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Social Science/Natural Science Perspectives on Wildfire and Climate Change

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Abstract

In western North America, wildfire is a critical component of many ecosystems and a natural hazard that can result in catastrophic losses of human lives and property. Billions of dollars are spent suppressing wildfires each year. In the past decades, academic research has made substantial contributions to the understanding of fire and its interaction with climate and land management. Most reviews of the academic literature, however, are centered in either natural or social science. We offer an integrated cross-disciplinary guide to state-of-the art fire science and use this review to identify research gaps. We focus on the modern era and understanding fire in the context of a changing climate in western North America. We find that studies combining social and natural science perspectives remain limited and that interactions among coupled system components are poorly understood. For example, while natural science studies have identified how fuel treatments alter fire regimes, few social science studies examine how decisions are made about fuel treatments and how these decisions respond to changes in fire regimes. A key challenge is to better quantify the effects of actual fire management policies in a way that accounts for the complexity of coupled natural and natural–human system interactions.

Introduction

How to appropriately prepare for and respond to wildfire are pressing issues facing environmental managers today, and recent studies indicate that fire frequency and severity will likely increase with a warming climate (Westerling et al. 2006; Dennison et al. 2014). Although fires are a natural and necessary part of a healthy ecosystem (Keane et al. 2002), they can also have destructive effects on human communities. In 2000, 12.5 million US homes were within the wildland-urban interface (WUI), a 52% increase since 1970 (Theobald and Romme 2007). Many of these homes face high risks of loss from wildfire, prompting the US Forest Service to respond with more fuel management near housing (Anderson et al., 2013). Over 1 billion US dollars are spent annually on fire suppression alone, with additional expenditures on post-fire rehabilitation and treatments.

There has been substantial natural science-based research on fires and their sensitivity to climate, although important knowledge gaps remain in understanding how interactions between climate change and forest ecosystems influence fire risk (Littell et al. 2009; McKenzie et al. 2011; Moritz et al. 2014)). Many models of fire risk, fire spread, and fire effects have been developed and applied over a range of scales in western North America (e.g the LANDIS model of fire regimes for Southern California Syphard et al. 2007a; Daily Severity Rating of the Canadian Forest Fire Weather Index System applied to an area of approximately 58,000 km^2 Krawchuk et al. 2009; local fire behavior modeling using FIRETEC Linn et al. 2002; a probabilistic model of fire regime for Yellowstone Hargrove et al. 2000; a model of post-fire assessment Veraverbeke et al. 2013). The social science literature on climate and fire, however, is less developed, suggesting there are gaps in knowledge about how best to use available scientific information to address complex management problems (Davis 2001; McCaffrey et al. 2013). Analyses of the natural system that ignore human influences as well as studies of human behavior will necessarily be incomplete. A broader perspective on the coupled natural and human system components linked to fire can identify what is known about fire and climate change and where significant knowledge gaps remain.

We provide a conceptual model of climate and fire for western North America that identifies key components of the natural and human systems and the potential linkages among them. The conceptual model helps us to organize existing studies on climate and fire. Our main contribution is to provide a guide to the literature that (i) identifies which areas are well studied, (ii) discusses the central findings that emerge from these studies, and (iii) identifies substantial gaps for which new research is needed. The topic of fire and climate change is too broad to provide a comprehensive treatment, and so we limit our attention to western North America, where there is a long history of fire related research, and the modern era.

Conceptual Model

Our conceptual model of fire and climate in western North America is illustrated in Figure 1. The conceptual model organizes our guide to current literature on fire regimes in order to capture natural and social science perspectives and highlights the linkages between them. The arrows indicate the interactions among components of the system. We selected these broad categories to organize information about important linkages, though we acknowledge that our distinctions are somewhat artificial. Individual wildfires or fire behavior are characterized in terms of the cause of ignition, the effect of weather on the fire, the combustible material present, and their physical properties such as speed of propagation (Flannigan et al. 2005). Fire regimes, on the other hand, refer to the long-term fire characteristics of a landscape and are described by a range of different measures including frequency, spatial extent, pattern, intensity, and severity (Keeley 2009). We focus primarily on fire regimes and their relationship with climate but consider fire behavior when relevant. Our model posits that fire regimes both influence and are influenced by human actions, natural system processes, and their interactions.

We restrict our review to studies with direct relevance to fire and fire management. In some areas (e.g., the interaction of ecosystems and fire), the literature is too vast for us to fully describe the state of knowledge. In these cases, we direct readers to review papers that summarize key findings.

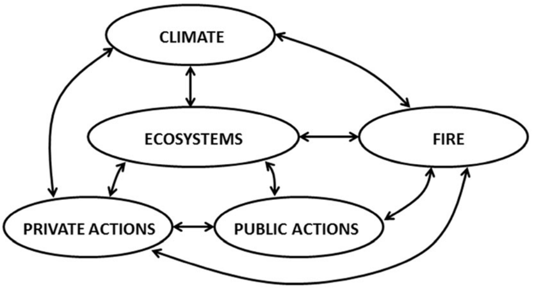

Fig. 1. Conceptual model of fire and biophysical and social processes in Western North.

Guide to the Literature

CLIMATE-FIRE

Climate is the primary determinant of the characteristics of individual fires and fire regimes. Short-term hourly to seasonal meteorological variables often drive fire behavior, while decadal and longer climatic variables influence fire regimes. Littell et al. (2009), for example, found that climate variables explained between 33% and 87% of the area burned by fire in the past decades in the western USA, although correlations vary substantially by ecosystem type. Similarly, Westerling et al. (2006) show that area burned increases in dry, warm summers for most of the western USA, with the exception of brush and grassland areas in the Great Basin and Mojave Desert. These grassland areas show greater area burned following wetter years that increase productivity and fuel volumes. Much of the California Sierra, Colorado Rockies and forested areas of Arizona, and New Mexico also show greater burned area with increased moisture in previous years. Longer-term analysis using fire scar data in tree rings reveals similar relationships for the western USA (Lombardo et al. 2009; Swetnam et al. 1999; Veblen et al. 2000). Fire behavior is also strongly shaped by antecedent climate and weather conditions (Rothermel 1983; Reinhardt et al. 1997), and most models of fire behavior are driven primarily by short-term seasonal climate and weather related inputs (Schott and Burgan 2005).

Predicted climate change is expected to result in higher average temperatures and increased frequency of extreme heat events in western North America over the next few decades (IPCC 2009). Regional estimates of temperature for the western USA show temperature increases ranging from 1 to 6°C by 2100 for Western USA (Cayan et al. 2010; Garfin et al. 2013). Estimated changes in precipitation are much less certain and show greater regional variation. Nonetheless, the combination of warmer temperature and reduced relative humidity are expected to lead to greater frequency of climatic droughts in the next decades and are expected to increase fire risk, severity, and frequency for much of western North America (Krawchuk et al. 2009; McKenzie et al. 2004; Robeson 2015; Williams et al. 2015). Recent increases in large wildfire frequency, fire severity, and fire season length throughout the western USA have already been linked to climate trends (Dennison et al. 2014; Littell et al. 2009; Westerling et al. 2006). Lightning frequency is also expected to increase in warming scenarios across much of the fire prone area in the southwestern USA, resulting in longer fire seasons and larger burned regions (Brown et al. 2004; Price and Rind 1994a, 1994b). Climate projections for the next several decades, however, are subject to great uncertainty, particularly at regional to local scales and uncertainty increases for longer-term projections (100 years and beyond). Finer spatial scale projections are also needed because vulnerability to climate change is likely to vary spatially within western North America. Areas with more frequent fires, such as the chaparral-dominated landscapes of Southern California, may be less sensitive to climate change (Moritz 1997; Syphard et al. 2007b). On the other hand, in the Sierra, increasingly higher intensity fires may threaten long-lived trees adapted to a system that was characterized historically by low-intensity ground fires (Swetnam 1993).

In summary, climate both in terms of short-term meteorology and longer-term decadal trends as a primary control on fire in western North America has received much attention in recent years, and there is consensus on its importance as a driver of fire at various temporal and spatial scales. Remaining debate and uncertainty concern the magnitude of climate change itself, and how climate change will alter site-specific fire regimes throughout the region over the next few decades.

Fire and fire regimes in turn can influence climate. The immediate impacts of fire include increased flux of CO_2, particulates, and other materials to the atmosphere. Post-fire change in land cover and longer term species shifts associated with fire can alter land surface energy, carbon, and moisture fluxes, all of which can influence regional and global climate (e.g. global estimates suggest that emissions from fires, including biomass burning can be as large as 50% of fossil fuel emissions (Bowman et al. 2009), although there is substantial uncertainty in these estimates and emissions from fires can have both warming and cooling impacts (Arneth et al. 2010). The attention on improving regional to global climate models has led to a new research on the impact of fires on climate, but significant uncertainties remain both with respect to the aggregate impacts of fires on the global climate system and the impacts of local fires on regional climate (Bonan 2008; Bowman et al. 2009).

ECOSYSTEM–FIRE

Wildfires are the primary disturbance agent affecting the structure and composition of many forest ecosystems in western North America (Liu et al. 2010; McKenzie et al. 2004). For most ecosystems in the western USA, wildfire is an integral component of reproductive and life history strategies, and there are numerous examples of fire-related adaptations such as post-fire re-sprouting of chaparral and heat-stimulated germination (Bond and Keeley 2005). Ecosystem composition and structure are tightly coupled with climate and fire. Fire can promote one species over another (e.g., Brown and Minnich 1986), while at the same time, fire regimes are influenced by ecosystem characteristics that alter fuel and microclimates (D'Antonio and Vitousek 1992). The continental scale importance of fire can be seen by examining outputs from dynamic global vegetation models. Models that do not include fire in their estimates of terrestrial ecosystem productivity over-estimate biomass throughout much of the globe, including the western USA, sometimes by more than 50% (Bond and Keeley 2005). The role of fire as a natural disturbance varies across the wide range of ecosystem types found within western North America. For example, southwestern ponderosa pine forests experience frequent low-severity fires (often more than once per decade) (Fulé et al. 1997), while low-frequency (100 s of years) but high-severity fires can occur in subalpine forests and throughout the Cascade ranges (Agee 1993). Ecosystems also differ in their life-history responses to fire and their sensitivity to specific fire characteristics, including frequency, intensity, severity, and spatial extent (Bond and Keeley 2005; Noss et al. 2006). This tight coupling between ecosystems and fire has been intensively studied, and a review of even the major findings is well beyond the scope of this paper. We note that there are entire books detailing the fire ecology of most of the ecosystem types found in western North America (e.g., Agee (1993); Baker 2009; Keeley 2009; McKenzie et al. 2011; Sugihara 2006). Nonetheless, research questions remain about the specific processes through which fires shape ecosystem structure and composition at different spatial and temporal scales and the degree to which ecosystems in turn influence fire at those scales (Falk et al. 2007).

In addition to linkages with ecosystem structure, fire also alters ecosystem function and the services they provide. There are short-term and long-term and direct and indirect effects of fire on biogeochemical cycling, hydrology, and non-vegetation species composition and abundance (Hyde et al. 2013). Generally, fires are followed by an increase in the transport of water (Mast and Clow 2008; Wondzell and King 2003), nutrients (Boerner et al. 2009; Cerdà and Lasanta 2005; Neary et al. 1999; Ojima et al. 1994; Vitousek et al. 1997; Waldrop and Harden 2008) and sediment (Backer et al. 2004; Cerdà and Lasanta 2005; Keeley 2009; Neary et al. 1999). The magnitude of these changes and the duration over which they are observed following the fire vary with ecosystem type, climate, topography, and other site characteristics as well as the severity, intensity, and spatial-temporal patterns of fire. Hyde et al. (2013) review current literature and models of post-fire impacts and conclude that substantial gaps remain in characterizing these post-fire effects for specific locations, limiting the accuracy and utility of models of post-fire effects. We also note that while the impact of fire on biogeochemical cycling and hydrology is moderately well studied, few papers address any potential impact of biogeochemical cycling on subsequent fire regimes.

CLIMATE–ECOSYSTEM

Productivity

Empirical evidence and model predictions indicate that climate change can alter forest productivity, and these changes in productivity may alter future fire regimes. Reviews of empirical and model-based studies on the impacts of climate change on natural forest productivity show that, in most cases, forest productivity is enhanced by climate change (Boisvenue and Running 2006; Chiang et al. 2008; Medlyn et al. 2011) In water-limited environments, however, including much of western North America, productivity declines are expected (Williams et al. 2013). Increases in wildfire intensity attributed to increases in temperature and forest fuel content (Running 2006) may in turn have both short and long-term impacts on ecosystem productivity (Chertov et al. 2009; Kang et al. 2006). In general, while changes in ecosystem productivity with climate warming have received substantial attention in the literature, the subsequent impact of these productivity changes on future fire regimes remains a source of substantial uncertainty (Bowman et al. 2009).

Species composition and range

One of the expected ecosystem responses to climate change is a shift in species composition. Many studies indicate that tree species can shift to higher latitudes and higher elevations in mountain environments in response to climate change (Dale et al. 2010; Hickler et al. 2012). Increasing severity or frequency of fire can accelerate species shifts associated with climate change (Brooks et al. 2004; Savage et al. 2013). Shift in species, whether driven by fire or other disturbances can, in turn, have consequences for subsequent fire regimes (Brooks et al. 2004; Dale et al. 2001; Hemp 2005; Walther et al. 2002). One of the few model-based studies that link changes in species composition with wildfires (Lenihan et al. 2003) indicates that predicted changes in vegetation composition would alter fire regimes in California.

Biotic disturbances

Biotic disturbances (insects, pests, pathogens, and invasive species) can dramatically alter ecosystem structure and composition (Dale et al. 2001; Dukes et al. 2009; Logan et al. 2003) and thus alter fire regimes. Many biotic agents are themselves altered by fire, thus creating a bi-directional relationship between fire and biotic disturbance (McCullough et al. 1998; Parker et al. 2006). While reviews and ecological theory indicate that fire severity and occurrence increase following significant insect outbreaks, there are also studies showing no significant changes. Several review papers caution that fire-insect linkages vary with ecosystem type and site conditions and suggest that further research is needed (Parker et al. 2006; Simard et al. 2011). There is a growing literature suggesting that recent climate trends and projected climate change in the western USA has substantial impacts on the survival and spread of insect pests, pathogens, and invasive species (Bentz et al. 2009; Volney and Fleming 2000; Williams et al. 2013), and many of these studies argue that increased biotic disturbances will likely increase fire risk (Fleming et al. 2002; Parker et al. 2006).

PUBLIC-FIRE

The primary motivation of fire-related public policies is to protect human life and property as well as to preserve ecologically sensitive areas. We consider policies in three phases (before, during, and after fires) as well as the ways that fire events may shape future policy.

Pre-fire policies

In many parts of the western USA, suppression of wildfires over the past 70 years has significantly increased surface and canopy fuels, increasing the likelihood of severe fires (Reinhardt et al. 2008). Fuels management strategies can address surface, ladder, and canopy fuels, influence surface fire and crown fire behavior, and provide continuous, programmatic fuel management (Reinhardt et al. 2008). The impacts of fire suppression and fuel treatments vary with spatial differences in climate and ecosystem structure, and it is challenging to disentangle the impact of human activities from the impact of climate variability on fire regimes (Bowman et al. 2011). Recent reviews highlight the need for site-specific analysis of fuel management policies and procedures (Moritz et al. 2014).

Fuel breaks are among the most common landscape-scale fuel treatments. Fuel breaks lower the volume and continuity of fuel with the goal of supporting fire suppression. Agee et al. (2000) provide a thorough review of research that analyzes the effectiveness of different types of fuel breaks. Construction standards, the behavior of an approaching fire, and the level of suppression effort all contribute to the effectiveness of fuel breaks. While there is a clear theoretical basis for concluding that fuel breaks can aid suppression, the empirical analysis of fuel break effectiveness has been mixed (Agee et al. 2000).

Prescribed burning of fuels is widely practiced on public lands in the western USA. Low-intensity prescribed burning can operate much like thinning to reduce surface and ladder fuels. Landscape-scale high intensity prescribed burning has been proposed as a way to comprehensively treat fuels, with the potential to return fuel levels and stand composition to pre-suppression conditions (Fule et al. 2004). Research reviewed in Agee and Skinner (2005) indicates that landscape-scale prescribed burns, along with stand-scale thinning, can be used to reduce surface fuels, increase height to live tree crown ratios, decrease crown density, and retain large trees of fire-resistant species. More analysis, including case studies of different forest types, is needed before general conclusions can be drawn about the effectiveness of high-intensity prescribed burns.

Managing ignition risk is often another component of pre-fire management policy. Many factors explain the spatial variation of fire ignition, including climate, population distribution, and land use. While existing research on fire regimes in the western USA provides some data on ignition patterns for specific regions (Barrows 1978; Baisan and Swetnam 1990; Mallek et al. 2013), these are not linked to specific risk management policies. Reinhardt et al. (2008) note that ignition is rarely affected by fuel treatment or other fuel management policies.

While the literature summarized earlier includes experimental evaluations of specific treatments (e.g., Stephens and Moghaddas 2005) and modeling approaches have been developed (e.g., Stratton 2004), we did not find papers that present empirical analysis of the effectiveness of fuel management policies that are actually in place (e.g., how a specific regulation or incentive alters spatial or temporal fire patterns). Similarly, little is known about the relative success of ignition management policies, such as fire awareness campaigns, and the regulation of hazardous activities.

Fire-event policies

During a fire, the critical management question is how best to allocate resources to the suppression effort. The effectiveness of suppression efforts is influenced by landscape conditions (topography, vegetation structure, the road network, etc.), land ownership status, and the professional expertise of local and regional fire-fighting agencies (Silva et al. 2010). However, the relationship between effectiveness and resource expenditure is not always clear. In Southern California, despite the increasing expenditures on fire suppression, property losses have steadily increased during the last two decades (Keeley 2002; Noss et al. 2006). Ward et al. (2001) examine fire history studies in Canadian forests and conclude that aggressive fire suppression has been effective in reducing the overall average annual area burned. While there are a number of local and regional fire history studies (Arno 1980 and 1983; Baisan and Swetnam 1990; Barrett et al. 1997; Kilgore and Taylor 1979; Pyne 1982; Taylor and Skinner 1998), there is not a broad review of fire history studies for the western USA that provides general insights about the effectiveness of fire suppression.

Post-fire policies

In western North America, post-burn landscapes demonstrate a substantial capacity for natural recovery. By altering successional and other forest dynamics, post-fire interventions may have impacts lasting for decades. Beschta et al. (2004) review research on post-fire management policies and conclude that most post-fire interventions do not contribute to ecological recovery and may interrupt ecological dynamics. In particular, the authors find that seeding and other erosion controls and ground-based salvage logging are inconsistent with the goal of restoring ecosystem functions. Chen et al. (2013) review recent literature on post-fire effects and find that the effectiveness of post-fire treatments varies by location and treatment type (e.g., reseeding or other erosion controls). These authors also note a lack of studies evaluating the effectiveness of treatments for satisfying multiple objectives (e.g., erosion control, ecological recovery, and reduced fire risk).

Effects of fire on public policy

Fire events, particularly if large and destructive, have the potential to shape public policies toward fire. Similarly, fire suppression and post-fire intervention are actions by public agencies that are directly influenced by fire characteristics. Examples can be drawn from US history. The 1910 fires in Washington, Idaho, and Montana galvanized support for the fledgling US Forest Service (Egan 2009). In the modern era, the 1988 fires in Yellowstone National Park led to the suspension of the prescribed natural fire policy that had governed fire management in national parks and wilderness areas across the USA and a review of national fire management policy (Schullery 1989). Although there has been a return to the "let-burn" policy in the decades following the Yellowstone fires (Aplet 2006), Fifer and Orr (2013) conclude that, as result of the Yellowstone fires, the National Park Service now places greater emphasis on fuels management and suppression. While the policy effects of the Yellowstone fires have been investigated, additional research is needed to identify more generally how fire events influence public policies toward fire management.

PRIVATE–FIRE

Fire risk perception, fire ignition awareness, fuels treatment, and choice of home buildings can all play a role in wildfire management. Homeowners in the WUI frequently face higher risks from wildfire and thus have the greatest potential to mitigate fire risk.

Previous studies have sought a better understanding of how individuals living in fire-prone areas perceive wildfire risk, with a smaller body of literature focused on actions by homeowners to mitigate that risk. Surveys and focus-group interviews are the most common methods used to identify how individual homeowners perceive fire risk (Brenkert–Smith et al. 2006; Gardner et al. 1985; McCaffrey 2004; McCaffrey 2008; Winter and Fried 2000), although additional work focuses on theoretical foundations of risk perceptions and uses laboratory experiments to model responses to fire risk (Maguire and Albright 2005; Talberth et al. 2006). McCaffrey (2008) finds that although homeowners want more information about how to mitigate fire risk, they fail to sufficiently reduce fuel loads on their property because they believe the government will control fires through suppression. Other reasons for the lack of private effort to treat fuels include misinformation about risk (Talberth et al. 2006) and the belief that risk mitigation is difficult or impossible (Winter and Fried 2000). Homeowner surveys yield mixed results on the influence of fire events on attitudes and behavior (Gardner et al. 1985). Some homeowners appear to grow more vigilant following a fire, while others seem even less inclined to make costly adjustments, due perhaps to a sense of futility (Winter and Fried 2000). The relative strength of these responses and their ultimate effect on mitigation activities remains an open question.

Economic studies of the effects of strategic interactions among private landowners provide more conclusive results. Theoretical analyses show that because defensible space creates positive spillovers, individual landowners have an incentive to free-ride on the efforts of their neighbors, with the result that too little action is taken (Butry and Donovan 2008; Busby et al. 2013; Crowley et al. 2009). These theoretical insights are supported by empirical analyses that use data on actual homeowner decisions. Taylor et al. (2013) find that Nevada homeowners in fire-prone areas have an adequate understanding of wildfire risk but nonetheless underinvest in defensible space. Shafran (2008) finds similar evidence of strategic interactions among property owners in Colorado.

While some insights have emerged regarding homeowner actions to mitigate wildfire risk, there does not appear to be any research identifying how such actions influence fire outcomes, such as total number of wildfires, acreage burned, or property losses. While use of defensible space, fuel treatments, and fire resistant building materials are well-established means to mitigate wildfire risk (Cohen and Saveland 1997; Cohen et al. 2000; Winter et al. 2002), empirical analyses of the effects of these activities on fire outcomes are lacking.

A separate line of inquiry examines the costs of fire in terms of human health and property. Moeltner et al. (2013) use measures of inpatient treatment expenses to quantify the cost of wildfire to human health and determine how those costs are influenced by factors such as fuel conditions and distance from the fire. Similar to Butry et al. (2001), their estimates indicate treatment costs between \$121 and \$467 for each additional 100 acres burned. Richardson et al. (2013) use averting behavior and contingent valuation approaches to measure individuals' willingness to pay to avoid costs of wildfire smoke. They find that the willingness to pay to avoid smoke events is much higher than hospitalization costs measured in other studies.

Wildfire risk has the potential to influence demand for homes in the WUI, which affects property prices as well as future housing development. Donovan et al. (2007) find that higher wildfire risk ratings in Colorado Springs are associated with lower home values. Similarly, Mueller et al. (2009) find that home prices decline significantly in Southern California following a fire, and even more so in locations that have experienced multiple fires. These localized findings suggest that additional research is needed on how fires impact not only costs but also the willingness of people to move into fire-prone areas; however, a comprehensive study of western North America has not been done.

Finally, theoretical analyses have considered optimal forest management in the face of wildfire risk. Reed (1984) finds that when timber stands are subject to fire risk, rotation lengths should be shortened to avoid the possibility of loss from fire. Amacher et al. (2005) extend Reed's stand-level analysis to include the level and timing of fuel management activities that reduce losses in the event of a fire. These authors find that fuels management activities undertaken during the timber rotation allow the manager to optimally extend rotation ages. Lastly, researchers have examined how non-timber benefits from forests affect the optimal management of forests subject to fire risk (Amacher et al. 2005; Englin et al. 2000).

PRIVATE–PUBLIC

Private individuals can influence wildfire policy in the United States in three general ways. Structured channels exist through which the public can provide input for decision-making, for example, community members can voice concerns directly with local and regional decision-makers, and other petition and public input processes exist for ecosystem management decisions that may influence wildfire policy. Additionally, wildfire management can be indirectly influenced through less formal channels such as media engagement on issues of prevention and suppression. Finally, public agency employees are also individuals, and their personal motivations may influence how wildfire policy is designed and implemented. At the same time, public actions may alter the incentives faced by private landowners in a variety of ways. Two important avenues are through (i) public fuels management programs that can potentially crowd out private action and (ii) insurance or disaster relief programs that may increase settlement in risky areas, such as the WUI.

Although structural channels of influence have been studied in other contexts (e.g., Ando 1999), Anderson et al. (2013) is the only study to examine the impact of public input on wildfire prevention in the USA. Using data on public programs to reduce hazardous fuels, these authors show that, although responsive to local political demands such as for treatments near housing developments, managers still primarily use technical factors, such as ecological conditions, to locate fuels reduction projects. How private individuals can influence wildfire management through informal channels has not been studied.

The bureaucratic decision-making process may be influenced by the personal motivations of public employees themselves. Leaver (2009) presents a general theory of how the concerns of bureaucrats about their career prospects may lead to overly cautious behavior, including lax enforcement of statutes or management plans. While Leaver's case study does not focus on wildfire management, her insights into bureaucratic motivations may be applicable. For example, Calkin et al. (2011) argue that new risk management frameworks and technologies could improve wildfire management but cite a number of reasons why these tools have not been adopted. The authors suggest that the incentives faced by public employees may not properly align with wildfire management goals. Moreover, risk management strategies may not be accepted by property owners in the WUI, making it difficult for managers to resist public demands for fire suppression.

Public agencies can provide incentives for private landowners to undertake fuel reduction or contribute to fire suppression activities. In a theoretical study, Amacher et al. (2006) evaluate government cost-sharing schemes, finding that fuel reduction and fire suppression programs can effectively incentivize private mitigation of fire damage. Overall, the suppression program is more cost-effective, but the fuel reduction program may perform better when landowners underestimate fire risk. The lack of empirical evidence on the efficacy of public policies for private fire prevention and suppression limits our understanding of which programs perform the best given local conditions.

Public provision of fire prevention and suppression may give rise to free-riding. Just as private individuals have an incentive to free-ride on the fuels treatments undertaken by neighboring homeowners, public managers may free-ride on actions by private individuals and vice-versa. Busby et al. (2013) conduct a theoretical analysis of fuels treatments using a model with private and public owners and find that ownership fragmentation reduces the effectiveness of wildfire risk management. Similarly, Busby and Albers (2010) find that public agencies free-ride when budgets are low and property values in the WUI are high, and that free-riding by private landowners increases with public liability for properties in the WUI and public budgets allocated for fire prevention.

Public subsidies for wildfire insurance and fire suppression may induce risky behavior by private individuals, such as settlement in the WUI and failure to reduce fuels on private property. Risk-smart insurance policies in the UK have been shown to affect landowners settlement decisions (Doherty 1980), but studies for western North America are lacking. Shafran (2008) proposes that conditional insurance premiums for early adopters of fire risk mitigation may induce optimal defensible space provision by all landowners.

PUBLIC–ECOSYSTEM

Public agencies at federal, state, and local levels use conservation planning and resource management in an effort to maintain ecosystem health and resilience. One of the priorities for conservation management is to restore ecosystems through recovery of their native species composition and mitigation of the negative effects of invasive species. Numerous studies have documented the impact of cheat grass, in invasive species in the Great Basin, on natural fire regimes (Brooks et al. 2004; Chornesky et al. 2005; Pimentel et al. 2008). Effective eradication policies might be expected to shift the system toward pre-invasive fire regimes, although this has not been explicitly evaluated. Furthermore, an unintended consequence of eradication may include spikes in fuel volumes if dead biomass is not disposed of after mechanical clearing. Similarly, management strategies for insect infestations may have indirect impacts on fire regimes. For example, the US Forest Service includes thinning practices as part of its 2012–2016 Western Bark Beetle Strategy. This moderate thinning and other post-epidemic treatments are expected to have consequences for fire regimes (Jenkins et al. 2008; Sims et al. 2013) but these have not been rigorously evaluated.

Conservation planning can also restrict human activities including timber harvesting and road construction (e.g., the Roadless Area Conservation Act), thus affecting ecosystem structure and function. Timber harvesting, especially clear-cutting, may reduce biomass accumulation and therefore fuel loads. On the other hand, inadequate reforestation and afforestation as well as poor management of logging slash have the potential to increase wildfire risk (Moreira et al. 2011). In general, by limiting or accelerating human activities that alter forest structure, conservation planning can also alter fire regimes. However, we did not find a comprehensive synthesis of the indirect effects of public conservation planning or resource management on fire regimes.

PRIVATE–ECOSYSTEM

Population growth has had widespread impacts on ecosystems and thus potentially on fire regimes in western North America. The environmental impacts of housing expansion into the WUI have been well researched, and several review papers (Radeloff et al. 2005; Syphard et al. 2007b) summarize the effects of residential expansion on fire regimes in the USA. From analysis of historical data, Syphard et al. find that development in the WUI had the greatest influence on fire by increasing area burned. This influence was strongest between 1960 and 1980 when the development was occurring most rapidly. Radeloff et al. (2005) determine that fragmentation and habitat loss were important contributors to increased fire risk and stress the need for land-use planning focused on mitigating wildfire. Theobald and Romme (2007) use a modeling approach to predict housing expansion, finding that the intermountain region of the western USA had the most rapid expansion into the WUI. They link this increased development to increased fire frequency. More fine-grained quantification of housing density and its link with fire regimes, however, remains an area for future research.

Besides urban development, logging and grazing are the primary means by which private individuals alter ecosystems. Ecosystem-specific reviews by Franklin et al. (2002) (Douglas fir), Romme et al. (2009) (piñon-juniper), and Allen et al. (2002) (ponderosa pine) assess the effects of logging and grazing on forest structure and function. In these reviews, there is consensus that anthropogenic alteration of these ecosystems has led to dramatic changes in fire regimes. Franklin et al. (2002) find that the change in forest structure resulting from logging alters the resiliency of forests after fire, particularly with regards to seed stock and regeneration. The other two papers conclude that grazing has an effect on fire frequency. These studies identify site-specific relationships between logging and grazing and ecosystem function. Synthesis studies that consider the effects of these anthropogenic disturbances across ecosystems or regions would clarify the influence of site-specific conditions.

Grazing is a major driver of grass invasion into native grasslands and has impacted regional and local fire regimes. A global study of grassland ecosystems by D'Antonio and Vitousek (1992) presents a model of invasion of predominantly African grasses into American rangelands. Their model suggests that invasive grasses are better able to recolonize following a fire, leading to a positive feedback cycle in which native grasses are increasingly displaced by invasive plants following fire events. Several other studies corroborate these findings (Brooks et al. 2004; Seabloom et al. 2003). There is an agreement that fragmentation of grassland habitat and destruction of native seed banks has a large impact on the success of exotics and, in turn, on the annual supply of light fuels. Several studies have examined the relationship between invasions, human intervention, and fire regime (Dukes and Mooney 2004; Keeley 2006). Belsky and Blumenthal (1997); Bachelet et al. (2000); Fuhlendorf and Engle (2004), and Diamond et al. (2010) analyze the importance of grazing as a control of fire risk and post-fire impacts at a regional scale.

CLIMATE–PRIVATE

Potential effects of climate change on private actions include altered human migration patterns (Karl et al. 2009) and changes in land use due to altered crop and forest yields (Haim et al. 2011), both of which could affect wildfire regimes and their consequences for humans. It is well established that weather is a key determinant of human settlement decisions (Rappaport 2007), but whether humans will adapt to a changing climate or migrate to more hospitable regions is an issue that has not been analyzed in depth (Hartmann 2010). Haim et al. (2011) project land use in the USA under alternative IPCC scenarios, accounting for climate change effects on yields and commodity prices. They find that forest area remains constant or declines in the western USA, while developed land area increases significantly. The implications of these results for wildfire are unclear. While a loss of forest area may decrease the amount of available fuel, if it is the result of homebuilding in the WUI, overall wildfire frequency may increase (Syphard et al. 2007b). Moreover, Bonan (1997) shows that vegetation patterns can influence climate at regional scales. Current managed vegetation patterns in western North America induce more warming than natural vegetation. In particular, forest clearing is associated with higher temperatures, which could increase the occurrence and severity of wildfires. Additional studies are needed to identify climate-induced land-use changes at finer scales so that the consequences for wildfire can be estimated. The modeling frameworks in Syphard et al. (2007a, 2007b) could potentially be adapted for this purpose.

Discussion and Conclusions

Our findings are summarized in Table 1. While many topics have been studied extensively and review papers exist, others have been investigated only in case studies or with theoretical models. Overall, the linkages among ecosystems, climate, and fire have been relatively well studied,

Table 1. Categorization of fire and climate change topics according to whether they have been studied extensively and reviewed, been the subject of case studies, or represent gaps in the literature.

Linkage	Studied extensively and reviewed, questions remain but synthesis available	Moderately well studied (e.g case studies or papers discussing issue but high uncertainty)	Gaps in the literature
Climate–Fire	Contribution of historic climate variation to fire regimes and behavior	Climate change influences on ignition	
	Contribution of historic climate variation to ignition	Climate changes influences on fire regimes	
		Contributions of fires to climate change	
Ecosystem–Fire	Influence of type, frequency, and severity of fires on ecosystems	Impact of fire regimes on ecosystem function and ecosystem services	Ecosystem biogeochemical cycling influences on fire
	Fire-related adaptations by ecosystems		
Climate–Ecosystem		The effect of climate-driven changes in ecosystem producitivity on fire	Effect of changes in forest productivity on wildfire
		The effect of climate driven changes in ecosystem composition and its influence on fire	
		The effect of climate driven disturbances (changes in pest/insect/disease) on fire	
Public–Fire	Suppression policy effects on ecosystems and fire vulnerability	Ignition patterns and fuel management policy impacts on ignition	
	Impact of fuel breaks, prescribed burns, and thinning on fire regimes	Effectiveness of suppression activities during fire	
	Impacts of post-fire management on ecosystem and future fire regimes	Policy response to fire events	
Private–Fire	Pre-fire risk perceptions	Post fire effects on property values and continued WUI expansion	Influence of risk perceptions on mitigation behaviors
		Fire effects on human health	Efficacy of mitigation activities on wildfire outcomes
		Post-fire risk perceptions	
		Free-rider problems and strategic interactions in WUI	
		Private forest management on fire regimes under wildfire risk	
Private–Public		Formal influence on fire policy through public demand and communication with officials	Informal private influence on fire policy
		Internal bureaucratic motivations and incentives	Empirical studies of the efficacy of incentive programs for landowners

(Continues)

Table 1. (Continued)

Linkage	Studied extensively and reviewed, questions remain but synthesis available	Moderately well studied (e.g case studies or papers discussing issue but high uncertainty)	Gaps in the literature
		Impact of policy on private risk mitigation externalities and moral hazard Theoretical analyses of the efficacy of incentive programs for landowners	
Public–Ecosystem		Indirect impacts on fire regimes from resource management Indirect impacts on fire regimes from conservation planning	
Private–Ecosystem	Indirect effects on fire regimes from logging and grazing Indirect effects on fire regimes from WUI development		
Climate–Private		Effects of climate change on land use patterns Local effects of land-use change on climate	Effects of climate change on human migration

although substantive uncertainties remain. The linkages between fire and private and public actions, particularly the topics of human risk perception, fuel management, and suppression, have also received a good deal of attention in the literature. Public and private interactions, indirect impacts on fire regimes through public and private modifications to ecosystems, as well as theeffects of climate on private actions that may ultimately alter fire regimes have been at most examined in case studies. For almost all of the linkages we examined, there are significant gaps in the literature.

Several major themes emerge from our examination of the literature on fire and climate change in western North America. First, studies of the linkages between human and natural systems often demonstrate that a particular phenomenon has an effect on wildfires but fail to quantify the magnitude of the effect. For example, many studies examine how human behavior, such as investment in defensible space, is affected by perceptions of wildfire risk, but how these behavioral changes influence the distribution of fire events is not known. Similarly, ecological studies may show a clear relationship between forest density and fire severity, but the impacts of forest harvesting regulations, such as the Healthy Forest Act in the USA, or other fire policies that support fuel management on fire regimes have not been quantified. Quantifying (or even demonstrating) a relationship between specific policies and fire-related outcomes is challenging. Fire is episodic, and patterns of fire on the landscape are clearly influenced by multiple interacting factors. Thus, it can be difficult disentangle the impact of specific public or private actions. Nonetheless, better understanding the magnitude of these effects is needed to formulate effective management strategies. Assessing how land management decisions affect fire regimes requires monitoring data, and remote sensing-based studies can facilitate this type of broad analysis of policy-fire-ecosystem interactions. Alternatively, integrated landscape models that account for interactions among components of the natural and human systems can be used to at least theoretically estimate these interactions.

Second, existing research tends to focus on direct effects among components of the system, giving less attention to indirect effects on fire. For example, how fires are affected by public expenditures on fuels management has been studied extensively, but how public expenditures might be influenced indirectly by climate change or private actions has not been examined. One of the explanations for this knowledge gap is the large differences in the spatial and temporal scales of biophysical studies on treatment effects and social science studies of policy drivers. In order to bridge this gap, an important goal for future research is to identify and analyze ecosystem and land-use changes at a finer scale over a larger spatial extent. Only then can the indirect consequences for fire be estimated. Additionally, there is a need to conduct more site-specific empirical analysis of areas affected by fire and then to compile a thorough review of fire histories, especially for the western USA. This will help researchers identify spatial and temporal patterns and draw conclusions about how fire affects the other components of the system, including climate, public policy, and private behavior.

Third, empirical analyses of private landowner behavior are needed to develop a better understanding of how private individuals interact with wildfire, and what this implies for wildfire management policy. There is a large literature in economics focused on free-riding and moral hazard problems, but the bulk of these studies are theoretical analyses. Fewer studies have tested these theories empirically, although the results have been supportive. Other social science research on wildfire risk perception relies primarily on surveys and focus-group responses, rather than on analyses of observed behavior. Taken together, these observations suggest that substantial work remains to be done on understanding human behavior for the purposes of designing more efficient and effective wildfire management policy.

Finally, we find in our review that, to a large degree, the literatures on the human and natural systems have developed independently of one another. As such, important interactions and feedbacks among system components are poorly understood. For example, there is considerable research analyzing how climate, fire, and ecosystem structure and composition interact and a growing body of work that identifies the impact of human actions that modify the landscape. Nonetheless, theories of why, how often and when these actions are likely to occur and how human actions themselves are influenced by fire and the spatial-temporal patterns of natural processes remain unclear. For example, while there is consensus that fire suppression has altered ecosystem structure in some regions, how decisions about fire suppression get made is less well studied. Similarly, although uncertainties remain, studies have documented cases where forest management practices such as harvesting, thinning, or invasive species management have altered fire regimes. Studies of these activities, however, rarely consider how public and private incentives influence the type, scale, and location of these activities, all of which may strongly influence fire events. We also note that fire, in turn, may influence private and public decisions (e.g., by altering fire policies). Models of future fire regimes and consequences for ecosystems, however, rarely account for potential behavioral and policy changes. Overall, our review identifies a need for integrated studies that consider the interactions between human and natural system drivers. In sum, the broader perspective on the coupled natural and human system that we provide in this article identifies the critical gaps in the research on fire and climate change, thus defining a future research agenda that can lead to a more effective wildfire management. A broader perspective also facilitates a deeper analysis of the interaction among fire, climate, ecosystems, and public and private behavior and motivates an extension of current research to include assessments of the effects of wildfire on the multitude of benefits that humans derive from ecosystems.

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