. In such cases, we presented results individually for each site within a study.

3. Results

The 71 papers examined for this literature review included 119

Table 2
Categories of wildfire effects metrics used in the literature review. The 'category' column gives the name of the category for which we are assigning metrics. The 'description' column describes our interpretation of the category of metrics. The 'metric included' column lists the exact metrics used in the literature compiled for this study that we assigned to specific categories.

Category	Description	Metrics included
Ecosystem carbon pools	Describes the state of above or below ground ecosystem carbon or biomass in different ecosystem pools.	Above ground fuel load Above ground biomass Total above ground carbon Carbon stores Total ecosystem carbon Live and dead tree carbon Carbon storage Basal area
Ecosystem carbon fluxes	Describes rates of inputs and outputs of carbon to an ecosystem and the degree to which a system operates as a carbon source or sink	Net ecosystem exchange Net ecosystem carbon balance
Wildfire emissions	Describes the release of carbon and other combustion byproducts from the burning of fuels during wildfires	Wildfire emissions Carbon loss from wildfire
Total emissions	Describes combined release of combustion byproducts from burning of fuels during prescribed fire and wildfire	Total emissions (wildfire and prescribed fire) Greenhouse gas abatement Carbon loss from burning
Watershed	Describes wildfire effects in terms of watershed services, such as impacts to runoff and erosion.	Sediment yield Runoff
Wildland urban interface	Describes wildfire effects in terms of direct impacts to human communities.	Burn probability near structures Fire intensity near structures Area burned in WUI Stand replacement fire in WUI Number of structures 1 km from wildfire
Suppression	Describes wildfire effects in terms of fire suppression efficiency and effectiveness.	Suppression costs Area suppressed
Economics	Describes wildfire effects in terms of their indirect economic impact.	Financial return Net present value Cost of greenhouse gas abatement Economic impact Expected value change
Wildlife	Describes wildfire effects in terms of wildlife habitat or populations.	Habitat loss Area of high quality habitat Burn probability in wildlife habitat Wildlife population size
Resilience	Describes the ability of a system to recover from disturbances without fundamental changes to ecosystem processes or structures	Area of resilient forest structure Abundance of drought-tolerant vegetation Abundance of fire-tolerant vegetation Area of shift from forest to non-forest vegetation

study sites, or areas of analysis, in 36 countries (Fig. 2). The majority of analyses have been conducted in forested lands of the western U.S. There are also a significant number of studies in Mediterranean countries and Australia. Additional details about the studies, such as their location, vegetation type, and whether or not they include mechanical fuel treatments, the implications of climate change, and the use of wildfire to meet resource management objectives are given in Appendix A.

3.1. Empirical studies

Most empirical studies showed that prescribed fire regimes result in reductions in wildfire frequency, extent, and behavior/severity (Fig. 3). In total, there were 17 papers that empirically addressed the relationship between prescribed fire and wildfire regimes by examining historical prescribed fire and wildfire data over 5–66 year periods and analyzing their relationships (see Appendix A). At 16 study sites, investigators documented a reduction in wildfire frequency or extent with increasing prescribed fire activity. At 10 study sites, investigators documented no significant effect of prescribed fire activity on wildfire frequency or extent (Fig. 3). Significant reductions in frequency or extent were documented in the southeastern and southwestern United States, Australia, and some Mediterranean countries, whereas no detectable effect was documented in other parts of the United States, Australia, and Europe. In one case, past prescribed fire area was positively related to wildfire area in South Africa (Price et al., 2015a). Such findings have led some authors to conclude that negative relationships between wildfire and prescribed fire frequency and area are likely to be seen only in areas with high frequency of wildfire or prescribed fire, as this increases the rates at which wildfire encounters areas with prescribed fires (Price et al., 2015a).

Fewer empirical studies examined the effects of prescribed fire regimes on total burned area and subsequent wildfire behavior/severity, with almost all showing prescribed fire regimes result in increased total burned area and reduced wildfire behavior/severity (Fig. 3). Investigators found that increases in prescribed fire activity were associated with decreases in subsequent wildfire behavior/severity in the southeastern and western United States (Butry, 2009; Malone et al., 2011; Mercer et al., 2007). One study showed no effect of prescribed fire on subsequent wildfire behavior/severity in the southeastern United States, but relied on incomplete records of prescribed fire area (Brewer and Rogers, 2006). Only two studies evaluated the effects of increasing prescribed fire on total burned area and found that even though prescribed fire decreased wildfire area, it led to an increase in total fire area in both the southeastern United States and Australia over 7–30 year periods (Mercer et al., 2007; Price and Bradstock, 2011).

Five empirical studies examined the impacts of prescribed fire regimes on wildfire and total emissions and found conflicting results (Fig. 4), likely due to different methodological approaches, vegetation types, and burning conditions. Although all of these studies utilize

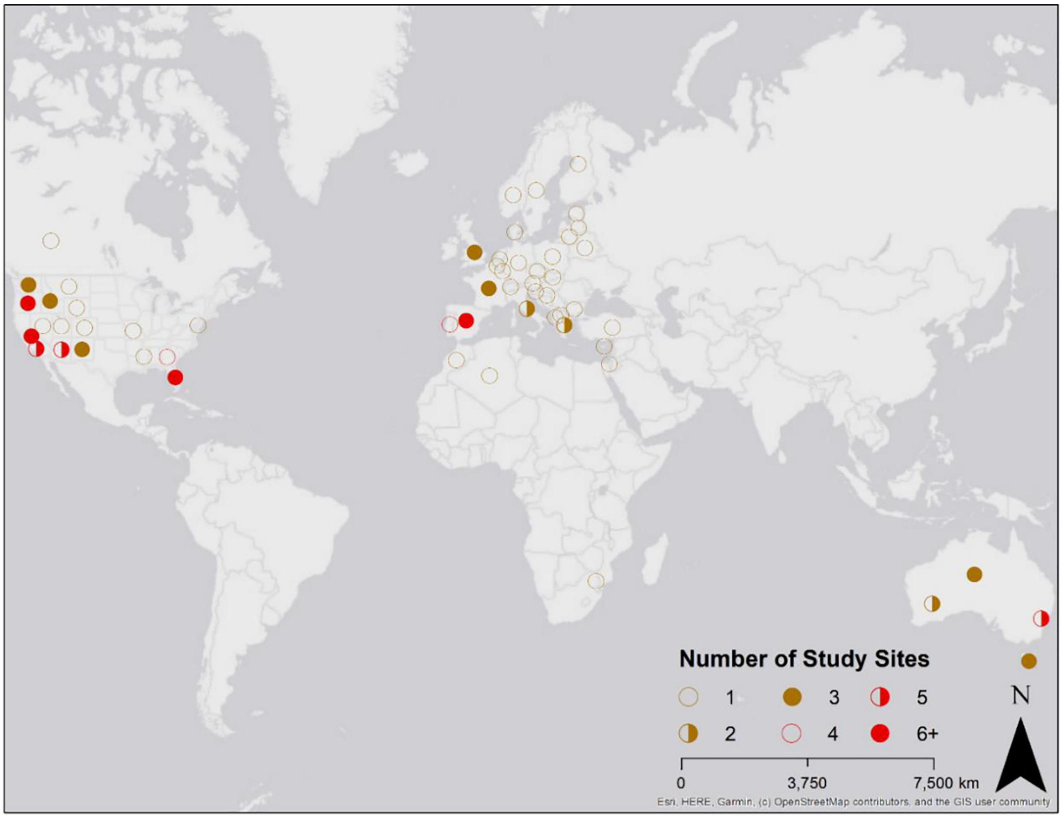

Fig. 2. Map of study sites, or areas of analysis, in the 71 papers examined for this literature review.

available data on prescribed fire and wildfire emissions, many also rely on different assumptions regarding the effects of prescribed fire on wildfire regimes to evaluate potential tradeoffs between prescribed fire and wildfire emissions. For example, Vilén and Fernandes (2011) calculated potential total emissions reduction from prescribed fire in five Mediterranean countries using two hypothetical values for prescribed fire leverage, representing high and low values. Narayan et al. (2007) calculated potential reduction in total emissions across 33 European countries using the assumption that prescribed fire applied to 20% of a landscape will reduce area burned in wildfire by 50% (based on Finney, 2001, 2003). Two studies in the United Kingdom used data on ecosystem carbon fluxes from a choronosequence of prescribed fires and experimental fires across moorlands to develop a matrix model and investigate the fates of ecosystem carbon under different prescribed fire and wildfire rotations (Allen et al., 2013; Santana et al., 2016).

The studies collectively suggest that the effects of prescribed fire on wildfire and total emissions is highly dependent on the level of wildfire activity, as this influences the rate at which wildfires encounter areas treated with prescribed fire. For studies that assume prescribed fire essentially replaces wildfire (i.e., same total area burned), increases in prescribed fire activity can lead to reductions in total fire emissions, but effects were significant only in areas with high rates of wildfire. This

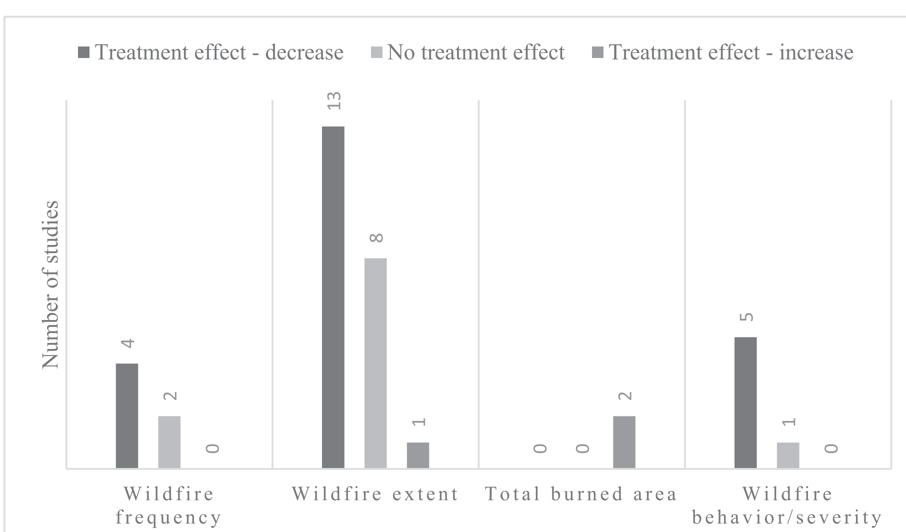

Fig. 3. Number of study sites where investigators empirically document a decreased treatment effect, no treatment effect, or increased treatment effect of prescribed fire on subsequent metrics of wildfire, including wildfire frequency, wildfire extent, total area burned, and wildfire behavior/severity.

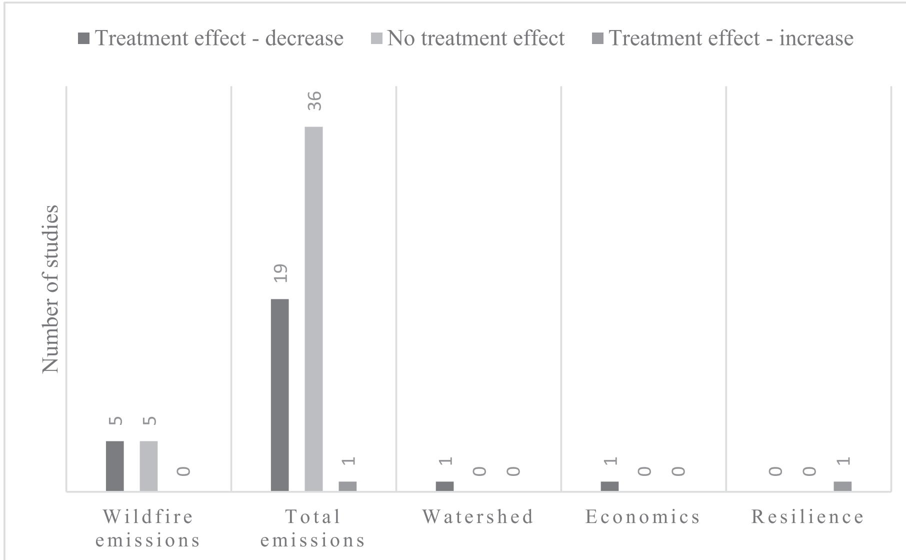

Fig. 4. Number of study sites where investigators empirically document a decreased treatment effect, no treatment effect, or increased treatment effect of prescribed fire regime on subsequent wildfire effects, including wildfire emissions, total emissions, watershed, economics, and resilience.

was demonstrated in several European countries (Narayan et al., 2007) and in several states in the western United States (Wiedinmyer and Hurteau, 2010). Other studies that utilize empirical data on emissions to evaluate hypothetical burning scenarios also found that wildfire and total emissions were reduced with increasing prescribed fire only when frequency of wildfire was high (Allen et al., 2013; Vilén and Fernandes, 2011). One study found that all prescribed fire scenarios resulted in increases in total emissions (Santana et al., 2016).

Empirical studies examining the effects of prescribed fire regimes on subsequent wildfire effects on other values are scant (Fig. 4) which makes it difficult to draw broader conclusions. Only two studies examined the implications of prescribed fire regimes on subsequent wildfire effects on watersheds, economics, and resilience. Using historical data on sediment discharge, wildfire history, rainfall, and topography over a 30 to 60 year period, Loomis et al. (2003) developed a sediment yield production function for an 86 km^2 area in Los Angeles County, California, and used it to estimate reduction in sediment production and associated cost savings from prescribed burning. They found that the longer the fire interval preceding a fire event, the greater sediment accumulated in debris basins the flowing year (Loomis et al., 2003). They conclude that a 5-year prescribed fire return interval would yield cost savings in terms of reducing the need for debris basin clean out (Loomis et al., 2003). Boisramé et al. (2017) compared a watershed in the Sierra Nevada, California, where wildfire had been utilized for 40 years to meet management objectives with adjacent watersheds which had been subject to fire suppression and wildfire over the same time frame. They found that the watershed with managed wildfire had lower drought-induced tree mortality (i.e., higher resilience) and higher mean annual runoff compared to adjacent watersheds and concluded that the frequent fire regime can result in benefits to ecosystems and society (Boisramé et al., 2017).

3.2. Simulation modeling studies

There were 32 studies that used simulation modeling to examine the effects of prescribed fire on subsequent wildfire regimes, the majority of which have been conducted in the western United States. These different studies used a variety of landscape models that differ in their approach to modeling disturbance and vegetation over time (see Keane et al., 2004 for a review of many landscape disturbance vegetation modeling approaches). Even for studies that utilized the same landscape models to address study questions, many relied on different assumptions regarding for example wildfire ignitions or post-fire succession. Six of these studies incorporate the implications of changing climate, whereas others simulate fire behavior under current conditions. These different modeling approaches makes comparison among modelling studies difficult. Regardless, some consistent patterns have emerged from these studies, which are detailed in the following paragraphs.

The majority of simulation modeling studies show results similar to empirical studies, with increasing prescribed fire extent or frequency resulting in decreased wildfire frequency, extent, or behavior/severity (Fig. 5). Most of these studies (23) were conducted in the western United States, and with few exceptions, these studies found that wildfire frequency, extent, or behavior/severity decreased with increasing level of prescribed fire over periods of 50–600 years (Fig. 5). Five studies were conducted in Australia, all of which showed negative relationships between prescribed fire activity and wildfire frequency, extent, or behavior/severity over a period of 25–250 years. Two studies were conducted in Europe, which found either negative effects of prescribed fire regime on wildfire extent and behavior/severity or no effect depending on the country over a period of up to 600 years. One study conducted in the central United States found that increasing use of prescribed fire led to a decrease in wildfire extent, but had no effect on fire behavior/severity over a 200 year period, a result they attribute to the inability of prescribed fire to reduce coarse fuels (Shang et al., 2004).

Most of these studies examining the effects of prescribed fire regimes on subsequent wildfire effects pertain to ecosystem carbon, including accounting for wildfire and total carbon emissions in forests of the western United States (Fig. 6). Results are conflicting regarding the effects of prescribed fire regimes on overall ecosystem carbon and total emissions (Fig. 6). Similar to empirical studies, simulation studies results were highly dependent on wildfire activity and climatic conditions (Krofcheck et al., 2017a). Because many of these studies were conducted in similar regions and vegetation types, the conflicting findings are likely the result of differences in modeling approaches and assumptions. For example, modeling studies differed in models utilized, carbon pools included, interactions with other disturbances, and parameters for wildfire occurrence, climate, and post-fire succession.

As with empirical studies, few simulation modeling studies examined the implications of prescribed fire regime on subsequent wildfire effects on wildlife, wildland urban interface, watershed services,

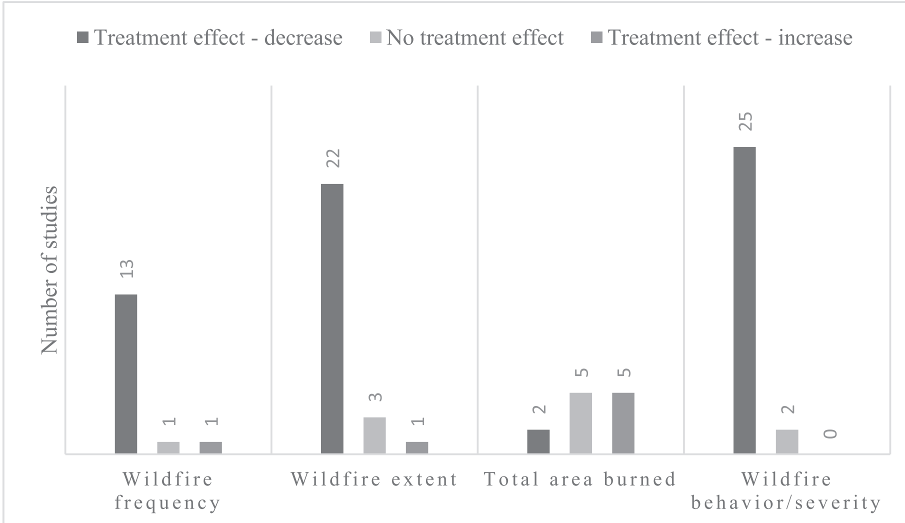

Fig. 5. Number of study sites where investigators use simulation modeling to document decreased treatment effect, no treatment effect, or increased treatment effect of prescribed fire regime on subsequent wildfire frequency, extent, total area burned, and behavior/severity.

economics, fire suppression, or resilience (Fig. 7). Almost all studies have been conducted in the western United States (Appendix A). Studies generally found conflicting results for wildlife with responses differing by species and their adaptations to fire. All available studies show that prescribed fire decreased suppression costs or other economic losses associated with wildfire (Fig. 7). Most studies show that prescribed fire is effective in terms of reducing exposure to WUI communities. One exception in which no effect was found (Barros et al., 2017) might have been due to differences in how prescribed fire was prioritized across the landscape. Only one study has evaluated effects in terms of watershed services, and found that prescribed fire reduced wildfire-induced potential runoff and erosion (O'Donnell et al., 2018). Studies utilized very different metrics to indicate ecosystem resilience (Table 2), but generally found that prescribed fire resulted in increased ecosystem resilience (Fig. 7). It is difficult to draw broad conclusions however, since the few investigators that do explicitly address resilience utilize very different metrics to indicate ecosystem resilience.

4. Discussion

The papers examined in this literature review adhered to some aspect of our conceptual framework (Fig. 1). The investigators examined prescribed fire and wildfire regimes at temporal and spatial scales that were beyond single events and modeling studies included the probability of wildfire occurrence. The body of work demonstrates that many studies on the relationships between prescribed fire and wildfire regimes have been published since the last known reviews of this topic (Fernandes and Botelho, 2003; Fernandes, 2015), and many investigators are considering the key factors in our conceptual framework.

These studies for the most part affirmed that increasing use of prescribed fire often result in wildfires of lower size and intensity. Some, but not all, have also suggested that a consequence associated with increased use of prescribed fire is an increase in the total, cumulative amount of fire on a landscape over time. The effects of prescribed fire regime on total fire area is likely a function of prescribed fire leverage, a factor which has been shown to vary by region (Price et al., 2015a). At this stage, however, the scientific literature is not rich enough to determine regional or ecosystem differences in relationships between prescribed fire and wildfire regimes. This information is needed to fully evaluate tradeoffs between wildfire and prescribed fire.

Prescribed fire and wildfire effects on ecosystem carbon dynamics

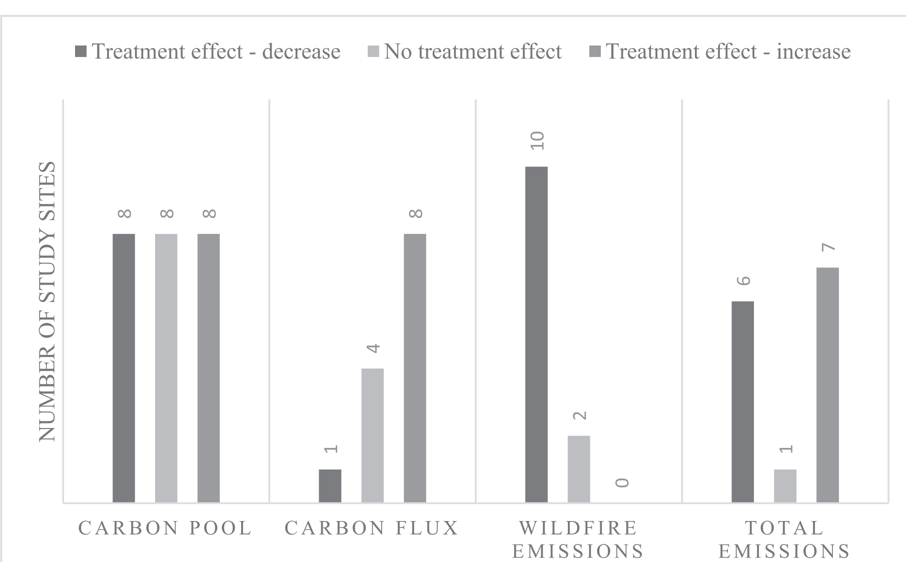

Fig. 6. Number of study sites where investigators use simulation modeling to document decreased treatment effect, no treatment effect, or increased treatment effect of prescribed fire regime on subsequent wildfire effects related to carbon, including carbon pools, carbon fluxes, wildfire emissions, and total emissions (prescribed fire + wildfire). In the case of carbon fluxes, treatment effect – increase indicates the prescribed fire regime resulted the system operating as a carbon sink relative to a no management scenario and treatment effect – decrease indicates the prescribed fire regime resulted in the system operating as a carbon source relative to a no management scenario.

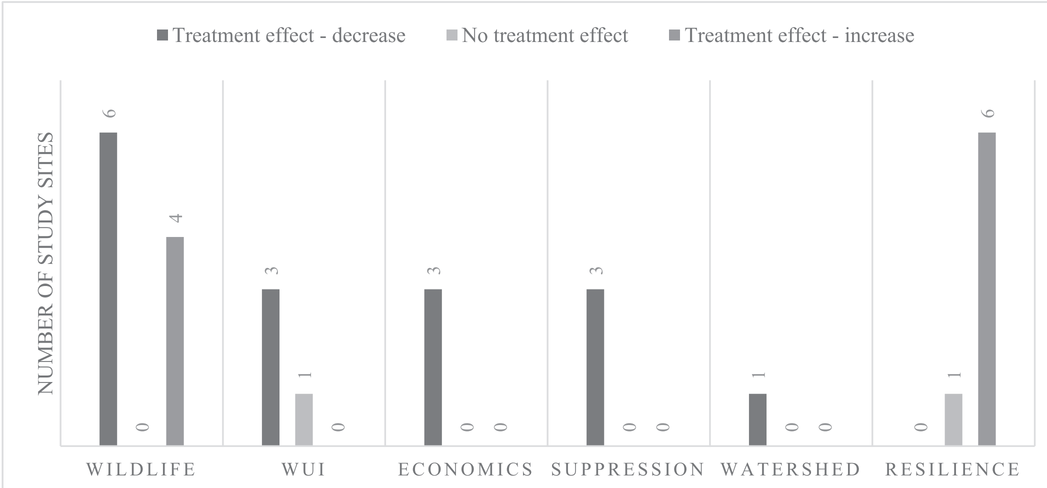

Fig. 7. Number of study sites where investigators use simulation modeling to document decreased treatment effect, no treatment effect, or increased treatment effect of prescribed fire regime on subsequent wildfire effects related to wildlife, wildland urban interface, economics, suppression, watersheds, and resilience.

are much less clear as results vary considerably across studies. Empirical studies at the stand-scale demonstrate that wildfire emissions increase with increasing wildfire severity (i.e., fuel consumption) and that prescribed fire can mitigate that severity in the short-term should a fire occur in the same area (Restaino and Peterson, 2013). When results are extended to landscapes at longer time horizons, however, many sources of uncertainty are introduced which have implications for long-term carbon dynamics. This includes uncertainty in the probability of wildfire, post-fire ecosystem response, and implications of climate change. Results likely vary because studies use various landscape models with different parameter settings for processes such as vegetation succession and wildfire ignitions and severities, and use different methodologies, time frames, and fire management and climate change scenarios (Campbell and Ager, 2013; Restaino and Peterson, 2013).

Data on prescribed fires and wildfires that are needed to parameterize simulation models are often not available at appropriate spatial and temporal scales. Some improvements in data availability have been made with respect to wildfire size and severity (Eidenshink et al., 2007). Progress is still needed, however, particularly with respect to accurate estimates of wildfire probabilities (including probability of treatment-wildfire encounters), portion of carbon pools emitted under different climatic and fire severity conditions (and effectiveness with which fuel treatments can diminish these emissions) and interacting effects of climate change on wildfires, drought and insect mortality, and post-disturbance regeneration.

In the course of completing this review, we found that researchers that use simulation models could provide more comprehensive and transparent documentation of their model parameters, assumptions, and limitations so that end users could more easily interpret results. Currently, model parameter settings are reported in disparate locations (methods, results, supporting information), or in some cases, not at all. A more centralized and standardized framework for reporting parameters, similar to the international metadata standards for geospatial data (https://www.fgdc.gov/metadata/*iso*-standards), would facilitate faster and more accurate interpretation of model results. This standard should include parameter definitions, use in simulation model, units, and source of values (empirical studies, expert opinion, others). Additionally, end-users would benefit from more comprehensive discussion of model assumptions and limitations for critical wildfire parameters such as probability of ignitions, spread rates, fire size distributions, and post-fire fuel type classification systems and vegetation responses. This includes the fact that simulation modeling efforts typically do not incorporate the critical role that prescribed fire can play in increasing the effectiveness of fire-fighting operations in limiting area burned in wildfire or wildfire-induced damages to valued resources (Thompson et al., 2016). While there are significant challenges associated with incorporating the effects of fire-fighting operations in simulation models (Thompson et al., 2017a), investigators could acknowledge that not accounting for this factor likely leads to over or under estimates of modeling results.

Despite these shortcomings, there is an urgent need to identify which set of management activities are most likely to sustain ecosystem structure and processes and where they will be most effective as wildfire activity and severities have increased across many countries (Dennison et al., 2014, Hanes et al., 2018). To address this challenge, researchers could leverage networks of sites with similar information on prescribed fire and wildfires (Boerner et al., 2008) to run the same simulation model across multiple landscapes. Especially for those parameters where uncertainties are high or empirical data is scarce, researchers could complete sensitivity analyses that illustrate how high to low parameter settings affect wildfire or ecosystem metrics and report findings accordingly (see Flatley and Fulé, 2016). At the more local scale, simulations from multiple models within the same landscape and using similar experimental design could identify both where models are in agreement on fuel treatment effects on wildfire processes, and where outcomes vary based on model assumptions or parameter settings (Loehman et al., 2018). Where models agree, managers could have more confidence that results are robust, and where model disagree, model developers could work together to conduct sensitivity analyses and bring in additional empirical data to refine models on key processes where uncertainties currently exist.

A consistent and robust framework for assessing prescribed fire and wildfire regimes does not currently exist. In this review we propose a simple framework that includes spatial and temporal scale and wildfire probability and examine the literature for studies that adhere to this framework to some degree. The review reveals that tradeoffs in ecosystem carbon and emissions occur when examining both wildfire and prescribed fire. Beyond carbon, any framework addressing prescribed fire and wildfire tradeoffs should have much broader considerations. Prescribed fire is also used with the intent of increasing ecosystem resilience, protecting watersheds, wildlife habitat, communities, and other values and these should be incorporated in any framework. Yet, literature on the effects of prescribed fire regimes on wildfire-induced impacts to these and other values is scant and this represents a critical research need. Empirical studies are needed to calibrate and provide magnitude of order comparisons with models and address tradeoffs with respect to other values. Empirical studies should inform new and innovative methodologies (including simulation modeling), informed by multiple disciplines, to address the full range of prescribed fire and wildfire regime tradeoffs (Williamson et al., 2016).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

List of studies that address wildfire regimes and effects empirically or with simulation modeling, along with locations of study sites, dominant vegetation types (when specified), and metric categories included in the study. Studies with * incorporated the effects of future climate change. Studies with ‡ included an additional fuel treatment (e.g., thinning) followed by prescribed fire. Studies with † considered the use of wildfire to meet resource management objectives. Studies pertaining to wildfire effects are listed under the effect studied.

Twenty-four studies (number of study sites in parentheses) that empirically address the effects of prescribed fire on wildfire regimes and subsequent wildfire effects.

Study	Sites	Metric category
Addington et al., 2015 (1)	Georgia, U.S.A.	Wildfire frequency; Wildfire extent
Allen et al., 2013 (1)	United Kingdom	Total emissions
Boer et al., 2009 (1)	southwestern Australia	Wildfire frequency; Wildfire extent
Boisramé et al., 2017 (1)	California, U.S.A.	Watershed; Resilience
Brewer and Rogers, 2006 (1)	Mississippi, U.S.A.	Wildfire frequency; Wildfire extent; Wildfire behavior/severity
Butry et al., 2008 (1)	Florida, U.S.A.	Wildfire extent
Butry, 2009 (1)	Florida, U.S.A.	Wildfire extent; Wildfire behavior/severity
Collins et al., 2009 (1)	California, U.S.A.	Wildfire behavior/severity
Davis and Cooper, 1963 (1)	southeastern, U.S.A.	Wildfire frequency; Wildfire extent
Haire et al., 2013 (3)	southwestern, northwestern, northern Rockies, U.S.A.	Wildfire extent
Loomis et al., 2003 (1)	southwestern U.S.A.	Watershed; Economics
Malone et al., 2011 (1)	Florida, U.S.A.	Wildfire behavior/severity
Mercer et al., 2007 (1)	Florida, U.S.A.	Wildfire extent; Wildfire behavior/severity; Total area burned
Miller et al., 2012 (1)	California, U.S.A.	Wildfire extent; Wildfire behavior/severity
Narayan et al., 2007 (33)	33 European countries	Total emissions
Prestemon et al., 2002 (1)	Florida, U.S.A.	Wildfire frequency
Price and Bradstock, 2011 (1)	southeastern Australia	Wildfire extent; Total area burned
Price et al., 2012a (1)	northern Australia	Wildfire extent
Price et al., 2012b (1)	southwestern, U.S.A.	Wildfire extent
Price et al., 2015a (6)	southwestern, U.S.A.; western Canada; Portugal; Spain, South Africa; northern Australia	Wildfire extent
Price et al., 2015b	southeastern Australia	Wildfire extent
Santana et al., 2016	United Kingdom	Total emissions
Vilén and Fernandes, 2011	France, Greece, Italy	Wildfire emissions; Total emissions
Wiedinmyer and Hurteau, 2010	Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming, USA	Total emissions

Forty-one studies (number of study sites in parentheses) that address prescribed fire and wildfire regimes with simulation modeling

Study	Location	Metric category
Ager et al., 2007‡ (1)	Oregon, U.S.A.	Wildfire frequency; Wildfire extent; Wildfire behavior/severity; Wildlife
Ager et al., 2010a‡ (1)	Oregon, U.S.A.	Wildfire frequency; Wildfire extent; Ecosystem carbon flux; Wildfire emissions; Total emissions
Ager et al., 2010b‡ (1)	Oregon, U.S.A	Wildfire frequency; Wildfire extent; Wildfire behavior/severity; WUI; Resilience
Ager et al., 2017 (1)	Oregon, U.S.A	Wildfire frequency; Wildfire extent; Wildfire behavior/severity; Total area burned; Wildlife
Ager et al., 2018 (1)	Oregon, U.S.A.	Wildfire extent; Wildfire behavior/severity
Barros et al., 2017‡ (1)	Oregon, U.S.A.	Wildfire extent; Wildfire behavior/severity; Total area burned; Wildlife; WUI; Resilience
Barros et al., 2018 (1)	Oregon, U.S.A.	Wildfire behavior/severity; Total emissions; Resilience
Bradstock et al., 2012‡ (1)	Southeastern Australia	Wildfire extent; Wildfire behavior/severity; WUI;
Campbell and Ager, 2013‡ (1)	Oregon, U.S.A.	Ecosystem carbon flux; Wildfire emissions; Total emissions
Chiono et al., 2017‡ (1)	California, U.S.A.	Wildfire frequency; Wildfire behavior/severity; Wildfire emissions; Total emissions
Connell et al., 2019	Southeastern Australia	Wildfre extent; Total burned area, Wildlife
Finney et al., 2007‡ (3)	Washington, Montana, California, U.S.A.	Wildfire frequency; Wildfire extent; Wildfire behavior/severity;
Flanagan et al., 2019 (1)	Georgia, U.S.A.	Ecosystem Carbon Pool; Ecosystem Carbon Flux; Resilience
Furland et al., 2018 (1)	Tasmania, Australia	Wildfire frequency; Wildfire behavior/severity
Heckbert et al., 2012 (1)	Northern Australia	Total emissions; economics

Houtman et al., 2013† (1)	Oregon, U.S.A.	Wildfire extent; Wildfire behavior/severity; Suppression
Hurteau and North, 2008‡ (1)	California, U.S.A.	Wildfire emissions; Total emissions
Hurteau et al., 2015‡ (1)	Arizona, U.S.A.	Ecosystem carbon flux
Hurteau, 2017*‡ (1)	Arizona, U.S.A.	Wildfire behavior/severity; Total emissions
King et al., 2006 (1)	Tasmania, U.S.A.	Wildfire frequency; Wildfire extent; Total area burned; Resilience
King et al., 2012* (1)	Tasmania, U.S.A.	Wildfire frequency; Wildfire extent;
Krofcheck et al., 2017a*‡ (1)	California, U.S.A.	Wildfire behavior/severity; Ecosystem carbon flux; Wildfire emissions; Total emissions;
Krofcheck et al., 2017b‡ (1)	California, U.S.A.	Wildfire behavior/severity; Ecosystem carbon flux; Wildfire emissions; Total emissions
Krofcheck et al., 2019*‡ (1)	Florida, U.S.A.	Wildfire behavior/severity; Total area burned; Wildfire emissions; Total emissions
Laflower et al., 2016*‡ (1)	Washington, U.S.A.	Ecosystem carbon flux; Resilience
Liang et al., 2018*‡ (1)	California, U.S.A.	Wildfire behavior/severity; Total area burned; Wildfire emissions; Total emissions
Loehman et al., 2018*‡ (2)	Arizona, New Mexico, U.S.A.	Wildfire extent; Wildfire behavior/severity; Ecosystem carbon flux; Resilience
Loudermilk et al., 2017*‡ (1)	California, U.S.A.	Wildfire extent; Ecosystem carbon flux; Resilience
McCauley et al., 2019*‡	Arizona, U.S.A.	Wildfire behavior/severity; Ecosystem carbon flux; Ecosystem carbon pool; Wildfire emissions
Mitchell et al., 2009‡† (1)	Northwestern, U.S.A.	Wildfire emissions
O'Donnell et al., 2018*‡ (1)	Arizona, U.S.A.	Wildfire extent; Wildfire behavior/severity; Watershed
Piñol et al., 2005 (1)	Spain and Portugal	Wildfire extent; Total area burned
Piñol et al., 2007 (3)	California, U.S.A., Spain, France	Wildfire extent; Wildfire behavior/severity; Total area burned
Regos et al., 2014*† (1)	Spain	Suppression
Schaff et al., 2008 (1)	California, U.S.A.	Wildfire extent; Total area burned; Total emissions; Economics
Scheller et al., 2011a‡ (1)	California, U.S.A.	Wildlife
Scheller et al., 2011b† (1)	New Jersey, U.S.A.	Ecosystem carbon flux; Wildlife
Shang et al., 2004‡ (1)	Missouri, U.S.A.	Wildfire frequency; Wildfire extent; Wildfire behavior/severity; Ecosystem carbon flux
Spies et al., 2017‡ (1)	Oregon, U.S.A.	Wildfire extent; Wildfire behavior/severity; Ecosystem carbon flux; Wildlife; WUI; Resilience
Swanteson-Franz et al., 2018*‡ (1)	Georgia, U.S.A.	Ecosystem carbon flux; Wildfire emissions
Syphard et al., 2011‡ (1)	California, U.S.A.	Wildfire frequency; Ecosystem carbon flux
Thompson et al., 2017b‡ (1)	California, U.S.A.	Wildfire frequency; Wildfire extent; Suppression; Economics

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