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The Economics of Wildfire in the United States

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Abstract

Wildfire is a natural phenomenon with substantial economic consequences, and its management is complex, dynamic, and rife with incentive problems. This article reviews the contribution of economics to our understanding of wildfire and highlights remaining knowledge gaps. We first summarize economic impacts to illustrate scale and trends. We then focus on wildfire management in three phases: mitigation before fires occur, response during fires, and response after fires. The literature highlights economic interdependencies and spillover effects across fire-prone landscapes as the source of economic inefficiencies and motivation for public institutional response. The literature illustrates the complexity of this problem with its myriad threads, including the trade-offs of living in fire-prone environments, the prospects for using controlled fire and mechanical fuel removal for reducing wildfire severity, the decision-making environment that firefighters face, and the economic consequences of wildfire smoke on health. Economics provides valuable insights, but fundamental questions remain unanswered.

1. INTRODUCTION

Wildfire is a natural phenomenon and an essential process in many ecosystems worldwide, but it poses substantial risks to society. Over the past several decades, wildfires in the United States have grown larger, causing billions of dollars' worth of damages despite billions more in response[1] (**Figure 1**). These measured costs are only a fraction of the societal impacts of wildfire. Research points to three factors driving the trends in wildfire: a changing climate (Abatzoglou & Williams 2016), an accumulation of fuels (Mercer et al. 2008), and a growing wildland-urban interface defined as the space where development intermingles with wildlands (Radeloff et al. 2018). Each of these factors involves a biophysical and social component. Economics has developed a set of conceptual and analytical tools well suited to study how individuals make decisions when faced with the complex trade-offs involved with wildfire management and how they affect wildfire outcomes.

Before delving into the wildfire economics literature, it is worth briefly reviewing the history of wildfire management in the United States.[2] A large wildfire in 1910 known as the Big Burn marked the beginning of modern wildfire management in the United States, initiating an active role for the US federal government and a strategy of aggressive wildfire suppression that was unique in human history outside of urban settings (Egan 2010; Pyne 1998, 2017). For most of the twentieth century, wildfire was approached as a threat to valuable timber and property and something to be extinguished. The United States Forest Service (USFS) maintained the so-called 10 AM policy through much of the twentieth century, dictating that all fires be immediately suppressed when discovered (Lueck & Yoder 2015). To the extent that this policy of aggressive

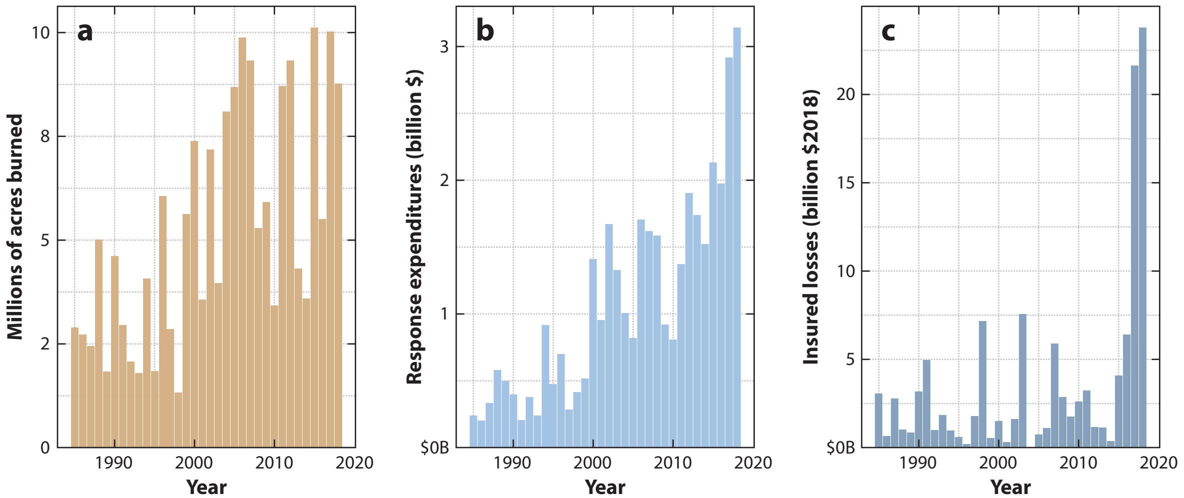

Figure 1

Trends in wildfire outcomes from 1985 to 2018. The outcomes include (*a*) acres burned annually, (*b*) annual response expenditures (nominal), and (*c*) annual insured losses in 2018 dollars. The data for panels *a* and *b* are from **https://www.nifc.gov/fire-information/statistics/suppression-costs**, and those for panel *c* are from **https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards/wildfires-as-the-climate-changes-so-do-the-risks.html**.

[1]Throughout the review, we use the term suppression to denote the act of reducing fire activity and response to include suppression as well as other activities undertaken by wildland firefighters during an active incident (e.g., asset protection, evacuation, emergency medical services).

[2]See Pyne (2017) for a detailed history of wildfire in the United States.

wildfire suppression was successful, it effectively excluded fire from US ecosystems that had evolved to exist with wildfire, resulting in an accumulation of fuels in many fire-prone landscapes (Omi 2015). During the same period, humans have increased their demographic and economic footprint, placing more highly valued property at risk. These two factors combined with a changing climate have led to unprecedented fire activity and consequences to society. **Figure 1*a*** shows how the size of wildfires has been increasing since the 1980s, and this growth is associated with a concomitant increase in the cost of wildfire response.

The objective of this article is to review the contributions of economics to our understanding of wildfire management and to highlight existing knowledge gaps. Wildfire is present on all continents but Antarctica, but to frame the review, the discussion focuses largely on the United States. In the conclusion we briefly discuss the extent to which the economics of wildfire in the United States corresponds to that in other parts of the world. The article begins with a review of the literature on the societal impacts of fire and then follows a natural progression focusing on wildfire risk mitigation and response. Within this progression, it builds from the literature on the economic fundamentals, incorporates economic incentives and behavior, and progresses through the economics of the institutional response to fire. We draw on relevant literature from ecology and other fields for context. The review ends with a broad synthesis and summary of knowledge gaps and possible future research directions.

2. IMPACTS OF FIRE ON SOCIETY

Wildfire impacts society and the environment in a number of ways. During an active incident, fire can directly impact people by posing an immediate threat to life, property, and local economies (Milne et al. 2014). Wildfires also diminish air quality, which can have significant impacts on human health both near the fire and up to thousands of miles away as the smoke is transported (O'Dell et al. 2021). Beyond these direct effects, fire can influence behavior as people evacuate or simply try to avoid smoke exposure (McCaffrey et al. 2018). Wildfires continue to affect people well after they are extinguished by impacting recreation opportunities (Hesseln et al. 2004), amenity values (Loomis & González-Cabán 1998), and property values (McCoy & Walsh 2018). In addition, fire affects society via its impact on the environment. While fire can promote healthy ecosystems by clearing understory, cycling nutrients, and reseeding various species of flora, fire can also dramatically alter ecosystem services in the years after a fire (Pausas & Keeley 2019). Precipitation in the year following a fire can lead to elevated sediment in watersheds that may affect water quality. In steep terrain, the loss of soil-stabilizing vegetation can also lead to landslides (Gannon et al. 2019).

Despite the management effort spent on property protection during wildfire incidents, structures are damaged and destroyed. In 2020, damages from wildfire totaled US$16.5 billion in the United States, with more than 10,000 structures damaged or destroyed in California alone (NOAA 2021). Fires do not burn uniformly, and many factors can influence whether structures are damaged or destroyed. Calkin et al. (2014a) develop a model of wildland-urban interface fire disasters—fires that burn hundreds of structures or more—and focus on those conditions where response capability is overwhelmed by extreme fire behavior. Alexandre et al. (2016) construct a data set of structures destroyed within known fire perimeters using satellite imagery from before and after the fire. They find that topography and building arrangements impact structure loss, but the relative importance of these factors varies across regions of the United States. Caggiano et al. (2020) find that structure proximity to fuels and lower structure density are associated with an increased probability of structure loss. While these studies provide useful information, they ignore the role of deliberate wildfire response operations during the fire. Olsen & Yoder (2021) show that holes in fire perimeters, known as refugia, are more common near structures, suggesting that firefighting resources play an important role in the survival of structures.

Wildfires can move quickly, posing a risk to people in their paths. Evacuation decisions have received some attention in the literature (McCaffrey et al. 2018, McNeill et al. 2016, Mozumder et al. 2008, Paveglio et al. 2014, Toledo et al. 2018). Wong et al. (2020) investigate whether evacuation decisions related to the 2017 Southern California wildfires are better described using a regret minimization model than the traditional random utility model. Although they find weak evidence of regret aversion, they attribute the weak results to the use of revealed preference data that limit attribute-level variation.

The smoke generated by wildfires can diminish air quality both near the conflagration and thousands of miles away (O'Dell et al. 2021). Burke et al. (2021) find that wildfires contributed approximately 25% of fine particulate matter (PM2.5) in recent years. The impact of air quality on human health is an active area of research in environmental health (Manisalidis et al. 2020) and economics (Currie et al. 2014). However, there are few economic studies of the morbidity and mortality costs associated with wildfire smoke exposure. Moeltner et al. (2013) use an instrumental variable approach to estimate that hospital admissions for respiratory conditions in Reno, Nevada increase by 0.3% per unit of smoke-induced PM2.5, which they value at $2.2 million. Kochi et al. (2016) find that smoke from 22 Southern California wildfires in 2007 led to excess hospital admissions with an associated health care cost of $3.4 million. Johnston et al. (2021) estimate the 2019–2020 Australian bushfire season led to health care costs of AUS$1.95 billion. The value estimates from these studies rely on health care costs, which underestimate the full economic cost of wildfire smoke. Richardson et al. (2013) use stated and revealed preference methods to estimate that people were willing to pay $85 to $95 per day to avoid fire smoke during the 2009 Station Fire in Southern California. Jones (2017, 2018) uses a life satisfaction approach to estimate willingness to pay (WTP) as high as $373 to avoid smoke exposure over one's county of residence. Jones & Berrens (2021) examine smoke attributable to prescribed burning in Georgia to estimate the impact on birth outcomes in Atlanta and show that these impacts are more pronounced in populations of color and those below the poverty line. A recent Environmental Protection Agency (EPA) report supported by the US Department of Agriculture and Department of the Interior devotes significant attention to the smoke impacts of wild and prescribed fire used to reduce wildfire risk (EPA 2021). These studies document the economic costs associated with both wildfires and prescribed fires that should be considered by fire-managing agencies and policymakers.

The diminished air quality caused by plausibly exogenous wildfire smoke creates an appealing study design to estimate causal impacts of air quality on various health and social outcomes. Since 2006, the National Oceanographic and Atmospheric Administration's Hazard Mapping System has produced daily geospatial estimates of smoke plumes (**https://www.ospo.noaa.gov/Products/land/hms.html#maps**). Borgschulte et al. (2020) use the plume data to estimate that wildfire smoke reduces labor market earnings by $93 billion per year across the entire United States, highlighting the large indirect costs associated with wildfires. Miller et al. (2021) use the smoke plume data to identify the effect of PM2.5 on mortality in the Medicare population and estimate the annual mortality cost of wildfire smoke is just over $6 billion. Research continues to reveal additional societal impacts of diminished air quality (Burkhardt et al. 2019, 2020), to which wildfire will continue to contribute.

Wildfire can also impact people by altering local amenities and affecting their perceptions of future wildfire risk. Economists have used hedonic methods to estimate the impact of wildfire on property values (Loomis 2004, Mueller & Loomis 2014, Mueller et al. 2009, Stetler et al. 2010). McCoy & Walsh (2018) use a similar technique to show that wildfire risk is salient after a fire but fades quickly in the years following the fire. Prior to a wildfire, the attributes related to parcel wildfire risk may also affect home sales prices. Donovan et al. (2007) find that housing price and wildfire risk are positively correlated before the local fire department publishes a parcel-level risk assessment, after which they find housing price and wildfire risk are negatively correlated. While location and topography are important determinants of wildfire risk, homeowners' choice of building materials can also be important. Champ et al. (2009) find that the amenity aspect of topography associated with higher fire risk is considered a desirable attribute by homeowners. However, fire-resistant building materials are also desirable. Hjerpe et al. (2016) find that preferences for proximity to dense forests depend on distance from the home; homeowners prefer more dense forest outside of 100 m from the home.

Outdoor recreation is estimated to account for 2.1% of US GDP in 2019, and even more in several western states where summer wildfires and smoke are common (BEA 2020). Wildfire can impact recreation by damaging facilities and recreation infrastructure such as campgrounds and trails (Englin et al. 2001, 2008) and through diminished air quality. The economics literature is relatively sparse on the impact of fire on recreation. Studies of hiking and biking activity after a wildfire find that both activities may decline, yet the per-trip benefits do not necessarily decline (Hesseln et al. 2003, 2004). More recently, Tanner et al. (2019) use revealed and stated preference methods and find that fire in the Angeles National Forest in California reduces welfare by $29 to $37 per trip. Most of these studies rely on survey data in selected locations. However, recent studies use administrative data containing campground reservations across the western United States to document the impact of wildfire on campground utilization (Gellman et al. 2022, Lee 2021).

Fire can have dramatic impacts on ecosystem services in the short and long term. Several tree species rely on fire for regeneration, and fire plays a role in biogeochemical processes (Pausas & Keeley 2019). Fire can also remove vegetation that stabilizes soil on steep slopes, leading to landslides as well as sediment deposits in waterways and drinking water sources (Gannon et al. 2019, Hohner et al. 2019). These events have acute impacts on society but have received little attention in the economics literature (Jones et al. 2017, Warziniack & Thompson 2013). In principle, data on water treatment costs could provide a lower bound on the impacts of wildfire on watersheds.

The impacts of fire on society prompt action both in anticipation of and in response to fire. However, the complex array of institutions and the lack of coordination among stakeholders can lead to economically inefficient mitigation and response strategies. Sections 3 and 4 describe these inefficiencies and the conditions within which they occur.

3. WILDFIRE RISK MITIGATION

The risk of damage to physical assets and harm to human well-being underscores the importance of mitigating wildfire risk by reducing vegetation and ignitability of structures. The economic risks of wildfire and the productivity of wildfire risk mitigation strategies vary across space and time, and effectively managing wildfire risks before a fire event entails accounting for this heterogeneity across the landscape (Hesseln 2000). The fire ecology literature has generally focused on fire behavior and how best to disrupt fuel contiguity and reduce density in order to reduce the extent and severity of fire (Mercer et al. 2008, Wei et al. 2008). In contrast, the economics literature has focused on the spatial wildfire risk spillovers, factors that influence the adoption of wildfire risk mitigation and the role of institutions in mitigation. We frame this section with a relatively simple economic model of wildfire mitigation to show how the spatiotemporal nature of fire along with misaligned incentives leads to economic inefficiencies.

We briefly describe the model in the text and provide detail in the **Supplemental Appendix**. Consider a landscape divided into a mosaic of private and publicly owned. The social planner chooses a level of mitigation to affect expected wildfire activity in order to maximize the net

Supplemental Material >

present benefits across the landscape. The direct costs of wildfires arise via damage to physical assets and impacts to human well-being (e.g., evacuation, smoke). The direct benefits of fire on the landscape accrue through impacts to ecosystem services. The spatial nature of fire and its impacts imply that fire on one parcel may impact people on other nearby parcels through transmission of fire and smoke.

Supplemental Material >

The first-order conditions of the social planner's problem highlight several potential economic inefficiencies (Equation 2 in the **Supplemental Appendix**). A private parcel owner only considers private benefits and costs of mitigation on their parcel, ignoring spatial spillover externalities (i.e., fire transmission across parcels) as well as conventional externalities (i.e., health impacts of smoke). The first-order conditions illustrate the many channels through which mitigation impacts society, and yet, this simple model does not consider the myriad institutional factors that further complicate private and public land management decisions.

The remainder of this section reviews the relevant literature on wildfire mitigation. We begin with the recognition of spatial externalities and their role in individuals' mitigation decisions as well as their consequences at the landscape scale. Second, we discuss the role of risk perception and other sociopolitical factors in shaping mitigation decisions. We end this section with a discussion of institutional factors that impact and are impacted by mitigation decisions.

3.1. The Role of Spatial Externalities

People make decisions about what property to own and how they develop, maintain, and use that property, all of which may reflect and affect wildfire risk or amenity attributes correlated with fire risk. Timberland owners' assets are often the actual fuel of wildfires, and forest fires behave and impact property differently than do grassland fires. Public electricity utility companies use infrastructure that can ignite fires (Arab et al. 2021, Kousky et al. 2018), and property owners who build and live in homes, especially in rural or peri-urban areas, not only face risk but increase the risk of economic loss by their choice to live in fire-prone areas. Beyond the risk of contact with actual wildfire flames, people choosing to live or work either in or downwind of fire-prone areas expose themselves to potential health consequences of wildfire smoke.

Wildfires often move through property boundaries, and smoke from them almost always does. So while private decisions affect private risk, they also affect the wildfire risk faced by their neighbors and their options and incentives for responding to it (Busby et al. 2012, Shafran 2008). Shafran (2008) formalizes a theory of these risk externalities and shows that they lead private landowners to mitigate less than the social optimum. Shafran (2008) and Warziniack et al. (2019a) find empirical evidence that defensible space (a form of private mitigation) is a strategic complement implying that a property owner is more likely to mitigate in response to mitigation on a neighbor's property. Busby et al. (2012) provide an explanation for this strategic complementarity with a game theoretic model of forest land owners.

3.2. Factors Influencing Private and Public Decisions to Mitigate Wildfire Risk

A homeowner's decision to mitigate risk via fuel reduction or structure hardening depends on risk perception, risk salience, information, and other social considerations. Brenkert-Smith et al. (2006) show that homeowners' decisions to mitigate fire risk are related to perceptions of fire risk and a complex set of social considerations. In addition, they find that whether community members talk with each other about wildfire is an important determinant of whether individuals engage in mitigation. Much of the literature finds wildfire risk perceptions and risk mitigation to be correlated (Brenkert-Smith et al. 2012, Fischer et al. 2013, Martin et al. 2009, McFarlane et al. 2011). However, few studies control for the joint determination of wildfire risk perceptions and risk mitigation action (Champ et al. 2013, Meldrum et al. 2019). Champ et al. (2013) find wildfire risk perceptions and reported mitigation actions to be jointly determined. Meldrum et al. (2019) use a simultaneous equations model to capture feedbacks and directionality between risk perceptions and risk mitigation.

Local government, fire departments, and nonprofits seek to incentivize individuals to manage vegetation on their properties and harden their homes. Incentives include site visits with a wildfire mitigation specialist to assess property-specific wildfire risk and mitigation strategies. Likewise, cost-sharing programs are often used to incentivize homeowners. Meldrum et al. (2014) find the decision to participate in a cost-sharing program and the decision about how much of the cost-share homeowners are willing to pay are related to different factors. In recent decades there has been an emergence of prescribed fire cooperatives for supporting the use of prescribed fire on private property (Toledo et al. 2014). The Firewise USA® program maintained by the National Fire Protection Association provides educational materials and maintains a nationwide community certification program. Although such programs have been examined in various ways (e.g., Wolters et al. 2017), the economics literature to date includes few studies that examine how local programs encourage private landowners to mitigate wildfire risk. A nudge experiment with private landowners in Western Colorado finds that providing parcel-specific wildfire risk information to private landowners can influence information-seeking behavior (Meldrum et al. 2021). The nexus between local wildfire education programs and mitigation efforts of private landowners is ripe for behavioral economics research.

Decisions to mitigate wildfire risk depend on the costs and perceived economic benefit of mitigation actions. Several studies have estimated the operational costs of fuel treatment (see Calkin & Gebert 2006 and references therein). These studies highlight that there are economies of scale in implementing fuel treatments but also institutional constraints that lead to higher costs. Contingent valuation methods have been used to estimate WTP for wildfire risk mitigation. People tend to have a higher WTP, in the hundreds of dollars, for reducing risk to homes in contrast to public lands (Kaval et al. 2007; Loomis & González-Cabán 1998, 2008; Talberth et al. 2006). Kaval et al. (2007) specifically address this spatial externality and find that Colorado residents living near public lands were willing to pay hundreds of dollars per year to reduce the risk of fire crossing from public land to their property. The WTP is also likely to depend on the type of fuel treatment. These studies provide clear evidence that people do value risk reduction. However, these estimated WTPs are becoming dated and may not reflect recent increases in wildfire activity that are expected to continue due to climate change.

In addition to homeowners, forest and grassland owners sometimes invest in expensive mechanical precommercial thinning of trees or carry out intentional controlled burns at some cost and risk to reduce the risk of losses from unplanned and uncontrolled fire (Amacher et al. 2005, Halbritter et al. 2020, Konoshima et al. 2008, Reed 1984). Public utilities invest in landscape management around electricity transmission infrastructure (Kousky et al. 2018), and homeowners affect the risk of loss in the event of a fire by their choice of building materials and landscape management.

Public land managers often face similar decisions about mitigation at the landscape scale. Fuel treatment decisions may be influenced by social and political factors. Wibbenmeyer et al. (2019) document that salient events like wildfire may bias risk perceptions and lead land managers to misallocate fuel treatments to areas with less risk by virtue of having recently burned.[3] Prescribed

[3]A similar mechanism may explain why Colorado has increased funding for fuel treatment grants in the year following a very active 2020 fire season (Davis 2021).

burning can be less expensive than mechanical treatments for public agencies but may be unpopular with the general public because it generates smoke, impacts natural amenities, and creates a risk of wildfire if it escapes control. Loomis et al. (2001) measure support for prescribed burning before and after an information campaign in Florida. The authors find that information campaigns can clarify the benefits of prescribed burning, which leads to increased support for prescribed burning. Understanding social and political barriers to fuel treatment is important given the urgent need to reduce fuel loads across the western United States.

As we discuss in Section 4, the public sector is often directly involved in wildfire response. Little if any of the costs of government firefighting are borne directly by property owners. However, these protection activities do reduce the costs of building and living in fire-prone areas (Kousky et al. 2012). Baylis & Boomhower (2019) find that the subsidy provided to property owners via wildfire response can exceed 20% of the value of property in high-risk areas. Kousky & Olmstead (2010) find that public fire suppression efforts have accelerated development in fire-prone landscapes.

3.3. The Role of Institutional Factors

Incentives to mitigate wildfire risk are affected by, and shape, a mosaic of regulatory and common law, administrative codes and standards, fiscal incentives, and market factors (Bradshaw & Lueck 2012). We focus on two examples of institutions here: liability law relating to fuel and ignition management, and insurance markets pertaining to wildfire.

3.3.1. Legal liability for ignition, fuels, and fuel management. Despite efforts to mitigate and regulate risk, wildfires happen, and legal liability follows. Liability rules affect the incidence of legal and economic responsibility for wildfire damage, and they can affect incentives for risk mitigation before fires happen and responses while fires are occurring. Legal liability over the ignition and spread usually follows typical negligence standards, but occasionally not. For a decade or more, California's Pacific Gas and Electric Company (PG&E) effectively faced a strict liability standard for wildfires ignited by their electricity transmission assets, and it filed for bankruptcy in 2019 after being found liable for a quarter of a billion dollars for fires in 2017 and 2018. Thereafter, the state legislature weakened their liability somewhat. The economic consequences of such regulations are substantial (Kousky et al. 2018).

Legal liability for fuel management and ignition varies across jurisdictions (Sun 2006). Yoder (2004, 2012) and Yoder et al. (2003) examine the economics of liability law and incentives over fuel and ignition, with emphasis on prescribed fire risk (Yoder et al. 2003) and liability for natural fuel accumulation (Yoder 2004). Yoder (2008) shows empirically that states with more stringent liability rules tend to have fewer escaped prescribed fires, except on federal lands where state liability law does not directly apply. More recently, Lauer et al. (2020) compare the effect of strict liability versus negligence standards on fuel treatment and timber harvest, and Langpap & Wu (2021) develop a theoretical model to examine the relative effectiveness of liability, cost-share agreements, and voluntary agreements on private mitigation incentives and outcomes. Florec et al. (2019) show that while the benefits of fuel treatments are highest in the Australian wildland-urban interface, the substantially higher costs, due to the risk of escape, do not always justify action.

3.3.2. Insurance. Most homeowners' insurance plans indemnify property losses to urban fire and wildland fire. However, like a flood, wildfire creates spatial correlation in risk that can create challenges for insurers that do not sufficiently diversify their portfolio. Climate change is also exacerbating wildfire risk, making it hard for insurance companies to quantify and price risks appropriately (Dixon et al. 2018). In California, uncertainty and regulatory restrictions on insurance premiums have led many insurers to exit high-risk markets completely (Flavelle 2020, Troy 2007).

Insurance can also alter the incentives of homeowners in fire-prone areas. First, insurance and regulation can influence the decision to own a home in fire-prone areas. Troy (2007) argues that California regulation to restrict insurance premiums encouraged an expansion of the wildland-urban interface. Second, insurance can create a moral hazard by reducing the incentive for a homeowner to mitigate risk to some extent (Talberth et al. 2006). Taylor (2019) shows that homeowners' decisions to mitigate risk not only depend on insurance, but also on the expectations that neighbors will rebuild lost homes in the event of a wildfire. Busby et al. (2013) highlight the interaction between insurance and government-provided wildfire suppression. The authors find that even proper risk-adjusted insurance may not incentivize mitigation in the presence of an implicit guarantee that the government will attempt to prevent damage to property. In contrast to the assumption of risk-adjusted premiums for wildfire assumed by Busby et al. (2013), few insurance plans impose wildfire risk-reduction contingencies, presumably increasing the disincentive to mitigate wildfire risk and insurance supply responses such as inefficiently high premiums and cancellation (Talberth et al. 2006).

4. WILDFIRE RESPONSE

Wildfire response[4] expenditures began growing in the early 2000s and have reached unprecedented levels in recent years, exceeding $2 billion in 2020 at the federal level alone (**Figure 1**). Expenditures tend to grow with the size and complexity of the wildfire incident. Importantly, response expenditures accrue when firefighting resources are requested by the fire manager, which depend on expectations about fire behavior, assets at risk of damage, the availability of resources, and institutional structures and sociopolitical pressures. Perhaps because of data availability and its amenableness to economic analysis, response expenditures have received more scrutiny by economists than other aspects of wildfire response. Here, we review the evolution of the economics literature focused on analyzing the determinants of response expenditures.

4.1. Response Costs

Over the past two decades, economists have used a variety of econometric approaches to analyze response expenditures (Abt et al. 2008, 2009; Calkin et al. 2005, 2014b; Gebert et al. 2007; Hand et al. 2014; Holmes et al. 2008a,b). These econometric models are the basis for the so-called Stratified Cost Index used by the USFS to benchmark recent fire expenditures and forecast future expenditures (Abt et al. 2008, 2009; Hand et al. 2016). Calkin et al. (2005) are one of the first to analyze the rising response expenditures and correlate them with acreage burned and drought conditions. Subsequent analyses also find that drought and fuel moisture, weather conditions, and topography are important determinants of response expenditures. Yoder & Gebert (2012) argue that expenditures and fire size are jointly determined outcomes, implying that models using fire size as an explanatory variable suffer from endogeneity. Bayham & Yoder (2020) build on this argument and advocate for analyzing the factors that drive dynamic resource allocation decisions over the course of the fire. While this approach can overcome endogeneity concerns

[4]We use the term response rather than suppression to capture the wide array of services that firefighters provide on incidents, including suppression activities as well as facilitating evacuation and structure protection.

when identifying the determinants of response expenditures, until recently, high-frequency data on resource assignments have not been readily available.

There is clear evidence that weather conditions and fuel moisture are important determinants of wildfire behavior (Finney et al. 2009, Young et al. 2019), which suggests that they influence response expenditures as well. Bayham et al. (2020) use high-frequency resource allocation data to determine whether fire managers order resources in anticipation of weather-driven wildfire growth events or in response to them. They find that fire managers request resources based on expectations of wildfire growth. These results suggest that climate-driven weather conditions conducive to wildfire that are expected to worsen in the coming decades could drive an increase in response expenditures.

Fuel treatments generate benefits by reducing fire severity, increasing the probability of control and reducing the likelihood that wildfires damage values at risk. Fuel treatments are shown to reduce the cost of fire response and the probability of loss should a fire occur (Butry et al. 2010, Taylor et al. 2013). Previous wildfires also act as a form of fuel treatment, can reduce future response costs (Belval et al. 2019, Houtman et al. 2013), and may increase containment probability and reduce risk to firefighters (Thompson et al. 2016, 2017). Lastly, fuel treatments can promote ecosystem services that directly and indirectly impact well-being (Loomis et al. 2003, Warziniack et al. 2019b).

4.2. Cost Drivers

Although many factors have led to rising response costs, including a changing climate and an accumulation of fuels, several factors involve human decisions. In this section, we focus on two drivers of response cost that have received attention in the economics literature: the role of threatened assets and growth in the wildland urban interface and resource and institutional constraints.

4.2.1. Threatened assets. Several studies have documented the association between threatened homes or the wildland-urban interface and response expenditures (Gebert et al. 2007, Gude et al. 2013, Liang et al. 2008, Yoder & Gebert 2012). This result corroborates anecdotes that wildfire management operations are more complex in areas near homes. Suppression resources may be assigned to protect specific assets rather than building containment lines. Clark et al. (2016) developed a data set on the precise location of homes in relation to fire perimeters in Wyoming, Montana, and Colorado to show that not just the presence of homes but their spatial configuration influences cost, suggesting that there exist economies of scale in point protection of more dense groups of homes rather than emphasizing fire perimeter containment. Baylis & Boomhower (2019) extend the approach of Clark et al. (2016) to most of the western United States by constructing a comprehensive data set of home locations and fires to estimate the fraction of response costs attributable to home protection. Plantinga et al. (2020) also document the increased response costs attributable to proximal homes. Bayham & Yoder (2020) again focus on resources rather than expenditures and show that more resources are dispatched to fires that threaten more homes. As a corollary, they show that the additional resources sent to the fire threatening more homes lead to a reduction of resources dispatched to other concurrent fires. Beyond the presence and configuration of homes, several studies document that response expenditures are higher in the presence of homes with higher market values, suggesting potential inequities of fire response (Bayham & Yoder 2020, Plantinga et al. 2020).

4.2.2. Resource and institutional constraints. Response resources are finite and often become scarce during periods of high wildfire activity in the summer months (Belval et al. 2020). Bayham &

Yoder (2020) integrate the allocation of firefighting resources across fires and show that binding resource constraints do affect allocations. A fire manager facing resource constraints may alter strategy, impacting the likelihood of achieving objectives (e.g., home protection). Climate change is expected to increase the probability of synchronous fire activity, increasing the chances that resource constraints will bind (Abatzoglou et al. 2021). The allocation of scarce response resources is fundamentally an economics problem and is ripe for future research.

Fire managers are humans working in an environment characterized by highly dynamic and changing conditions, expected to act under emergency conditions subject to a high degree of uncertainty about the effectiveness and risks of the choices they make. They also own neither the resources they are protecting nor the resources they are expending while making those decisions (Lueck & Yoder 2015). A series of studies have used qualitative and quantitative methods to assess the influence of these human decision-making factors on response and costs (Canton-Thompson et al. 2008; Donovan et al. 2011; Hand et al. 2015, 2017; Rossi & Kuusela 2020; Stonesifer et al. 2017). Hand et al. (2017) find that resource assignments dramatically vary by incident management teams on large incidents after controlling for other known determinants, suggesting substantial heterogeneity in management approaches, which are influenced by risk preferences, socioeconomic factors, and political pressures. Donovan et al. (2011) document associations between media attention, political pressure, and response expenditures. Rossi & Kuusela (2020) develop a theoretical model to show how sequential decision making and risk aversion can lead to higher response expenditures.

4.3. Benefits of Response

Both costs and benefits of management strategies are necessary to determine the appropriate level of response. The benefits of response activity are the avoided damages and impacts to human well-being. Measuring the benefits of response strategies is challenging because location-specific data on response activity and fire progression have not been systematically collected. Nevertheless, several studies have developed clever strategies to analyze the benefits of response strategies (Calkin et al. 2014b, Gannon et al. 2020, Houtman et al. 2013, Olsen & Yoder 2021, Plantinga et al. 2020). Plantinga et al. (2020) and Olsen & Yoder (2021) develop indirect approaches to quantify the benefits of response by characterizing the difference between expected and observed burn patterns in proximity to homes. Where spatial data on response effort exist, several studies have developed techniques to measure components of the response benefits. Gannon et al. (2020) use spatial data on built fire lines to estimate fire line effectiveness by quantifying lines that engaged fire, held, and burned over.

Katuwal et al. (2016) use daily fire progression maps and resource assignments to infer effort and containment effectiveness. Finney et al. (2009) quantify associations between weather conditions and periods of slow fire growth to characterize conditions under which aggressive response strategies may be most effective. Young et al. (2019) extend this framework to assess the association between weather conditions and the likelihood of containment.

The empirical challenge of quantifying response benefits lies in characterizing the counterfactual: What would have happened in the absence of response? Wildfire simulation models offer a promising tool for estimating counterfactual fire behavior (Plantinga et al. 2020 use this approach). However, these models were developed as decision support tools and generally require specialized software, detailed weather and topographic data, and model-specific knowledge to generate simulations. Moreover, these models tend to be parameterized based on historical fire footprints, which implicitly but not explicitly contain the effect of suppression operations on those historical fires.

4.4. Institutions for Wildfire Response

The complex public response infrastructure and organization described earlier in this section have been interpreted in economic terms. Bradshaw & Lueck (2012) and Lueck & Yoder (2015) provide an economic history of the emergence of modern wildfire response in the United States. Lueck & Yoder (2015) suggest that public response is fundamentally a response to a difficult contracting and coordination problem among property owners who face a common risk of wildfire and inefficiently weak incentives to invest in firefighting infrastructure and effort. These and other factors such as the structure of information, the incidence of asset ownership, and economies of scale and scope may inform the structure of firefighting as a hierarchical, military-like organization. Asymmetry of information between the costs and benefits from risk management and firefighting activity itself also provides insight into the fiscal structure of wildfire management funding (Donovan & Brown 2005, Donovan et al. 2008). There are myriad economic implications for wildfire response organizations. Among them is that there are weak incentives to mitigate risk before fires happen, and there are weak incentives to limit costs once fires have started (Donovan & Brown 2005, Lueck & Yoder 2015, Rossi & Kuusela 2020).

5. POSTFIRE RESPONSE

After a fire is extinguished and the so-called mop-up is complete, there are still decisions to be made about what follows a fire. In forest environments, salvage logging may be carried out, the extent to which depends on the characteristics of the timber at the time of the fire and the severity of the fire. Prestemon & Holmes (2008) provide an overview of timber salvage economics with a case study of the Biscuit Fire of 2002 in Oregon. Amacher et al. (2005) develop related dynamic timber rotation models in which the fraction of timber salvaged is a function of stand age, planting density, and mechanical thinning, the latter of which occurs in an environment with adjacent management externalities. Prestemon et al. (2006) estimate that administrative delays in salvage logging on public land reduced federal salvage logging sales revenues by 25% (about $1.5 million) between 2001 and 2002 alone.

An important category of postfire impacts is excess erosion and sedimentation resulting from the soil destabilization effect of high-intensity wildfires (Robichaud & Elliot 2006). Loomis et al. (2003) estimate that using prescribed fire to reduce the incidence of more severe wildfires could reduce erosion-related public works maintenance costs by $24 million per year. A great deal of literature has been published on burned area treatments to reduce erosion (Shakesby et al. 2016), but few articles have included economic analyses.

The extent and rate at which properties and communities are rebuilt after destruction by wildfires are an economic decision. Alexandre et al. (2014) found that for the coterminous United States between 2000 and 2005, only 25% of homes burned within fire perimeters were rebuilt within five years. Liao & Kousky (2022) find that municipalities within fire perimeters in California between 1990 and 2015 show increased revenues and expenditures, permanent property tax increases, and an overall negative impact on municipal budgets. Kousky (2019) examines the role of disaster insurance markets on economic recovery and, based on limited empirical work in this area, finds that insurance coverage tends to improve economic recovery outcomes.

6. KNOWLEDGE GAPS AND FUTURE RESEARCH

Climate change is expected to continue driving extreme fire behavior in the United States and around the world, and increasing development in fire-prone areas is introducing more economic value at risk. Complex and misaligned incentives arguably drive economically inefficient private mitigation and wildfire response. Spatial spillovers arise because of a mosaic of private and public land ownership. There exist textbook externalities (e.g., smoke) that drive a wedge between private and social costs and benefits. Decisions regarding mitigation and response are dynamic, fraught with uncertainties, and made by different parties with misaligned incentives. These incentive and information problems have driven the development of complex wildfire management institutions that often bring with them incentive problems of their own. A challenge ahead is to design a wildfire management system that minimizes these inefficiencies. Economics can play an important role in identifying priorities, focusing attention on inefficiencies, and can provide policy guidance to correct them.

6.1. Impacts

Careful accounting of the costs and benefits of wildland fire is a prerequisite for the design and implementation of evidence-based policy. Literature in economics and elsewhere documents many impacts but has yet to provide a complete accounting. We highlight a need for economic valuation of the impacts of fire on the displacement of people and migration, recreation activities, and ecosystem services while recognizing the challenges of incorporating these values into decision making (Venn & Calkin 2011). Data availability and disparity have posed challenges to researchers seeking to evaluate the impacts of wildfires on society, but data are becoming more comprehensive, compatible, and available. Geospatial databases now exist that contain historical fire perimeters, smoke plumes, environmental information, and values at risk (see Related Resources). In recent years, mobile device location data have created new possibilities for studying evacuation during fire and behavior response to smoke (Melendez et al. 2021). Innovative researchers are integrating wildfire data with administrative data (e.g., reserving camping spots online; **https://www.recreation.gov**) to analyze wildfire impacts at high spatial resolution across much of the United States (Gellman et al. 2022, Lee 2021). These data can enable a more comprehensive accounting of wildfire impacts and can better capture important heterogeneous impacts and identify behavioral contributors (i.e., vulnerable populations) to better inform policy.

An important area for future work is on the heterogeneous impacts of wild and prescribed fire on vulnerable populations. Jones & Berrens (2021) provide evidence that the negative effects of prescribed burning smoke are more pronounced in children born to African American and Hispanic mothers as well as mothers under the poverty line. The authors suggest that vulnerable populations may be less able to undertake defensive measures. O'Dell et al. (2022) compare indoor and outdoor personal air monitor data during smoke events across several western US cities and find that although indoor air quality tends to be better than outdoor air quality, the difference is less pronounced in areas with a higher social vulnerability index. This result suggests that socially vulnerable populations may be less able to undertake defensive measures like shutting windows and running air conditioning. However, further research is needed to understand inequities in the impact of wildfire and different populations' ability to mitigate risk.

The health impacts of short-term smoke exposure are becoming clearer, but the long-term impacts are more difficult to identify. There is preliminary evidence linking PM2.5 exposure to dementia (Bishop et al. 2018). Even monetized health effects do not represent the full economic cost of wildfire smoke. People invest in defensive measures to mitigate their exposure to wildfire smoke and may forgo activities, both of which are costs borne by society.

As large and severe wildfires become more prevalent, postfire erosion will increasingly impact water quality and impose costs on water treatment facilities that will ultimately be passed on to consumers. While the fire ecology literature has characterized some of the impacts of wildfire on ecosystem service provision, there is little economic research estimating the economic costs and benefits of these impacts. Environmental and resource economics is well suited to address many of the knowledge gaps in the impacts of wildfire on society.

6.2. Mitigation

Supplemental Material >

Our model detailed in the **Supplemental Appendix** and described in Section 3 highlights the complexity of identifying, fully accounting for, and equating the social marginal benefits and costs of the many dimensions of wildfire management. In practice, the problem is complicated by the interdependence of risk across parcels, the existence and structure of property insurance, public land ownership, and the albeit justifiable direct involvement of the public sector in firefighting. Shafran (2008) shows the strategic complementarity of wildfire risk mitigation on private land with different owners. The empirical results also suggest that private landowners adjacent to public lands are less likely to mitigate, but a question for public land managers is whether mitigation on public land induces more or less mitigation on adjacent private lands.

The increasing prevalence of destructive fires is prompting many individuals and communities to reconsider wildfire mitigation at multiple scales. More research would improve our understanding of decisions around risk mitigation at the individual and community levels. Organizations such as the Wildfire Research Center are actively engaged in community partnerships that collect and analyze data to provide information to the community partners and to the broader research community (Champ et al. 2021). In addition, federal, state, and local governments are recognizing the need to support risk mitigation. Theory suggests that fuel treatments that mitigate risk to parcels with high-valued assets yield the largest benefits. Yet, many of those parcels are owned by private landowners. Governments can incentivize mitigation on these parcels via grants that reduce the cost of fuel treatment. Economics can contribute to the design of such fuel treatment grant programs.

Home and other structures are often among the densest asset values at risk of wildfire, and their construction and spatial distribution can affect the likelihood of economic loss (Calkin et al. 2014a). Fire-relevant building codes were developed historically with an emphasis on fires originating within the home (Merrill 2012). However, structural design and building materials affect a home's susceptibility to external fire threats (Quarles et al. 2010). Building codes have been found to be related to housing values (Dumm et al. 2011) and to affect other outcomes such as energy consumption (Kotchen 2017). Little work has focused on the relationship between fire-related building codes and wildfire outcomes. In a recent working paper, Baylis & Boomhower (2021) use data from California to infer that building codes, ostensibly prompted by a destructive 1991 wildfire, reduced economic losses from subsequent fires.

Insurance is the market solution to many risk problems in economics. Insuring against wildfire damages is extremely challenging because the risk is spatially and temporally dependent, is influenced by the government-provided response (suppression), and is subject to government regulation. Climate change is creating further complications, as past events are no longer representative of current and future risks. California is dealing with an insurance crisis at the moment where most insurers have pulled out of markets with high fire risk (Flavelle 2020). When it comes to fire, California tends to serve as the bellwether. Economic research on insurance could yield large gains to society as fire risks continue to grow.

Utilities are both the recipient and the source of wildfire risk. In California, while facing the equivalent of strict liability for damage by wildfire due to ignitions from their infrastructure, PG&E has been found legally responsible for several large wildfires and is navigating bankruptcy, and the state has mandated that PG&E maintain a wildfire mitigation plan. As part of the plan, PG&E implements public safety power shutoffs during weather events that may lead to damaging wildfire in the event of ignition. The loss of power clearly represents a cost to society and to

PG&E, but current regulations in California prevent utilities from increasing rates to cover risk mitigation costs (Kousky et al. 2018). Some empirical work has been done on the economic consequences of liability law in the context of wildfire (Yoder 2008), but more analysis could usefully inform the design of appropriate policies and regulatory frameworks to balance the costs of wildfire against the costs of mitigating risk as more regions face increasing wildfire risk in the United States and worldwide.

Wildfire smoke is one of the most costly impacts because of its potential to affect many people. Prescribed burning also generates smoke, but recent evidence suggests that it does so at lower concentrations than uncontrolled wildfire (Selimovic et al. 2020). How much prescribed burning is warranted to reduce the risk of extremely poor air quality caused by wildfire? Importantly, prescribed fire is subject to Clean Air Act regulations, while uncontrolled wildfire is not.[5] Furthermore, there is a risk that the controlled prescribed fire escapes control and becomes a wildfire. This is a question ripe for economic analysis.

6.3. Response

Wildfire response is dynamic, complex, and uncertain. The militaristic structure of the wildfire-fighting apparatus is remarkably effective at containing and suppressing most fire. Arguably, we are now victims of 100 years of their success as climate-induced aridity and changing fuel composition summon fire back into many of the landscapes where it has been effectively excluded. These landscapes are now speckled with houses and other valued assets for which society demands protection. As wildfire response expenditures have increased, so has the attention focused on the determinants of expenditures. Fire statistics readily provide a picture of total acres burned, average fire size, and the costs incurred fighting these fires, but to understand the economics of firefighting resource allocation requires better-detailed data on resource allocation and what has not burned because of it. Wildfire managers are forward-looking, they strive to mitigate damage to valued assets, and they face little incentive to minimize expenditures. Aside from a recent internal study (USDA & USFS 2020), there is almost no direct evidence about the relative effectiveness of suppression and protection strategies. Until recently, the data to conduct effectiveness analyses have not been systematically recorded. Contemporary causal inference methods may help quantify the effectiveness, if not the benefits, of the wide array of response strategies currently used.

The structure of resource allocation decisions under times of high fire activity and resource scarcity is highly complex and typically made by individuals representing various levels of government and land management responsibilities under a Multi-Agency Coordination (MAC) system (Belval et al. 2017). How these MAC systems assign priorities, how they evaluate resource allocation, and the structure of the decision environment can have substantial impacts on fire management outcomes and costs and are areas worthy of future research.

The wildland firefighting system is already strained, and wildfire trends suggest it will be strained further. Firefighters work long hours in arduous conditions without clearly defined long-term health coverage. The USFS already faces challenges with workforce retention.[6] Economic

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[5] Days dominated by very high PM2.5 attributable to a wildfire are flagged and generally excluded when calculating exceedance according to the US National Ambient Air Quality Standards (**https://www.epa.gov/air-quality-analysis/treatment-air-quality-data-influenced-exceptional-events-homepage-exceptional**).

[6] Public hearings on firefighting workforce reforms have been held recently, e.g., by the Subcommittee on National Parks, Forests, and Public Lands in California: **https://naturalresources.house.gov/hearings/wildland-firefighting-workforce-reforms**.

analysis can help identify the reasons for current retention challenges and their implications for agencies' ability to respond to future demands.

7. CONCLUSION

Since Sparhawk's (1925) seminal model of cost minimization for managing wildfire, economists have improved our understanding of the many dimensions of this complex land management problem. During this same period, wildfire management in the United States has undergone a remarkable evolution in objectives, methods, and scope, carried out in environments that are being reshaped by demographic, biological, and climate change.

While this review focuses on the United States, all of the biophysical and economic fundamentals apply across the globe wherever wildfire occurs. As the literature highlights, the details relating to fuel characteristics, demographics, land ownership and land use, and public and private institutions matter for wildfire management and outcomes. Australia is well known for its reliance on local volunteer bushfire brigades, a form of local collective action applied in rural areas with large, private landholdings. However, the inertia is shifting toward more centralized, public wildfire management (Bennett 2012, McLennan & Birch 2005), facing effectively the same categories of incentive issues faced in the United States, despite a very different institutional history and trajectory of public firefighting than the United States. Some of the largest wildfires ever recorded have been in Siberia, and estimates suggest that in 2021, more acres there were burned by wildfires than the rest of the world combined (Dixon 2021), distributing smoke across the globe. In their analysis of the changing wildfire regime in Siberia, Kharuk et al. (2021, p. 1953) identify some of the same policy recommendations that have been forwarded for the United States: "Focus fire suppression efforts on areas of high social, natural, and economic value, while allowing a greater number of wildfires to burn in the vast Siberian forest landscape." Wildfires and their smoke in Indonesia are having an increasing impact on human health due to land clearing practices and climate change and related wildfire activity, and Indonesia has responded by instituting fire brigades in 2002 and imposing increasingly strict regulation and land management requirements among large landowners (Herawati & Santoso 2011). The institutional and economic history of wildfires and their management have counterparts throughout most of the world but vary in approachable ways in detail.

As we contemplate the design of institutions and policies appropriate for twenty-first-century wildfire, economics can contribute in several important areas. First, empirical economists can leverage the great strides we have made in causal inference methods to measure the impacts of wildfire on society. Second, economists can redouble our efforts to understand the determinants of mitigation on private lands and acceptance of it on public lands. We can use those insights to design creative solutions to collective action problems in fire-prone communities. Lastly, economists can help government agencies design more economically efficient wildfire response strategies.

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RELATED RESOURCES

Fire Perimeters: **https://www.mtbs.gov/**. Monitors trends in burn severity

National Wildfire Coordinating Group: **https://maps.nwcg.gov/**

Environmental: LANDFIRE (**https://landfire.gov/**). Source of national geospatial layers, databases, and ecological models

gridMET: **http://www.climatologylab.org/gridmet.html**. Data set of daily high-spatial-resolution surface meteorological data in the United States

Values at Risk: **https://github.com/microsoft/USBuildingFootprints**. Microsoft building footprints data sets in the United States

LandScan: **https://landscan.ornl.gov/**. Human geography foundation population data sets

Housing Transaction Data: **http://silvis.forest.wisc.edu/maps-data/**. Spatial analysis data sets on the wildland-urban interface from the Silvis Lab at the University of Wisconsin–Madison

Wildfire Risk to Communities: **https://wildfirerisk.org/**. Website with interactive maps and resources from the US Forest Service