Before the Burn: The Economic Benefits of Fuel-Reduction Treatments in Wildfire-Prone Forests

Frederik Strabo[†*] and Matthew N. Reimer[†]

2024-12-19

Abstract

A century of wildfire suppression policies has led to the build-up of combustible fuel loads in forests, increasing the size, severity, and costs of wildfires. This study explores whether fuel-reduction treatments reduce wildfire suppression costs. Focusing on wildfires igniting on U.S. Forest Service lands in the Pacific Northwest, we leverage exogenous variation in protections for the Northern Spotted Owl that unintentionally restrict fuel treatments. Conservative estimates indicate that four to seven dollars are saved in suppression costs for every dollar spent on fuel treatments. Our results highlight the potential for reforming environmental protections to achieve economic savings and conservation benefits.

JEL Codes: H41, Q23, Q28, Q54, R52

Keywords: wildfire, conservation, fuel treatments, natural disasters, climate change

[†]Department of Agricultural and Resource Economics, University of California, Davis

[*]*Corresponding Author*, `ftstrabo@ucdavis.edu`

[††]For helpful feedback and discussion, we thank Jo Albers, T.J. Anderson, Jamie Hansen-Lewis, Alex James, Hugh Safford, Jose Sanchez, James Sanchirico, and James Wilen. We are grateful to seminar participants at the NatuRE Policy and Safford Labs at UC Davis, as well as the AERE Summer Conference. All errors are our own.

"You own the fuel, you own the fire"—Urban fire specialist's adage

In May 2001, U.S. governmental officials were alarmed to detect a mysterious aerosol signature in the form of a smoke plume in Central Alberta, Canada. The signal was so extreme that U.S. government officials called the Canadian government to ask if a nuclear device had been detonated. The source was not a bomb, but a wildfire, the Chrisholm Fire, which at its peak seven-hour run, released the energy equivalent of four Hiroshima bombs per minute (Vaillant, 2023). Fires of this size are known to create their own weather systems with hurricane-force winds and lightning that ignite more fires many miles away. This is just a glimmer of the frightening intensity and destructive capability of wildfires in the 21st century.

As the size and severity of wildfires have increased in recent decades (Miller et al., 2009), so too have the economic costs and damages, with the estimated total annual cost in the U.S. ranging from $394-893 billion USD (JEC, 2023). Wildfires incur economic costs through various channels, such as losses in human-made and natural assets (Bayham et al., 2022; Wang and Lewis, 2024), fire suppression costs (Baylis and Boomhower, 2023), human health (Molitor et al., 2023; Heft-Neal et al., 2023), labor market impacts (Borgschulte et al., 2022), and losses in ecosystem services (Smith, 1993). Such costs are expected to rise across the globe with climate change (Abatzoglou and Williams, 2016), increasing development in the wildland-urban interface (WUI; Radeloff et al., 2018), and fire exclusion policies (Schoennagel et al., 2017).

The build-up of combustible material in forests, often referred to as fuel loads, is one of the leading causes of increasing wildfire severity (Miller et al., 2009). Fuel loads have built up over time far beyond their natural carrying capacity in response to current and historical fire suppression policies (Stephens et al., 2007; North et al., 2022). Fuel treatment activities, such as prescribed fires or mechanical tree removal, reduce fuel loads and have the potential to significantly alter the economic costs of wildfires. However, despite widespread consensus in the forest ecology literature that fuel treatments are effective at reducing wildfire severity, they have been strikingly underemployed in the Western U.S. (Agee and Skinner, 2005; Kolden, 2019).

Fuel treatments may be underemployed because public agencies are chronically underfunded and face contradicting expectations from the public. For example, the United States Forest Service (USFS) employs less than 30,000 people despite owning more than 193 million acres of public land.[1] Public pressure and risk aversion skew an already scarce resource base towards fire suppression at the expense of fuel treatments to avoid public lawsuits and condemnation. Regulatory constraints based on environmental objectives and policies, such as endangered species protec-

[1]Unlike the Eastern U.S., public lands in the Western U.S. comprise the majority of forest land and burned area from wildfires. For example, in the Pacific Northwest, federally managed lands accounted for around 68% of the total burned area footprint from 1984-2018 (Barros et al., 2021).

tions, federal and state air quality standards, survey and manage protocols, wilderness areas, and the National Environmental Policy Act (NEPA), significantly hinder the ability of public agencies to conduct fuel treatments on public lands (North et al., 2012, 2015; Edwards and Sutherland, 2022). Such environmental regulations lead to instances where the costs associated with no action are overlooked, and the "precautionary principle" becomes the "paralyzing principle" (Hessburg et al., 2021).

This paper presents the first causally identified estimate of the effectiveness of fuel treatments in reducing wildfire costs. Although prior forest ecology research has demonstrated the effectiveness of fuel treatments in reducing fire severity (Agee and Skinner, 2005; Kolden, 2019), quantifying their economic benefits remains limited (Kline, 2004).[2] Despite calls for the widespread adoption of these practices as a means to reduce economic costs (USFS and State of California, 2020; State of California, 2021), the existing economic literature has focused on identifying the determinants of fuel treatment activity and fire suppression efforts rather than the relationship between the two (Plantinga et al., 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer et al., 2019; Anderson et al., 2023).

We assess whether fuel treatments mitigate the economic costs of wildfires by investigating fires igniting on United States Forest Service (USFS) land in the Pacific Northwest from 2006 to 2023. Our analysis focuses on two key wildfire outcomes: fire size and suppression costs. While suppression costs represent only a portion of the total social cost imposed by wildfires, their contribution is significant. According to the National Interagency Fire Center, federal agencies spent $55 billion on wildfire suppression from 1985 to 2022.[3] Similarly, fire size is often cited as a proxy for broader wildfire impacts, including smoke-related health costs and structure loss (e.g., Wen et al., 2023). We find evidence that fuel treatments jointly reduce fire size and suppression costs and are cost-effective for mitigating wildfire damages.

The lack of research linking fuel treatment activities' impact on economic outcomes is likely due to the environmental and spatial-temporal complexities of wildfires, fuel treatments, and fire suppression efforts, resulting in at least two empirical challenges in identifying the causal effects of fuel treatments. First, the location and extent of fuel treatments and fire suppression efforts are jointly determined by socio-economic and environmental factors (Plantinga et al., 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer et al., 2019; Anderson et al., 2023). For example, fuel treatments and fire suppression efforts are often allocated to protect areas with assets at risk. Consequently, estimation strategies that compare fires (or areas) with and

[2]Previous studies have focused on the cost-effectiveness of fuel treatments in reducing high-severity fires (Hartsough et al., 2008). Research on economic benefits, however, has relied on fire simulations (Taylor et al., 2015; Thompson et al., 2013b) or meta-analyses of individual case studies (Hjerpe et al., 2024; Hunter and Taylor, 2022) to assess the economic impact of fuel treatments.

[3]Measured in 2017 dollars, not including expenditures from state and local suppression efforts.

without nearby fuel treatments will suffer from simultaneity bias and likely result in findings of small to zero impacts on suppression costs (Sánchez et al., 2019; Yoder and Ervin, 2012). Second, even if fuel treatments are conducted exogenously, the allocation of suppression effort across fires mediates the effect of fuel treatments on the size and cost of suppressing a fire. For example, if fuel treatments and suppression effort are complements-in-production, more resources will be allocated toward fires igniting near fuel treatments, increasing suppression costs. Indeed, we demonstrate that fuel treatments could actually increase the size and suppression cost of nearby fires, even if they collectively decrease the size and costs of all fires.[4] Thus, comparing fires adjacent to fuel treatments to those that are not may not provide an accurate assessment of the overall benefits associated with fuel treatments.

We address the empirical challenges of identifying the economic benefits of fuel treatments in the following ways. First, building on Baylis and Boomhower (2023), we employ a fixed-effects strategy that compares fires igniting within the same national forest and time of year but are exposed to varying levels of nearby fuel treatments. Our strategy controls for a broad suite of factors known to influence wildfire behavior and suppression costs, including topographic (e.g., slope, aspect), weather (e.g., temperature, wind), vegetation (e.g., fuel type, canopy cover), economic (e.g., proximity to roads and housing units), and historical wildfire risk factors (e.g., mean fire return interval). Second, we employ an instrumental variable strategy that exploits exogenous variation in fuel treatments arising from spatial variation in protected areas established under the Northwest Forest Plan (NWFP). These protected areas, created to conserve the northern spotted owl (NSO) under the Endangered Species Act (ESA), inadvertently restrict fuel treatment activities due to increased management restrictions and litigation risks (Johnson et al., 2023). Spatial variation in protected areas generates quasi-random variation in fuel treatment activity because their boundaries were based on the ecological needs of the NSO, other endangered species, and sensitive habitats (Gaines et al., 2022; Johnson et al., 2023). However, because the NWFP represented a compromise between timber production and species conservation, substantial portions of NSO critical habitat and old-growth forests were left unprotected (Gaines et al., 2010; Johnson et al., 2023; USFWS, 2012). As a result, fires ignite in comparable environments inside and outside protected areas but are exposed to differing levels of nearby fuel treatments for reasons unrelated to potential fire suppression costs or fire size. Finally, using a stylized model of fire suppression effort allocation, we derive a sufficient condition under which fuel treatments generate overall economic benefits, considering both wildfire damages and suppression costs. We demonstrate that a negative effect of fuel treatments on both fire size and suppression costs is sufficient evidence that fuel treatments accrue collective economic benefits across all fires.

We find that fires igniting in protected areas are similar in their observable characteristics to

[4] Rideout et al. (2008) derives a similar result using a similar model of fuel treatments and fire suppression effort.

those igniting in unprotected areas yet receive 13.9% less fuel treatments close to their ignition point, highlighting the impact of environmental protections on treatment activities. Fires igniting in protected areas are also 17.9% more costly to suppress than those igniting outside of protected areas, on average. Taken together, these estimates imply that a one-percent increase in nearby fuel treatments reduces the cost of suppressing wildfires by 1.287 percent. We also find that fuel treatments reduce fire size, but the statistical significance of this effect is not robust to different samples or specifications. Our theoretical results suggest the effect of fuel treatments on fire size may be attenuated due to the endogenous reallocation of suppression resources away from fires that ignite near treated areas. Applying a bootstrap intersection-union hypothesis test to our sufficient condition, we find evidence that fuel treatments jointly reduce fire size and suppression costs, thereby providing overall economic gains. Building on this evidence, we estimate the counterfactual economic benefits from reduced suppression costs that would have been realized had the size of all fuel treatments in our sample period been proportionally larger. Our conservative back-of-the-envelope calculations suggest that for every dollar spent on fuel treatments, four to seven dollars are saved in fire suppression costs, depending on the level of increased treatment activity. These results indicate that fuel treatments are a cost-effective strategy for mitigating wildfire risks.

Our study makes several contributions. We demonstrate the potential role of public investments in natural capital as a cost-effective means of mitigating risks from natural disasters. Previous research has highlighted the government's role in bearing the cost of protection from natural disasters, often unintentionally encouraging development in high-risk areas (Kousky et al., 2006; Boustan et al., 2012; Baylis and Boomhower, 2023). While insurance can provide financial protection to private property, insurance markets face significant challenges adapting to the increasing risks posed by natural disasters due to risk information asymmetries and the spatially correlated, catastrophic nature of natural disasters (Busby et al., 2013; Kousky, 2019; Wagner, 2022a,b; Boomhower et al., 2024). Moreover, property insurance does not protect against the costs of natural disasters that accrue indirectly, such as through smoke exposure from wildfires that frequently ignite on public land.[5] This has led policymakers to seek cost-effective investments to mitigate natural disaster risks, including mandating fire-resilient building codes for new homes built in California (Baylis and Boomhower, 2021). We demonstrate that public investments in natural capital, such as fuel-reduction treatments, can also be a cost-effective means of protection from natural disasters.

Our analysis also highlights how environmental protections can inadvertently hinder wildfire management and fuel treatment activities, potentially placing the very species they aim to protect at greater risk. Land managers and fire ecologists have long acknowledged the unintended effects of the NWFP reserves on fuel treatment and wildfire activity in the Pacific Northwest (Spies et al.,

[5]For example, Borgschulte et al. (2022) estimate a $125 billion/year reduction in quarterly earnings due to smoke exposure.

2019; Hessburg et al., 2021). Previous studies have shown that increasing areas of high-severity fire have been the leading cause of loss in northern spotted owl habitat (Davis et al., 2016) and old-growth forests (Davis et al., 2015) since the NWFP's inception. Others have pointed out the conflicting incentives of land managers under the ESA due to fuel treatments' short-term negative impacts on northern spotted owl habitat (Spies et al., 2018; North et al., 2012). The present study contributes to this literature by estimating the magnitude by which these policies have hampered fuel treatment activity in the region and how this has translated into increasing the public burden of fighting wildfires.

More broadly, our study underscores the importance of reconciling competing objectives between environmental protections and climate adaptation strategies. Existing literature has emphasized the impact of environmental protections on private land values, land use, and labor markets (Auffhammer et al., 2020; Nelson et al., 2017; Ferris and Frank, 2021). These challenges are not unique to wildfire management. Indeed, similar tensions are likely to emerge in other contexts, such as invasive species management, where restrictions on proactive measures may enable harmful species to spread (Bradley et al., 2023); carbon crediting programs, which may prioritize carbon sequestration over broader ecosystem services (Venter et al., 2009); and the extraction of critical minerals for renewable energy, which may conflict with habitat conservation efforts (Sovacool et al., 2020). Addressing these conflicts requires thoughtful policy design that balances long-term climate adaptation goals with immediate and local environmental priorities.

The paper is organized as follows. Section 1 provides background on wildland fire institutions, fuel treatments, and the Northwest Forest Plan. Section 2 establishes a simple model of fuel treatment and fire suppression effort to motivate our empirical approach and inform the interpretation of our estimates. Section 3 introduces our research design and discusses the data. Section 4 presents our estimates of the marginal effect of fuel treatment on fire suppression costs and size, discusses several robustness checks, and explores the counterfactual benefits of increased fuel treatment activity. Section 5 concludes the paper.

1 Background

1.1 Wildland Firefighting & Fuel Treatments in the Western U.S.

The Great Fire of 1910, an apocalyptic blaze that burned 3 million acres in 2 days in Washington, Idaho, and Montana, marked an important turning point in the management of U.S. national forests (Egan, 2011). Only five years after its founding, the USFS was severely underfunded and under political threat of dismantling.[6] However, the heroic deeds of forest service rangers, along with the shock and terror from the fire, dramatically changed the public perceptions of the USFS, ultimately leading to the USFS's expansion and a major shift in its mission statement: from prioritizing conservation to fighting forest fires. Prioritizing wildfire suppression led to the "10 a.m." policy instituted by the USFS in 1935, which stated the goal to successfully contain any fires by 10 a.m. the following day in its initial report (Loveridge, 1944).

Shortly thereafter, other federal, state, and local government agencies followed in the USFS's footsteps to implement similar wildfire suppression policies (Pyne, 2008). A wildfire's ignition location and geographic extent broadly determine the financial and operational responsibility for suppressing a wildfire (Hoover and Lindsay, 2017), with the nearest fire management authority usually attempting to quickly extinguish it in what is known as the "initial attack." For example, the primary responsibility for fires igniting on National Forest land rests with the USFS. In contrast, the state is responsible for fires starting in unincorporated private land (e.g., CAL FIRE in California). When wildfires are large enough to affect multiple agencies and jurisdictions, local Emergency Operation Centers and multi-agency coordinating groups facilitate the sharing of information, objectives, and the allocation of resources between agencies.

Successful wildfire suppression by federal, state, and local government agencies has unintentionally led to increased fuel loads that are in marked disequilibrium with the underlying ecological template across much of the western U.S. (North et al., 2022). For example, 5-12% of California burned annually pre-1800, a large portion of which occurred through cultural indigenous burning (Stephens et al., 2007). Indeed, it is an often-repeated mantra that the major ecological issue facing western forests today is the relative absence of fire, which is in direct conflict with popular information campaigns like "Smoky the Bear" that emphasize wildfire suppression.

Fuel treatments, such as prescribed fires or mechanical tree removal, aim to return forest ecosystems to their more natural state by emulating the natural processes of low-severity fires by reducing fuel loads, maintaining open stands of trees, and eliminating shade-tolerant species of trees that are more susceptible to wildfire. Because such ecosystems are adapted to frequent low-severity fires, forests that receive such fuel treatments experience fewer high-severity wildfires and thus enhance the ecosystem services associated with such forests through reduced smoke exposure, increased nutrient cycling, water quality, and carbon sequestration post-wildfire, along with the promotion of biodiversity (Kalies and Yocom Kent, 2016; Converse et al., 2006; Boerner et al., 2009; Finkral and Evans, 2008; Yocom Kent et al., 2015; Richter et al., 2019).

Although there is no rigorous causal evidence directly linking fuel treatments to reductions in fire suppression costs, both qualitative and fire simulation evidence suggests that fuel treatments

[6] For example, one forest service ranger working at poverty level wages was the sole employee responsible for over 300,000 acres of land (Egan, 2011).

help decrease these costs by reducing the size and severity of wildfires (Romero and Menakis, 2013; Murphy et al., 2007; Graham et al., 2009; Thompson et al., 2013b). Fuel treatments can enhance the effectiveness of both "direct" and "indirect" firefighting efforts, which likely contributes to cost savings (Romero and Menakis, 2013). Direct attack involves firefighting actions performed near the fireline, such as constructing control lines, smothering flames, or applying water or chemical retardants. These efforts are only feasible when wildfires have sufficiently low flame lengths—a condition that fuel treatments help create. Indirect attack, on the other hand, consists of operations conducted at some distance from the fire's perimeter. This may involve using fuel breaks or creating firelines where combustible material is removed to halt a fire's progression.[7]

By increasing the effectiveness of direct and indirect attacks, fuel treatments reduce reliance on the more costly aerial attack methods, which involve applying water or chemical retardant via helicopters or fixed-wing aircraft. Aerial attacks require significant capital investment and are considerably more expensive than ground-based suppression tactics (Calkin et al., 2014; Thompson et al., 2013a; Stonesifer et al., 2021).

1.2 The Northwest Forest Plan Reserve System

It is said that when President Jimmy Carter was on his way to view the devastation caused by the eruption of Mt. St. Helens in 1980, he expressed horror at the sight of a shaven landscape. State officials had to gently explain that what Carter saw was clear-cut logging and not the aftermath of the explosion (Dietrich, 2010). The emotion brought about by the sight of clear-cuts and their deleterious effects on ecosystems led to one of the most hotly contested public debates: What should be the management objectives of federal forest owners? The northern spotted owl (NSO) was the centerpiece of this debate. It became not only a symbol for old-growth forest preservation but also the legal basis from which federal forest owner objectives changed through the ESA. The debate culminated in the early 1990s, and within only five years, federal forests in the Pacific Northwest underwent a sudden and tremendous shift in management focus from providing sustained yield timber to conserving biodiversity with emphasis on endangered species (Thomas et al., 2006).

After listing the NSO as threatened by the U.S. Fish & Wildlife Service (USFWS), 6.9 million acres of federal forest were designated as critical habitat in 1992, encompassing parts of Washington, Oregon, and northern California. To build on this protection, the Clinton administration subsequently initiated the Northwest Forest Plan (NWFP) in 1994, significantly reducing old-growth logging and timber harvest by establishing a system of reserves spanning over 24.4 million acres of federal forest land aimed at conserving old-growth habitats, NSO populations, and essential wa-

[7]Fuel treatments also facilitate "back-burning," a form of indirect attack where a fire is deliberately set to reduce fuel ahead of the wildfire. Typically, back-burning requires favorable wind conditions, but fuel treatments lessen the reliance on such conditions by proactively removing fuel before a fire occurs.

tersheds and riparian zones making it one of the largest temperate forest serve systems in the world (Gaines et al., 2022; Spies et al., 2018). Ultimately, timber harvests on federal lands in the region declined by 80–90%, resulting in significant job losses and economic hardships for many rural, timber-dependent communities (Spies et al., 2019; Ferris and Frank, 2021).

During the formulation of the NWFP, the Clinton administration faced stark trade-offs between timber production and species conservation (Johnson et al., 2023). Various reserve options were proposed, each with different protections for "working" forests—lands deemed sufficiently productive for timber harvest. The final plan established two main land designations (Figure 1). Late-Successional Reserves (LSRs), spanning 7.4 million acres, were designed to support the nesting, roosting, foraging, and dispersal needs of the northern spotted owl (NSO), along with other endangered species and sensitive habitats.[8] These reserves were subject to strict management restrictions limiting timber harvest. Meanwhile, Matrix lands, comprising approximately 4 million acres (including 2 million acres of old-growth forest), were designated as areas where most silvicultural activities would continue, primarily through selective logging and thinning.[9] This compromise meant that while many old-growth forests gained protection from LSR designation (3.7 million acres), a substantial portion remained open to more intensive management practices. Notably, while LSRs were designed to protect the NSO, they do not entirely align with either historical or critical habitat designations by the USFWS. For example, approximately 40% of historical nesting owl pairs and 40% of critical habitat areas designated in 2012 are located within Matrix lands rather than reserved areas (Gaines et al., 2010; Johnson et al., 2023; USFWS, 2012).

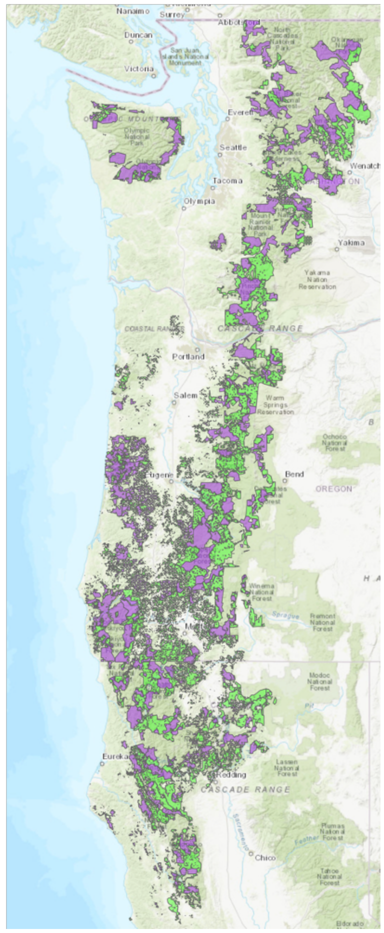
Despite recognizing the importance of active management in fire-prone forests, the NWFP has unintentionally restricted fuel treatment activities in LSRs due to conservative interpretations of its rules and the potential for litigation from environmental groups (Johnson et al., 2023). Coupled with a century of active fire suppression, forested areas within LSRs have experienced significant fuel build-up, particularly in dry forests east of the Cascade Mountain Range, where fuel levels have diverged considerably from their natural state. These dry forests, historically shaped by frequent low-severity wildfires, are much more fire-prone than the wetter forests to the west (Reilly et al., 2018), leading many scientists to criticize the inclusion of dry forests in the NWFP reserve system (Gaines et al., 2022).[10] Conversely, Matrix lands, with fewer management restrictions, permit more intensive timber harvests and silvicultural activities, which have enabled significantly more acres of fuel treatment compared to LSRs. This contrast highlights the uneven spatial distribution of fuel

[8] For example, LSRs were planned to be large enough to sustain NSO populations and positioned close enough to facilitate owl dispersal (Johnson et al., 2023).

[9] Thinning and selective logging dominate silvicultural activities in Matrix areas due to the collapse of traditional timber sales in the early 2000s, largely driven by environmental litigation. This shift led agencies to focus on thinning younger forests to offset the reduced harvest from older forests in Matrix areas (Johnson et al., 2023).

[10] For example, dry conifer forests historically experienced wildfires every 5-35 years, while wet conifer forests experienced wildfires every one to four hundred years (Parks et al., 2023; Johnson et al., 2023).

Figure 1: Distribution of Matrix and LSR land designations in the Northwest Forest Plan area



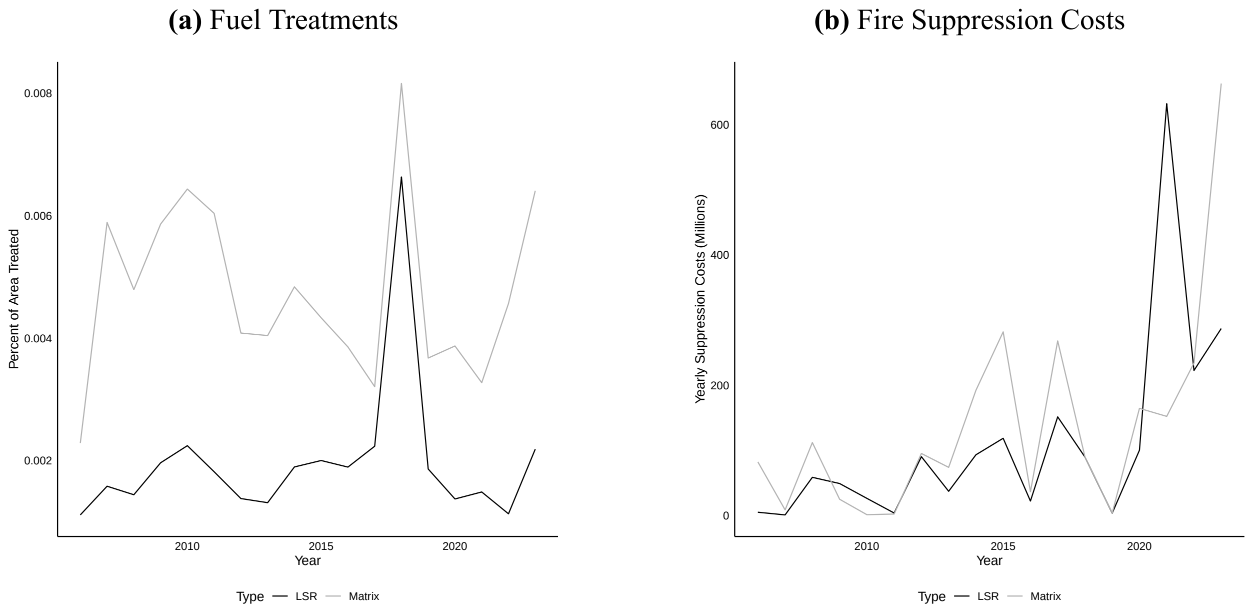
Notes: Matrix areas are shaded in bright green, LSRs in purple, and national forests in light green.

treatments across national forests in the Pacific Northwest (Figure 2a).

2 Conceptual Framework

In this section, we present a stylized model to identify the mechanisms through which fuel treatments influence fire size and suppression costs and to clarify the main empirical challenges we face in identifying and interpreting such effects. The model illustrates how the effect of fuel treatments is mediated by the endogenous response of a fire manager as they allocate suppression effort across fires. In turn, the model explains why fuel treatments may or may not reduce the size or suppression cost of a nearby fire, even if they reduce the total acres burned and suppression costs across all fires. We use the model to derive a sufficient condition under which fuel treatments collectively provide economic benefits across all fires, resulting in a testable hypothesis that informs

Figure 2: Trends in Fuel Treatments & Fire Suppression Costs in Matrix & LSRs



Notes: "Percent of Area Treated" (left) is the total annual acres of fuel treatment divided by the total area of Matrix or LSR areas. Suppression costs (right) are adjusted for inflation and are measured in 2020 USD.

our empirical framework.[11]

2.1 Setup

A fire manager allocates fire suppression effort E_i toward fighting $i = 1, \ldots, N$ fires burning simultaneously, conditional on an existing distribution of fuel treatments across the landscape. We assume that a fire manager's objective is to minimize expected losses, which are equal to the sum of expected damages and fire suppression costs, subject to a resource constraint on suppression effort.[12] The fire manager's problem can be expressed as:

$$\max_{E_1,\ldots,E_N} -\sum_{i=1}^{N} \left[L(X_i) \cdot S(E_i, F_i) + C(E_i)\right] \quad \text{s.t.} \quad \sum_{i=1}^{N} E_i \leq \bar{E},$$

where F_i denotes the volume of fuel treatments near fire i. For simplicity, we assume suppression costs $C(E_i)$ are the same across fires, conditional on effort. We also assume that resources move from cheaper sources (e.g., hand crews) to more expensive sources (e.g., dozers and air tankers)

[11] All derivations of our results can be found in Appendix 1.

[12] This is a version of the "least cost plus loss" model, which has been used to model fire manager behavior for many economic fire suppression models (Donovan and Rideout, 2003). More general models provide similar, yet more nuanced, insights on the tradeoffs facing a fire manager (Bayham and Yoder, 2020).

as effort is expanded, resulting in a suppression cost function that is increasing and convex in effort. Expected fire damages are assumed to be linear in fire size $S(E, F)$, which is assumed to be decreasing and convex in effort and fuel treatments due to diminishing returns. $L(X_i)$ represents the constant loss associated with a one-unit increase in fire size, which is a function of assets-at-risk, X_i. Since fuel treatments are pre-determined, the costs of implementing fuel treatments do not enter into the calculus of a fire manager. We compare the economic benefits of fuel treatments to their implementation costs in our empirical application in Section 4.2.

The necessary and sufficient conditions associated with a fire manager's effort allocation, E_i^*, are:

$$-L(X_i)\frac{\partial S_i(E_i^*, F_i)}{\partial E_i} = \frac{\partial C(E_i^*)}{\partial E_i} + \lambda \quad \forall i \in \{1, ..., N\}$$
$$\lambda \cdot \left(\sum_{i=1}^{N} E_i^* - \bar{E} \right) = 0,$$

where λ denotes the Lagrange multiplier associated with the resource constraint. The first-order conditions reflect that the marginal benefit of allocating one unit of effort to suppress a fire, in terms of the foregone damages, must be equal to its marginal suppression cost and the shadow cost of effort for E_i^* to be optimal. They also reflect the equi-marginal principle: effort is optimally allocated across fires when the marginal net benefit of effort is equal across all fires. Further, the first-order conditions demonstrate that more suppression effort will be devoted to fires with higher levels of assets-at-risk (Plantinga et al., 2022; Baylis and Boomhower, 2023).

2.2 The Economic Benefits of Fuel Treatments

We are ultimately interested in understanding the economic benefits provided by fuel treatments. Within the context of our conceptual model, this equates to answering: how does the optimal value of a fire manager's program change in response to a marginal increase in fuel treatments? Letting $V(F_1, ..., F_N)$ denote the value function of a fire manager's program evaluated at the optimal allocation of suppression effort, we can employ the envelope theorem to show that fuel treatments are economically beneficial under one condition.

Result 1. Fuel treatments increase the value of a fire manager's economic program provided the direct effect of fuel treatments on fire size is negative:

$$\frac{dV(F_1, ..., F_N)}{dF_i} = -L(X_i) \cdot \frac{\partial S(E_i^*, F_i)}{\partial F_i} > 0 \iff \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0. \tag{1}$$

Intuitively, while fuel treatments will induce changes in suppression effort allocation, effort will be adjusted to balance the marginal benefits of reduced fire damages with the marginal cost of fire suppression so that the behavioral response will not have a first-order effect. Thus, the direct effect of fuel treatments on fire size $\frac{\partial S(E,F)}{\partial F}$ is a sufficient condition for determining whether fuel treatments have positive economic benefits.

Unfortunately, Equation (1) has several practical limitations. First, even if fuel treatments were randomly assigned, we cannot empirically identify the direct effect of fuel treatments on fire size. Rather, we can only identify the total effect of fuel treatments on fire size, $\frac{dS(E,F)}{dF}$, which includes the mediating response of fire suppression effort, $\frac{dE^*}{dF}$. Second, quantifying the marginal benefit of fuel treatments is complicated by the fact that they depend on the potential losses associated with assets-at-risk, $L(X)$, which are heterogeneous and generally difficult to assess. Finally, the benefits associated with marginal changes in fuel treatments cannot be used directly to evaluate counterfactual policy changes that induce large, non-marginal increases in fuel treatments, as we do here (Chetty, 2009). In light of these limitations, how can we assess whether fuel treatments provide economic benefits?

2.3 The Impacts of Fuel Treatments on Fire Size and Suppression Costs

We now turn to understanding how fire suppression effort, costs, and fire size respond to differences in the volume of nearby fuel treatments, and, in turn, whether such effects can be used to assess the overall benefits of fuel treatments. The results depend on whether fuel treatments and fire suppression effort are q-complements or q-substitutes (Hicks, 1970). Specifically, fuel treatments and fire suppression effort are q-substitutes if an increase in fuel treatments $decreases$ the marginal productivity of suppression effort on fire size, which can be expressed formally as $-\frac{\partial^2 S(E,F)}{\partial F \partial E} < 0$.[13] Intuitively, if fuel treatments decrease the marginal productivity of suppression effort, a fire manager will reallocate effort away from fires with nearby fuel treatments until the marginal benefit is equal to its marginal cost (including the shadow cost of effort if the resource constraint is binding). The opposite is true if fuel treatments increase the marginal productivity of suppression effort. This result has implications for fuel treatments' effects on suppression costs and fire size.

Result 2. Fuel treatments will decrease fire suppression effort if and only if fuel treatments and suppression effort are q-substitutes:

$$\frac{dE_i^*}{dF_i} < 0 \iff -\frac{\partial^2 S(E_i, F_i)}{\partial F_i \partial E_i} < 0.$$

[13]Note that since $\frac{\partial S(E,F)}{\partial E} < 0$, we can characterize the marginal benefit of suppression effort as $-L(X) \cdot \frac{\partial S(E,F)}{\partial E}$. Hence, we write the effect of fuel treatments on the marginal productivity of suppression effort using the cross-partial elasticity with a negative.

The opposite is true if fuel treatments and suppression effort are q-complements.

Corollary 2.1. Fuel treatments will decrease fire suppression costs if and only if fuel treatments and suppression effort are q-substitutes.

$$\frac{dC(E_i^*)}{dF_i} = \frac{dC(E_i^*)}{dE_i} \cdot \frac{dE_i^*}{dF_i} < 0 \iff \frac{dE_i^*}{dF_i} < 0 \iff -\frac{\partial^2 S(E_i, F_i)}{\partial F_i \partial E_i} < 0.$$

The opposite is true if fuel treatments and suppression effort are q-complements.

Corollary 2.2. Fuel treatments will decrease fire size if fuel treatments and suppression effort are q-complements.

$$\frac{dS(E_i^*, F_i)}{dF_i} = \frac{\partial S(E_i^*, F_i)}{\partial E_i} \cdot \frac{dE_i^*}{dF_i} + \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0 \iff \frac{dE_i^*}{dF_i} > 0 \iff -\frac{\partial^2 S(E_i, F_i)}{\partial F_i \partial E_i} > 0.$$

In contrast, fuel treatments may or may not decrease fire size if fuel treatments and suppression effort are q-substitutes.

Corollary 2.1 is a direct implication of Result 2, as suppression costs are assumed to be a monotonically increasing function of suppression effort. Thus, fuel treatments will not necessarily reduce the suppression costs of nearby fires. Corollary 2.2 reaches a similar conclusion for a fire's size. Intuitively, the negative direct effect of fuel treatments on a fire's size, $\frac{\partial S(E_i, F_i)}{\partial F_i}$, will be enhanced through the indirect effect of increasing suppression effort, $\frac{\partial S(E_i, F_i)}{\partial E_i} \cdot \frac{dE_i}{dF_i}$, under q-complementarity. In contrast, if fuel treatments and suppression effort are q-substitutes, then the direct effect of fuel treatments on a fire's size will be offset by a reduction of suppression effort, leaving the total effect ambiguous. Thus, fuel treatments are not guaranteed to reduce the size of nearby fires and depend critically on the endogenous effort allocation response of fire managers.

The relationship between fuel treatments and suppression effort has important implications for suppression costs and fire size. Determining whether fuel treatments and suppression effort are q-complements or q-substitutes requires an understanding of whether fuel treatments disproportionately enhance some units of effort relative to others. For example, fuel treatments and suppression effort are q-substitutes if fuel treatments disproportionately enhance the effectiveness of hand crews relative to air tankers, and q-complements if fuel treatments disproportionately enhance the effectiveness of air tankers relative to hand crews. Qualitative evidence suggests that fuel treatments enhance the ability of hand crews to conduct direct and indirect attacks, suggesting that fuel treatments may reduce expected fire sizes relatively more for low levels of fire suppression effort allocations (Romero and Menakis, 2013). If so, then fuel treatments become substitutable for fire suppression effort and lead the fire manager to allocate fewer resources to fighting fires that occur close to fuel treatments.

Our results thus far have focused on the effects of fuel treatments on a nearby fire. The binding constraint of effort resources also has implications for the effects of fuel treatments on other fires. Intuitively, if fuel treatments decrease the marginal productivity of suppression effort, a fire manager will reallocate effort away from the fire near fuel treatments. If the effort constraint is binding, then this effort is allocated toward other fires until marginal benefits minus marginal costs are equal across all fires. The opposite is true if fuel treatments increase the marginal productivity of suppression effort.

Result 3. Fuel treatments will induce spillovers onto other fires if the suppression effort resource constraint binds. Specifically, fuel treatments will direct suppression effort toward other fires if they are q-substitutes,

$$\frac{dE_j^*}{dF_i} > 0 \iff -\frac{\partial^2 S(E_i, F_i)}{\partial F_i \partial E_i} < 0,$$

and draw suppression effort away from other fires if they are q-complements.

Corollary 3.1. If the effort resource constraint binds, fuel treatments may increase or decrease total fire suppression costs, regardless of whether fuel treatments and suppression effort are q-complements or q-substitutes.

Corollary 3.2. If the effort resource constraint does not bind, fuel treatments will decrease total fire suppression costs if and only if fuel treatments and fire suppression efforts are q-substitutes.

The immediate implication of Result 3 is that our empirical strategy will need to consider a possible violation of the stable unit treatment value assumption (SUTVA). That is, one fire's effect of being close to a fuel treatment will depend on the proximity of all other fires to fuel treatments. We discuss how we address this challenge in Section 3. Corollary 3.1 demonstrates that these spillover effects also have implications for fuel treatments' effect on total fire suppression costs across all fires. To understand how total suppression costs could go up, consider the situation in which there are only two fires and $E_1^* > E_2^*$ since there are more assets at risk for Fire 1. Now, suppose that Fire 2 is close to a fuel treatment and that fuel treatments are q-substitutes to suppression effort, which implies that even more effort is now directed toward Fire 1. Since suppression costs are convex in effort, this implies that total suppression costs would increase. Corollary 3.2 demonstrates that total suppression costs are guaranteed to decrease with fuel treatments in a situation of q-substitutability and a non-binding resource constraint—i.e., effort is directed away from nearby fires and not re-allocated to other fires, thereby decreasing suppression costs.

2.4 Testable Implications

The results thus far suggest that fuel treatments will provide positive economic benefits so long as they have a negative direct effect on fire size. However, we cannot directly test for the existence of such an effect as we can only empirically identify the total effect of fuel treatments on fire size, which includes the mediating response of fire suppression effort. Moreover, we have also demonstrated that fuel treatments may not reduce suppression costs or fire size in the presence of endogenous fire suppression effort, even if they provide overall economic benefits. Thus, fuel treatments' effect on fire suppression costs and fire size may not provide an accurate assessment of the overall benefits associated with fuel treatments. How, then, can we know if fuel treatments are economically beneficial?

We now demonstrate how our sufficient condition for economic benefits (Result 1) can be tested empirically by implication. We then show that if this condition is met, then the effect of fuel treatments on suppression costs can be used to (partially) quantify these benefits, so long as the resource constraint is not binding.

Recall that the total effect of fuel treatments on fire size is

$$\frac{dS(E_i^*, F_i)}{dF_i} = \frac{\partial S(E_i^*, F_i)}{\partial E_i} \cdot \frac{dE_i^*}{dF_i} + \frac{\partial S(E_i^*, F_i)}{\partial F_i}.$$

Now, suppose that fuel treatments and suppression effort are q-substitutes, which implies $\frac{dE_i^*}{dF_i} < 0$ (Result 2). Then we have the following:

$$\frac{dS(E_i^*, F_i)}{dF_i} < 0 \iff \frac{\partial S(E_i^*, F_i)}{\partial F_i} < -\frac{\partial S(E_i^*, F_i)}{\partial E_i} \cdot \frac{dE_i^*}{dF_i} < 0 \implies \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0.$$

That is, a negative total effect of fuel treatments on fire size, including the endogenous effort response, implies the direct effect of fuel treatments on fire size is negative, so long as fuel treatments and suppression effort are q-substitutes. From Corollary 2.1, we know that the impact of fuel treatments on suppression costs is a sufficient condition for the q-substitutability of fuel treatments and suppression effort:

$$\frac{dC(E_i^*)}{dF_i} < 0 \iff \frac{dE_i^*}{dF_i} < 0.$$

Thus, if the total effect of fuel treatments on fire size and suppression costs are both negative, then fuel treatments are economically beneficial. Additionally, if the resource constraint is also not binding, then fuel treatments will decrease total fire suppression costs (Corollary 3.2) without increasing the size of fires. In this case, we can say that fuel treatments' effect on suppression costs is a partial measure of their economic benefits.

To summarize, fuel treatments are economically beneficial if they have a direct and negative effect on fire size, but we cannot empirically identify this effect. Instead, we can test for their economic benefits by implication through the null hypothesis $H_o : \frac{dS(E_i^*, F_i)}{dF_i} \geq 0$ or $\frac{dC(E_i^*)}{dF_i} \geq 0$. Rejecting the null implies $\frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0$, i.e., that fuel treatments are economically beneficial. If we can further show that fire suppression effort is not subject to a binding resource constraint, then we can partially quantify the economic benefits of fuel treatments by estimating their effect on suppression costs. The following empirical framework draws from these results to quantify and test for the economic benefits of fuel treatments and compare them to their implementation costs.

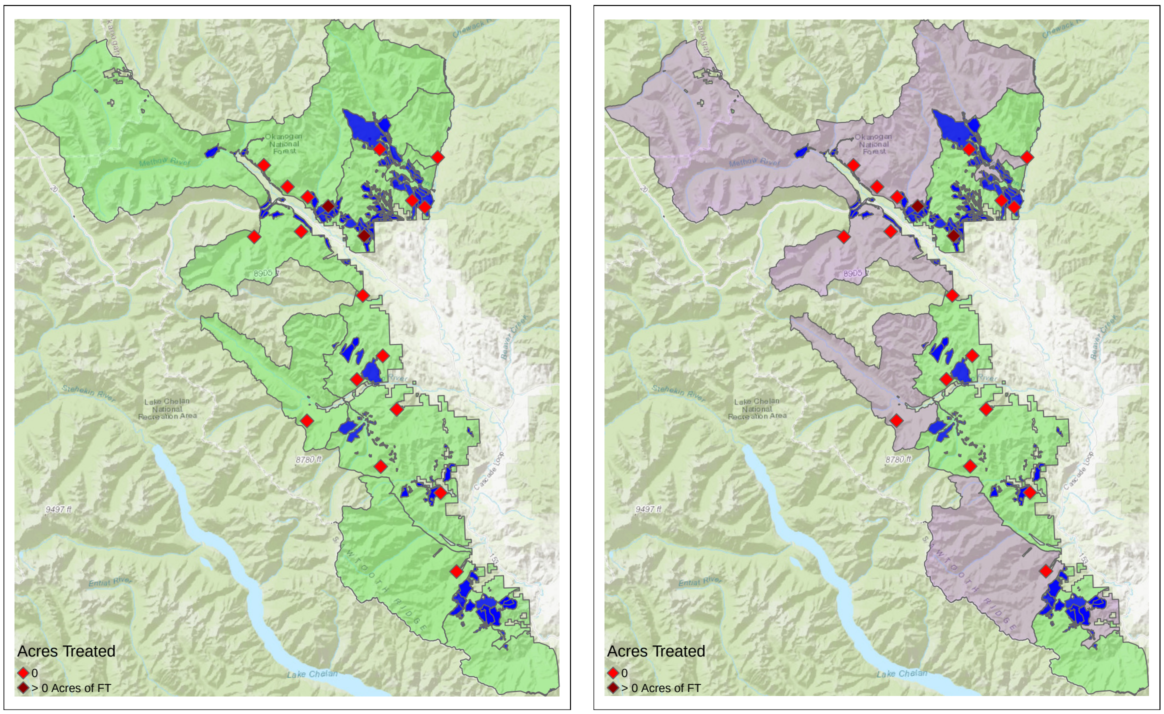
3 Empirical Framework

We aim to identify the effect of fuel treatments on fire suppression costs and fire size by taking advantage of variations in fire ignition and fuel treatment locations within national forests. Intuitively, this strategy compares the suppression cost and size of fires that start within the same national forest but are exposed to different amounts of fuel treatments within a certain radius of their ignition location (Figure 3a). Such comparisons, however, may be subject to bias as fuel treatments and fire suppression effort are jointly determined via socioeconomic and environmental factors. For example, one of the main goals of implementing fuel treatments is to protect communities most at risk from wildfires. Hence, fuel treatments are typically located closer to homes in the WUI. At the same time, wildfire suppression effort, and thus costs, are disproportionately higher for fires that threaten homes (Bayham and Yoder, 2020; Baylis and Boomhower, 2023; Plantinga et al., 2022). Additionally, the costs of conducting fuel treatments correlate with topographic (e.g., lower slopes and elevations), vegetation characteristics (e.g., site productivity), and economic (e.g., proximity to roads) variables that also influence fire suppression costs. To address these concerns, we take advantage of exogenous variation in fuel treatment locations arising from spatial variation of late-successional reserves (LSRs) from the Northwest Forest Plan.[14]

[14]The interested reader can turn to Figure A1 and Section A3 in the Supplemental Appendix for a visual representation of the data generating process of fuel treatments and wildfires along with a more detailed discussion of the sources endogeneity driving fuel treatment location and fire suppression costs.

Figure 3: Baseline & IV Identification Strategies

(a) Baseline **(b)** Instrumental Variables



Notes: The panels above display fire ignition locations (red) and fuel treatments (blue) within the Methow Valley Ranger District during the 2013 fire season. The left panel illustrates the "Baseline" estimation strategy, which leverages the proximity of fire ignitions to fuel treatments occurring within the same national forest and season. The right panel depicts the "Instrumental Variable" approach, highlighting protected areas (LSRs) in purple and unreserved areas (Matrix) in light green.

3.1 Data

We construct a dataset that combines administrative data of NWFP land use allocations with fuel treatment and wildfire outcomes in the Pacific Northwest from 2006-2023. Our data come from various sources with varying degrees of spatial and temporal coverage. A summary of the main data sources for wildfire costs, fuel treatments, NWFP land use allocations, and the name, source, and description of all control variables used in our analysis are provided in Table A6 and Table A7.

Information on the cost, date, and ignition location of wildfires come from two sources spanning different periods. The National Fire and Aviation Management Web Applications (FAMWEB), used in Baylis and Boomhower (2023), comprises wildfires igniting from 2006-2014 (FAMWEB, 2023). Since the FAMWEB collection system was discontinued in 2014, we supplement this with post-2014 data from the National Interagency Fire Center (NIFC)'s "Wildland Fire Incident Locations" (NIFC, 2024b). For each fire, we obtain environmental and socio-economic determinants of wildfire behavior and fire suppression effort. Environmental variables include topographic (e.g., elevation, slope, and aspect), vegetation (e.g., fuel type and fuel loads), and historic fire risk (e.g., mean fire return interval) at the ignition point from LANDFIRE, along with weather conditions (e.g., temperature, precipitation, wind speed, and vapor pressure deficit) at the time of ignition from PRISM and GridMET.[15] We also compute distances between ignition points and high-value resources that influence fire suppression effort, such as the nearest Census Block in the WUI, USFS roads, and total housing value within a 10-kilometer radius (Radeloff et al., 2022; USFS, 2023a).

Fuel treatment data come from the USFS Forest Service Activity Tracking System (FACTS) Hazardous Fuel Treatment Reduction database (USFS, 2024). The USFS has systematically recorded management activities in FACTS since 2005 (Adams and Charnley, 2018). Hence, we restrict our sample to fuel treatment activity post-2005. Fuel treatment activities typically fall into three main categories: mechanical and hand (henceforth "mechanical") removal (e.g., tree removal, mastication of small trees and shrubs, and hand thinning or pruning followed by piling and burning), prescribed burning (e.g., intentional application of fire), and wildfire use (e.g., unplanned wildfires left to burn). We restrict our attention to the effectiveness of mechanical and prescribed burning fuel treatments since they are the types of treatment conducted by USFS and impacted by the NWFP reserves.

Spatial data on NWFP LSRs and Matrix areas come from the Regional Ecosystem Office (REO), which provides the location of these reserves across the Pacific Northwest (REO, 2013). The REO dataset has the precise location of LSRs. Matrix areas are grouped in the "Other" category, overlapping with Riparian Reserves.[16] We broaden our definition of Matrix to include other NWFP designations with similar management protocols, such as "Adaptive Management Areas."[17] Throughout the rest of this paper, we refer to Matrix areas as being inclusive of Adaptive Management Areas and Riparian Reserves within Matrix areas from the NWFP.

Our sample is inclusive of small fires to capture the impact of fuel treatments on reducing the costs of initial attack efforts or preventing small fires from becoming large. Because small fire suppression costs are not systematically recorded, our sample contains many "zero-cost" fires, most of which are successfully suppressed through initial attack.[18] Our analysis is robust to alternative inclusions and treatments of zero-cost fires, described in Section 4.1.

[15]LANDFIRE data can be accessed at `https://landfire.gov/`, PRISM at `https://prism.oregonstate.edu/explorer/`, and GridMET from `https://www.climatologylab.org/gridmet.html`

[16]To account for the fact that Riparian Reserves have their own set of restrictions and regulations, we control for whether a fire ignites inside of a Riparian Area (as defined by Existing Vegetation Group Type from LANDFIRE). Consistent with the additional regulatory restrictions in Riparian Areas, we find that fires igniting in such areas receive significantly fewer fuel treatments close to their ignition point than fires that ignite in other vegetation types.

[17]See Section A2 and Table A5 in the Supplemental Appendix for a list and description of all the land-use categories from the NWFP.

[18]Approximately 45% of small fires (<100 acres) are zero-cost fires in our sample.

Since the spatial distribution of private land ownership is correlated with economic and environmental determinants of fire suppression efforts and fuel treatments, we restrict our sample to only those fires that ignite within National Forests. For example, private forest lands are typically located near communities, along river bottoms, and around valley fringes, while National forests were created primarily from lands left after land grants and homesteading had privatized lower-elevation forests (Johnson et al., 2023). To focus on the impact of NWFP reserves, we further restrict our sample to fires that ignite inside the NWFP boundary. In a less restrictive sample, we also include fires that ignite within any of the 17 National Forests that are a part of the NWFP. This sample is less restrictive since some National Forests only lie partly within the NWFP boundary.

As NWFP LSRs and Matrix areas lie outside wilderness areas, we restrict our sample to fires igniting outside wilderness areas or national parks in all our samples.[19] Restricting our sample to fires that ignite within non-wilderness portions of national forests is essential because fire behavior and suppression strategies are systematically different in wilderness areas (Gebert et al., 2007). Lastly, we remove fires igniting in "wet" National Forests that are at little risk of wildfire and where fuel treatments are not a management priority.[20]

These filtering steps ensure that our sample focuses on fires igniting within either LSRs or Matrix areas on USFS land—i.e., areas that are most comparable, as both types of land would have faced similar protection (or lack thereof) under alternative NWFP plans. In total, our main sample includes 9,797 fires from 2006-2023 where $4.64 billion USD was spent on fire suppression, the majority of which occurred during the second half of the sample period (Figure 2b).[21] Table 1 provides a summary of our fuel treatment and fire cost data. Consistent with qualitative accounts, fuel treatment costs are markedly lower than suppression costs, with only $279 million spent on all fuel treatments in Matrix and LSRs over this period.[22] Matrix and LSR areas, collectively, represent 93% of treated acres and 67% of suppression costs within the NWFP region on USFS land (see Table A8).

Table 1 also shows major discrepancies between the median and averages in our dataset, which are consistent with previous literature showing that fire suppression costs and acres burned are a right-tail-driven process. For example, the average cost of suppressing a fire ($474,354) is orders of magnitude larger than the median cost of suppressing a fire ($222.5). We see a similar pattern for acres burned as the average is 546 and the median is 0.1. These results are consistent with the fire

[19]Parks and wilderness areas were lobbied by the timber industry to be located in high alpine areas and were mostly located in areas with no development before designation (Johnson et al., 2023).

[20]We remove 188 fires igniting in "Olympic" or "Suislaw" national forests.

[21]For reference, the USFS spent $30.5 billion in fire suppression costs over the same time period, with $38.1 billion across all federal agencies (NIFC, 2024a).

[22]The $279 million costs should be interpreted as an overestimate of the true cost because the $222 million spent on mechanical treatments in the FACTS data does not include the revenues from thinning, which often fund other fuel treatment activities, and in some cases, cover the full cost of other surface fuel treatments (Belavenutti et al., 2021).

Table 1: Fuel Treatments & Wildfires Descriptive Statistics

	Prescribed Fire	Mechanical	Total Treatments	Wildfires
Average Cost	\$7,578	\$13,423	\$14,159	\$474,354
Median Cost	\$1,476.2	\$2,069.9	\$1,940.3	\$222.5
Total Cost	\$56,654,906	\$222,963,295	\$279,618,201	\$4,647,248,435
Average Acres	56.6	63.1	74.5	546.6
Median Acres	18.3	24	24	0.1
Total Acres	423,221	1,048,673	1,471,894	5,354,781
Total Cost/Acre	\$133.9	\$212.6	\$190	\$867.9
No. Obs	7,476	16,611	19,748	9,797
Coverage	2006-2023	2006-2023	2006-2023	2006-2023

Note: The first three columns show size and cost statistics for Prescribed Fires, Mechanical, and Total Fuel Treatments (Prescribed Fire + Mechanical) that occur in Matrix and LSR areas in USFS lands in the NWFP area. Cost data for fuel treatments should be interpreted cautiously because FACTS does not have a systematic way of recording cost data. For example, mechanical treatments do not record revenues from sold timber, so some treatments will be recorded with zero cost, while others will not consider revenues in their cost calculation. The fourth column shows size and cost statistics for wildfires that ignite in Matrix and LSR areas in USFS lands in the NWFP area.

suppression policies and practices of the Forest Service, where 98% of fires started are successfully suppressed within a day, while the other 2% account for 95% of fire damages and effects (Calkin et al., 2005).[23]

3.2 Baseline Estimation Strategy

Following Baylis and Boomhower (2023), we start with the following fixed-effects specification as our baseline regression model:

$$Y_{ift} = \phi \log(FT_{it}) + X'_{it}\beta + E'_{it}\Lambda + \mu_f + \lambda_t + \epsilon_{ift}, \tag{2}$$

where Y_{ift} is the natural log of the cost (or size) of fire i, that starts in national forest f, in month t. Our parameter of interest is ϕ, which represents the percentage difference in suppression costs (or size) associated with a one-percent difference in the acres of fuel treatments occurring within a certain distance of fire i, FT_{it}.[24]

We specify FT_{it} as the acres of fuel treatment, both mechanical and prescribed fires, occurring within a 100-acre circle surrounding the ignition point of the fire within the last ten years of the

[23] See Figure A2a in the Supplemental Appendix for plots of the distributions of fire size and suppression cost in our sample.

[24] We model the relationship between fuel treatments and fire size/cost as a log-log specification to be consistent with the fire ecology literature that shows the fuel treatment effectiveness is non-linear and exhibits diminishing returns to scale (Ott et al., 2023). To account for the fact that many fires have zero cost or zero acres of fuel treatment close to the fire, we take the $\log(x + 1)$ transformation of suppression costs and fuel treatments. We discuss alternative ways of dealing with fires with zero costs or zero fuel treatments in Section 4.1.

fire.[25] Taking the sum of both mechanical and prescribed fire fuel treatments recognizes that fuel treatments incorporating both mechanical and prescribed fire treatments are considered best practice for reducing wildfire severity (Wimberly et al., 2009; Prichard and Kennedy, 2014). Figure 4 provides an example of how we calculate fuel treatments for a particular fire. We calculate the acres of fuel treatment "close" to a fire instead of the acres of fuel treatment that intersect with a fire's footprint because larger fires are more likely to intersect with fuel treatments due to their size, thus leading to a spurious positive correlation by construction. Additionally, if fuel treatments are used to construct fire lines where the fire is to be stopped and contained, then a fire is unlikely to intersect with the proximate fuel treatments.[26] Because our treatment variable measures the acres of fuel treatment close to an ignition point, our results do not capture all the potential benefits of fuel treatments on wildfire size or suppression costs. For example, fuel treatments that occur further away from an ignition point may still influence the cost and size of large fires that encounter fuel treatments further away from their ignition point.[27]

We include sets of socio-economic and environmental control variables, X_{it} and E_{it}, that influence a fire's size and its cost of suppression (Table A7). Environmental variables include topographic (e.g., slope, elevation, or aspect at ignition point), weather (e.g., temperature or vapor pressure deficit), vegetation (e.g., fuel type), and historic fire risk (e.g., mean fire return interval) characteristics near the ignition point.[28] Socio-economic variables include the distance of a fire's ignition to the nearest WUI or Forest Service road. To account for the role of previous wildfires in influencing wildfire behavior, we calculate the previous acres burned within the 100-acre circle surrounding an ignition point in the last 10 years.[29]

National forest fixed effects, μ_f, control for time-invariant unobserved determinants of firefighting costs that are specific to a national forest. Year-month fixed effects, λ_t, control for unob-

[25]We choose ten years to be the cutoff for counting fuel treatments as previous studies have shown that fuel treatment effectiveness is diminished after 9–14 years (Collins et al., 2009; Lydersen et al., 2014). We explore the sensitivity of our estimates to different distances and time-since-fire in Section 4.1. Because mechanical fuel treatments are often conducted in a series of treatments that are followed up by a prescribed burn (e.g., a commercial thin is typically conducted in tandem with other mechanical treatments such as biomass removal or fuel piling), we avoid double counting such fuel treatments by only counting mechanical treatments associated with a given project area once.

[26]Perimeters of fires are only systematically recorded for large fires ($>$ 1000 acres), and hence any analysis using intersected areas would require restricting the sample to only large fires.

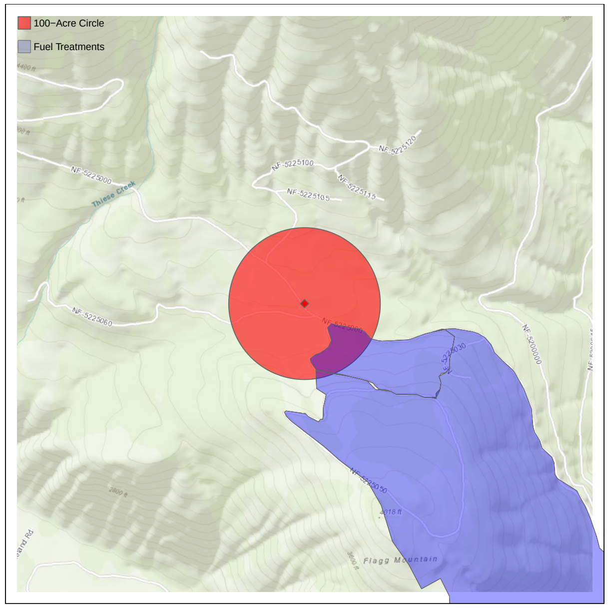
[27]We demonstrate this point in Section A4 of the Supplemental Appendix by decomposing the total marginal benefit of fuel treatments on fire size and suppression cost across multiple channels.

[28]We do not control for vegetation characteristics that are influenced by fuel treatments in our sample, such as canopy base height, as this would condition on one of the mechanisms through which fuel treatments influence our outcomes of interest. Instead, we calculate all vegetation characteristics, like canopy base height, based on their 2001 levels so that they represent pre-treatment vegetation characteristics. See Table A7 in the Supplemental Appendix for more details on such variables.

[29]Note that previous burned acres is sometimes considered another form of fuel treatment and have been shown to reduce wildfire severity (Belval et al., 2019). For fires that do not threaten structures and assets at risk, the USFS lets such fires burn as "Wildfire Use" (WFU).

served changes in firefighting resources, conditions, and costs over time that are constant across national forests. We cluster standard errors at the national forest level.

Figure 4: Example Construction of FT_{it} for Flagg Mountain Fire - 2020



Notes: The above map visually demonstrates how FT_{it} is calculated for a particular fire, the Flagg Mountain Fire, a 0.1 acre fire that occurred close to Mazama, WA, in 2020. The red star shows the ignition point location, the red circle is the area from which fuel treatments are to be calculated (in this case, 100 acres surrounding the ignition point), and the blue shows the location of fuel treatments close to the fire. Multiple treatments occur within the same blue polygon: a mechanical thin in 2015, a machine pile in 2016, and a pile burn in 2019. The intersected area of the fuel treatments and red circle is 10 acres. Since our fuel treatment variable is defined to be the acres of mechanical treatments (no double counting) plus prescribed fire acres, FT_{it} is equal to 20 acres.

The identifying assumption in our baseline regression analysis is that unobserved determinants of fire cost and size, ϵ_{ift}, are independent of FT_{it}, conditional on national-forest fixed effects and our other controls. Because both fuel treatments and fire suppression effort are jointly determined via socio-economic and environmental factors, we may expect estimates of ϕ to still suffer from bias even after the inclusion of our controls because of measurement error and unobserved factors that vary within a national forest, like fire risk. For example, while we control for a fire's proximity to WUI and historic fire risk factors, we do not observe the precise locations of homes or ex-ante wildfire risk at the time a fire ignites or a fuel treatment is conducted.[30] Since we would expect both home proximity and ex-ante fire risk to be positively correlated with fire suppression effort and fuel treatments, our baseline estimate of fuel treatments' effect on suppression costs is likely to suffer from an upward bias—i.e., the expected negative effect of fuel treatments on suppression

[30]Measures of wildfire risk, such as wildfire hazard potential (Dillon and Gilbertson-Day, 2020), measure risk based on conditions in 2014 or later. As a result, this variable is a function of both our dependent and main independent variables for many of the fires in our sample; hence, it would be improper to control for it. Instead, we control for historic fire risk factors since they are not influenced by wildfires or fuel treatments in our sample.

costs will be understated.

A regression of $\log(FT_{it})$ on the observable characteristics of fire suppression effort, X_{it}, and environmental factors that influence wildfire behavior, E_{it}, confirms that fuel treatments highly correlate with such factors (Table 2). Specifically, fires that ignite closer to fuel treatments are, on average, closer in proximity to the WUI, housing units, and wealthier neighborhoods. Consistent with our hypothesis that fuel treatments are located in areas of higher fire risk, we find that fuel treatments occur in areas that historically experienced more frequent fire and that are typically drier and warmer in the summer.

Table 2: Balance Test Regressions - Endogenous Regressor v. Instrument

			Economic Variables		
	Dist WUI	Dist FS Road	Total Housing Value	Population	No. Housing Units
$\log(FT_{it})$	-0.531***	-0.070***	43.351**	164.677**	94.791***
	(0.084)	(0.013)	(17.929)	(61.759)	(29.990)
LSR_{it}	0.890*	0.108	-9.819	-83.635	-34.170
	(0.460)	(0.063)	(20.522)	(122.272)	(65.423)
N	9923				
			Topography & Weather		
	Slope	Elevation	South Slope	Wind Speed	ERC
$\log(FT_{it})$	-0.888***	-39.930***	0.003	0.016	0.188
	(0.181)	(7.615)	(0.006)	(0.011)	(0.141)
LSR_{it}	2.673***	41.181	0.015	-0.032	-0.548
	(0.347)	(49.107)	(0.010)	(0.033)	(0.439)
N	9923				
			Historic Fire Risk Variables		
	MFRI	Precip - CN	Temp Mean - CN	Temp Max - CN	VPD - CN
$\log(FT_{it})$	-0.343*	-0.462***	0.159***	0.266***	0.521***
	(0.163)	(0.132)	(0.025)	(0.028)	(0.058)
LSR_{it}	-0.138	0.529	-0.219	-0.484	-1.375**
	(0.837)	(0.500)	(0.229)	(0.290)	(0.582)
N	9923				

* p < 0.1, ** p < 0.05, *** p < 0.01

Notes: The table reports the results of 30 separate regressions of the natural log of fuel treatment acres, $\log(FT_{it})$, and an indicator of whether a fire occurs in a late-successional reserve, LSR_i, on sets of economic and environmental (topography, weather, & historic fire risk) variables with the inclusion of National Forest and year-month of sample fixed effects. The sample includes wildfires igniting inside Matrix and LSR lands within 15 National Forests apart of NWFP from 2006–2023. Economic variables are distance to WUI & USFS road and the total housing value, population, and housing units within 10km of the ignition point. Topographic variables are the slope and elevation at a fire's ignition point, and a dummy variable equal to one if the slope at the ignition point is on a south-facing slope aspect. Weather variables include the wind speed and energy release component (ERC) on the day of ignition. Historic fire risk control variables include mean fire return interval (MFRI) and the 30-year climate normals in August for precipitation, temperature mean, temperature max, and max vapor pressure deficit (VPD) at the ignition point for a given fire. Standard errors are clustered at the national forest level.

3.3 Instrumental Variables Strategy

To address endogeneity concerns, we use spatial variation in late-successional reserves (LSRs) established under the NWFP within National Forests as an instrument for the extent of fuel treatment activity near a fire. The intuition behind this strategy is to compare fires igniting within the same National Forest during the same time of year but under different land designations—those igniting within LSRs (protected) versus those in Matrix (unprotected) areas (Figure 3b).

As we discuss in Section 1, LSRs have inadvertently restricted fuel treatment activities due to the conservation-focused management constraints they impose. Consequently, we hypothesize that fires igniting within LSRs are surrounded by less extensive fuel treatments near their ignition points compared to those in Matrix lands. This variation in fuel treatments can be considered exogenous due to the idiosyncratic processes involved in delineating LSR and Matrix areas. While LSR boundaries were primarily motivated by ecological criteria, such as the nesting, foraging, and dispersal needs of the NSO, substantial portions of NSO critical habitat were left unprotected in Matrix lands due to the compromise between timber production and species conservation in the creation of the NWFP (Gaines et al., 2010; Johnson et al., 2023). Indeed, most fires in our sample occur in dry forests, where scientists have noted the arbitrary ecological distinctions between LSRs and Matrix areas (Spies et al., 2019). For this reason, LSR designations are unlikely to correlate with unobserved factors influencing wildfire behavior, reinforcing the plausibility of our instrument.

More formally, our instrument is a binary variable equal to one if a fire ignites inside an LSR and zero otherwise.[31] Denoting our instrument as LSR_i, the first-stage equation relating fuel treatments and fires igniting in an LSR is:

$$\log(FT_{it}) = \delta LSR_i + X'_{ift}\Pi + E'_{ift}\Psi + \mu_f + \lambda_t + u_{ift}, \tag{3}$$

and the reduced-form equation relating fire suppression costs and LSR status is

$$Y_{ift} = \eta LSR_i + X'_{ift}\Gamma + E'_{ift}\Omega + \mu_f + \lambda_t + v_{ift}. \tag{4}$$

The ratio of the reduced-form and first-stage coefficients, η/δ, is equivalent to the IV estimand of the percentage difference in fire suppression costs (or size) from a one-percent difference in fuel treatments within a certain distance of a fire's ignition.

The identifying assumptions underlying our IV approach are i) relevance: LSR_i has a strong correlation with fuel treatments; ii) exogeneity: LSR_i is (conditionally) uncorrelated with the unobservable determinants of fire size and suppression costs; iii) exclusion: LSR status has (con-

[31] In alternative specifications, we define the instrument as the number of acres of land within an LSR surrounding the ignition point of a fire to account for the fact that a fire may occur close to the border of Matrix-LSR.

ditionally) no direct impact on fire size and suppression costs; and iv) monotonicity: LSR status should only reduce a fire's exposure to fuel treatments within LSRs or have no effect.

Our instrument would violate the first assumption if LSR status did not substantially hinder the Forest Service's ability to conduct fuel treatments. We test this assumption directly by estimating equation (3). We also examine the plausibility of the exogeneity assumption by regressing LSR_i on the observable determinants of fire size and suppression costs with the inclusion of National Forest and year-month fixed effects. We find LSR is generally balanced across observable characteristics and is a considerable improvement over $\log(FT_{it})$ (Table 2). The exclusion restriction would fail if fire suppression efforts were directly responsive to characteristics associated with LSRs—e.g., a concern for saving old-growth forests and NSO habitat. Although we cannot directly test this assumption, this is not likely to be the case because the Forest Service's top priorities in fire suppression are human life, then structures, and lastly natural resources (USFS, 2000).[32] Similarly, the monotonicity assumption would fail if the USFS conducted more fuel treatments in certain areas within LSRs in order to protect the NSO. We do not believe this to be the case because the stated goals of fuel treatments are to protect human assets at risk (USFS, 2022) and minimize the potential harm that fuel treatments may have on the NSO habitat (USFWS, 2008).

We can interpret our IV estimate of the impact of fuel treatments on fire size and suppression costs as a local average treatment effect (LATE), which represents the treatment effect for a specific subgroup of compliers (Imbens and Angrist, 1994). In our case, compliers are fires that would have experienced more fuel treatments close to their ignition point if not for the LSR designation. This contrasts with the average treatment effect on the treated (ATT), which is a weighted average of the treatment effects for compliers and always-takers, the latter representing fires that would have received the same level of fuel treatments close to their ignition point regardless of LSR or Matrix designation. Under a generalized Roy model with positive selection on expected gains (Heckman, 2010), we expect the treatment effect for always-takers to be larger (in magnitude) than for compliers. That is, always-takers occur in areas that were perceived to have large enough benefits from fuel treatments to overcome any implementation challenges associated with an LSR designation. Thus, we posit that our estimate of LATE is an underestimate, in magnitude, of the ATT.

[32] Correspondingly, Plantinga et al. (2022) find no evidence of increased fire suppression effort in ESA or sensitive watershed habitats.

Table 3: IV First Stage & Reduced Form Regression Results

	First Stage	Reduced Form		IV		OLS	
	$\log(FT_{it})$	Size	Cost	Size	Cost	Size	Cost
LSR_{it}	-0.139***	0.107*	0.179***				
	(0.021)	(0.057)	(0.044)				
$\log(FT_{it})$				-0.770*	-1.287***	-0.036*	-0.007
				(0.439)	(0.393)	(0.019)	(0.029)
1st Stage F-Stat	45.3						
R^2	0.19	0.19	0.69	0.07	0.60	0.19	0.69
N	9797	9797	9797	9797	9797	9797	9797

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The table reports the results of seven separate regressions for the first stage, reduced form, full IV estimates, and OLS estimates using an indicator for whether a fire occurs within a late-successional reserve, LSR_i, as an instrument for the natural log of fuel treatments $\log(FT_{it})$. The sample includes wildfires inside of Matrix and LSR areas in the NWFP area from 2006–2023. The first column reports the coefficient estimates for the first stage, $\log(FT_{it})$, while the second and third columns are the reduced form results for the natural log of fire size and suppression costs. The fourth and fifth columns are the full IV regression results on the natural log of wildfire size and suppression cost. The sixth and seventh columns are the baseline OLS estimates of the natural log of wildfire size and suppression cost. Each regression includes economic and environmental control variables. Economic controls include a cubic function of distance to WUI Census Block and USFS road, along with the total population, housing units, and housing value within 10km of the ignition point. Environmental controls include vegetation characteristics (previous acres burned in the last ten years within the 100-acre ignition circle, an indicator if in a Riparian area, fuel model type, canopy height, canopy bulk density, and canopy base height), topographic characteristics (slope, elevation, aspect class, and topographic ruggedness (TRI) at the ignition point), weather controls (mean and max temperature, wind speed, precipitation, energy release component (ERC), and vapor pressure deficit (VPD) on day of ignition), and historic fire risk controls (mean fire return interval (MFRI) and the 30-year climate normals in August for precipitation, temperature mean, temperature max, and max vapor pressure deficit (VPD)). National Forest fixed effects include the 15 national forests apart of the NWFP. Standard errors are clustered at the national forest level. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R (Laurent, 2018).

4 The Effect of Fuel Treatments on Fire Size and Suppression Costs

Table 3 presents the first-stage (3), reduced-form (4), IV, and baseline (2) regression results for both the natural log of fire suppression costs and size. The IV regression uses an indicator variable equal to one if a fire ignites inside of an LSR, LSR_i, as an instrument for $\log(FT_{it})$. The estimated first-stage relationship implies that fires igniting inside of LSRs receive 13.9% fewer acres of fuel treatments within a 100-acre radius of their ignition point than fires igniting inside of Matrix areas, on average. This first-stage relationship is statistically different from zero, with a Kleibergen-Paap F-statistic equal to 45.3, calculated with clustering adjustments, suggesting that LSR status is a strong instrument for fuel treatments. The estimated reduced-form relationships demonstrate that fires igniting inside of LSRs are 10.7% larger (p-value of 0.0770) and 17.9% more expensive (p-value of 0.0010), on average. Taken together, these estimates imply that a one-percent increase in fuel treatments within a 100-acre radius of a fire's ignition reduces fire suppression costs by 1.287 percent (p-value of 0.0051) and fire size by 0.770 percent (p-value of 0.0999), on average. These IV estimates are considerably larger in magnitude than their corresponding baseline fixed-effects OLS estimates, as expected.

The IV estimate on cost implies that fuel treatments and fire suppression effort are q-substitutes—that is, fire managers allocate less suppression effort toward fires that are in close proximity to fuel treatments. This is consistent with qualitative evidence suggesting that fuel treatments enhance the ability of hand crews to conduct direct and indirect attacks, thereby reducing reliance on more costly aerial attack methods (Romero and Menakis, 2013). While this has the effect of decreasing the suppression costs of such fires, it also offsets any direct reductions that fuel treatments have on fire size. Thus, fuel treatments are not guaranteed to reduce a fire's size in such situations, although we find weak evidence that they do in our context.

Following from our conceptual model, a negative direct effect of fuel treatments on fire size is a sufficient condition for the economic benefits of fuel treatments. While the direct effect cannot be empirically identified, we test for its existence indirectly by testing the null hypothesis that the effects of fuel treatments on fire size *or* cost are weakly positive. We find strong evidence to reject the null hypothesis (p-value of 0.0001) using an intersection-union hypothesis test (Casella and Berger, 2002).[33] This result supports the conclusion that fuel treatments are economically beneficial in our context.

Our conceptual model also highlighted the challenges of interpreting our results if resources for fire suppression are scarce. Under a binding resource constraint, effort may be disproportionately allocated away from fires with fuel treatments to those with no fuel treatments if effort and fuel treatments are q-substitutes. Such spillovers have two implications. First, they would violate SUTVA, resulting in an overestimation (underestimation) of the magnitude of fuel treatments' effect on fire suppression costs (fire size). Second, they would imply that reductions in suppression costs from fuel treatments are not guaranteed to be an accurate assessment of the economic benefits of fuel treatments (Corollary 3.1).

To explore the possibility of potential spillovers and a binding resource constraint, we re-estimate our IV regression with additional controls. First, we control for the number of concurrent fires that are within close proximity to fuel treatments ($FT_{it} > 0$) to account for potential spillovers. Implicitly, we are assuming that fires are exchangeable and linear in their spillover effects on other fires so that a fire's potential size and cost only depend on the number of other treated fires (Vazquez-Bare, 2023). Under q-substitutability, we expect the effect of this control to be positive for suppression costs and negative for fire size, as suppression resources shift toward other fires. Second, we account for resource scarcity at the state level, following Gebert et al. (2007). Specifically, we calculate the difference between the weekly average number of fires in a state (2000–2020) and the observed number of fires during the week of a fire's ignition. This measure captures deviations from typical suppression resource availability.[34]

[33] See Section A5 in the Supplemental Appendix for more details on how we conduct this hypothesis test.

[34] Because our sample lacks information on fire containment dates, we supplement it with a wildfire ignition dataset

The IV estimates for fire size (-0.510, p-value of 0.253) and suppression costs (-1.099, p-value of 0.007) do not change meaningfully with the inclusion of these controls (Table A9), although the effect on fire size is no longer statistically significant at conventional levels. We find no significant evidence that spillovers from other treated fires affect suppression costs or fire size (0.001, p-value of 0.95), suggesting spillovers are not a meaningful factor. However, the positive and significant effect of the number of concurrent fires (0.001, p-value of 0.0213) indicates that resource scarcity may influence fire suppression outcomes. The magnitude of this effect is small—each additional concurrent fire (above average) increases fire size and suppression costs by 0.1%. This finding could also reflect variation in general fire conditions within a state that is not fully captured by our fixed effects or other controls. Overall, there is limited evidence that resource constraints meaningfully affect suppression effort allocation. Consequently, the reduction in suppression costs due to fuel treatments remains a valid partial measure of their economic benefits, which we quantify below.

4.1 Robustness Checks

We conduct a variety of robustness checks to evaluate the sensitivity of our results to alternative variable definitions, specifications, and samples. To address concerns that Matrix and LSR areas may be systematically different, even after controlling for observable determinants of fire suppression efforts, we implement a matching procedure to improve comparability between fires igniting in Matrix and LSR areas. This approach relaxes the parametric assumptions of our regression framework and avoids extrapolation when covariate overlap is limited. Each fire igniting in an LSR is matched exactly to a Matrix fire that occurs in the same National Forest, fuel type, and month. Fires are then inexactly matched using a genetic search algorithm to optimize covariate balance across the primary determinants of fire suppression costs and size, including distance to WUI and USFS roads, elevation, slope, vapor pressure deficit, and wind speed. This procedure results in 3,225 matches and 6,450 fires in total. The matched IV estimation yields estimated elasticities for suppression costs and fire size that closely align in magnitude and statistical significance with our baseline results (Table A10). While the matching procedure provides the strongest internal validity for our estimates, we prefer the estimates resulting from our IV regression specification because its estimation sample more closely represents the landscape encompassed by the NWFP and is, therefore, more externally valid for our counterfactual cost-benefit estimates in Section 4.2.

Another concern with our approach is that our estimates may be sensitive to changes in the specified distance for which we calculate fuel treatments close to an ignition point. To explore this, we re-estimate the IV regression for suppression costs using treatment circles of varying sizes: 50,

from the USFS that includes containment information (Short, 2023). This dataset, however, covers fires only up to 2020, reducing the sample size to 8,297 fires from our main sample of 9,797 fires.

75, 100, 125, and 150 acres. We find that the magnitude of the IV estimate is larger for smaller treatment circles but less precisely estimated as there are fewer treated fires (Figure A3). Increasing the treatment circle improves precision but attenuates the estimate towards zero, as fuel treatments that are further away from a fire's ignition point are less likely to influence fire size and suppression costs. Nevertheless, our IV estimates for suppression costs are statistically significant at the 1% level across all specifications.

We also explore the sensitivity of our IV estimates to four alternative estimation samples: i) lightning fires only, ii) all fires occurring in a national forest that intersects with the NWFP, iii) fires that are within 2km of a Matrix-LSR border, and iv) fires that are not associated with a complex (Table A11).[35] The lightning-only sample addresses concerns that human ignition probabilities may correlate with a fire's LSR or Matrix designation. Including fires that occur in any part of a national forest in the NWFP explores how the results generalize across a larger area of interest.[36] Restricting the sample to fires that occur close to Matrix-LSR boundaries addresses concerns that Matrix and LSR areas are systematically different by focusing on areas in which they are most likely to be similar. Limiting the sample to non-complex fires addresses concerns about potential inaccuracies in size and cost reporting for fires within complexes. Overall, the estimated cost elasticity remains robust across samples, while the size elasticity shows less consistency.

Next, we explore how our IV estimates change when using different specifications of our endogenous regressor and instrument: i) a linear specification of FT_{it}, ii) taking the inverse hyperbolic sine transformation of FT_{it}, iii) calculating fuel treatments that occur within the last five years (instead of 10), and iv) using a continuous measure of LSR as an instrument for $\log(FT_{it})$ (Table A13).[37] Across all specifications, the IV estimates for suppression costs are statistically significant at the 1% level, while the significance of fire size is relatively sensitive across specifications.

We also examine the robustness of our IV estimates to three alternative dependent variable specifications: i) excluding zero-cost fires, ii) imputing the cost of zero-cost fires by the median cost of suppressing a small fire, and iii) indicators for above-median fire size or cost (Table A13). The first two approaches address concerns with our choice of including small zero-cost fires in our sample by specifying our dependent variable as the natural log of one plus cost. When estimating i), the signs and magnitudes of our estimates are unchanged, with statistically significant results

[35] A complex fire is one in which multiple ignitions merge into a single fire. Costs for such fires are recorded separately for each ignition point, allowing for multiple fires in our sample associated with a single complex. We are only able to identify a fire complex for the years 2015-2023.

[36] Note that some National Forests lie only partly within the NWFP boundary. Following our original filtering steps, we remove fires occurring in wilderness areas or the two "wet" national forests—Olympic and Suislaw National Forests.

[37] This continuous measure is analogous to FT_{it}: it is the number of LSR-designated acres inside a 100-acre circle around a fire's ignition point.

for both the first stage and reduced form for cost. However, the IV cost estimate loses statistical significance at the 5% level, likely due to reduced sample size, lower statistical power, and the fact that we are now focusing on larger fires. For imputation (ii), small zero-cost fires (<100 acres) are assigned the median cost of small non-zero-cost fires, assuming they represent low-cost initial attacks. Large zero-cost fires (>100 acres) are excluded due to potential misreporting of cost.[38] Imputed results show no change in signs or magnitudes. For above-median indicators (iii), we find that fuel treatments significantly reduce the probability of a fire exceeding the median cost, with no significant effect on fire size.

Finally, we test the robustness of our IV estimates to alternative fixed-effect specifications: i) replacing national forest for ranger district fixed effects, ii) replacing year-month fixed effects for year and month (of year) fixed effects, iii) replacing year-month fixed effects for state-year and state-month (of year) fixed effects, and iv) replacing year-month fixed effects for state-year-month fixed effects (Table A14). Ranger districts are smaller units than National Forests and are more directly involved in land management implementation, and thus, such fixed effects can capture time-invariant unobserved heterogeneity that occurs within the ranger district level. Including time-by-state fixed effects addresses concerns that different states within the NWFP may be following different trends in fire sizes or suppression costs over time. In general, we find that our estimates do not meaningfully change with the inclusion of these various fixed effects.

4.2 Counterfactual Costs & Benefits of Fuel Treatments

To quantify the economic benefits of fuel treatments, we estimate the counterfactual benefits that would have arisen from a landscape-wide expansion of fuel treatments during our sample period relative to the associated costs of expanding fuel treatments. Our empirical strategy does not focus on quantifying damages from wildfires, such as smoke and property loss. Therefore, our main measure of economic benefits is the reduction in fire suppression costs. This approach contrasts with our test of the direct effect of fuel treatments on fire size, which assesses whether any economic benefits stem from fuel treatments in general.

Suppose that all fuel treatments during our sample period increased proportionately by one percent. We assume this leads to a corresponding one-percent increase in fuel treatment costs, equal to \$2.79 million (Table 1).[39] Given a proportionate one-percent increase in fuel treatments, we then calculate the percent increase in 100-acre fuel treatment intersections for each fire (see Figure A4 for a demonstration). For each fire, we calculate the counterfactual suppression cost savings by

[38]Fifty-one fires meet this criterion.

[39]Note that although we are counting the labor costs of fuel treatments as part of our cost measure, many initatives have cited job creation in rural communities as another benefit to increasing the pace and scale of fuel treatments (State of California, 2021). This is especially prescient in the Northwest where 30,000 timber jobs were lost from the NWFP (Ferris and Frank, 2021).

multiplying the percent increase in fuel treatment intersections by our estimated elasticity of fire suppression costs (-1.287; Table 3) and by the cost of suppressing the fire. Summing the counterfactual savings across all of the fires in our sample provides an estimate of the total benefits from fuel treatments. We find that a one-percent uniform expansion of fuel treatments across the landscape would have resulted in suppression-cost savings of around \$10.7 million and 5,896 fewer acres burned, corresponding to a benefit-cost ratio of 3.84.

We further explore whether fuel treatments yield increasing, constant, or decreasing economic returns to scale by increasing fuel treatments proportionately by five and ten percent. Our analysis reveals that the cost-benefit ratio increases to 6.50 and 7.02, respectively, suggesting increasing returns to scale at current levels of fuel treatment activity. We hypothesize that as fuel treatments increase in size, the frequency of intersections with fire areas also rises, thereby enhancing the likelihood of influencing fire behavior across the landscape.

Our finding that fuel treatments yield increasing economic returns to scale indicates that current treatment levels fall short of the social optimum. This strengthens the case for recent efforts by federal and state agencies to expand both the scope and intensity of fuel treatment programs on public lands. For example, California and the U.S. Forest Service have set ambitious targets, committing to treat one million acres annually by 2025—a significant shift from the status quo (USFS and State of California, 2020). Our results suggest that such initiatives are likely to generate substantial economic benefits.

While our estimated benefit-cost ratio highlights the potential benefits of fuel treatments, there are several reasons why it is likely a considerable underestimate of the true economic benefits of fuel treatments. First, our only measure of benefits from fuel treatments is the reduction of fire suppression costs, which account for less than 1% of the total estimated annual economic cost of wildfires (JEC, 2023). Second, the relevant parameter for our counterfactual analysis is the ATT, which tells us the average change in suppression costs that would be experienced by fires intersecting with more fuel treatments relative to a regime where there were fewer fuel treatments.[40] However, our IV strategy identifies the LATE for compliers, which we argue is likely an underestimate (in magnitude) of the ATT (Section 3.3). Third, our fuel treatment cost data do not include revenues from mechanical removal fuel treatments.[41] Finally, fuel treatments likely reduce suppression costs through other channels (i.e., treatments further away from an ignition point may also

[40]The ATT is valid in our counterfactual analysis under the assumption that adjacent untreated areas where fuel treatments expand share similar unobservable characteristics of the treated areas.

[41]Note that we do not model other potential costs from prescribed burns, such as smoke emissions, as this would require analyzing trade-offs in smoke emissions with and without fuel treatments. However, prescribed burns are typically localized and planned to allow communities to prepare for protective measures. Therefore, we believe the benefits of smoke exposure from fuel treatments outweigh their costs. In fact, simulation studies indicate that increasing prescribed burns in the Pacific Northwest and Northern California would significantly reduce population exposure to particulate matter (Kelp et al., 2023).

influence the cost and behavior of large wildfires).[42] Thus, a proper accounting of the benefits provided by fuel treatments would likely result in a benefit-cost ratio that is considerably higher than the conservative estimate we provide here.

Table 4: Counterfactual Benefits of Increasing Fuel Treatments

	Cost of Treatment	Suppression Savings	Benefit-Cost Ratio	Reduction Acres Burned
1% Increase	\$2,796,182	\$10,745,940	\$3.84	5,896
5% Increase	\$13,980,910	\$90,878,301	\$6.5	50,602
10% Increase	\$27,961,820	\$196,272,719	\$7.02	108,603

Notes: The table above presents the cost, benefits, and benefit-cost ratio under different counterfactual scenarios of increasing fuel treatment activity. In the first row, fuel treatments are increased proportionately by one percent, assuming that costs increase accordingly by one percent of the total cost of conducting fuel treatment from 2006-2023. In rows two and three, fuel treatments and costs are increased by five and ten percent.

5 Discussion

A century of wildfire suppression policies has left much of the western U.S. in ecological disequilibrium, with accumulated fuel loads driving larger, more severe, and costlier wildfires. To address this crisis, expanding the pace and scale of fuel-reduction treatments has been proposed as a key strategy. Despite commitments like the U.S. Forest Service's plan to treat 50 million acres of vulnerable landscapes over the next decade (USFS, 2022), empirical evidence on the cost-effectiveness of fuel treatments has remained sparse. Our study bridges this gap by quantifying the economic benefits of fuel treatments in reducing fire suppression costs and fire sizes, two primary drivers of wildfire costs.

To test whether fuel treatments reduce fire suppression costs and fire sizes, we employ an instrumental variable research design that leverages exogenous variation in the location of fuel treatments arising from spatial variation in late-successional reserves (LSR) from the Northwest Forest Plan (NWFP). We find that fires starting in LSRs receive significantly fewer fuel treatments close to their ignition point and are more costly to suppress, on average, suggesting that fuel treatments significantly reduce the cost of wildfires. This result suggests that fuel treatments and fire suppression efforts act as q-substitutes: suppression efforts shift away from fires igniting close to fuel treatments, reducing suppression costs but attenuating the treatments' effectiveness in limiting fire size. Further, q-substitutability implies suppression effort can be reallocated to fight other wild-

[42] If fuel treatments do indeed influence the behavior and costs of larger fires, this has implications for many fires outside of our sample. For example, some of the most costly fires start on private lands but spill over onto public lands (Levine et al., 2022). It is likely that fuel treatments will also reduce the costs of fighting such fires, which our counterfactual analysis does not account for.

fires, although we find little empirical support that fuel treatments have spillover effects on other fires.

To interpret our findings in an economic framework, we develop a stylized model and test a sufficient condition for the presence of overall economic benefits, considering both wildfire damages and suppression costs. Applying a bootstrap intersection-union hypothesis test to our sufficient condition, we find evidence that fuel treatments jointly reduce fire size and suppression costs, thereby providing overall economic gains. We then explore and quantify a lower bound of such economic benefits through counterfactual fire suppression cost savings with proportionate increases in the size of fuel treatments in our sample. Our conservative back-of-the-envelope estimates suggest that for every dollar spent on fuel treatments, four to seven are saved in fire suppression costs, depending on the level of increased treatment activity.

Our results indicate that fuel treatments are a cost-effective means of addressing wildfire costs, despite identifying only one dimension through which fuel treatments can influence fire size and suppression costs. In particular, we do not identify the potential role that fuel treatments play in influencing fire ignitions, nor do we account for the impact that fuel treatments may have in mitigating the spread of large fires located further away from a fire's ignition point (Section A4). Further, our results do not capture how fuel treatments' impact on fire size and severity influences other significant contributors to the costs of wildfires, such as health effects, property damage, and labor market impacts (Bayham et al., 2022; Borgschulte et al., 2022; Heft-Neal et al., 2023). Thus, our estimates of the economic benefits of fuel treatments are likely conservative and could be significantly larger once all potential sources are accounted for.

Our study underscores the need to align conservation and wildfire management policies with climate adaptation goals. We find that well-intentioned policies, such as the establishment of LSRs under the NWFP to protect endangered species, have unintentionally increased wildfire risks by limiting fuel treatments. Similar challenges arise from other environmental regulations such as the Clean Air Act, Wilderness Area restrictions, and NEPA, which collectively constrain proactive forest management on public lands (North et al., 2012, 2015). Reforms to these policies could help reduce wildfire risks, protect vulnerable ecosystems, and lower public expenditures on wildfire suppression. Furthermore, our findings suggest that scaling up fuel treatments could serve as a critical component of climate resilience strategies, complementing efforts to mitigate greenhouse gas emissions and adapt to intensifying wildfire regimes.

In sum, our results provide strong evidence that fuel treatments are a cost-effective tool for mitigating wildfire costs, even when accounting for only a subset of their potential benefits. By reducing suppression costs and potentially alleviating wildfire damages, fuel treatments offer a pathway to address one of the most pressing challenges facing public land management in the western United States. However, realizing the full economic and ecological benefits of fuel treatments will require thoughtful integration of wildfire management policies with broader environmental and climate adaptation goals. We suggest the public take a closer look at how such policies have unintentionally prevented the management of forests on public lands and explore appropriate reforms that encourage proactive management.

References

Abatzoglou, J. T. and Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42):11770–11775. doi: 10.1073/pnas.1607171113.

Adams, M. D. and Charnley, S. (2018). Environmental justice and U.S. Forest Service hazardous fuels reduction: A spatial method for impact assessment of federal resource management actions. *Applied Geography*, 90:257–271.

Agee, J. K. and Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Relative Risk Assessments for Decision –Making Related To Uncharacteristic Wildfire*, 211(1):83–96.

Anderson, S. E., Plantinga, A. J., and Wibbenmeyer, M. (2023). Inequality in Agency Response: Evidence from Salient Wildfire Events. *The Journal of Politics*, 85(2):625–639.

Auffhammer, M., Duru, M., Rubin, E., and Sunding, D. L. (2020). The Economic Impact of Critical-Habitat Designation: Evidence from Vacant-Land Transactions. *Land Economics*, 96(2):188.

Barros, A. M. G., Day, M. A., Spies, T. A., and Ager, A. A. (2021). Effects of ownership patterns on cross-boundary wildfires. *Scientific Reports*, 11(1).

Bayham, J. and Yoder, J. (2020). Resource Allocation under Fire. *Land Economics*, 96(1):92.

Bayham, J., Yoder, J. K., Champ, P. A., and Calkin, D. E. (2022). The Economics of Wildfire in the United States. *Annual Review of Resource Economics*, 14(1):379–401.

Baylis, P. and Boomhower, J. (2023). The Economic Incidence of Wildfire Suppression in the United States. *American Economic Journal: Applied Economics*, 15(1):442–73.

Baylis, P. W. and Boomhower, J. (2021). Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires. *National Bureau of Economic Research Working Paper Series*, No. 29621.

Belavenutti, P., Chung, W., and Ager, A. A. (2021). The economic reality of the forest and fuel management deficit on a fire prone western US national forest. *Journal of Environmental Management*, 293:112825.

Belval, E. J., O'Connor, C. D., Thompson, M. P., and Hand, M. S. (2019). The Role of Previous Fires in the Management and Expenditures of Subsequent Large Wildfires. *Fire*, 2(4).

Boerner, R. E. J., Huang, J., and Hart, S. C. (2009). Impacts of Fire and Fire Surrogate treatments on forest soil properties: A meta-analytical approach. *Ecological Applications*, 19(2):338–358.

Boomhower, J., Fowlie, M., Gellman, J., and Plantinga, A. (2024). *How Are Insurance Markets Adapting to Climate Change? Risk Selection and Regulation in the Market for Homeowners Insurance*. Number 32625 in NBER Working Paper Series. National Bureau of Economic Research, Cambridge, Mass.

Borgschulte, M., Molitor, D., and Zou, E. Y. (2022). Air Pollution and the Labor Market: Evidence from Wildfire Smoke. *The Review of Economics and Statistics*, pages 1–46.

Boustan, L. P., Kahn, M. E., and Rhode, P. W. (2012). Moving to Higher Ground: Migration Response to Natural Disasters in the Early Twentieth Century. *American Economic Review*, 102(3):238–44.

Bradley, B. A., Beaury, E. M., Fusco, E. J., and Lopez, B. E. (2023). Invasive species policy must embrace a changing climate. *BioScience*, 73(2):124–133.

Busby, G., Amacher, G. S., and Haight, R. G. (2013). The social costs of homeowner decisions in fire-prone communities: Information, insurance, and amenities. *Land Use*, 92:104–113.

Calkin, D. E., Cohen, J. D., Finney, M. A., and Thompson, M. P. (2014). How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences*, 111(2):746–751. doi: 10.1073/pnas.1315088111.

Calkin, D. E., Gebert, K. M., Jones, J. G., and Neilson, R. P. (2005). Forest Service Large Fire Area Burned and Suppression Expenditure Trends, 1970–2002. *Journal of Forestry*, 103(4):179–183.

Cameron, A. C. and Trivedi, P. K. (2005). *Microeconometrics: Methods and Applications*. Cambridge University Press, Cambridge.

Casella, G. and Berger, R. (2002). *Statistical inference*. Thomson Learning, Pacific Grove, CA, 2nd edition.

Chetty, R. (2009). Sufficient Statistics for Welfare Analysis: A Bridge Between Structural and Reduced-Form Methods. *Annual Review of Economics*, 1(1):451–488.

Collins, B. M., Miller, J. D., Thode, A. E., Kelly, M., van Wagtendonk, J. W., and Stephens, S. L. (2009). Interactions Among Wildland Fires in a Long-Established Sierra Nevada Natural Fire Area. *Ecosystems*, 12(1):114–128.

Converse, S. J., White, G. C., Farris, K. L., and Zack, S. (2006). SMALL MAMMALS AND FOREST FUEL REDUCTION: NATIONAL-SCALE RESPONSES TO FIRE AND FIRE SURROGATES. *Ecological Applications*, 16(5):1717–1729.

Davis, R. J., Hollen, B., Hobson, J., Gower, J. E., and Keenum, D. (2016). Northwest Forest Plan—the first 20 years (1994-2013): Status and trends of northern spotted owl habitats. Technical report, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Davis, R. J., Ohmann, J. L., Kennedy, R. E., Cohen, W. B., Gregory, M. J., Yang, Z., Roberts, H. M., Gray, A. N., and Spies, T. A. (2015). Northwest Forest Plan–the first 20 years (1994-2013): Status and trends of late-successional and old-growth forests. Technical report, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Dietrich, W. (2010). *The Final Forest: Big Trees, Forks, and the Pacific Northwest*. University of Washington Press, Seattle. ”Originally published in 1992 by Simon & Schuster.” Includes index.

Dillon, G. K. and Gilbertson-Day, J. W. (2020). Wildfire Hazard Potential for the United States (270-m), version 2020 (3rd Edition). `https://www.fs.usda.gov/rds/archive/Catalog/RDS-2015-0047-3`.

Donovan, G. H. and Rideout, D. B. (2003). A Reformulation of the Cost Plus Net Value Change (C+NVC) Model of Wildfire Economics. *Forest Science*, 49(2):318–323.

Edwards, E. and Sutherland, S. (2022). Does Environmental Review Worsen the Wildfire Crisis? Technical report, Property Environment Research Center (PERC).

Egan, T. (2011). *The Big Burn: Teddy Roosevelt and the Fire That Saved America*. Houghton Mifflin Harcourt, Boston, Mass.

FAMWEB, N. (2023). Fire and weather data. `https://www.wildfire.gov/application/fire-and-weather-data` [Accessed: April 17, 2023].

Ferris, A. E. and Frank, E. G. (2021). Labor market impacts of land protection: The Northern Spotted Owl. *Journal of Environmental Economics and Management*, 109:102480.

Finkral, A. and Evans, A. (2008). The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. *Large-scale experimentation and oak regeneration*, 255(7):2743–2750.

Gaines, W. L., Harrod, R. J., Dickinson, J., Lyons, A. L., and Halupka, K. (2010). Integration of Northern spotted owl habitat and fuels treatments in the eastern Cascades, Washington, USA. *Forest Ecology and Management*, 260(11):2045–2052.

Gaines, W. L., Hessburg, P. F., Aplet, G. H., Henson, P., Prichard, S. J., Churchill, D. J., Jones, G. M., Isaak, D. J., and Vynne, C. (2022). Climate change and forest management on federal lands in the Pacific Northwest, USA: Managing for dynamic landscapes. *Forest Ecology and Management*, 504:119794.

Gebert, K. M., Calkin, D. E., and Yoder, J. (2007). Estimating Suppression Expenditures for Individual Large Wildland Fires. *Western Journal of Applied Forestry*, 22(3):188–196.

Graham, R., Jain, T., and Loseke, M. (2009). *Fuel Treatments, Fire Suppression, and Their Interaction with Wildfire and Its Impacts: The Warm Lake Experience during the Cascade Complex of Wildfires in Central Idaho*.

Hartsough, B. R., Abrams, S., Barbour, R. J., Drews, E. S., McIver, J. D., Moghaddas, J. J., Schwilk, D. W., and Stephens, S. L. (2008). The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and Fire Surrogate Study. *Wildfire mitigation*, 10(6):344–354.

Heckman, J. J. (2010). Building Bridges Between Structural and Program Evaluation Approaches to Evaluating Policy. *Journal of Economic Literature*, 48(2):356–398.

Heft-Neal, S., Gould, C. F., Childs, M. L., Kiang, M. V., Nadeau, K. C., Duggan, M., Bendavid, E., and Burke, M. (2023). Emergency department visits respond nonlinearly to wildfire smoke. *Proceedings of the National Academy of Sciences*, 120(39):e2302409120.

Hessburg, P. F., Prichard, S. J., Hagmann, R. K., Povak, N. A., and Lake, F. K. (2021). Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, 31(8):e02432.

Hicks, John. (1970). Elasticity of substitution again: Substitutes and complements. *Oxford Economic Papers*, 22(3):289–296.

Hjerpe, E. E., Colavito, M. M., Waltz, A. E., and Meador, A. S. (2024). Return on investments in restoration and fuel treatments in frequent-fire forests of the American west: A meta-analysis. *Ecological Economics*, 223:108244.

Hoover, K. and Lindsay, B. R. (2017). Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress. Technical report, Congressional Research Service.

Hunter, M. E. and Taylor, M. H. (2022). The Economic Value of Fuel Treatments: A Review of the Recent Literature for Fuel Treatment Planning. *Forests*, 13(12).

Imbens, G. W. and Angrist, J. D. (1994). Identification and Estimation of Local Average Treatment Effects. *Econometrica*, 62(2):467–475.

JEC, J. E. C. D. (2023). Climate-exacerbated wildfires cost the U.S. between $394 to $893 billion each year in economic costs and damages. Technical report, Joint Economic Committee Democrats.

Johnson, K. N., Franklin, J. F., Reeves, G. H., Johnson, D. L., and Brown, S. J. M. (2023). *The Making of the Northwest Forest Plan: The Wild Science of Saving Old Growth Ecosystems*. Oregon State University Press, Corvallis, Oregon.

Kalies, E. L. and Yocom Kent, L. L. (2016). Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management*, 375:84–95.

Kelp, M. M., Carroll, M. C., Liu, T., Yantosca, R. M., Hockenberry, H. E., and Mickley, L. J. (2023). Prescribed Burns as a Tool to Mitigate Future Wildfire Smoke Exposure: Lessons for States and Rural Environmental Justice Communities. *Earth's Future*, 11(6):e2022EF003468.

Kline, J. D. (2004). Issues in evaluating the costs and benefits of fuel treatments to reduce wildfire in the Nation's forests. Technical report, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Kolden, C. A. (2019). We're Not Doing Enough Prescribed Fire in the Western United States to Mitigate Wildfire Risk. *Fire*, 2(2).

Kousky, C. (2019). The role of natural disaster insurance in recovery and risk reduction. *Annual Review of Resource Economics*, 11(Volume 11, 2019):399–418.

Kousky, C., Luttmer, E. F. P., and Zeckhauser, R. J. (2006). *Private Investment and Government Protection*. Number no. w12255 in NBER Working Paper Series. National Bureau of Economic Research, Cambridge, Mass.

Laurent, B. (2018). Efficient estimation of maximum likelihood models with multiple fixed-effects: the R package FENmlm. *CREA Discussion Papers*.

Levine, J. I., Collins, B. M., Steel, Z. L., de Valpine, P., and Stephens, S. L. (2022). Higher incidence of high-severity fire in and near industrially managed forests. *Frontiers in Ecology and the Environment*, 20(7):397–404.

Loveridge, E. W. (1944). The Fire Suppression Policy of the U. S. Forest Service. *Journal of Forestry*, 42(8):549–554.

Lydersen, J., North, M., and Collins, B. (2014). Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. *Forest Ecology and Management*, 328:326–334.

Miller, J. D., Safford, H. D., Crimmins, M., and Thode, A. E. (2009). Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. *Ecosystems*, 12(1):16–32.

Molitor, D., Mullins, J. T., and White, C. (2023). Air pollution and suicide in rural and urban America: Evidence from wildfire smoke. *Proceedings of the National Academy of Sciences*, 120(38):e2221621120. doi: 10.1073/pnas.2221621120.

Murphy, K., Rich, T., and Sexton, T. (2007). An Assessment of Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition on the Angora Fire. Technical report, U.S. Department of Agriculture, Forest Service, Lake Tahoe Basin Management Unit.

Nelson, E. J., Withey, J. C., Pennington, D., and Lawler, J. J. (2017). Identifying the impacts of critical habitat designation on land cover change. *Resource and Energy Economics*, 47:89–125.

NIFC (2024a). Suppression Costs. `https://www.nifc.gov/fire-information/statistics/suppression-costs`. NIFC: National Interagency Fire Center. Accessed: November 9, 2024.

NIFC (2024b). Wildland fire incident locations. `https://www.wildfire.gov/application/fire-and-weather-data`. NIFC: National Interagency Fire Center. Accessed: March 11, 2024.

North, M., Brough, A., Long, J., Collins, B., Bowden, P., Yasuda, D., Miller, J., and Sugihara, N. (2015). Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in the Sierra Nevada. *Journal of Forestry*, 113(1):40–48.

North, M., Collins, B. M., and Stephens, S. (2012). Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments. *Journal of Forestry*, 110(7):392–401.

North, M. P., Tompkins, R. E., Bernal, A. A., Collins, B. M., Stephens, S. L., and York, R. A. (2022). Operational resilience in western US frequent-fire forests. *Forest Ecology and Management*, 507:120004.

Ott, J. E., Kilkenny, F. F., and Jain, T. B. (2023). Fuel treatment effectiveness at the landscape scale: A systematic review of simulation studies comparing treatment scenarios in North America. *Fire Ecology*, 19(1):10.

Parks, S. A., Holsinger, L. M., Blankenship, K., Dillon, G. K., Goeking, S. A., and Swaty, R. (2023). Contemporary wildfires are more severe compared to the historical reference period in western US dry conifer forests. *Forest Ecology and Management*, 544:121232.

Plantinga, A. J., Walsh, R., and Wibbenmeyer, M. (2022). Priorities and Effectiveness in Wildfire Management: Evidence from Fire Spread in the Western United States. *Journal of the Association of Environmental and Resource Economists*, 9(4):603–639.

Prichard, S. J. and Kennedy, M. C. (2014). Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. *Ecological Applications*, 24(3):571–590.

Pyne, S. J. (2008). *Year of the Fires: The Story of the Great Fires of 1910*. Mountain Press Pub. Co, Missoula, Mont.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S., Syphard, A. D., and Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences*, 115(13):3314–3319. doi: 10.1073/pnas.1718850115.

Radeloff, V. C., Helmers, D. P., Mockrin, M. H., Carlson, A. R., Hawbaker, T. J., and Martinuzzi, S. (2022). The 1990-2020 wildland-urban interface of the conterminous United States - geospatial data (3rd Edition).

Reilly, M. J., Elia, M., Spies, T. A., Gregory, M. J., Sanesi, G., and Lafortezza, R. (2018). Cumulative effects of wildfires on forest dynamics in the eastern Cascade Mountains, USA. *Ecological Applications*, 28(2):291–308.

REO (2013). Land use allocations 2013. `https://www.fs.usda.gov/r6/reo/library/maps.php`. REO: Regional Ecosystem Office. Accessed: April 17, 2023.

Richter, C., Rejmánek, M., Miller, J. E. D., Welch, K. R., Weeks, J., and Safford, H. (2019). The species diversity × fire severity relationship is hump-shaped in semiarid yellow pine and mixed conifer forests. *Ecosphere*, 10(10):e02882.

Rideout, D. B., Wei, Y., Kirsch, A., and Botti, S. J. (2008). Toward a Unified Economic Theory of Fire Program Analysis with Strategies for Empirical Modeling. In Holmes, T. P., Prestemon, J. P., and Abt, K. L., editors, *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species*, pages 361–380. Springer Netherlands, Dordrecht.

Romero, F. and Menakis, J. (2013). Fire season 2012: The impact of fuel treatments on wildfire outcomes. *Fire Management Today*, 73(2):15–24.

Sánchez, J. J., Loomis, J., González-Cabán, A., Rideout, D., and Reich, R. (2019). Do Fuel Treatments in U.S. National Forests Reduce Wildfire Suppression Costs and Property Damage? *Journal of Natural Resources Policy Research*, 9(1):42–73.

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., Mietkiewicz, N., Morgan, P., Moritz, M. A., Rasker, R., Turner, M. G., and Whitlock, C. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, 114(18):4582–4590.

Sekhon, J. S. (2011). Multivariate and Propensity Score Matching Software with Automated Balance Optimization: The Matching package for R. *Journal of Statistical Software*, 42(7):1–52.

Short, K. C. (2023). Spatial wildfire occurrence data for the United States, 1992-2020 [FPA_FOD_20221014] (6th Edition). `https://www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.6`.

Smith, V. K. (1993). Nonmarket Valuation of Environmental Resources: An Interpretive Appraisal. *Land Economics*, 69(1):1–26.

Sovacool, B. K., Ali, S. H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., and Mulvaney, D. (2020). Sustainable minerals and metals for a low-carbon future. *Science*, 367(6473):30–33.

Spies, T. A., Long, J. W., Charnley, S., Hessburg, P. F., Marcot, B. G., Reeves, G. H., Lesmeister, D. B., Reilly, M. J., Cerveny, L. K., Stine, P. A., and Raphael, M. G. (2019). Twenty-five years of the Northwest Forest Plan: What have we learned? *Frontiers in Ecology and the Environment*, 17(9):511–520. https://doi.org/10.1002/fee.2101.

Spies, T. A., Long, J. W., Stine, P., Charnley, S., Cerveny, L., Marcot, B. G., Reeves, G., Hessburg, P. F., Lesmeister, D., Reilly, M. J., and Davis, R. J. (2018). Chapter 12: Integrating ecological and social science to inform land management in the area of the northwest forest plan. Technical report, In: Spies, T.A.; Stine, P.A.; Gravenmier, R.; Long, J.W.; Reilly, M.J., tech. coords. 2018. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 919-1020.

State of California (2021). California's Wildfire and Forest Resilience Action Plan. `https://wildfiretaskforce.org/wp-content/uploads/2022/04/californiawildfireandforestresilienceactionplan.pdf`.

Stephens, S. L., Martin, R. E., and Clinton, N. E. (2007). Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management*, 251(3):205–216.

Stonesifer, C. S., Calkin, D. E., Thompson, M. P., and Belval, E. J. (2021). Is This Flight Necessary? The Aviation Use Summary (AUS): A Framework for Strategic, Risk-Informed Aviation Decision Support. *Forests*, 12(8).

Taylor, M. H., Sanchez Meador, A. J., Kim, Y.-S., Rollins, K., and Will, H. (2015). The Economics of Ecological Restoration and Hazardous Fuel Reduction Treatments in the Ponderosa Pine Forest Ecosystem. *Forest Science*, 61(6):988–1008.

Thomas, J. W., Franklin, J. E., Gordon, J., and Johnson, K. N. (2006). The Northwest Forest Plan: Origins, components, implementation experience, and suggestions for change. *Conservation Biology: The Journal of the Society for Conservation Biology*, 20(2):277–287.

Thompson, M. P., Calkin, D. E., Herynk, J., McHugh, C. W., and Short, K. C. (2013a). Airtankers and wildfire management in the US Forest Service: Examining data availability and exploring usage and cost trends. *International Journal of Wildland Fire*, 22(2):223.

Thompson, M. P., Vaillant, N. M., Haas, J. R., Gebert, K. M., and Stockmann, K. D. (2013b). Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs. *Journal of Forestry*, 111(1):49–58.

USFS (2000). Protecting people and sustaining resources in fire adapted ecosystems: A cohesive strategy. Forest Service response to General Accounting Office Report GAO-RCED-99-65. Technical report, United States Forest Service.

USFS (2022). Wildfire Crisis Strategy Implementation Plan. Technical report, United States Forest Service.

USFS (2023a). National Forest System Roads. `https://data.fs.usda.gov/geodata/edw/datasets.php` [Accessed: April 6, 2023].

USFS (2024). Hazardous Fuel Treatments - Polygon. `https://data.fs.usda.gov/geodata/edw/datasets.php` [Accessed: April 19, 2024].

USFS and State of California (2020). Agreement for Shared Stewardship of California's Forests and Rangelands.

USFS, U. S. F. S. (2023b). Administrative Forest Boundaries.

USFS, U. S. F. S. (2023c). Ranger District Boundaries.

USFWS, U. S. F. . W. S. (2008). Revised Designation of Critical Habitat for the Northern Spotted Owl; Final Rule. Technical report, U.S. Fish and Wildlife Service.

USFWS, U. S. F. . W. S. (2012). Endangered and Threatened Wildlife and Plants; Designation of Revised Critical Habitat for the Northern Spotted Owl; Final Rule. Technical report, U.S. Fish and Wildlife Service, Portland, OR.

Vaillant, J. (2023). *Fire Weather: A True Story from a Hotter World*. Alfred A. Knopf, New York, first edition edition.

Vazquez-Bare, G. (2023). Identification and estimation of spillover effects in randomized experiments. *Journal of Econometrics*, 237(1):105237.

Venter, O., Laurance, W. F., Iwamura, T., Wilson, K. A., Fuller, R. A., and Possingham, H. P. (2009). Harnessing carbon payments to protect biodiversity. *Science*, 326(5958):1368–1368.

Wagner, K. R. H. (2022a). Adaptation and Adverse Selection in Markets for Natural Disaster Insurance. *American Economic Journal: Economic Policy*, 14(3):380–421.

Wagner, K. R. H. (2022b). Designing insurance for climate change. *Nature Climate Change*, 12(12):1070–1072.

Wang, Y. and Lewis, D. J. (2024). Wildfires and climate change have lowered the economic value of western U.S. forests by altering risk expectations. *Journal of Environmental Economics and Management*, 123:102894.

Wen, J., Heft-Neal, S., Baylis, P., Boomhower, J., and Burke, M. (2023). Quantifying fire-specific smoke exposure and health impacts. *Proceedings of the National Academy of Sciences*, 120(51):e2309325120.

Wibbenmeyer, M., Anderson, S. E., and Plantinga, A. J. (2019). SALIENCE AND THE GOVERNMENT PROVISION OF PUBLIC GOODS. *Economic Inquiry*, 57(3):1547–1567. https://doi.org/10.1111/ecin.12781.

Wimberly, M. C., Cochrane, M. A., Baer, A. D., and Pabst, K. (2009). Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. *Ecological Applications: A Publication of the Ecological Society of America*, 19(6):1377–1384.

Yocom Kent, L. L., Shive, K. L., Strom, B. A., Sieg, C. H., Hunter, M. E., Stevens-Rumann, C. S., and Fulé, P. Z. (2015). Interactions of fuel treatments, wildfire severity, and carbon dynamics in dry conifer forests. *Forest Ecology and Management*, 349:66–72.

Yoder, J. and Ervin, P. (2012). County-level effects of fuel treatments, wui growth, and weather changes on wildfire acres burned suppression costs. *School of Economic Sciences, Washington State University*.

Appendix 1 Theoretical Results: A Two-Fire Example

In this section, we provide the derivations for the main results of our conceptual model presented in section 2. For clarity, we present the results for a system consisting of two fires; however, our results are easily generalized to a system with more fires (at the cost of additional notation).

Consider the system of equations associated with the first-order conditions for a two-fire problem:

$$\begin{aligned}
G_1(E_1, \lambda, F_1) &= -L(X_1)\frac{\partial S(E_1, F_1)}{\partial E_1} - \frac{\partial C(E_1)}{\partial E_1} - \lambda = 0 \\
G_2(E_2, \lambda, F_2) &= -L(X_2)\frac{\partial S(E_2, F_2)}{\partial E_2} - \frac{\partial C(E_2)}{\partial E_2} - \lambda = 0 \\
G_3(E_1, E_2) &= E_1 + E_2 - \bar{E} = 0,
\end{aligned}$$

where we've assumed that the resource constraint is binding—i.e., $\lambda > 0$. Linearizing this system, we have:

$$\begin{pmatrix} \frac{\partial G_1}{\partial E_1} & \frac{\partial G_1}{\partial E_2} & \frac{\partial G_1}{\partial \lambda} \\ \frac{\partial G_2}{\partial E_1} & \frac{\partial G_2}{\partial E_2} & \frac{\partial G_2}{\partial \lambda} \\ \frac{\partial G_3}{\partial E_1} & \frac{\partial G3}{\partial E_2} & \frac{\partial G_3}{\partial \lambda} \end{pmatrix} \begin{pmatrix} dE_1 \\ dE_2 \\ d\lambda \end{pmatrix} = - \begin{pmatrix} \frac{\partial G_1}{\partial F_1} & \frac{\partial G_1}{\partial F_2} \\ \frac{\partial G_2}{\partial F_1} & \frac{\partial G_2}{\partial F_2} \\ \frac{\partial G_3}{\partial F_1} & \frac{\partial G_3}{\partial F_2} \end{pmatrix} \begin{pmatrix} dF_1 \\ dF_2 \end{pmatrix}.$$

Suppose we are only interested in the comparative statics associated with a marginal change in F_1 holding F_2 constant. Then we can write this system as:

$$\begin{pmatrix} \partial E_1/\partial F_1 \\ \partial E_2/\partial F_1 \\ \partial \lambda/\partial F_1 \end{pmatrix} = - \begin{pmatrix} \frac{\partial G_1}{\partial E_1} & \frac{\partial G_1}{\partial E_2} & \frac{\partial G_1}{\partial \lambda} \\ \frac{\partial G_2}{\partial E_1} & \frac{\partial G_2}{\partial E_2} & \frac{\partial G_2}{\partial \lambda} \\ \frac{\partial G_3}{\partial E_1} & \frac{\partial G3}{\partial E_2} & \frac{\partial G_3}{\partial \lambda} \end{pmatrix}^{-1} \begin{pmatrix} \frac{\partial G_1}{\partial F_1} \\ \frac{\partial G_2}{\partial F_1} \\ \frac{\partial G_3}{\partial F_1} \end{pmatrix} = -H^{-1}x,$$

where H is the bordered Hessian.

Proof of Result 1. Let $V(F_1, F_2)$ denote the value function of a fire manager's program evaluated at the optimal allocation of suppression effort. Then, using the envelope theorem, the marginal value of a fuel treatment that intersects with a fire is:

$$\frac{\partial V(F_1, F_2)}{\partial F_1} = -L(X_1) \cdot \frac{\partial S(E_1, F_1)}{\partial F_1} > 0 \iff \frac{\partial S(E_1, F_1)}{\partial F_1} < 0.$$

□

Proof Result 2. Let H_1 denote the bordered Hessian H with the first column replaced by the vector

x. Applying Cramer's rule, we have:

$$\frac{\partial E_1}{\partial F_1} = -\frac{\det(H_1)}{\det(H)}$$
$$= -\frac{-L(X_1)\cdot\dfrac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1}}{\det(H)}.$$

Given our assumptions regarding the convexity of suppression costs $C(E)$ and fire size $S(E,F)$, the bordered Hessian H is negative definite, and thus $\det(H) < 0$. Therefore,

$$\frac{\partial E_1}{\partial F_1} < 0 \iff -\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} < 0$$

and

$$\frac{\partial E_1}{\partial F_1} > 0 \iff -\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} > 0,$$

where $-\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} < 0$ if fuel treatments and suppression effort are q-substitutes and $-\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} > 0$ if they are q-complements. □

Proof of Corollary 2.1. It follows from Result 2 that

$$\frac{\partial C(E_1)}{\partial F_1} = \frac{\partial C(E_1)}{\partial E_1}\cdot\frac{\partial E_1}{\partial F_1} < 0 \iff \frac{\partial E_1}{\partial F_1} < 0 \iff -\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} < 0.$$

□

Proof of Corollary 2.2. It follows from Result 2 that

$$\frac{dS(E_1,F_1)}{dF_1} = \frac{\partial S(E_1,F_1)}{\partial E_1}\cdot\frac{\partial E_1}{\partial F_1} + \frac{\partial S(E_1,F_1)}{\partial F_1},$$

which is negative if $\frac{\partial E_1}{\partial F_1} > 0$ but indeterminate if $\frac{\partial E_1}{\partial F_1} < 0$ since $\frac{\partial S(E_1,F_1)}{\partial E_1}$ and $\frac{\partial S(E_1,F_1)}{\partial F_1}$ are assumed to be negative. □

Proof of Result 3. Let H_2 denote the bordered Hessian H with the second column replaced by the vector x. Applying Cramer's rule, we have:

$$\frac{\partial E_2}{\partial F_1} = -\frac{\det(H_2)}{\det(H)}$$
$$= -\frac{L(X_1)\cdot\dfrac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1}}{\det(H)}.$$

Given the negative definiteness of the bordered Hessian H, $\det(H) < 0$. Therefore,

$$\frac{\partial E_2}{\partial F_1} > 0 \iff -\frac{\partial^2 S(E_1, F_1)}{\partial F_1 \partial E_1} < 0$$

and

$$\frac{\partial E_2}{\partial F_1} < 0 \iff -\frac{\partial^2 S(E_1, F_1)}{\partial F_1 \partial E_1} > 0,$$

where $-\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} < 0$ if fuel treatments and suppression effort are q-substitutes and $-\frac{\partial^2 S(E_1,F_1)}{\partial F_1 \partial E_1} > 0$ if they are q-complements. □

Proof of Corollary 3.1.

$$\begin{aligned}\frac{\partial[\sum_i C(E_i)]}{\partial F_1} &= \frac{\partial C(E_1)}{\partial E_1} \cdot \frac{\partial E_1}{\partial F_1} + \frac{\partial C(E_2)}{\partial E_2} \cdot \frac{\partial E_2}{\partial F_1} \\ &= \frac{\partial E_1}{\partial F_1} \cdot \left(\frac{\partial C(E_1)}{\partial E_1} - \frac{\partial C(E_2)}{\partial E_2} \right),\end{aligned}$$

where the second equality follows from the fact that $\frac{\partial E_1}{\partial F_1} = -\frac{\partial E_2}{\partial F_1}$ (from Results 2 and 3). Thus, regardless of the sign of $\frac{\partial E_1}{\partial F_1}$, the sign of the expression above depends on whether $\frac{\partial C(E_1)}{\partial E_1} > \frac{\partial C(E_2)}{\partial E_2}$ or $\frac{\partial C(E_1)}{\partial E_1} < \frac{\partial C(E_2)}{\partial E_2}$. □

Proof of Corollary 3.2. If the effort resource constraint does not bind, then $\lambda = 0$ and $\frac{\partial E_2}{\partial F_1} = 0$. Thus,

$$\frac{\partial[\sum_i C(E_i)]}{\partial F_1} = \frac{\partial C(E_1)}{\partial E_1} \cdot \frac{\partial E_1}{\partial F_1} < 0 \iff \frac{\partial E_1}{\partial F_1} < 0.$$

□

A2 Land-Use Designations Under The NWFP

Thirty percent of the NWFP area comprises a network of late-successional reserves (LSRs) designed to protect remaining old-growth forests and habitat for the NSO and marbled murrelet. Another thirty percent of the NWFP area comprises "Congressionally Reserved" (CR) areas, such as national parks or wilderness areas. Riparian reserves—areas designed to protect and restore salmonid habitat—comprise another 11 percent of the NWFP area. In both LSRs and riparian reserves, fuel treatment activity is possible, though limited due to the potential for litigations and management restrictions. However, in a good portion of CR areas, such as wilderness areas, fuel treatment is not allowed. Non-reserved "matrix" lands are regions in which the majority of timber harvest and other silvicultural activities take place, comprising 16 percent of the NWFP area. See Table A5 for a list and description of all land allocations under the plan.

A3 The Data Generating Process for Fuel Treatments & Fire Suppression Costs

Figure A1 presents a visual representation of the hypothesized data-generating process for fuel treatments and fire suppression costs, both of which are a function of topographic, socio-economic, and fire risk variables. The endogenous decision of both the land manager choosing the optimal location of fuel treatments and the fire manager allocating fire suppression effort results in jointly determined fuel treatment locations and fire suppression costs.[43]

The objective of land managers, who decide the location of fuel treatments, is often to maximize the effectiveness of treatments at protecting assets at risk while minimizing the costs of treatment. As a result, fuel treatments are typically located close to homes and other assets at risk (socio-economic variables) while occurring in areas where fire is more likely to occur or spread (fire risk). Because resources for land managers are limited, fuel treatments typically occur in areas where the costs of fuel treatment are minimized and, as a result, typically occur closer to forest service roads and at lower elevations and slopes (topographic variables).

The objective of a fire manager, who is tasked with deciding the allocation of fire suppression effort across multiple fires burning simultaneously, is to minimize the sum of fire suppression costs and damages from wildfires. As a result, more fire suppression effort is spent on fighting fires closer to homes and other assets at risk relative to fires occurring further away from such assets. Topography and fire weather also influence the cost of fighting a given fire because fires that occur in inaccessible terrain require more expensive resources to suppress the fire (e.g., smoke jumpers or aerial attack) while fires that occur in extreme weather conditions (fire risk) require more time and effort to suppress.

An estimation strategy that controls for all the relevant factors determining fuel treatments and fire suppression costs may still suffer from bias because assets at risk (e.g., homes) and fire risk are imperfectly measured, resulting in omitted factors that determine both fuel treatments and fire suppression effort. In particular, we expect home proximity and fire risk to be positively correlated with fire suppression effort and fuel treatments because of the influencing factors discussed above. Thus, any estimation strategy that compares fires that occur close to fuel treatments with fires that do not will likely suffer from an upward bias (i.e., the expected negative effect of fuel treatments on suppression costs will be understated.). This motivates our use of an instrument that does not correlate with socio-economic and fire risk characteristics.

A4 Land Managers Optimal Fuel Treatment Allocation Problem

In this section, we formally demonstrate that the effect of fuel treatments on suppression costs and fire size that we identify empirically is only a portion of the total effect they may have across the landscape. To do so, we depict a land manager who chooses the optimal allocation of fuel treatment across the landscape to minimize the sum of expected suppression costs and damages from wildfires. For simplicity, suppose there is a probability of ignition on $i = 1, \dots, N$, identical

[43] See Appendix A4 for an overview of the land manager's fuel treatment location problem and section 2 for the fire manager's fire allocation problem.

plots of land. The probability of a fire occurring on that plot of land is a function of fuel treatments in that area: $\pi_i(F_i)$. Further, suppose that, conditional on a fire occurring on plot i, the expected size of the fire, S_i, depends not only on fuel treatments on plot i, F_i, but also fuel treatments further away from the fire on other plots of land, F_{-i}. As in Rideout et al. (2008), we assume that damages from wildfires (property losses, timber, etc.) are proportional to fire size: $L_i(X_i)S_i(F_1, \dots, F_N)$ where losses, L_i are a function of assets at risk, X_i.

Given an objective of conducting fuel treatments to minimize the expected damages and fire suppression costs across the landscape subject to a budget constraint, we can write the optimization problem as:

$$\max_{F_1,\dots,F_N} -\sum_{i=1}^{N} \pi_i(F_i)\left[L_i(X_i)S_i(F_1,\dots,F_N) + SC_i(F_1,\dots,F_N)\right]$$

$$\text{s.t. } \sum_{i}^{N} c_i(F_i) \leq B,$$

where $c_i(F_i)$ is the cost of conducting F_i units of fuel treatment on plot i and B is the fixed amount of resources that can be devoted to conducting fuel treatments. Letting λ denote the Lagrange multiplier associated with the budget constraint, the necessary first-order conditions are:

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial F_i} &= \underbrace{-\pi_i'(F_i)\left[L_i(X_i)S_i(F_1,\dots,F_N) + SC_i(F_1,\dots,F_N)\right]}_{\text{Ignition Effect}} \\ &\quad \underbrace{-\pi_i(F_i)\left[L_i(X_i)\frac{\partial S_i(F_1,\dots,F_N)}{\partial F_i} + \frac{\partial SC_i(F_1,\dots,F_N)}{\partial F_i}\right]}_{\text{Prevention Effect}} \\ &\quad \underbrace{-\sum_{j\neq i}\pi_j(F_j)\left[\frac{L_j(X_j)\partial S_j(F_1,\dots,F_N)}{\partial F_i} + \frac{\partial SC_j(F_1,\dots,F_N)}{\partial F_i}\right]}_{\text{Landscape Effect}} = c_i'(F_i)\ \forall i = 1,\dots,N\end{aligned}$$

The first term, which we call the "ignition effect," represents the effect of fuel treatments from reducing the likelihood that fires ignite on a parcel of land ($\pi_i'(F_i) < 0$). The second term, which we call the "prevention effect," represents how suppression costs and the size of fires are influenced by the proximity of fuel treatments close to the ignition point of a fire. The third term, which we call the "landscape effect," represents the effect of fuel treatments on the spread of wildfires across the landscape. That is, if there exists parcels of land i and j such that $\frac{L_j(X_j)\partial S_j(F_1,\dots,F_N)}{\partial F_i} + \frac{\partial SC_j(F_1,\dots,F_N)}{\partial F_i} < 0$, then fuel treatments will influence the cost and size of large fires, which spread into fuel treatments that occur further from their ignition point.

Our empirical analysis only identifies the prevention effect since we are conditioning on fires that ignite close to fuel treatments. If the ignition and landscape effects of fuel treatments are significant, then our estimates are only capturing a portion of the total benefits that arise from fuel treatments. We leave the identification of the ignition and landscape effects to future research.

A5 The Intersection-Union Hypothesis Test

Our model of the fire manager's effort allocation problem demonstrates that a negative direct effect of fuel treatments on fire size is a sufficient statistic for the economic benefits of fuel treatments. We test for its existence indirectly by testing the null hypothesis that the effects of fuel treatments on fire size or cost are weakly positive. Specifically, let ϕ_c and ϕ_s denote the elasticity of suppression costs and fire size with respect to fuel treatments. We want to test the null hypothesis

$$H_o : \phi_c \geq 0 \text{ or } \phi_s \geq 0$$

against the alternative hypothesis of

$$H_a : \phi_c < 0 \text{ and } \phi_s < 0.$$

The intersection-union hypothesis test (Casella and Berger, 2002) considers the overall null hypothesis of the union of several individual null hypotheses to be true if at least one of the individual null hypotheses is true. Thus, to reject the null, we must have both $\phi_c < 0$ and $\phi_s < 0$. This suggests the following implementation:

1. Conduct a one-sided test for $\phi_c \geq 0$ and a one-sided test for $\phi_s \geq 0$.
2. Reject overall H_o if both of the one-sided tests for ϕ_c and ϕ_s are rejected.

We implement this hypothesis test using a bootstrap approach that adapts the percentile-t bootstrap with asymptotic refinement procedure presented in Cameron and Trivedi (2005). Specifically, we bootstrap the following t-statistics:

$$t_c = \frac{\widehat{\phi}_c - \phi_{c0}}{se(\widehat{\phi}_c)} \text{ and } t_s = \frac{\widehat{\phi}_s - \phi_{s0}}{se(\widehat{\phi}_s)},$$

where $\widehat{\phi}_c$ and $\widehat{\phi}_s$ are our instrumental variable estimates and $\phi_{c0} = 0$ and $\phi_{s0} = 0$ are the values under the null hypothesis. The bootstrap views the original sample as the data generating process (dgp), so the bootstrap sets the dgp values of ϕ_c and ϕ_s to be $\widehat{\phi}_c$ and $\widehat{\phi}_s$. In each bootstrap resample, we compute the following t-statistics:

$$t^*_{c,b} = \frac{\widehat{\phi}^*_{c,b} - \widehat{\phi}_c}{se(\widehat{\phi}^*_{c,b})} \text{ and } t^*_{s,b} = \frac{\widehat{\phi}^*_{s,b} - \widehat{\phi}_s}{se(\widehat{\phi}^*_{s,b})},$$

where $\widehat{\phi}^*_{c,b}$ and $\widehat{\phi}^*_{s,b}$ are the parameter estimates in the bth bootstrap and $se(\widehat{\phi}^*_{c,b})$ and $se(\widehat{\phi}^*_{s,b})$ are the estimates of the standard error of $\widehat{\phi}^*_{c,b}$ and $\widehat{\phi}^*_{s,b}$ using the same method (i.e., cluster-robust) as the computation of $se(\widehat{\phi}_c)$ and $se(\widehat{\phi}_s)$.

The B bootstraps yield the t-values $t^*_{c,1}, ..., t^*_{c,B}$ and $t^*_{s,1}, ..., t^*_{s,B}$, whose empirical joint distribution is used as the estimate of the joint distribution of t_c and t_s. The p-value for the overall hypothesis test is the probability of observing values of the test statistics as extreme as t_s and t_s under the null hypothesis. We can calculate the empirical p-value as the proportion of bootstrap samples in which both t-statistics lie below their observed values:

$$p = \frac{\sum_{b=1}^{B} \mathbf{1}(t^*_{c,b} < t_c \text{ and } t^*_{s,b} < t_s)}{B}.$$

We reject the null if $p < \alpha$, where $1 - \alpha$ is the confidence level of the test. Given the clustered nature of our data, we conduct the bootstrap sampling by drawing independent clusters of fires (with replacement).

A6 Supplementary Figures

Figure A1: The Data generating process for Fuel Treatments & Fire Suppression Costs

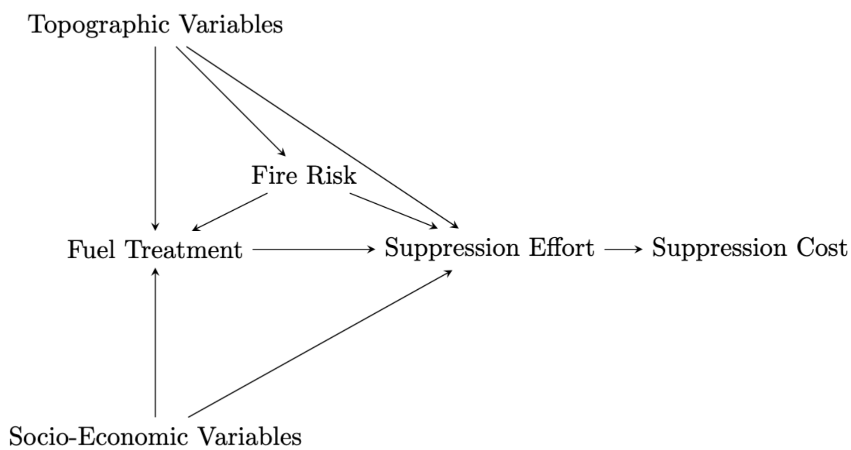
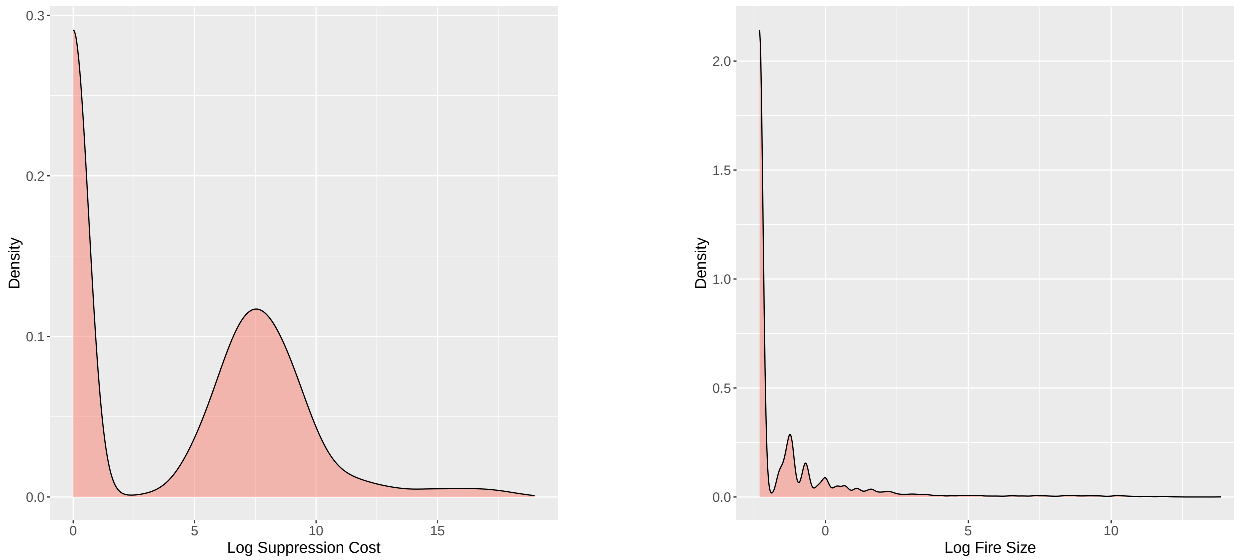


Figure A2: Distribution of fire suppression costs and fire size.

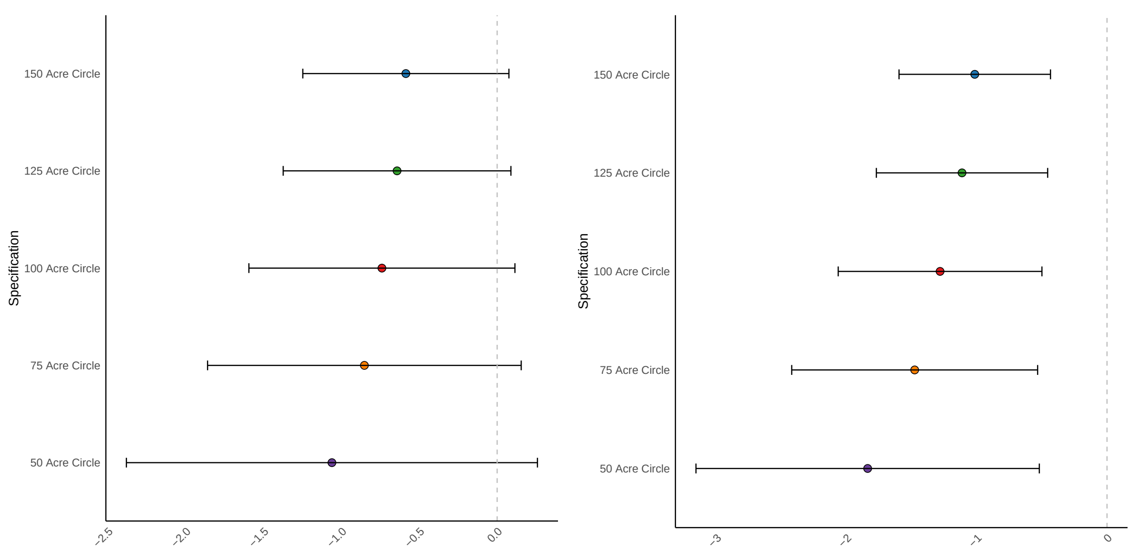


(a) Log Suppression Costs **(b)** Log Fire Size

Notes: "Log Suppression Costs" is the $\log(Y+1)$ transformation associated with our main specification.

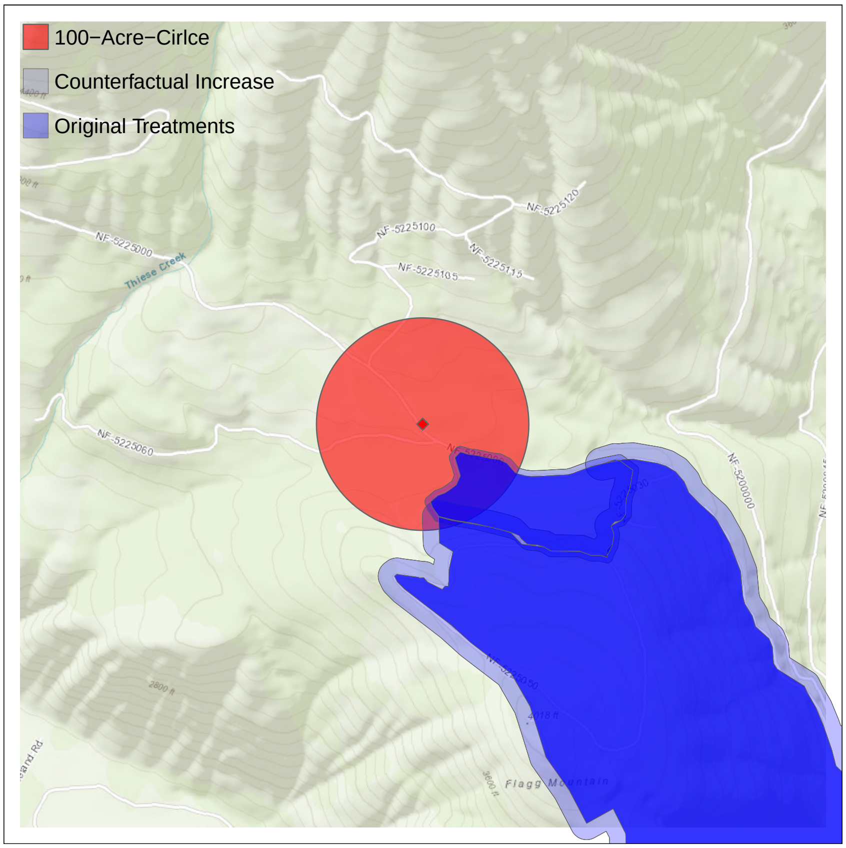
Figure A3: IV estimates by fuel treatment acre circle size

(a) Fire Size **(b)** Suppression Costs



Notes: The above figures plot the IV suppression cost and fire size estimates based on different specifications of fire fuel treatment acre circle size.

Figure A4: Example Counterfactual Increases in Fuel Treatments - Flagg Mountain Fire - 2020



Notes: The above map visually demonstrates how fuel treatments are scaled up proportionately in our counterfactual analysis for a particular fire, the Flagg Mountain Fire, a 0.1 acre fire that occurred close to Mazama, WA, in 2020. The red star shows the ignition point location, the red circle is the area from which fuel treatments are to be calculated (in this case, 100 acres surrounding the ignition point), and the dark blue shows the original location of fuel treatments close to the fire. The light blue areas are the counterfactual increased area that receives fuel treatment. In our counterfactual analysis, we recalculate the total acres intersected with the fire to garner an estimated increase in 100-acre fire-fuel treatment intersections. To avoid double counting, we take the union of fuel treatments within the circle and count mechanical and prescribed fire treatments separately.

A7 Supplementary Tables

Table A5: Land allocations under the Northwest Forest Plan

Land Allocation	Description	Acres	% NWFP
Late-Successional Reserves (LSRs)	Lands reserved for the protection and restoration of old growth forest ecosystems and habitat for marbled murrelet (LSR3) and northern spotted owl activity core reserves (LSR4).	7.4 mil	30%
Congressional Reserved (CR) Areas	Lands reserved by the U.S. Congress such as wilderness areas, wild and scenic rivers, and national parks and monuments.	7.3 mil	30%
Riparian Reserves	Protective buffers along streams, lakes, and wetlands designed to enhance habitat for riparian-dependent organisms, provide good water-quality dispersal corridors for terrestrial species, and provide connectivity within watersheds.	2.6 mil	11%
Matrix	Federal lands outside of reserved allocations where most timber harvest and silvicultural activities were expected to occur.	4 mil	16%
Administrative Withdrawn Areas	Areas identified in local forest and district plans; they include recreation and visual areas, back country, and other areas where management emphasis does not include scheduled timber harvest.	1.5 mil	6%
Adaptive Management Areas–nonreserved	Identified to develop and test innovative management to integrate and achieve ecological, economic, and other social and community objectives. Some commercial timber harvest was expected to occur in these areas, but with ecological objectives.	1.5 mil	6%
Managed Late-Successional Areas	Areas for the restoration and maintenance of optimum levels of old growth stands on a landscape scale, where regular and frequent wildfires occur. Silvicultural and fire hazard reduction treatments are allowed to help prevent older forest losses from large wildfires.	.1 mil	$< 1\%$

Table A6: Main Variables & Data Sources

Category	Variables	Sources
Fires	Cost per fire, Acres Burned & Ignition Date	FAMWEB (2023) NIFC (2024b)
Fuel Treatments	Acres treated, cost, & treatment type	USFS (2024)
Institutional Variables	NWFP Land-use Designations	REO (2013)
Topography	Slope, Aspect, & Elevation	LANDFIRE
Weather	Temperature, Precipitation, Vapor Pressure Deficit Wind Speed & ERC	PRISM GridMET
Vegetation Characteristics	Fuel Group Type Previous Acres Burned	LANDFIRE
Historic Fire Risk	Mean Fire Return Interval (MFRI) Climate Normals	LANDFIRE PRISM
Economic Variables	Distance to WUI Cenus Block, Number of Households & Population Total housing value, total household income Forest Service Roads	Radeloff et al. (2022) ACS USFS (2023a)

Table A7: Control Variable Names, Descriptions, & Sources

Name	Definition	Source
Topographic Variables		
Slope	Slope percent at origin of ignition	LANDFIRE
Elevation	Elevation (ft) at origin of ignition	LANDFIRE
Aspect Class	8 aspect classes based on the cardinal directions[44]	LANDFIRE
TRI	Terrain Ruggedness Index (TRI)[45]	LANDFIRE
Weather		
Temperature Max	Maximum temperature on day of discovery and point of ignition	PRISM
Temperature Mean	Mean temperature on day of discovery and point of ignition	PRISM
VPD	Max vapor pressure deficit on day of discovery and point of ignition	PRISM
Wind Speed	Average wind speed meter/second on day of discovery and point of ignition	gridMET
ERC	Average energy release component (ERC) on day of discovery and point of ignition	gridMET
Vegetation Characteristics		
Previous Acres Burned	The number of acres previously burned inside of the 100-acre ignition circle within the last 10 years	MTBS

Continued on next page

[44] See `https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-aspect-works.htm` for the classes used.

[45] Constructed using the elevation layer from LANDFIRE and then using the terrain function from terra.

Table A1 Continued

Name	Definition	Source
Riparian	Dummy variable equal to one if the existing vegetation group type associated with the point of ignition is Riparian	LANDFIRE
Fuel Group Type	The fuel group type associated with a fires ignition point in 2001 based on the 13 Anderson Fire Behavior Fuel Model	LANDFIRE
Canopy Bulk Density	The density of available canopy fuel in a stand based on a fires ignition point in 2001. Measurements are kg m-3 * 100.	LANDFIRE
Canopy Bulk Density	The average height of the top of the vegetated canopy based on a fires ignition point in 2001. Measurement units are meters * 10	LANDFIRE
Canopy Base Height	The average height from the ground to a forest stand's canopy bottom based on a fires ignition point in 2001. Measurement units are meters*10	LANDFIRE
Determinants of Fire Suppression Effort		
Distance WUI	Distance from ignition to nearest U.S. Census WUI Block	Radeloff et al. (2022)
Distance USFS Road	Distance from ignition to nearest USFS road	USFS (2023a)
Total Housing Value	The total housing value in 10 kilometer radius from point of ignition/100,000	ACS
Total Population	The total population within 10 kilometers of ignition point based on 2010 US Census Blocks (assuming uniform distribution)	(Radeloff et al., 2022)
Total Housing Units	The total housing units within 10 kilometers of ignition point based on 2010 US Census Blocks (assuming uniform distribution)	(Radeloff et al., 2022)

Continued on next page

Table A1 Continued

Name	Definition	Source
Historic Fire Risk Variables		
MFRI	Mean Fire Return Interval (MFRI), the average period between fires under presumed historical fire regime	LANDFIRE
Precip - CN	Precipitation 30 year (1991-2020) climate normal. Calculated as the average monthly precipitation in August based on the ignition point of a fire	PRISM
Temp Mean - CN	Temperature Mean 30 year (1991-2020) climate normal. Calculated as the average monthly temperature mean in August based on the ignition point of a fire	PRISM
Temp Max - CN	Temperature Max 30 year (1991-2020) climate normal. Calculated as the average monthly temperature max in August based on the ignition point of a fire	PRISM
VPD - CN	Max Vapor Pressure Deficit 30 year (1991-2020) climate normal. Calculated as the average monthly temperature max vapor pressure deficit in August based on the ignition point of a fire	PRISM
Administrative Units		
National Forest	Dummy variables for National Forest	USFS (2023b)
Ranger District	Dummy variables for Ranger District (subset of National Forest)	USFS (2023c)

Table A8: USFS Suppression & Fuel Treatments Costs

	Suppression Costs	Acres Burned	Acres Treated	Costs of Treatment
Matrix & LSR	4,647,248,435	5,354,781	1,471,894	279,618,201
Full NWFP Area	6,866,239,500	9,223,544	1,582,755	301,385,737
WA, OR, & Nor CA	12,115,983,010	16,629,129	5,747,733	1,041,179,711
U.S.	30,530,809,000	-	-	-

Notes: The first two columns show the suppression costs and acres burned (2006-2023) while the third and fourth columns show fuel treatment costs and acres treated (2006-2023). The three rows are different samples of fires and treatments across three different regions in WA, OR, and Nor CA. The first row corresponds to our sample of Matrix and LSR areas inside of the NWFP region. The second row corresponds to treatments and fires that occur inside of the entire NWFP region, while the third row corresponds to fires and treatments inside the entire WA, OR, and Nor CA region. Northern CA is defined by any fires or treatments that occur above the southernmost latitude of the NWFP region. The fourth row shows the total suppression costs spent by the USFS (2006-2023).

Table A9: LSR IV - Robustness Check - Spillovers

	First Stage	**Reduced Form**		**IV**		**OLS**	
	$\log(FT_{it})$	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**
LSR_{it}	-0.140***	0.071	0.154***				
	(0.026)	(0.058)	(0.042)				
$\log(FT_{it})$				-0.510	-1.099**	-0.045**	-0.021
				(0.446)	(0.404)	(0.018)	(0.021)
No. Fires	0.000	0.001**	0.001**	0.001**	0.001**	0.001**	0.002**
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)
No. Fires FT > 0	-0.004	0.020	0.005	0.018	0.001	0.020	0.005
	(0.004)	(0.012)	(0.015)	(0.011)	(0.016)	(0.012)	(0.015)
1st Stage F-Stat	28.1						
R^2	0.18	0.18	0.73	0.13	0.67	0.18	0.73
N	8297	8297	8297	8297	8297	8297	8297

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The above table explores the robustness of the main IV regression results when adding controls that measure the scarcity of suppression resources: "No. Fires" and "No. Fires FT > 0". "No. Fires" is the difference in the average number of fires occurring in a week for a state from 2000-2020 to the realized number of co-occurring fires in the week and state where a fire ignites, while "No. Fires FT > 0" is the number of fires that have a non-zero fuel treatment-100 acre intersection occurring in the same state where a fire ignites. The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using an indicator for whether a fire occurs within a late-successional reserve, LSR_i as an instrument for the natural log of fuel treatments $\log(FT_{it})$. The sample includes wildfires in 15 National Forests that are apart of the NWFP from 2006–2020. The first column reports the coefficient estimates for the first stage, $\log(FT_{it})$, while the second and third columns are the reduced form results on the natural log of fire size and suppression costs. The fourth and fifth columns are the full 2SLS regression results on the natural log of wildfire size and suppression cost. Each regression includes the same control variables and fixed effects described in Table 3. Standard errors are clustered at the national-forest level. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R.

Table A10: IV Matching Estimate Results

	Log Fire Size - LSR IV	Log Fire Cost - LSR IV
Point Estimate	-0.823	-1.329
95% CI	[-1.911,0.264]	[-2.501,-0.156]
N	6450	6450

Notes: The above table presents the IV estimate using matching. Fires are matched via a mixed exact and inexact matching using Genetic Search Algorithm (the GenMatch function from the Matching package in R (Sekhon, 2011)): i) fires are exactly matched such that they occur in the same National Forest during the same month (of a given year), ii) fires are inexactly matched to find the optimal covariate balance across the most important determinants of fire suppression costs and fire size: Distance to WUI and FS road, elevation and slope (at ignition point), and VPD and wind speed (on day of ignition). Standard errors are calculated via the Delta Method.

Table A11: LSR IV - Robustness Checks - Estimation On Different Samples

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Lightning Only Fires					
LSR_{it}	-0.147***	0.185**	0.274***		
	(0.039)	(0.072)	(0.063)		
$\log(FT_{it})$				-1.260*	-1.864**
				(0.695)	(0.740)
1st Stage F-Stat	13.8				
N	5060	5060	5060	5060	5060
All Fires in NWFP National Forests					
LSR_{it}	-0.105***	0.111*	0.196***		
	(0.028)	(0.056)	(0.048)		
$\log(FT_{it})$				-1.056	-1.861**
				(0.665)	(0.736)
1st Stage F-Stat	13.8				
N	17547	17547	17547	17547	17547
< 2km from Matrix-LSR Border					
LSR_{it}	-0.109***	0.043	0.127*		
	(0.018)	(0.067)	(0.063)		
$\log(FT_{it})$				-0.391	-1.162*
				(0.616)	(0.607)
1st Stage F-Stat	11.2				
N	7783	7783	7783	7783	7783
No Complex Fires					
LSR_{it}	-0.174***	0.125	0.213***		
	(0.046)	(0.082)	(0.066)		
$\log(FT_{it})$				-0.719	-1.227***
				(0.487)	(0.414)
1st Stage F-Stat	14.3				
N	4685	4685	4685	4685	4685

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The above table explores the robustness of the main IV regression results when using different samples of fires. The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using an indicator for whether a fire occurs within a late-successional reserve, LSR_i as an instrument for the natural log of fuel treatments $\log(FT_{it})$. Each regression includes the controls and fixed effects used in Table 3. The first sample includes only fires ignited by lightning strikes, and the second includes fires that ignite inside any National Forest apart from the NWFP, excluding fires in wilderness areas. The third sample uses only fires that are within 2 kilometers of Matrix-LSR borders. The fourth sample only includes fires that are not part of a complex from the NIFC fire cost data source (2015-2023). Standard errors are clustered at the national forest level. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R.

Table A12: LSR IV - Robustness Checks - Dealing with Zero Cost Fires

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
No Zero Cost Fires					
LSR_{it}	-0.114***	0.078	0.136**		
	(0.033)	(0.068)	(0.063)		
$\log(FT_{it})$				-0.678	-1.189
				(0.643)	(0.750)
1st Stage F-Stat	12.2				
N	5286	5286	5286	5286	5286
Imputed Zero Cost					
LSR_{it}	-0.139***	0.103*	0.134***		
	(0.021)	(0.057)	(0.041)		
$\log(FT_{it})$				-0.740	-0.949**
				(0.436)	(0.371)
1st Stage F-Stat	42.0				
N	9797	9797	9797	9797	9797
Above Median Cost & Size					
LSR_{it}	-0.139***	0.021	0.012**		
	(0.021)	(0.013)	(0.005)		
$\log(FT_{it})$				-0.150	-0.089**
				(0.088)	(0.035)
1st Stage F-Stat	13.5				
N	9797	9797	9797	9797	9797

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The above table explores the robustness of the main IV regression results to different ways of dealing with zero cost fires. The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using an indicator for whether a fire occurs within a late-successional reserve, LSR_i as an instrument for the natural log of fuel treatments $\log(FT_{it})$. Each regression includes the same instrument, controls, and fixed effects used in Table 3. The first set of regressions removes all zero-cost fires from our sample. The second set of regressions imputes the cost of all small zero-cost fires (<100 acres) with the median cost of small non-zero-cost fires. The third set of regressions replaces the natural log of fire size and suppression costs for indicators of whether a fire is above the median size or cost. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R.

Table A13: LSR IV - Robustness Checks - Changes to Instrument & Endogenous Regressors

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Linear Fuel Treatments: FT_{it}					
LSR_{it}	-1.777***	0.103*	0.179***		
	(0.512)	(0.057)	(0.046)		
FT_{it}				-0.058	-0.101**
				(0.040)	(0.042)
1st Stage F-Stat	12.0				
N	9797	9797	9797	9797	9797
IVHS Fuel Treatments					
LSR_{it}	-0.167***	0.103*	0.179***		
	(0.024)	(0.057)	(0.046)		
$ashin(FT_{it})$				-0.619	-1.072***
				(0.362)	(0.329)
1st Stage F-Stat	46.8				
N	9797	9797	9797	9797	9797
Previous 5 Years Fuel Treatments					
LSR_{it}	-0.078***	0.103*	0.179***		
	(0.013)	(0.057)	(0.046)		
$\log(FT_{it,5Y})$				-1.319	-2.284***
				(0.790)	(0.754)
1st Stage F-Stat	34.1				
N	9797	9797	9797	9797	9797
Continuous IV					
$AcresLSR_{it}$	-0.008***	0.013*	0.021***		
	(0.001)	(0.006)	(0.005)		
$\log(FT_{it})$				-0.860*	-1.403***
				(0.451)	(0.437)
1st Stage F-Stat	43.8				
N	9797	9797	9797	9797	9797

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The above table explores the robustness of the main IV regression results to different specifications of the endogenous variable and instrument. The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using different instruments and endogenous regressors. Each regression includes the same sample, controls, and fixed effects used in Table 3. The first set of regressions replaces the natural log of fuel treatments, $\log(FT_{it})$, for fuel treatments in levels FT_{it}. The second set of regressions replaces the natural log of fuel treatments, $\log(FT_{it})$, for the inverse hyperbolic sine transform of fuel treatments $asinh(FT_{it})$. The third set of regressions replaces the natural log of fuel treatments, $\log(FT_{it})$, which is calculated using the total acres of fuel treatment within the past 10 years of a fire for natural log of fuel treatments in the past 5 years $\log(FT_{it,5Y})$. The fourth set of regressions replaces an indicator for whether a fire starts in an LSR, LSR_i, with a continuous measure, $AcresLSR_i$, which is the total acres within the 100-acre circle of a fire that falls under LSR status. Standard errors are clustered at the national forest level. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R.

Table A14: LSR IV - Robustness Checks - Using Different Fixed Effects

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Ranger District FEs					
LSR_{it}	-0.162***	0.091	0.133***		
	(0.025)	(0.055)	(0.044)		
$\log(FT_{it})$				-0.559	-0.819**
				(0.373)	(0.293)
1st Stage F-Stat	40.6				
N	9766	9766	9766	9766	9766
Year & Month (of Year) FEs					
LSR_{it}	-0.140***	0.099	0.169***		
	(0.020)	(0.059)	(0.045)		
$\log(FT_{it})$				-0.705	-1.210***
				(0.458)	(0.397)
1st Stage F-Stat	48.1				
N	9797	9797	9797	9797	9797
State-Year & State-Month FEs					
LSR_{it}	-0.142***	0.100	0.168***		
	(0.021)	(0.060)	(0.046)		
$\log(FT_{it})$				-0.704	-1.187**
				(0.470)	(0.416)
1st Stage F-Stat	46.5				
N	9797	9797	9797	9797	9797
State-Year-Month FEs					
LSR_{it}	-0.134***	0.108*	0.180***		
	(0.020)	(0.060)	(0.045)		
$\log(FT_{it})$				-0.801	-1.343***
				(0.501)	(0.437)
1st Stage F-Stat	46.4				
N	9797	9797	9797	9797	9797

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: The above table explores the robustness of the main IV regression results with the use of different fixed effects. The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using an indicator for whether a fire occurs within a late-successional reserve, LSR_i as an instrument for the natural log of fuel treatments $\log(FT_{it})$. Each regression includes the same sample and controls in Table 3. The first set of regressions replaces National Forest fixed effects for Ranger District fixed effects. The second set of regressions replaces year-month fixed effects with year and month (of year) fixed effects. The third set of regressions replaces year-month fixed effects with state-year and state-month fixed effects. The fourth set of regressions replaces year-month fixed effects with state-year-month fixed effects. Standard errors are clustered at the national-forest level. First stage Kleibergen-Paap F-statistic are calculated via cluster robust-standard errors from the Fixest package in R.