

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

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Abstract

A century of wildfire suppression policies have resulted in the build-up of combustible fuel loads in forests, leading to increases in the size, severity, and costs of wildfires. This study explores whether fuel-reduction treatments decrease the cost of fighting wildfires. We investigate fires igniting on U.S. Forest Service land in the Pacific Northwest between 2006 and 2023, leveraging exogenous variation in fuel treatments arising from a system of protected areas designed to conserve the northern spotted owl, old growth forest, and other endangered species. We find that fires starting in the protected areas are less likely to occur close to fuel treatments and are more costly to suppress, on average. Conservative back-of-the-envelope estimates suggest that three to five dollars are saved in fire suppression costs for every dollar spent on fuel treatments. We also find that fuel treatments do reduce fire size, though this effect is attenuated by the endogenous allocation of fire suppression effort away from fires igniting near fuel treatments. Our results suggest that environmental protections have increased the public burden of fighting wildfires and placed the species they were intended to protect at greater risk from wildfire. Taken together, these findings highlight the potential for reforming environmental protections to achieve both economic savings and conservation benefits.

“You own the fuel, you own the fire”

Urban fire specialist’s adage

1 Introduction

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, or fuel loads, in forests 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 other environmental objectives, such as endangered species protections, federal and state

¹Unlike the Eastern U.S., public lands in the Western U.S. comprise of 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](#)).

air quality standards, survey and manage protocols, wilderness areas, and the NEPA process, significantly hinder the ability of public agencies to conduct fuel treatments on public lands (North et al., 2012, 2015; Edwards and Sutherland, 2022). Environmental regulations such as these 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 empirical, 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 investigate how fuel treatments can mitigate the economic costs of wildfires by assessing their impact on two key factors: fire size and suppression costs.³ Analyzing fires igniting on United States Forest Service (USFS) land in the Pacific Northwest from 2006 to 2023, we find evidence that fuel treatments effectively reduce the economic costs and damages associated with wildfires.

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). Consequently, estimation strategies that compare fires (or areas) with and without nearby fuel treatments will suffer from simultaneity bias and likely result in findings of small to zero impacts (Sánchez et al., 2019; Yoder and Ervin, 2012). Second, even if fuel treatments are conducted exogenously, the endogenous allocation of suppression effort across fires mediates the effect of fuel treatments on the size and cost of suppressing a fire. As we demonstrate, 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, we employ an instrumental variable (IV) strategy that exploits exogenous

²Previous 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.

³According to the National Interagency Fire Center, federal agencies spent \$55 billion (2017) on wildfire suppression from 1985 to 2022, with a total of 211 million acres burned, not including state and local suppression efforts.

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

variation in fuel treatments arising from spatial variation in protected areas— specifically, late-successional reserves (LSRs) established under the Northwest Forest Plan (NWFP). These protected areas were designed to protect the northern spotted owl, listed under the Endangered Species Act (ESA), but have had the unintended consequence of restricting fuel treatment activity within such areas because of increased management restrictions and litigation potential from environmental groups (Johnson et al., 2023). Spatial variation in protected areas generates quasi-random variation in fuel treatment activity because their boundaries were established based on the nesting, roosting, foraging, and dispersal habits of the northern spotted owl, as well as the ecological needs of other endangered species and riparian habitats (Gaines et al., 2022; Johnson et al., 2023). Second, 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 receive 13.7% less fuel treatments close to their ignition point compared to fires igniting in otherwise similar unprotected areas, demonstrating the limiting effect that environmental protections have had on fuel treatment activities. Fires igniting in protected areas are also 12.2% 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 0.89 percent. We also find that fuel treatments reduce fire size, but this effect is not statistically significant at conventional levels. 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, three to five 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. First, we demonstrate the potential role of public investments in ecosystem health 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; Troy, 2007). 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.

Second, we examine the impacts of the Northwest Forest Plan, one of the largest temperate forest reserve systems in the world. 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., 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.

Finally, we demonstrate that conflicting environmental policies—such as those aimed at protecting endangered species—can unintentionally hinder critical climate adaptation strategies, such as fuel treatments. The literature has emphasized the impact of environmental protections on private land values, land use, and the labor market (Maximilian Auffhammer et al., 2020; Nelson et al., 2017; Ferris and Frank, 2021). We examine how environmental protections can impact wildfire management and fuel treatment activities and place the very species they were intended to protect at risk. Our study thus highlights the need to consider policy reform that reconciles conflicting environmental objectives in the face of climate change.

The paper is organized as follows: Section 2 provides a brief overview of wildland fire institutions and fuel treatments along with background of the Northwest Forest Plan. Section 3 establishes a simple model of fuel treatment and fire suppression effort to motivate our empirical approach and inform the interpretation of our estimates. Section 4 provides an overview of our research design and Section 4.1 discusses the data. Section 5 estimates the marginal effect of fuel treatment on fire suppression costs along with robustness checks (Section 5.1). Section 5.2 explores the counterfactual benefits of increased fuel treatment activity in our sample and Section 6 concludes.

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

2 Background

2.1 Fighting Fire with Fire: 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 (Miller, 2007).

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

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

biodiversity (Murphy et al., 2007; 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 help decrease these costs by reducing the size and severity of wildfires (Romero and Menakis, 2013; 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).

2.2 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, establishing a system of reserves over 24.4 million acres of federal forest land aimed at conserving old-growth habitats, NSO populations,

⁷Fuel treatments also facilitate “back-burning,” a form of indirect attack where 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.

and essential watersheds and riparian zones. This plan is one of the largest temperate forest reserve system in the world (Gaines et al., 2022; Spies et al., 2018).

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 (Johnson et al., 2023). The final plan established two main land designations. Late-Successional Reserves (LSRs) were designated based on the nesting, roosting, foraging, and dispersal needs of the NSO and other endangered species, covering 7.4 million acres with strict limitations on timber harvest. Meanwhile, Matrix lands were designated as areas to continue timber harvest and encompassed approximately 4 million acres, including around 2 million acres of late-successional old-growth forest. 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.⁸

Despite recognizing the importance of active management in fire-prone, “dry 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).⁹ 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 treatments across national forests in the Pacific Northwest (Figure 2a).

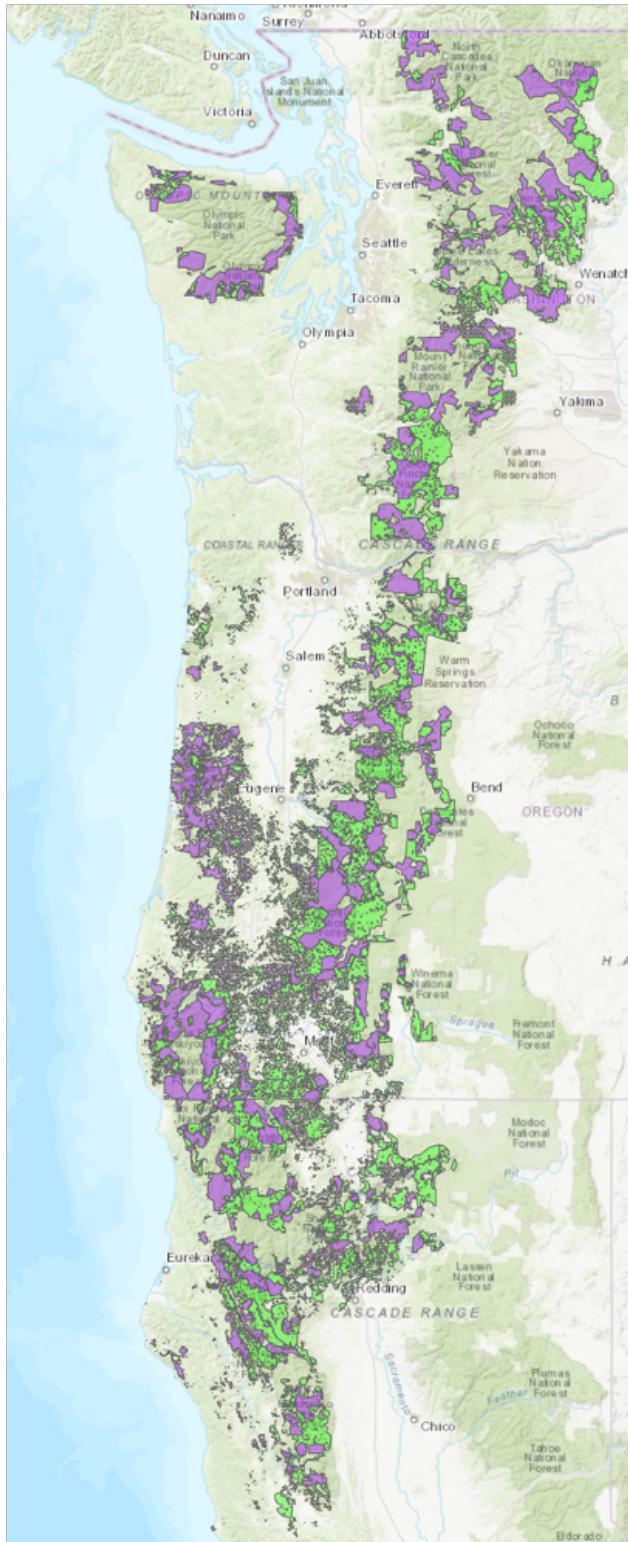
3 Conceptual Framework

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

⁸While LSRs aimed to protect the NSO, they do not always coincide with the critical habitat designated by the USFWS. For instance, around 40% of the critical habitat designated in 2012 is located within Matrix areas in Eastern Washington (Gaines et al., 2010).

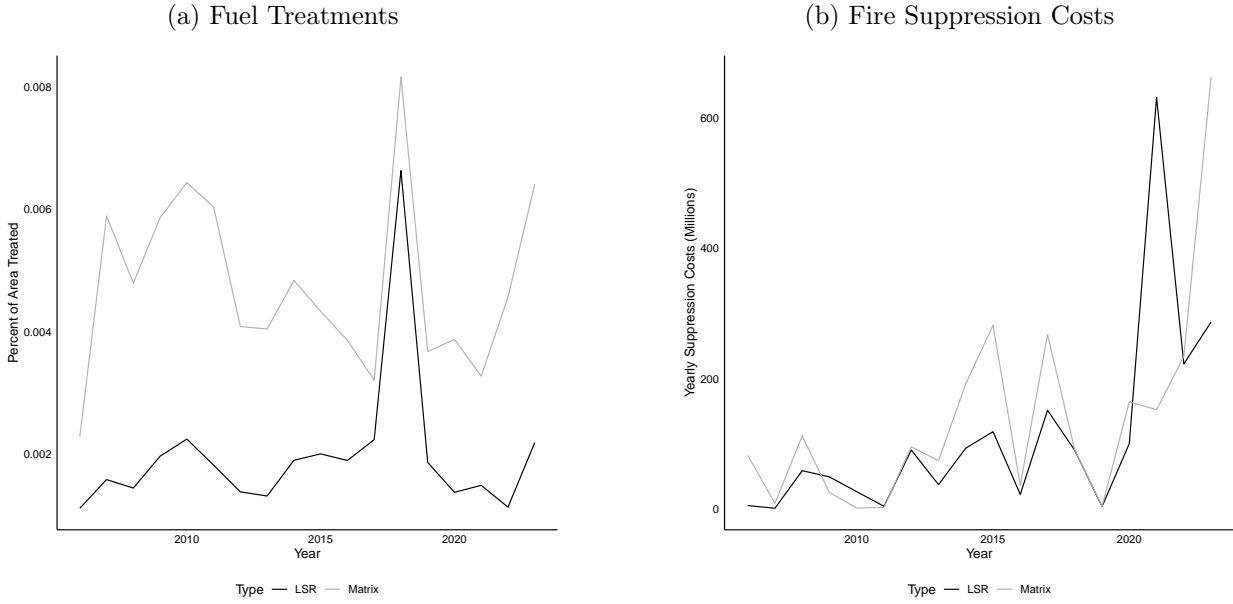
⁹For example, dry conifer forests historically experienced wildfires every 5-35 years, while wet conifer forests experienced wildfires every one to four hundred years (Parks et al., 2023; Johnson et al., 2023) Given these systematic differences, many scientists have criticized the inclusion of dry forests in the NWFP reserve system (Gaines et al., 2022).

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



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

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



“Percent of Area Treated” is the total annual acres of fuel treatment divided by the total area of Matrix or LSR areas.

Suppression costs are adjusted for inflation and are in terms of 2020 USD

economic benefits across all fires, resulting in a testable hypothesis that informs our empirical framework.¹⁰

3.1 Setup

A fire manager allocates fire suppression effort E_i toward fighting $i = 1, \dots, N$ 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.¹¹ The fire manager’s problem can be expressed as:

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

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) 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

¹⁰All derivations of our results can be found in Appendix A.

¹¹This 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 (e.g., Bayham and Yoder, 2020).

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 .

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

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

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).

3.2 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 $V(F_1, \dots, F_N)$ 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:

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

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 (Thomas et al., 2017). 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?

3.3 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 $-\frac{\partial^2 S(E,F)}{\partial F \partial E} < 0$.¹² 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:

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

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.

¹²Note 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.

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 4. 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.

3.4 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:

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

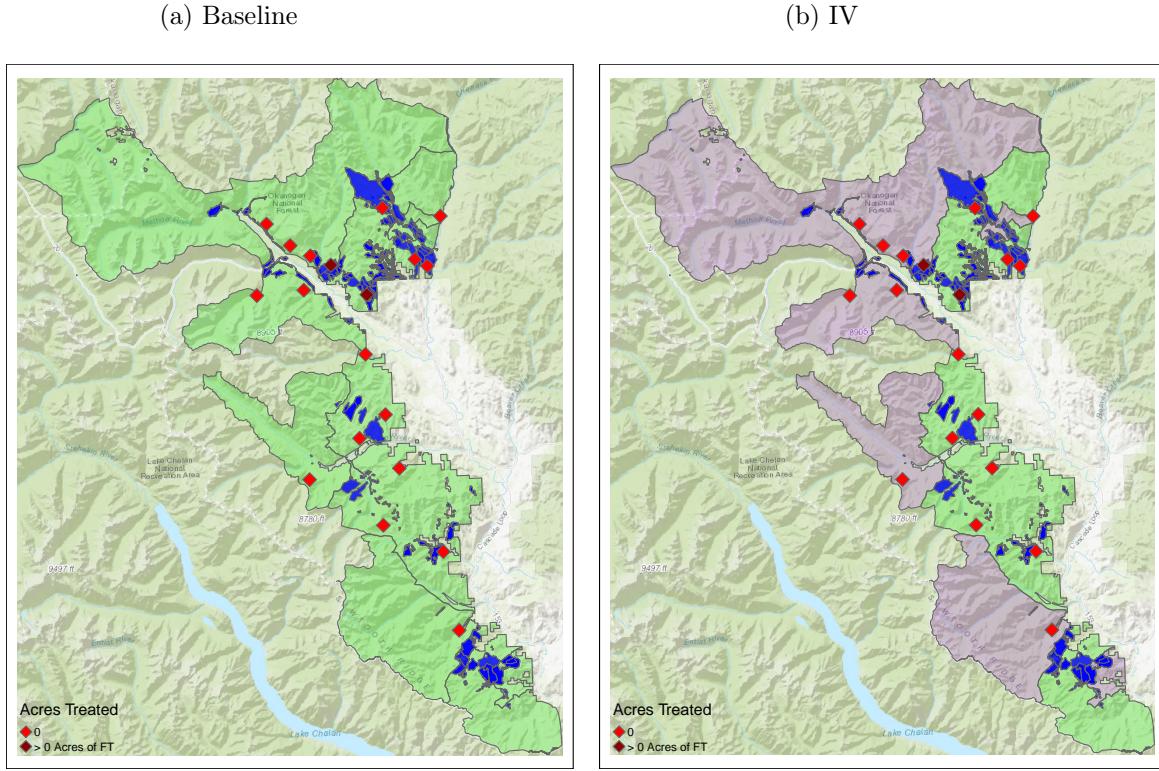
Thus, if the total effect of fuel treatments on fire size and suppression costs are both negative, then fuel treatments are economically beneficial. Additionally, if the resource constraint is also not binding, then fuel treatments will decrease total fire suppression costs (Corollary 3.2) without increasing 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 $H_0 : \frac{dS(E_i^*, F_i)}{dF_i} \geq 0$ or $\frac{dC(E_i^*)}{dF_i} \geq 0$. Rejecting the null implies $\frac{dS(E_i^*, F_i)}{dF_i} < 0$, 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.

4 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

Figure 3: Baseline & IV Identification Strategies Intuition



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” (IV) approach, highlighting protected areas (LSRs) in purple and unreserved areas (Matrix) in light green.

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 (Schoennagel et al., 2009). 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.¹³

¹³The interested reader can turn to Figure S.1 and Appendix C 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.

4.1 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 S.2](#) and [Table S.3](#).

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.¹⁴ 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, 2023b](#)).

Fuel treatment data come from the USFS FACTS (Forest Service Activity Tracking System) 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 (we refer to this category as “mechanical”; 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 impacted by the NWFP reserves and most relevant to our counterfactual benefits analysis.

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 precisely locates LSRs, while Matrix areas are grouped in the “Other” category, overlapping with Riparian Reserves.¹⁵ We broaden our definition of Matrix to include other NWFP designations with similar management protocols such as, “Adaptive Management Areas.”¹⁶ Throughout

¹⁴LANDFIRE data can be accessed at <https://landfire.gov/>, PRISM at <https://prism.oregonstate.edu/explorer/>, and GridMET from <https://www.climatologylab.org/gridmet.html>

¹⁵To 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.

¹⁶See [Appendix F](#) for a list and description of all the land-use categories from the NWFP

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.

To capture the impact of fuel treatments close to ignition points on fire size and suppression costs, we include small fires. Excluding them would obscure the effects of fuel treatments on reducing small fire costs 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.¹⁷ We impute the cost of all small zero-cost fires (<100 acres) with the median cost of small non-zero-cost fires, assuming these fires were low-cost initial attacks. Large (>100 acres) zero-cost fires are excluded due to their likely unique cost dynamics.¹⁸ Our analysis is robust to alternative inclusions and treatments of zero-cost fires, described in subsection 5.1.

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 apart 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.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).

These filtering steps ensure that our sample focuses on fires igniting within either LSRs or Matrix areas on USFS land - areas that are most comparable, as both types of land would have faced similar protection or lack thereof under alternative NWFP plans. In total, the two samples include 9,923 and 18,722 fires from 2006-2023 where \$4.68-5.7 billion USD was spent on fire suppression, the majority of which occurred during the second half of the sample period (Figure 2b).²⁰ 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 \$270 million spent on all fuel treatments in Matrix and LSR areas over this period.²¹ Matrix and LSR areas, collectively, represent

¹⁷ Approximately 45% of small fires (<100 acres) are zero-cost fires in our sample.

¹⁸ 51 fires meet this criterion.

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

²¹ The \$270 million costs should be interpreted as an overestimate of the true cost because the \$217 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).

over 93% of treated acres and 68% of suppression costs within the NWFP region on USFS land (see ??).

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 (\$471,708) is approximately three hundred times as large as the median cost of suppressing a fire (\$1,568). We see a similar pattern for acres burned as the average is 503 and the median is 0.1. These results are consistent with the fire 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).²²

Table 1: Fuel Treatments & Wildfires Descriptive Statistics

	Prescribed Fire	Mechanical	Total Treatments	Wildfires
Average Cost	\$7,578	\$13,423	\$14,160	\$471,897
Median Cost	\$1,476.2	\$2,069.8	\$1,940.7	\$1,568.3
Total Cost	\$56,654,865	\$222,963,214	\$279,618,079	\$4,682,637,293
Average Acres	56.6	63.1	74.5	503.1
Median Acres	18.3	24	24	0.1
Total Acres	423,221	1,048,673	1,471,894	4,991,788
Total Cost/Acre	\$133.9	\$212.6	\$190	\$938.1
No. Obs	7,476	16,611	19,747	9,923
Coverage	2006-2023	2006-2023	2006-2023	2006-2023

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 0 cost while others will not take into account revenues into 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.

4.2 Baseline Estimation Strategy

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

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

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 change in suppression costs (or

²²See Figure S.2a for plots of the distributions of the natural log of fire size and cost in our sample.

size) from a one-percent increase in the acres of fuel treatments occurring within a certain distance of fire i , FT_{it} .²³

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 fire.²⁴ Taking the sum of both mechanical and prescribed fire fuel treatments recognizes that fuel treatments incorporating both mechanical and prescribed fire treatments are the most effective at 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.²⁵ 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 S.3). Examples of environmental variables include topographic (i.e., slope, elevation, or aspect at ignition point), weather (i.e., temperature or vapor pressure deficit), vegetation characteristics (i.e. fuel type), and historic fire risk (i.e. mean fire return interval) near the ignition point, while examples of socio-economic variables are the ignition’s distance to the WUI or Forest Service Road.²⁸ 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 Our national forest, μ_f , and time-fixed ef-

²³We model the relationship between fuel treatments and fire size/cost through the natural log 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 acres of fuel treatment close to the fire, we take the $\log(x+1)$ transformation of FT_{it} . Our estimates are robust to linear and inverse hyperbolic sine specifications.

²⁴We 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; van Wagendonk et al., 2012; Lydersen et al., 2014). Because mechanical fuel treatments are often conducted in a series of treatments which is 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.

²⁵We explore the sensitivity of our estimates to different distances and time since fire in Section 5.1

²⁶Perimeters 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.

²⁷We demonstrate this point in Appendix B by decomposing the total marginal benefit of fuel treatments on fire size and cost across multiple channels.

²⁸We 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 main mechanisms through which fuel treatments influence our outcomes of interest. To address this we calculate all vegetation characteristics as of 2001, so that they represent pre-treatment vegetation characteristics. See Table S.3 for more details on such variables.

²⁹Note that previous burned acres is sometimes considered another form of fuel treatment and have been shown

fects, λ_t , address various omitted variable bias concerns. National forest fixed effects control for time-invariant unobserved determinants of firefighting costs that are specific to a national forest. Year-month fixed effects control for unobserved changes in firefighting resources and costs over time that are constant across national forests. Lastly, we cluster standard errors at the national forest level.

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 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, more 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.

4.3 Instrumental Variables Strategy

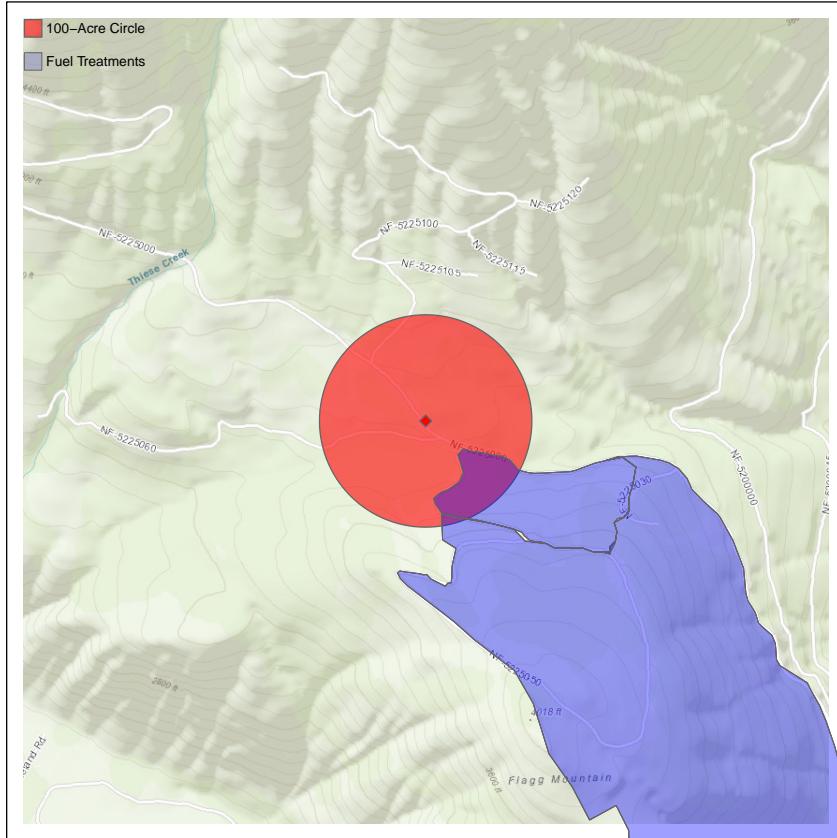
To overcome endogeneity concerns, we use spatial variation in NWFP reserves (LSRs) within National Forests as an instrument for the extent of fuel treatment activity occurring close to a fire. The intuition behind this estimation strategy is to compare fires that occur within the same national forest during the same time of year but differ in whether the fire ignites within an LSR or a Matrix area (Figure 3b).

We argue that variation in fuel treatments due to the presence of LSRs is quasi-random, as the NWFP was designed as a compromise between timber production and species conservation. In a less

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) (van Wagendonk, 2007).

³⁰Measures 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.

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



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.

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

Economic Variables					
	Dist WUI	Dist FS Road	Total Housing Value	Population	No. Housing Units
$\log(FT_{it})$	-0.533*** (0.086)	-0.069*** (0.013)	43.510** (17.889)	165.720** (61.460)	95.382*** (29.789)
LSR_i	0.908* (0.453)	0.107 (0.063)	-11.046 (20.494)	-86.682 (120.620)	-39.854 (64.908)
N	9923				

Topography & Weather					
	Slope	Elevation	South Slope	Wind Speed	ERC
$\log(FT_{it})$	-0.869*** (0.183)	-40.344*** (7.623)	0.003 (0.006)	-0.022*** (0.007)	0.095 (0.117)
LSR_i	2.735*** (0.345)	43.985 (48.324)	0.015 (0.011)	-0.009 (0.029)	0.362 (0.390)
N	9923				

Historic Fire Risk Variables					
	MFRI	Precip - CN	Temp Mean - CN	Temp Max - CN	VPD - CN
$\log(FT_{it})$	-0.331* (0.162)	-0.460*** (0.132)	0.160*** (0.025)	0.266*** (0.028)	0.523*** (0.060)
LSR_i	-0.170 (0.837)	0.495 (0.496)	-0.211 (0.224)	-0.466 (0.286)	-1.341** (0.574)
N	9923				

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

The table reports the results of 30 separate regressions regressing the natural log of acres of total fuel treatment, $\log(FT_{it})$ 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 in 17 National Forests that are apart of the 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 fires ignition point, a dummy variable equal to 1 if the slope at the ignition point is on a south facing slope aspect, while weather variables are the wind speed and energy release component (ERC) on 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.

restrictive conservation scenario, LSR lands might also have been unprotected. Furthermore, LSRs were designated based on the northern spotted owl's nesting, roosting, and foraging patterns (Gaines et al., 2022), which are unlikely to correlate with unobserved factors influencing wildfire behavior and fire suppression effort. Since most fires in our sample occur in dry forests, where scientists have noted the arbitrary distinctions between LSRs and Matrix areas (Spies et al., 2019), we expect any correlation with unobserved wildfire determinants to be minimal in these areas. Lastly, because LSRs inadvertently restrict fuel treatment activity, we hypothesize that fires igniting within these reserves are less likely to be near fuel treatments.

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:

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

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

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

The ratio of the reduced-form and first-stage coefficients, η/δ , is equivalent to the IV estimand of the percentage change in fire suppression costs (or size) from a one-percent increase 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 suppression costs, iii) exclusion: LSR status has no direct impact on fire suppression costs, and iv) monotonicity, LSR status should always reduce a fires 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) in Section 5. We also examine the plausibility of the exogeneity assumption by regressing LSR_i on the observable determinants of fire suppression costs with the inclusion of National Forest and year-month fixed effects. In general, we find a considerably better balance on observable characteristics when using LSR_i than $\log(FT_{it})$ (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. Although we cannot directly test this assumption, we hypothesize this not to be the case because the Forest Service's top priorities in fire suppression are human life, then structures, and lastly natural resources (ESA habitat, watersheds, etc.) (USFS, 2000).³² Similarly, the monotonicity assumption would fail if the USFS conducted more fuel treatments in

³¹In 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.

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

certain areas within LSRs in order to protect the NSO, which we believe to be of little concern because the stated goals of fuel treatments are to protect human assets at risk (USFS, 2022) and 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 suppression costs/sizes as a local average treatment effect (LATE), which uses variation from a specific subgroup of compliers (Imbens and Angrist, 1994). In our case compliers are fires that would have experienced more (less) fuel treatments close to their ignition point if not for the LSR (Matrix) designation. In contrast a parameter like the average treatment effect on the treated (ATT) is a weighted average of effects on compliers and always-takers. We find it plausible to assume that the effect on always-takers - fires that would have received the same level of fuel treatments close to their ignition point regardless of designation - would have a larger impact, in magnitude, than compliers because such areas are located at in areas that have the highest assets at risk or strategic importance. Hence we posit that our IV estimate is an underestimate, in magnitude, of the ATT.

5 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 using an indicator variable equal to one if a fire ignites inside of a LSR as an instrument for $\log(FT_{it})$. The estimated first-stage relationship implies that fires igniting inside of LSRs receive 13.7% 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 an F-statistic equal to 42.5, suggesting that LSR status is a strong instrument for fuel treatments. The estimated reduced-form relationships demonstrate that fires igniting inside of LSRs are 7.4% larger (p-value of 0.1961) and 12.2% more expensive (p-value of 0.0148), on average.

The IV estimates show that a one-percent increase in fuel treatments within a 100-acre radius of a fire's ignition reduces fire suppression costs by 0.89 percent (p-value of 0.0356) and fire size by 0.61 percent (p-value of 0.1997), on average. The IV estimates are considerably larger in magnitude than their corresponding baseline fixed-effects OLS estimates, as expected, but less precisely estimated.

The IV estimates imply 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. While this has the effect of decreasing the suppression costs of such fires, it also has the effect of offsetting 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 statistic for the economic benefits of fuel treatments. Since we cannot empirically identify the direct effect of fuel treatments on fire size, 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

Table 3: IV First Stage & Reduced Form Regression Results

	First Stage	Reduced Form		IV		OLS	
		log(FT_{it})	Size	Cost	Size	Cost	Size
LSR_i	-0.137*** (0.021)	0.074 (0.055)	0.122** (0.045)				
$\log(FT_{it})$				-0.540 (0.405)	-0.893** (0.391)	-0.035* (0.018)	-0.016 (0.018)
1st Stage F-Stat	42.5						
R^2	0.19	0.13	0.13	0.07	-0.10	0.13	0.13
N	9923	9923	9923	9923	9923	9923	9923

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

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 & 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 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. The sixth and seventh columns are the baseline OLS estimates on the natural log of wildfire size and suppression cost. Each regression includes economic and environmental control variables. Economic controls include a cubic for distance to WUI Census Block & 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 17 national forests apart of the NWFP. Standard errors are clustered at the national-forest level. First stage F-statistics are calculated via cluster robust-standard errors from the Fixest package in R ([Laurent, 2018](#)).

evidence to reject the null hypothesis (p-value of 0.0014) using an intersection-union hypothesis test ([Casella and Berger, 2002](#)).³³ Rejecting the null implies that the effects of fuel treatments on fire size and cost are strictly negative, suggesting that fuel treatments are generally economically beneficial.

5.1 Robustness Checks

We conduct a variety of robustness checks to evaluate the sensitivity of results to alternative variable definitions, specifications, and samples. To address concerns that Matrix and LSRs areas may be systematically different across observable determinants of fire suppression efforts, we conduct a matching procedure in which each fire in our sample is matched exactly to a fire that occurs in the same vegetation type, National Forest, and during the same month. Fires are then inexactly matched to find the optimal covariate balance across the most important determinants of fire suppression

³³See [Appendix D](#) for more details on how we conduct this hypothesis test.

costs and size (distance to WUI and USFS roads, elevation, slope, vapor pressure deficit, and wind speed) through the use of a genetic search algorithm, resulting in 3274 matches and 6548 fires in total. The matched IV estimation results are slightly smaller in magnitude than our unmatched IV regression results but are more precisely estimated and both statistically significant at the 5% level ([Table S.5](#)).

Our conceptual model ([section 3](#)) raised the concern that we may see violations of SUTVA due to suppression effort spillovers when resources for fire suppression are scarce. Namely, 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, leading to an overestimate (underestimate) of the magnitude of fuel treatments' effect on fire suppression costs (fire size). We explore this possibility by re-estimating our IV regression with added controls for scarcity in fire suppression resources and the number of concurrent fires that are within close proximity to fuel treatments ($FT_{it} > 0$).³⁴ Following [Gebert et al. \(2007\)](#), we control for the scarcity of fire suppression resources by calculating the difference in the average number of fires occurring in a state from 2000-2020 to the realized number of co-occurring fires in the state where a fire ignites.³⁵ The main IV results do not change meaningfully with the inclusion of these controls ([Table S.6](#)), suggesting that fuel treatments may not have meaningful spillover effects on other fires. This is corroborated by the insignificant effect of the number of concurrent fires close to fuel treatments. In contrast, the positive and significant effect of the number of concurrent fires suggests that scarce resources may influence the size and costs of suppressing fires; however, the effect is relatively small—e.g., one additional concurrent fire (above average) increases a fire's size by 0.1%—and may be picking up variation in general fire conditions that are not controlled for by our other control variables. Overall, there is not much evidence suggesting scarce firefighting resources plays a meaningful role in the allocation of suppression effort across fires.

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. We explore this possibility by re-estimating our IV regression for fire suppression cost using different specifications of the fuel treatment circle size: 50, 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 S.3](#)). 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 5% level across all specifications.

We also explore the sensitivity of our IV estimates to changes in our estimation sample. [Table S.7](#) shows the IV estimation results when estimating on 4 different samples of fires: i) lightning fires

³⁴Implicitly, we are assuming that fires are exchangeable—i.e., potential fire size and cost only depend on the number of treated fires—and linear in their spillover effects on other fires ([Vazquez-Bare, 2023](#)).

³⁵Our sample of fires does not have information on when a fire is contained; thus, we supplement our data with a wildfire ignition dataset from the USFS that has containment information ([Short, 2023](#)). Unfortunately, this dataset only consists of fires up to 2020; hence, the sample estimated in [Table S.6](#) is smaller (8407 fires) than our main sample of 9923 fires.

only, ii) fires occurring in the 17 National Forests apart of the NWFP, iii) fires that are within 2km of a Matrix-LSR border, and iv) fires that are not associated with a complex (2015-2023).³⁶ The lightning-only sample addresses concern that the probability of a human ignition may be correlated with a fire's LSR or Matrix status. Including fires that occur in any part of the 17 national forests in the NWFP explores how the results generalize across a larger area of interest. 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. Lastly, limiting our sample to non-complex fires addresses concerns that fire sizes and costs may not be accurately recorded for fires that are part of a complex. In general, we find that the signs and magnitudes of coefficients are not altered much by the change in samples.

We explore how our IV estimates are sensitive to different specifications of our endogenous regressor and instrument. [Table S.9](#) shows how the results of our IV estimate change when using: i) a linear specification on FT_{it} , ii) taking the inverse hyperbolic sine transformation of FT_{it} , iii) calculating fuel treatments that occur within the last 5 years instead of 10, and iv) using a continuous measure of LSR as an instrument for $\log(FT_{it})$.³⁷ We find that our IV estimates for suppression costs are statistically significant at the 5% level across all specifications (with the exception of our linear specification which is significant at the 10% level).

We also explore how our IV estimates are sensitive to different specifications of our dependent variable of interest. [Table S.9](#) shows how the results of our IV estimate change when: i) dropping fires that have an originally reported zero cost, ii) indicators for above median fire size or cost iii) average burn severity.³⁸ The first two robustness checks address concerns with our choice of including small (< 100 acre) zero-cost fires and replacing them with the median cost of suppressing small fires in our sample. When estimating i), the signs and magnitudes of our estimates are unchanged; however, our IV estimate is no longer statistically significant, which we argue is due to the fewer observations and, consequently, counterfactual comparisons across small fires that occur in the same national forest and time of year. Consistent with our main IV results, we find that fuel treatments significantly reduce the probability of a fire's cost being above the median, with no significant effect on fire size. When estimating iii), we find that fuel treatments do, in fact, reduce burn severity, consistent with the fire ecology literature ([Kalies and Yocom Kent, 2016](#); [Wimberly et al., 2009](#); [Safford et al., 2012](#)).

Lastly, we check the robustness of our IV estimates to the inclusion of different sets of fixed effects. [Table S.10](#) shows how the IV estimation results change when: 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

³⁶A complex is a fire in which multiple fires (with different ignition locations) merge into a single fire. Costs for such fires are recorded separately for each wildfire ignition point so we can have multiple fires in our sample associated with a single complex.

³⁷This continuous measure is analogous to FT_{it} , in that it is the number of acres inside of a 100-acre circle around the fires ignition point that are under a LSR designation status.

³⁸This continuous measure is analogous to FT_{it} , in that it is average burn severity within the 100-acre circle around the fires ignition point. Burn severity is calculated based on the year of fire from MTBS.

effects, and iv) replacing year-month fixed effects for state-year-month fixed effects. 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 across 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.

5.2 Counterfactual Costs & Benefits of Fuel Treatments

To illustrate the economic significance of fuel treatments on fire size and suppression costs, 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. 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, which account for less than 1% of the total estimated annual economic cost of wildfires (JEC, 2023). 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.

In order to conduct this counterfactual analysis we are interested in a parameter estimate of the average treatment effect on the treated (ATT), which tells us the average change in suppression costs that would be experienced by fires intersecting more fuel treatments relative to a regime where there were less fuel treatments. The ATT is valid in our counterfactual analysis under the assumption that adjacent untreated lands where treatment expands into share similar unobservable characteristics of the treated group. To so we use our IV estimate, which as explained in subsection 4.3 is likely an underestimate (in magnitude) of the ATT.

We first consider a crude and conservative back-of-the-envelope calculation that likely represents a lower bound for the true cost-effectiveness of fuel treatments. This is due to three additional factors: i) we measure only reductions in suppression costs, ii) our fuel treatment cost data do not include revenues from mechanical removal fuel treatments³⁹ and iii) fuel treatments likely reduce suppression costs through other channels (i.e., treatments further away from an ignition point may also influence the cost and behavior of large wildfires).⁴⁰

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,

³⁹Note 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 in 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).

⁴⁰If 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.

resulting in an increased fuel treatment cost of \$2.79 million (Table 1).⁴¹ 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 S.4 for a demonstration). For each fire, we calculate the counterfactual suppression cost savings by multiplying the percent increase in fuel treatment intersections by our estimated elasticity of fire suppression costs, -0.893 (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 \$8 million and 4,229 fewer acres burned, corresponding to a benefit-cost ratio of \$2.88 USD.

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 4.91 and 5.32, 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, even under conservative benefit estimates, 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 long-term economic benefits.

Table 4: Counterfactual Benefits of Increasing Fuel Treatments

	Cost of Treatment	Suppression Savings	Benefit-Cost Ratio	Reduction Acres Burned
1% Increase	\$2,796,181	\$8,043,549	\$2.88	4,229
5% Increase	\$13,980,904	\$68,700,649	\$4.91	36,568
10% Increase	\$27,961,808	\$148,864,169	\$5.32	78,518

The following table shows the cost, benefits, and benefit-cost ratio of what the benefits would have been under different counterfactual scenarios of increasing fuel treatment activity. In the first row fuel treatments are increased proportionately by one percent and we assume 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 accordingly.

⁴¹Note that although we are counting the labor costs of fuel treatments as part of our cost measure, many initiatives 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).

6 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. This study bridges that 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 a instrumental variables (IV) 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 less 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 wildfires, 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, three to five 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 fires ignition point ([Appendix B](#)). 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](#)). In fact fire suppression costs make up less than one percent of the total annual economic costs from wildfires ([JEC, 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 the National Environmental Policy Act (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 minor 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.

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Appendix

A Model Results: A Two-Fire Example

In this section, we provide the derivations for the main results of our conceptual model presented in section 3. 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:

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

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:

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

where H is the bordered Hessian.

Result 1. Fuel treatments will decrease fire suppression effort if and only if fuel treatments and suppression effort are q-substitutes. In contrast, fuel treatments will increase fire suppression effort if and only if fuel treatments and suppression effort are q-complements.

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

Applying Cramer's rule, we have:

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

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. \square

Corollary 1.1. Fuel treatments will decrease fire suppression costs if and only if fuel treatments and suppression effort are q-substitutes. In contrast, fuel treatments will increase fire suppression costs if and only if fuel treatments and suppression effort are q-complements.

Proof.

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

\square

Corollary 1.2. Fuel treatments will decrease fire size if fuel treatments and suppression effort are q-complements. In contrast, fuel treatments may or may not decrease fire size if fuel treatments and suppression effort are q-substitutes.

Proof.

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

which is negative if $\frac{\partial E_1}{\partial F_1} > 0$ (i.e., if fuel treatments and suppression effort are q-complements) but indeterminate if $\frac{\partial E_1}{\partial F_1} < 0$ (i.e., if fuel treatments and suppression effort are q-substitutes) 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. \square

Result 2. Fuel treatments will induce spillovers onto other fires if the suppression effort resource constraint binds. Specifically, fuel treatments will draw suppression effort away from other fires if they are q-complements and direct suppression effort toward other fires if they are q-substitutes.

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

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

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. \square

Corollary 2.1. Fuel treatments may increase or decrease total fire suppression costs, regardless of whether fuel treatments are q-complements or q-substitutes.

Proof.

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

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 1 and 2). 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 $\frac{\partial C(E_1)}{\partial E_1} < \frac{\partial C(E_2)}{\partial E_2}$. \square

Corollary 2.2. 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.

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

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

\square

Result 3. Fuel treatments increase the value of a fire manager's economic program provided the direct effect of fuel treatments on fire size is negative.

Proof. 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:

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

□

B 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 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:

$$\begin{aligned} \max_{F_1, \dots, F_N} & - \sum_{i=1}^N \pi_i(F_i) [L_i(X_i)S_i(F_1, \dots, F_N) + SC_i(F_1, \dots, F_N)] \\ \text{s.t. } & \sum_i c_i(F_i) \leq B, \end{aligned}$$

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:

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

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.

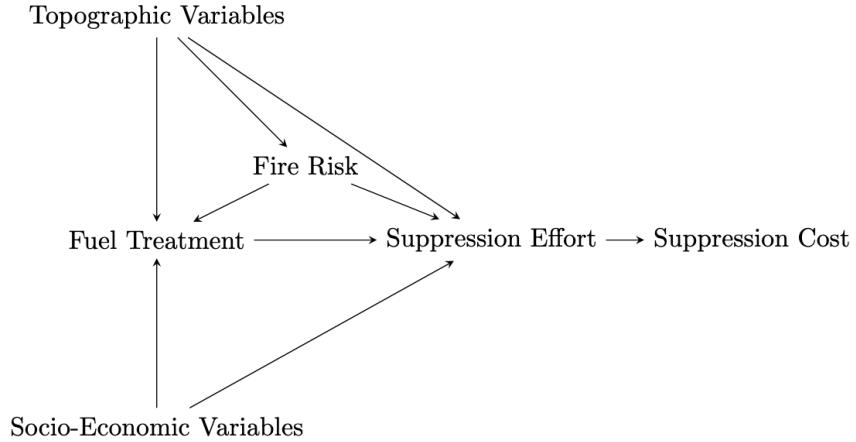
C The Data Generating Process for Fuel Treatments & Fire Suppression Costs

Figure S.1 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.⁴²

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

⁴²See Appendix B for an overview of the land manager’s fuel treatment location problem and section 3 for the fire manager’s fire allocation problem.

Figure S.1: The Data generating process for Fuel Treatments & Fire Suppression Costs



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.

D 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-side 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:

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

where $\hat{\phi}_c$ and $\hat{\phi}_s$ 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 $\hat{\phi}_c$ and $\hat{\phi}_s$. In each bootstrap resample, we compute the following t -statistics:

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

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

The B bootstraps yield the t -values $t_{c,1}^*, \dots, t_{c,B}^*$ and $t_{s,1}^*, \dots, t_{s,B}^*$, 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).

E Interpreting the IV Estimate

To do a counterfactual analysis of proportionate increases in fuel treatments we want an estimate of the ATT, which tells us the average change in suppression costs that would be experienced by fires intersecting more fuel treatments relative to a regime where there was less fuel treatments intersecting such fires. The ATT is valid in our counterfactual if we assume that areas where treatments are expanded into are similar on unobservable characteristics of the treated group. Lets call these two areas “Feasibly Treated” areas. We can also think of another group of “Never Treated” areas, areas where the USFS cannot feasibly conduct treatment because of exisiting laws like wilderness areas or areas of sufficiently high slopes ([North et al., 2015](#)). We might expect the treatment effect to be different, and most likely lower the “Never Treated” areas because they occur in areas further from assets at risk. For our counterfactual analysis we are only interested in the treatment effect for “Feasibly Treated” areas.

Our IV estimate, on the other hand, estimates a LATE, which uses variation from 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. By definition compliers fall into “Feasibly Treated” areas and so I think our IV estimate is using variation from our population of interest.

However, we might run into an issue if Matrix and LSRs are systematically different. For example, suppose we can break up the “Feasibly Treated” group into “Difficult” and “Easy” to treat groups and that the treatment effect is higher for the “Easy” to treat group since they are likely closer to assets at risk. If LSR contains a higher proportion of “Difficult” to treat areas and Matrix a higher proportion of “Easy” to treat areas then our IV estimate identifies the treatment effect for the subpopulation of “Difficult” areas, whereas our counterfactual analysis uses this estimate on “Easy” areas. In this example, our IV estimate would be underestimating the impact of expanding fuel treatments in Matrix areas.

F Land-Use Allocations Under The NWFP

Thirty percent of the NWFP area comprises of 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 NWFP area is comprised of “Congressionally Reserved” (CR) areas, 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 potential for litigation’s

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 comprises 16 percent of NWFP area See [Figure 1](#) for a map of NWFP areas and [Table S.1](#) for a list of and description of all land allocations under the plan.

G Supplementary Figures

Figure S.2: Distribution of fire suppression costs and fire size.

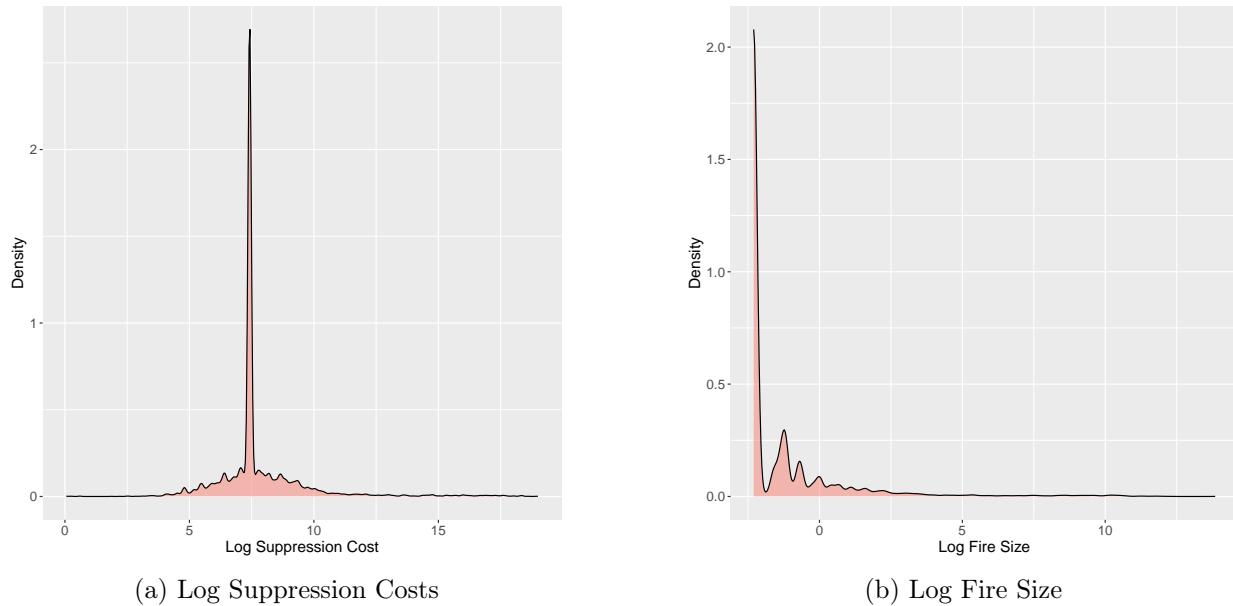
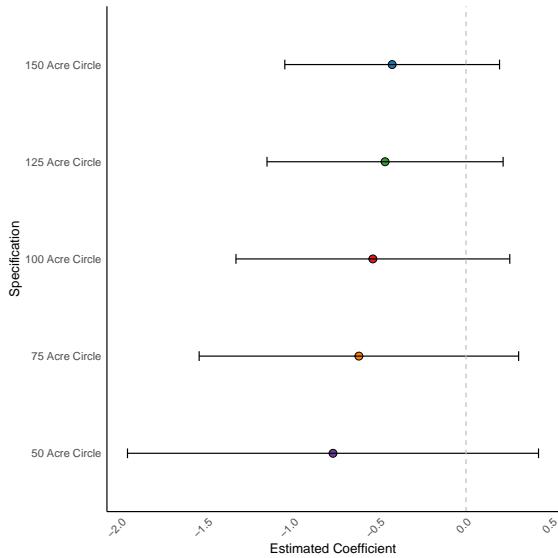
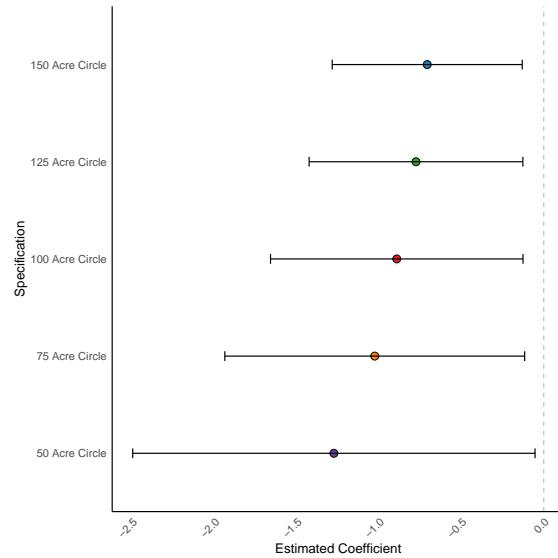


Figure S.3: IV estimates by fuel treatment acre circle size

(a) Fire Size

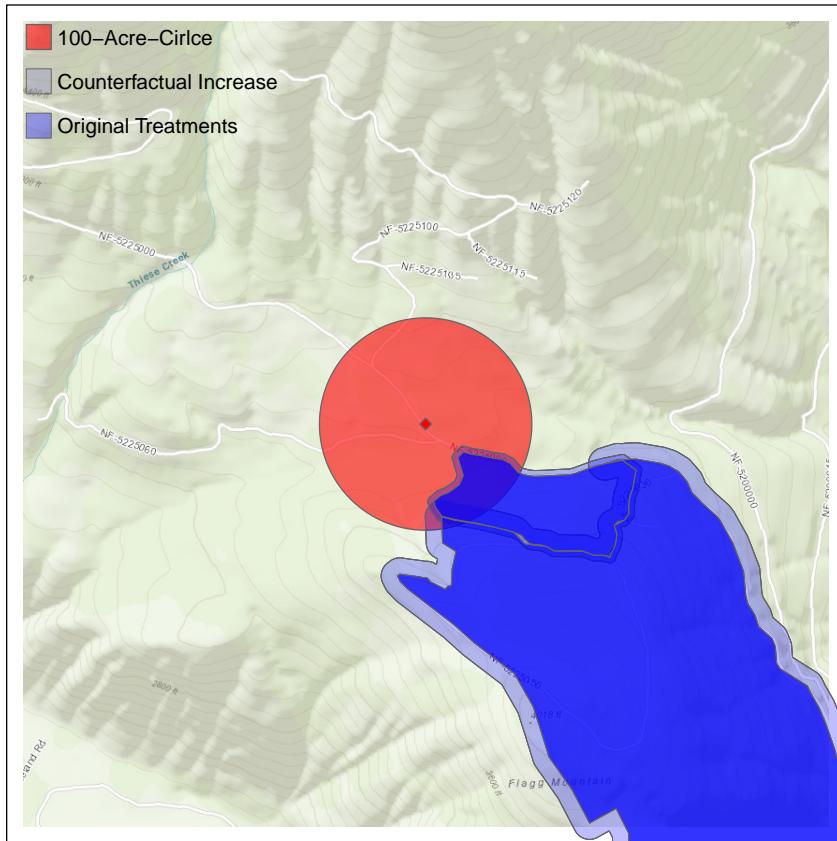


(b) Suppression Costs



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

Figure S.4: Example Counterfactual Increases in Fuel Treatments - Flagg Mountain Fire - 2020



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 which occurred close to Mazama WA in 2020. The red star shows the ignition point location, the red circle is 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 as before.

H Supplementary Tables

Table S.1: 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 S.2: 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	PRISM
	Wind Speed & ERC	GridMET
Vegetation Characteristics	Fuel Group Type Previous Acres Burned	LANDFIRE
Historic Fire Risk	Mean Fire Return Interval (MFRI)	LANDFIRE
	Climate Normals	PRISM
	Distance to WUI Census Block, Number of Households & Population	Radeloff et al. (2022)
Economic Variables	Total housing value, total household income	ACS
	Forest Service Roads	USFS (2023b)

Table S.3: 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 ⁴³	LANDFIRE
TRI	Terrain Ruggedness Index (TRI) ⁴⁴	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
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

Continued on next page

⁴³See <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-aspect-works.htm> for the classes used.

⁴⁴Constructed using the elevation layer from LANDFIRE and then using the terrain function from terra.

Table S.3 Continued

Name	Definition	Source
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 (2023b)
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)
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

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Table S.3 Continued

Name	Definition	Source
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 (2023a)
Ranger District	Dummy variables for Ranger District (subset of National Forest)	USFS (2023c)

Table S.4: USFS Suppression & Fuel Treatments Costs

	Suppression Costs	Acres Burned	Acres Treated	Costs of Treatment
Matrix & LSR	4,682,637,293	4,991,788	1,471,894	279,618,079
Full NWFP Area	7,006,130,772	9,223,544	1,582,755	301,385,584
WA, OR, & Nor CA	12,115,983,010	16,629,129	5,747,731	1,041,178,292
U.S.	30,530,809,000	-	-	-

The first two columns show the suppression costs and acres burned (2006-2023) on USFS land while the third and fourth columns show fuel treatment costs and acres treated (2006-2023) on USFS land. The three rows are different samples of fires and treatments across three different regions of USFS land 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 southern most latitude inside the NWFP region. The fourth row shows the total suppression costs spent by the USFS (2006-2023) as taken from [NIFC \(2024a\)](#).

Table S.5: IV Matching Estimate Results

	Log Fire Size - LSR IV	Log Fire Cost - LSR IV
Point Estimate	-0.598	-0.716
95% CI	[-1.139,-0.058]	[-1.204,-0.227]
N	6548	6548

Above shows 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 year) and have the same existing vegetation group type, ii) fires are inexact 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 S.6: LSR IV - Robustness Check - Spillovers

	First Stage		Reduced Form		IV		OLS	
	log(FT_{it})	Size	Cost	Size	Cost	Size	Cost	
LSR_i	-0.137*** (0.026)	0.048 (0.057)	0.113** (0.041)					
$\log(FT_{it})$				-0.346 (0.434)	-0.825* (0.407)	-0.040** (0.014)	-0.025 (0.015)	
No. Fires	0.000 (0.000)	0.001** (0.001)	0.002*** (0.001)	0.001*** (0.000)	0.002*** (0.001)	0.001** (0.001)	0.002*** (0.001)	
No. Fires FT > 0	-0.004 (0.003)	0.012 (0.011)	0.002 (0.009)	0.010 (0.011)	-0.001 (0.009)	0.011 (0.011)	0.002 (0.009)	
1st Stage F-Stat	27.3							
R2	0.19	0.14	0.15	0.11	-0.04	0.14	0.15	
N	8407	8407	8407	8407	8407	8407	8407	

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

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 state from 2000–2020 to the realized number of co-occurring fires in the 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 17 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 F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.

Table S.7: LSR IV - Robustness Checks - Estimation On Different Subsamples

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Lightning Only Fires					
LSR_i	-0.150*** (0.041)	0.156* (0.078)	0.199*** (0.054)		
$\log(FT_{it})$				-1.043 (0.677)	-1.325** (0.591)
1st Stage F-Stat	13.5				
N	5052	5052	5052	5052	5052
All NWFP National Forests					
LSR_i	-0.105*** (0.028)	0.069 (0.052)	0.123** (0.049)		
$\log(FT_{it})$				-0.658 (0.541)	-1.176* (0.577)
1st Stage F-Stat	42.5				
N	18722	18722	18722	18722	18722
< 2km from Matrix-LSR Border					
LSR_i	-0.106*** (0.019)	0.026 (0.067)	0.095 (0.056)		
$\log(FT_{it})$				-0.245 (0.621)	-0.893 (0.573)
1st Stage F-Stat	11.5				
N	7904	7904	7904	7904	7904
No Complex Fires					
LSR_i	-0.174*** (0.044)	0.102 (0.062)	0.091** (0.034)		
$\log(FT_{it})$				-0.583 (0.358)	-0.521** (0.198)
1st Stage F-Stat	15.8				
N	4732	4732	4732	4732	4732

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

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 started by lightning, the second fires that start inside of Matrix and LSRs within all 17 NWFP National Forests. The third sample uses only fires that are within 2 kilometers of Matrix-LSR borders. The fourth sample only includes fires that not apart of a complex from the NIFC fire cost data source (2015-2023). Standard errors are clustered at the national forest level. First stage F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.

Table S.8: LSR IV - Robustness Checks - Changes to Dependent Variable

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
No Zero Cost Fires					
LSR_i	-0.112*** (0.032)	0.057 (0.069)	0.120* (0.065)		
$\log(FT_{it})$				-0.506 (0.661)	-1.074 (0.774)
1st Stage F-Stat	12.1				
N	5380	5380	5380	5380	5380
Above Median Size & Cost					
LSR_i	-0.137*** (0.021)	0.018 (0.014)	0.011** (0.005)		
$\log(FT_{it})$				-0.133 (0.098)	-0.082* (0.039)
1st Stage F-Stat	42.5				
N	9923	9923	9923	9923	9923
Average Burn Severity					
LSR_i	-0.150*** (0.041)	0.056** (0.021)	-		
$\log(FT_{it})$				-0.375* (0.211)	-
1st Stage F-Stat	13.5				
N	5052	5052	-	5052	-

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

The above table explores the robustness of the main IV regression results to different outcomes of interest. 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 where previously all small fires were replaced with the median cost of suppressing non-zero fires. The second 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. The third set of regressions replaces the natural log of fire size with the average burn severity within the 100-acre circle of a fire. Standard errors are clustered at the national forest level. First stage F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.

Table S.9: 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_i	-1.762*** (0.494)	0.074 (0.055)	0.122** (0.045)		
FT_{it}				-0.042 (0.035)	-0.069* (0.037)
1st Stage F-Stat	10.3				
R^2	0.14	0.13	0.13	0.03	-0.21
N	9923	9923	9923	9923	9923
IVHS Fuel Treatments					
LSR_i	-0.164*** (0.025)	0.074 (0.055)	0.122** (0.045)		
$ashin(FT_{it})$				-0.452 (0.338)	-0.748** (0.324)
1st Stage F-Stat	43.7				
N	9923	9923	9923	9923	9923
Previous 5 Years Fuel Treatments					
LSR_i	-0.076*** (0.013)	0.074 (0.055)	0.122** (0.045)		
$\log(FT_{it,5Y})$				-0.976 (0.743)	-1.613** (0.720)
1st Stage F-Stat	35.1				
N	9923	9923	9923	9923	9923
Continuous IV					
$AcresLSR_i$	-0.014*** (0.002)	0.009 (0.006)	0.014*** (0.005)		
$\log(FT_{it})$				-0.640 (0.403)	-0.998** (0.424)
1st Stage F-Stat	41.5				
N	9923	9923	9923	9923	9923

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

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 $ashin(FT_{it})$. 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 F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.

Table S.10: LSR IV - Robustness Checks - Using Different Fixed Effects

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Ranger District FEs					
LSR_i	-0.156*** (0.022)	0.058 (0.053)	0.072* (0.037)		
$\log(FT_{it})$				-0.371 (0.343)	-0.459* (0.253)
1st Stage F-Stat	50.0				
N	9076	9076	9076	9076	9076
Year & Month (of Year) FEs					
LSR_i	-0.133*** (0.021)	0.072 (0.055)	0.115** (0.041)		
$\log(FT_{it})$				-0.545 (0.431)	-0.868** (0.388)
1st Stage F-Stat	39.5				
N	9098	9098	9098	9098	9098
State-Year & State-Month FEs					
LSR_i	-0.134*** (0.023)	0.076 (0.055)	0.109** (0.040)		
$\log(FT_{it})$				-0.568	-0.818**
1st Stage F-Stat	32.4				
N	9098	9098	9098	9098	9098
State-Year-Month FEs					
LSR_i	-0.130*** (0.022)	0.090* (0.051)	0.126*** (0.037)		
$\log(FT_{it})$				-0.692 (0.432)	-0.972** (0.393)
1st Stage F-Stat	34.5				
N	9098	9098	9098	9098	9098

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

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 F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.