### Title
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# Before the burn: The economic benefits of fuel-reduction treatments in wildfire-prone forests

The economic benefits of fuel treatments

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

**Keywords:** wildfire; conservation; fuel treatments; natural disasters; climate change

**Classification:** H41, Q23, Q28, Q54, R52

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*"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 unprecedented 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. The estimated total annual cost of wildfires in the U.S. ranges from $394-893 billion USD (JEC, 2023), encompassing losses to both human-made and natural assets (Bayham *et al.*, 2022; Wang and Lewis, 2024), fire suppression costs (Baylis and Boomhower, 2023), impacts on human health (Molitor *et al.*, 2023; Heft-Neal *et al.*, 2023), labour market disruptions (Borgschulte *et al.*, 2024), and reductions in ecosystem services (Smith, 1993). These costs are expected to rise globally with climate change (Abatzoglou and Williams, 2016), increased development in the wildland-urban interface (WUI; Radeloff *et al.*, 2018), and fire exclusion policies (Schoennagel *et al.*, 2017).

The build-up of combustible material in forests, often referred to as fuel loads, is one of the leading causes of increasing wildfire severity (Miller *et al.*, 2009). Fuel loads have built up over time far beyond their natural carrying capacity in response to current and historical fire suppression policies (Stephens *et al.*, 2007; North *et al.*, 2022). Fuel treatment activities, such as prescribed burns or mechanical fuel removal, reduce wildfire risk 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 fewer than 30,000 people despite owning more than 193 million acres of public land.[1] Public pressure and risk aversion skew an already scarce resource base towards fire suppression at the expense of fuel treatments to avoid public lawsuits and condemnation. Regulatory constraints based on environmental objectives and policies, such as endangered species protections, federal and state air quality standards, survey and manage protocols, federally designated Wilderness areas, and the National Environmental Policy Act (NEPA), significantly hinder the ability of public agencies to conduct fuel treatments on public lands (North *et al.*, 2012, 2015; Johnson *et al.*, 2023; Edwards and Sutherland, 2022). Such environmental regulations lead to instances where the costs associated with no action are overlooked, and the “precautionary principle” becomes the “paralysing principle” (Hessburg *et al.*, 2021).

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

This paper presents the first causally identified estimate of the effectiveness of fuel treatments in reducing wildfire costs. Although prior forest ecology research has demonstrated the effectiveness of fuel treatments in reducing fire severity (Agee and Skinner, 2005; Kalies and Yocom Kent, 2016), quantifying their economic benefits remains limited (Kline, 2004).[2] Despite calls for the widespread adoption of these practices as a means to reduce economic costs (USFS and State of California, 2020; State of California, 2021), the existing economic literature has focused on identifying the determinants of fuel treatment activity and fire suppression efforts rather than the relationship between the two (Plantinga *et al.*, 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer *et al.*, 2019; Anderson *et al.*, 2023).

We assess whether fuel treatments mitigate the economic costs of wildfires by investigating fires igniting on USFS land in the Pacific Northwest from 2006 to 2023. Our analysis focuses on two key wildfire outcomes: fire size and suppression costs. While suppression costs represent only a small portion of the total social cost imposed by wildfires, their contribution is significant. According to the National Interagency Fire Center, federal agencies spent \$55 billion on wildfire suppression from 1985 to 2022.[3] Suppression spending also has important implications for land-management agency budgets: since suppression and restoration activities often draw from the same limited funding, higher suppression costs can crowd out investments in restoration and resilience.[4] Similarly, fire size is often cited as a proxy for broader wildfire impacts, including smoke-related health costs and structure loss (e.g., Wen

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

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

[4] In recent years, rising suppression expenditures have coincided with a growing backlog of deferred maintenance within the U.S. Forest Service—estimated at over \$8.6 billion in fiscal year 2023—spanning roads, trails, recreation facilities, ecological restoration, and forest resilience projects (USFS, 2025).

*et al.*, 2023). We find evidence that fuel treatments jointly reduce fire size and suppression costs and are a cost-effective means of doing so.

The lack of research linking fuel treatments' impact on economic outcomes is likely due to the environmental and spatiotemporal complexities of wildfires, treatments, and fire suppression efforts, resulting in at least two empirical challenges for identifying causal effects. First, the location and extent of fuel treatments and fire suppression efforts are jointly determined by socio-economic and environmental factors (Plantinga *et al.*, 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer *et al.*, 2019; Anderson *et al.*, 2023). For example, treatments and suppression effort are often allocated in areas to protect assets at risk. 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 on suppression costs (Sánchez *et al.*, 2019; Yoder and Ervin, 2012). Second, even if fuel treatments are conducted exogenously, the allocation of suppression effort across fires mediates the effect of fuel treatments on the size and cost of suppressing fires. For example, if fuel treatments and suppression effort are complements-in-production, more resources will be allocated toward fires igniting near fuel treatments, increasing suppression costs. Indeed, we demonstrate that fuel treatments could actually increase the size and suppression cost of nearby fires, even if they collectively decrease the size and costs of all fires.[5] 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, using a stylised model of fire suppression effort allocation, we

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

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. Second, building on Baylis and Boomhower (2023), we employ a fixed-effects strategy that compares fires igniting within the same national forest and time of year but exposed to varying levels of nearby fuel treatments. Our strategy controls for a broad suite of factors known to influence wildfire behaviour and suppression costs, including topography, weather, vegetation, economic, and historical wildfire risk factors. Finally, we employ an instrumental variable strategy that exploits exogenous variation in fuel treatments arising from spatial variation in protected areas established under the Northwest Forest Plan (NWFP). These protected areas, created to conserve the northern spotted owl (NSO) under the Endangered Species Act (ESA), inadvertently restrict fuel treatment activities due to increased management restrictions and litigation risks (Johnson *et al.*, 2023). Spatial variation in protected areas generates quasi-random variation in fuel treatment activity because their boundaries were based on the ecological needs of the NSO, other endangered species, and sensitive habitats (Gaines *et al.*, 2022). However, because the NWFP did not protect all NSO habitat—due in part to limited ecological understanding of the species and reserve design constraints at the time—substantial portions of critical habitat and old-growth forests were left unprotected (Gaines *et al.*, 2010). As a result, fires ignite in comparable environments inside and outside protected areas but are exposed to differing levels of nearby fuel treatments for reasons unrelated to potential fire suppression costs or fire size.

We find that fires igniting in protected areas are similar in their observable characteristics to those igniting in unprotected areas, yet receive 11.3% less fuel treatment area near their ignition points, highlighting the impact of environmental protections on treatment activities. Fires in protected areas are also, on average, 13.1% more costly to suppress than those igniting outside of protected areas. Taken together, these estimates imply that a one-percent increase in nearby fuel treatment area reduces wildfire suppression costs by 0.96%. Notably, falsification tests provide evidence that our estimates are not driven by differences in management protocols or underlying suppression difficulties between protected and unprotected areas. We also find that fuel treatments reduce fire size, but the effect is not statistically different from zero–consistent with our theoretical framework, which predicts that treatment effects on fire size may be attenuated as suppression resources are reallocated away from fires that ignite near treated areas. We test our sufficient condition using a bootstrap intersection-union hypothesis test and find evidence that fuel treatments jointly reduce fire size and suppression costs, indicating that fuel treatments provide economic gains and that suppression cost savings are a conservative measure of such benefits. Building on this evidence, we estimate counterfactual suppression cost savings that would have arisen had the size of all fuel treatments in our sample been proportionally larger. We find that five to six dollars in fire suppression costs are saved for every dollar spent on fuel treatments, depending on the level of increased treatment activity. These results indicate that fuel treatments are a cost-effective strategy for mitigating wildfire risks.

Our study makes several contributions. We demonstrate the potential role of public investments in natural capital as a cost-effective means of mitigating risks posed by natural disasters. Previous research has highlighted the government's role in bearing the cost of protection from natural disasters, often unintentionally encouraging development in high-risk areas (Kousky *et al.*, 2006; Boustan *et al.*, 2012; Baylis and Boomhower, 2023). While insurance can provide financial protection for private property, insurance markets face significant challenges in adapting to rising natural disaster risks due to information asymmetries and the spatially correlated, catastrophic nature of such events (Busby *et al.*, 2013; Kousky, 2019; Wagner, 2022a,b; Boomhower *et al.*, 2024). In response, policymakers have turned to targeted risk-reduction measures, such as mandating fire-resilient building codes for new homes in California (Baylis and Boomhower, 2021). However, neither insurance nor home hardening measures address the substantial indirect costs of natural disasters, such as the widespread economic damage from wildfire smoke exposure.[6] We demonstrate that public investments in natural capital—such as fuel-reduction treatments—provide a complementary and cost-effective means of protection from natural disasters, while mitigating many indirect costs that insurance markets and home hardening measures do not.

Our analysis also highlights how well-intentioned environmental protections can lead to conflicting objectives between species conservation and wildfire management. Land managers and fire ecologists have long acknowledged that reserves established under the NWFP can limit fuel treatment activity, particularly in dry forests in need of restoration in the Pacific Northwest (Spies *et al.*, 2019; Hessburg *et al.*, 2021). Although high-severity fires are only one of several threats to NSO populations, they have led to considerable loss in NSO habitat (Davis *et al.*, 2016). Recent discussions increasingly weigh the negative short-term consequences of fuel treatments on NSO habitat against their long-term benefits for ecosystem resilience and fire risk reduction (Spies *et al.*, 2018; North *et al.*, 2012). Our study contributes

[6] For example, Borgschulte *et al.* (2024) estimate a $125 billion/year reduction in quarterly earnings due to smoke exposure.

to this literature by quantifying the extent to which the NWFP has restricted fuel treatment activity and increased the public burden of fighting wildfires—an unintended outcome that has likely diverted scarce resources away from restoration and other conservation priorities.

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

The paper is organised as follows. Section 2 provides background on wildland fire institutions, fuel treatments, and 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 introduces our research design and discusses the data. Section 5 presents our estimates of the marginal effect of fuel treatment on fire suppression costs and size, discusses several robustness checks, and explores the counterfactual benefits of increased fuel treatment activity. Section 6 concludes the paper.

# 2 Background

## 2.1 Wildland firefighting and fuel treatments in the western U.S.

The Great Fire of 1910 marked an important turning point in the management of U.S. national forests (Egan, 2011). The dedicated efforts of Forest Service rangers, along with widespread alarm caused by the fire, ultimately led to the USFS's expansion and a major shift in its mission statement: from prioritising conservation to fighting forest fires. Prioritising 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 of its initial report (Loveridge, 1944).

Local, state, and other federal agencies followed in the USFS's footsteps to implement similar wildfire suppression policies (Pyne, 2008), unintentionally leading to increased fuel loads that are in marked disequilibrium with natural forest structure 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, ecologists now recognise that the major issue facing western forests today is the relative absence of fire—a view that contrasts with decades of public messaging, such as the Smokey Bear campaign, which emphasised preventing human-caused fires.

Fuel treatments, such as prescribed fires or mechanical fuel removals, aim to restore forest ecosystems to a more natural state by mimicking the processes of low-severity fires, which reduce fuel loads, maintain open stands of trees, and eliminate shade-tolerant species that are more susceptible to wildfire. Because many ecosystems are adapted to frequent low-severity fires, forests that receive such fuel treatments experience fewer high-severity wildfires and thus enhance the ecosystem services associated with such forests through reduced smoke exposure, increased nutrient cycling, water quality, and carbon sequestration post-wildfire, along with the promotion of biodiversity (Kalies and Yocom Kent, 2016; Converse *et al.*, 2006; Boerner *et al.*, 2009; Finkral and Evans, 2008; Yocom Kent *et al.*, 2015; Richter *et al.*, 2019). Although generally considered less ecologically beneficial, mechanical treatments, such as commercial thinning, are often implemented first to generate revenue that can help fund non-revenue-generating treatments like prescribed burns (Belavenutti *et al.*, 2021).

Although there is no causal evidence directly linking fuel treatments to reductions in fire suppression costs, both qualitative and simulation evidence suggest that fuel treatments help decrease these costs by reducing the size and severity of wildfires (Romero and Menakis, 2013; Murphy *et al.*, 2007; Graham *et al.*, 2009; Thompson *et al.*, 2013b). Fuel treatments can enhance the effectiveness of both "direct" and "indirect" firefighting efforts, which likely contributes to cost savings (Romero and Menakis, 2013). Direct attack involves firefighting actions performed near the fireline, such as constructing control lines, smothering flames, or applying water or chemical retardants. These efforts are only feasible when wildfires have sufficiently low flame lengths—a condition that fuel treatments help create. Indirect attack, on the other hand, consists of operations conducted at some distance from the fire's perimeter. This may involve using fuel breaks or creating firelines where combustible material is removed to halt a fire's progression.[7]

By increasing the effectiveness of direct and indirect attacks, fuel treatments reduce reliance on more costly aerial attack methods that involve applying water or chemical retardant via helicopters or fixed-wing aircraft. Aerial attacks require significant capital investment

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

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 dismay at the sight of a shaven landscape. State officials had to explain that what Carter saw was clear-cut logging and not the aftermath of the explosion (Dietrich, 2010). The sight of clear-cutting and its deleterious effects on ecosystems fueled public debate over the management objectives of federal forest owners. In the 1980s, the northern spotted owl (NSO) became the centrepiece of this debate, serving not only as a symbol for old-growth conservation but also as the legal basis for changing federal forest management objectives under the ESA. This debate culminated in the early 1990s, when federal forests in the Pacific Northwest underwent a sudden shift in management focus–from providing sustained yield timber to prioritising biodiversity conservation and protection of 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 Northwest Forest Plan (NWFP) was established in 1994, creating a system of reserves spanning over 24.4 million acres of federal forest land aimed at conserving old-growth habitats, NSO populations, and essential watersheds and riparian zones, making it one of the largest temperate forest reserve systems in the world (Gaines *et al.*, 2022; Spies *et al.*, 2018).

The formulation of the NWFP required balancing trade-offs between timber production and species conservation (Johnson *et al.*, 2023). Several reserve options were considered, each offering varying levels of protection for so-called "working" forests—lands deemed sufficiently productive for timber harvesting. The final plan established two main land designations (Figure 1a). Late-Successional Reserves (LSRs), spanning 7.4 million acres, were designed to support the nesting, roosting, foraging, and dispersal needs of the NSO, as well as other endangered species and sensitive habitats.[8] Meanwhile, Matrix lands, comprising approximately 4 million acres (including 2 million acres of old-growth forest), were designated as areas where most timber harvests and silvicultural activities would continue. However, given the limited understanding of the NSO and old-growth forest conditions at the time, this compromise meant that while many old-growth forests gained protection from LSR designation (3.7 million acres), a substantial portion remained open to more intensive management practices. Notably, although LSRs were designed to protect the NSO, they do not entirely align with either historical or critical habitat designations by the USFWS. For example, approximately 40% of historical nesting owl pairs and 40% of critical habitat areas designated in 2012 are located within Matrix lands rather than reserved areas (Gaines *et al.*, 2010; Johnson *et al.*, 2023; USFWS, 2012).

A major consequence of the NWFP was a significant reduction in old-growth logging, timber harvest, and the practice of clear-cutting. Indeed, timber harvests on federal lands in the region have declined by 80–90%, resulting in significant job losses and economic hardships for many rural, timber-dependent communities (Spies *et al.*, 2019; Ferris and Frank, 2021). Moreover, in response to environmental litigation over clear-cutting projects, the bulk of the

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

remaining timber harvests have occurred through commercial thinning and selective logging operations aimed at younger forests to offset reduced harvest from old-growth (Johnson *et al.*, 2023).

Despite recognising the importance of active management in fire-prone forests, the NWFP has unintentionally restricted fuel treatment activities in LSRs due to conservative interpretations of its rules and the potential for litigation from environmental groups (Johnson *et al.*, 2023). Coupled with a century of active fire suppression, forested areas within LSRs have experienced significant fuel build-up, particularly in dry forests east of the Cascade Mountain Range, where fuel levels have diverged considerably from their natural state. These dry forests, historically shaped by frequent low-severity wildfires, are much more fire-prone than the wetter forests to the west, leading many scientists to criticise the inclusion of dry forests in the NWFP reserve system (Gaines *et al.*, 2022).[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 1b).

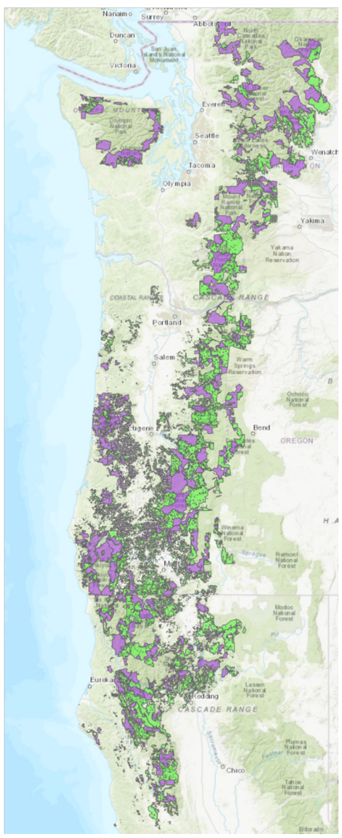
## 3 Conceptual framework

In this section, we present a stylised 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

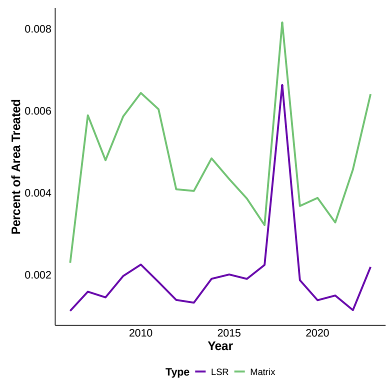
[9]For example, dry conifer forests historically experienced wildfires every 5-35 years, while wet conifer forests experienced wildfires every one to four hundred years (Johnson *et al.*, 2023).

Figure 1: Fuel treatments, fire suppression costs, and NWFP land designations

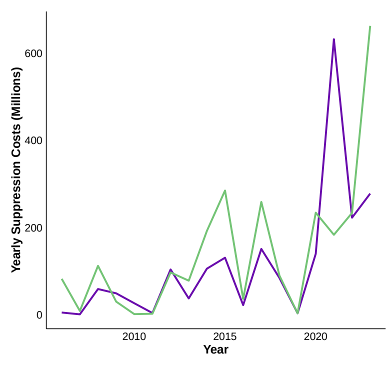
(a) Northwest Forest Plan




(b) Fuel Treatments




(c) Fire Suppression Costs




*Notes:* (a) Matrix areas are shaded in bright green, LSRs in purple, and National Forests in light green; (b) "Percent of Area Treated" is the total annual acres of fuel treatment divided by the total area designated as Matrix or LSR; (c) Suppression costs are adjusted for inflation and are measured in 2020 USD.

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 cost of a nearby fire, even if they reduce the total acres burned and suppression costs across all fires. We use the model to derive a sufficient condition under which fuel treatments collectively provide economic benefits across all fires, resulting in a testable hypothesis that informs our empirical framework and counterfactual analysis.[10]

## 3.1 Setup

A fire manager allocates fire suppression effort $E_i$ toward fighting $i = 1, \ldots, N$ fires burning simultaneously, conditional on an existing distribution of fuel treatments across the landscape. In our framework, the fire manager represents the incident or regional commander responsible for allocating real-time suppression resources—such as hand crews, engines, or air tankers—across active fires. We assume that a fire manager's objective is to minimise expected losses, defined as the sum of expected damages and fire suppression costs. The fire manager is also subject to a resource constraint on suppression effort, reflecting real-time physical limitations on suppression personnel and equipment that may become binding during peak fire seasons or when multiple large fires burn simultaneously.[11] The fire manager's problem can be expressed as:[12]

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

[10]All derivations of our results can be found in A1.

[11]We assume a fire manager's constraint reflects physical limits on suppression resources rather than financial budgets, as suppression costs are often reimbursed post hoc via emergency funds (Wang and Blackband, 2023).

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

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.[13] 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, $S(E, F)$, scaled by a constant loss, $L(A_i) > 0$, which is a function of assets at risk, $A_i$.[14] We assume fire size is strictly positive, decreasing, and convex in suppression effort and fuel treatments, reflecting diminishing returns. Since fuel treatments are predetermined, the costs of implementing them do not enter into a fire manager's calculus. We compare the economic benefits of fuel treatments to their implementation costs in our empirical application in Section 5.3.

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

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

where $\lambda$ 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

[13]We note that our results do not rely on this assumption and remain unchanged when allowing for idiosyncratic suppression costs across fires.

[14]Observed wildfire damage often exhibits a nonlinear relationship with fire size (Gebert *et al.*, 2007; Wen *et al.*, 2023), reflecting variation in assets at risk and suppression effort across fires. We capture these nonlinearities by allowing damages to scale with $L(A_i)$ and by letting suppression effort be endogenously allocated in response to assets at risk. While any remaining nonlinearities could be modelled by allowing damages to depend nonlinearly on fire size, we maintain linearity for tractability and to obtain sharper predictions regarding outcomes observed in our data.

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. Furthermore, the first-order conditions demonstrate that more suppression effort will be devoted to fires with higher levels of assets at risk, suggesting that fire size may be an imperfect proxy for economic damages.[15]

## 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 $V(F_1, ..., F_N)$ 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.

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

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

Intuitively, while fuel treatments will induce changes in suppression effort allocation, effort will be adjusted to balance the marginal benefits of reduced fire damages with the marginal cost of fire suppression so that the behavioural response will not have a first-order effect.

[15] For example, managers often allow low-risk fires to burn for ecological benefit, while aggressively containing smaller fires near assets at risk (Baylis and Boomhower, 2023; Plantinga *et al.*, 2022; Gellman and Wibbenmeyer, 2025)

Thus, the direct effect of fuel treatments on fire size ($\partial S(E, F)/\partial F$) 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 in our empirical setting, we cannot identify the direct effect of fuel treatments on fire size since our identifying variation does not hold suppression effort constant across fires with low and high fuel treatments, for instance. Thus, we can only identify the total effect of fuel treatments on fire size ($dS(E, F)/dF$), which includes the mediating response of fire suppression effort, ($dE^*/dF$). 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, $L(A)$, which are heterogeneous and generally difficult to assess. 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 $-\left(\partial^2 S(E,F)/\partial F \partial E\right) < 0$.[16] 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 the effects of fuel treatments on suppression costs and fire size.

PROPOSITION 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 1. *Fuel treatments will decrease fire suppression costs of nearby fires if and only if fuel treatments and suppression effort are q-substitutes.*

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

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

COROLLARY 2. *Fuel treatments will decrease the size of nearby fires if fuel treatments and suppression effort are q-complements.*

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

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

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

Corollary 1 is a direct implication of Proposition 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 reaches a similar conclusion for a fire's size. Under q-complementarity, the negative direct effect of fuel treatments on a fire's size, $(\partial S(E_i, F_i)/\partial F_i)$, will be enhanced through the indirect effect of increasing suppression effort, $(\partial S(E_i, F_i)/\partial E_i) \cdot (dE_i/dF_i)$. 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 fire managers' endogenous effort allocation responses.

Thus far, we have focused on the effects of fuel treatments on a nearby fire. The binding constraint on suppression effort 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 resource constraint is binding, this effort is allocated toward other fires until the marginal benefit minus the marginal cost is equal across all fires. The opposite is true if fuel treatments increase the marginal productivity of suppression effort.

Proposition 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. *If the suppression 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 4. *If the suppression 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 Proposition 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 demonstrates that these spillover effects also have implications for fuel treatments' effect on total fire suppression costs across all fires.[17] Corollary 4 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.

[17]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.

### 3.4 Testable implications

The preceding results suggest that fuel treatments will provide positive economic benefits so long as they directly reduce the size of nearby fires: $(\partial S(E_i^*, F_i)/\partial F_i) < 0$. However, we cannot explicitly test for the existence of such an effect, as we can only empirically identify the total effect of fuel treatments on fire size $(dS(E_i^*, F_i)/dF_i)$ , 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, the effect of fuel treatments on the suppression costs and size of nearby fires may not accurately assess the overall benefits provided by fuel treatments. How, then, can we know if fuel treatments are economically beneficial?

We now demonstrate how our sufficient condition for the economic benefits of fuel treatments can be tested empirically by implication. We then show that if this condition is met, 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 the size of nearby fires can be expressed as:

$$\underbrace{\frac{dS(E_i^*, F_i)}{dF_i}}_{\text{Total Effect}} = \underbrace{\frac{\partial S(E_i^*, F_i)}{\partial E_i} \cdot \frac{dE_i^*}{dF_i}}_{\text{Mediating Effect}} + \underbrace{\frac{\partial S(E_i^*, F_i)}{\partial F_i}}_{\text{Direct Effect}},$$

where the mediating effect captures the effect of fuel treatments on fire size through its influence on suppression effort. Suppose that fuel treatments and suppression effort are q-substitutes, which implies $(dE_i^*/dF_i) < 0$ (Proposition 2). The mediating effect is then positive, capturing the increase in fire size as suppression effort shifts away from the fire. Now suppose that the total effect of fuel treatments is negative. Then it must be because the direct effect of fuel treatments is also negative, enough so to overcome the positive mediating effect of fuel treatments. In other words, a negative total effect of fuel treatments on fire size is a sufficient condition for a negative direct effect of fuel treatments on fire size, so long as fuel treatments and suppression effort are q-substitutes:

$$\frac{dS(E_i^*, F_i)}{dF_i} < 0 \quad \text{and} \quad \frac{dE_i^*}{dF_i} < 0 \implies \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0. \tag{2}$$

We can use the sufficient condition in (2) to test for the economic benefits of fuel treatments as follows. From Corollary 1, we know that fuel treatments and suppression effort are q-substitutes so long as fuel treatments reduce suppression costs: $(dE_i^*/dF_i) < 0 \iff (dC(E_i^*)/dF_i) < 0$. Thus, if the total effect of fuel treatments on fire size and suppression costs are both negative, then fuel treatments are economically beneficial:

$$\frac{dS(E_i^*, F_i)}{dF_i} < 0 \quad \text{and} \quad \frac{dC(E_i^*)}{dF_i} < 0 \implies \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0.$$

We can therefore test for the existence of economic benefits through the following null hypothesis:

$$H_o : \frac{dS(E_i^*, F_i)}{dF_i} \geq 0 \quad \text{or} \quad \frac{dC(E_i^*)}{dF_i} \geq 0; \quad H_a : \frac{\partial S(E_i^*, F_i)}{\partial F_i} < 0. \tag{3}$$

Rejecting the null implies that fuel treatments are economically beneficial.[18] Additionally, if the resource constraint is not binding, then fuel treatments will decrease total fire suppression costs (Corollary 4) without increasing the size of fires. In this case, we can say that the effect of fuel treatments on suppression costs is a partial measure of their economic benefits.

To summarise, 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 in Equation 3. 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 on these results to quantify and test for the economic benefits of fuel treatments and compare them with their implementation costs.

## 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 and time of year but are exposed to different amounts of fuel treatments within a certain radius of their ignition location (Figure 2a). Such comparisons, however, may be subject to bias as fuel treatments and fire suppression effort are jointly determined via socioeconomic and environmental factors. For example, one of the main

[18] Note that failing to reject the null does not imply fuel treatments are not economically beneficial, as the sufficient condition in (2) is not a necessary condition. Thus, this is a conservative test for the existence of economic benefits from fuel treatments.

goals of implementing fuel treatments is to protect communities most at risk from wildfires. Hence, fuel treatments are typically located closer to homes in the WUI. At the same time, wildfire suppression effort, and thus costs, are disproportionately higher for fires that threaten homes (Bayham and Yoder, 2020; Baylis and Boomhower, 2023; Plantinga *et al.*, 2022). Additionally, the costs of conducting fuel treatments correlate with topographic (e.g., lower slopes and elevations), vegetation characteristics (e.g., fuel 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.[19]

## 4.1 Data

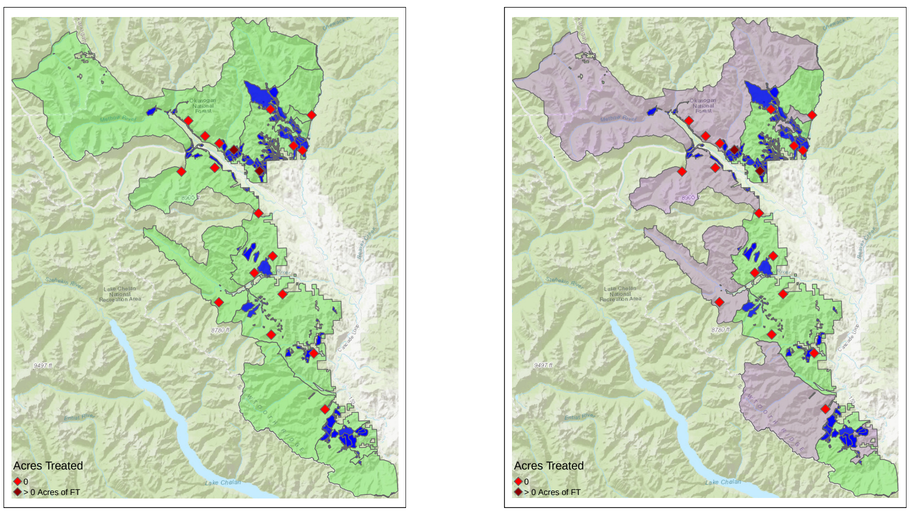
We construct a dataset that combines administrative data of NWFP land use allocations with fuel treatment and wildfire outcomes in the Pacific Northwest from 2006-2023. Our data come from various sources with varying degrees of spatial and temporal coverage. A summary of the main data sources for wildfire costs, fuel treatments, NWFP land use allocations, and the name, source, and description of all control variables used in our analysis are provided in Tables A2 and A3.

Information on the cost, size, date, and ignition location of wildfires comes from two sources spanning different periods. The National Fire and Aviation Management Web Applications (FAMWEB, 2023) comprises wildfires igniting from 2006-2014. Since the FAMWEB collection system was discontinued in 2014, we rely on data from the National Interagency

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

Figure 2: Baseline and IV identification strategies

(a) Baseline (b) Instrumental Variables




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

Fire Center's "Wildland Fire Incident Locations" for 2015-2023 (NIFC, 2024b).[20] For each fire, we obtain environmental and socio-economic determinants of wildfire behaviour 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 (2013), along with weather conditions (e.g., temperature, precipitation, wind speed, and vapour pressure deficit) at the time of ignition from PRISM (2014) and GridMET (Abatzoglou, 2013). 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-kilometre radius (Radeloff *et al.*, 2022; USFS, 2023). Lastly, we include localised measures of terrain ruggedness, accessibility, and management intensity by calculating the mean elevation, average slope, total Forest Service road length, and nearby timber harvest activity within a 100-acre circle surrounding each fire's ignition point.

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

[20]Systematic reporting in NIFC began only after the discontinuation of FAMWEB, and the dataset is extremely sparse prior to 2015 (fewer than 70 fires are recorded before 2014). Both datasets originate from the same interagency fire reporting systems and share consistent variable definitions following harmonisation.

our attention to the effectiveness of mechanical and prescribed burning fuel treatments since they are the types of treatment conducted by USFS and impacted by the NWFP reserves.[21]

Spatial data on NWFP LSRs and Matrix areas come from the Regional Ecosystem Office (REO), which provides the location of these reserves across the Pacific Northwest (REO, 2013). The REO dataset has the precise location of LSRs. Matrix areas are grouped in the "Other" category, overlapping with Riparian Reserves.[22] We broaden our definition of Matrix to include other NWFP designations with similar management protocols, such as "Adaptive Management Areas."[23] Throughout the rest of this paper, we refer to Matrix areas as being inclusive of Adaptive Management Areas and Riparian Reserves within Matrix areas from the NWFP.

Our sample is inclusive of small fires to capture the impact of fuel treatments on reducing the costs of initial attack efforts or preventing small fires from becoming large. Because small fire suppression costs are not systematically recorded, our sample contains many "zero-cost" fires, most of which are successfully suppressed through initial attack.[24] Our analysis is robust to alternative inclusions and treatments of zero-cost fires, described in Section 5.2.

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

[21] We identify relevant treatments using the `CAT_NM` (category name) and `TREATMENT_TYPE` fields in the FACTS database. Specifically, we include treatments classified as either "Mechanical" or "Fire" under `CAT_NM`. These categories contain treatments of the following `TREATMENT_TYPE`s: "Thinning," "Machine Pile," "Machine Pile Burn," "Biomass Removal," "Crushing," "Lop and Scatter," "Chipping," "Broadcast Burn," "Jackpot Burn," and "Mastication/Mowing."

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

[23] See Section A2 and Table A1 in the Supplemental Appendix for a list and description of all the land-use categories from the NWFP.

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

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 privatised lower-elevation forests (Johnson *et al.*, 2023). To focus on the impact of NWFP reserves, we further restrict our sample to fires that ignite inside the NWFP boundary. In a less restrictive sample, we also include fires that ignite within any of the 17 National Forests that are a part of the NWFP. This sample is less restrictive since some National Forests only lie partly within the NWFP boundary.

As NWFP LSRs and Matrix areas lie outside wilderness areas, we restrict our sample to fires igniting outside wilderness areas or national parks in all our samples.[25] Restricting our sample to fires that ignite within non-wilderness portions of national forests is essential because fire behaviour and suppression strategies are systematically different in wilderness areas (Gebert *et al.*, 2007). Lastly, we remove fires igniting in "wet" National Forests that are at little risk of wildfire and where fuel treatments are not a management priority.[26]

These filtering steps ensure that our sample focuses on fires igniting within either LSRs or Matrix areas on USFS land—i.e., areas that are most comparable, as both types of land would have faced similar protection (or lack thereof) under alternative NWFP plans. In total, our main sample includes 9,797 fires from 2006-2023 where $4.64 billion USD was spent on fire suppression, the majority of which occurred during the second half of the sample period (Figure 1c).[27] Table 1 provides a summary of our fuel treatment and fire cost

[25] 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).
[26] Specifically, we remove 188 fires igniting in Olympic or Siuslaw National Forests. The extent of Matrix & LSR lands within each of the 15 national forests in our sample is depicted in Figure A3.
[27] For reference, the USFS spent $30.5 billion in fire suppression costs over the same time period, with $38.1 billion across all federal agencies (NIFC, 2024a).

data. Consistent with qualitative accounts, fuel treatment costs are markedly lower than suppression costs, with only $279 million spent on all fuel treatments in Matrix and LSRs over this period.[28] Matrix and LSR areas, collectively, represent 93% of treated acres and 67% of suppression costs within the NWFP region on USFS land (see Table A4).

Table 1: Fuel treatments and wildfires: Descriptive statistics

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

*Note:* The first three columns present size and cost statistics for Prescribed Fire, Mechanical, and Total Fuel Treatments conducted in Matrix and LSR areas on USFS lands within the NWFP area. The unit of observation is a project, which may include multiple activities, such as prescribed fire, mechanical treatments, or both. A project appears in the Prescribed Fire (Mechanical) column if it includes at least one prescribed fire (mechanical) activity, with only the cost and acreage associated with those activity types reported in the corresponding column. In contrast, the Total Fuel Treatments column sums all treatment activities within the project—regardless of type. Note that cost data from the FACTS database should be interpreted with caution, as it lacks systematic reporting standards (Loomis *et al.*, 2019). For example, mechanical treatments may omit revenues from timber sales or may be recorded with zero cost depending on reporting practices. The fourth column presents size and cost statistics for wildfires that ignited in Matrix and LSR areas on USFS lands in the NWFP area.

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

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

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).[29]

## 4.2 Baseline estimation strategy

Following Baylis and Boomhower (2023), we start with the following fixed-effects specification using individual fire ignitions as the unit of analysis:[30]

$$Y_{ift} = \phi \log(FT_{it}) + X_{it}'\beta + \mu_f + \lambda_t + \epsilon_{ift}, \tag{4}$$

where $Y_{ift}$ is the natural log of the cost (or size) of fire $i$, that starts in national forest $f$, in month-of-sample $t$. Our parameter of interest is $\phi$, which represents the percentage difference in suppression costs (or size) associated with a one-percent difference in the acres of fuel treatments occurring within a certain distance of fire $i$, $FT_{it}$.[31]

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.[32] Taking the sum of both mechanical and prescribed fire fuel treatments

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

[30] A potential concern with using fires as the unit of analysis is sample selection bias: if fuel treatments are effective, they may prevent fires from igniting. However, there is little empirical evidence that fuel treatments influence ignition probability, as fuel treatments are designed to alter fire behaviour once ignition occurs—not to prevent ignitions, which primarily depend on weather conditions or human activity (Reinhardt *et al.*, 2008). We acknowledge this as a possibility and note that, if present, our results would be biased toward zero by excluding the most effective fuel treatments.

[31] We model the relationship between fuel treatments and fire size/cost as a log-log specification to be consistent with the fire ecology literature that shows the fuel treatment effectiveness is non-linear and exhibits diminishing returns to scale (Ott *et al.*, 2023). To account for the fact that many fires have zero cost or zero acres of fuel treatment close to the fire, we take the $\log(x + 1)$ transformation of suppression costs and fuel treatments. We discuss alternative ways of dealing with fires with zero costs or zero fuel treatments in Section 5.2.

[32] We choose ten years to be the cutoff for counting fuel treatments as previous studies have shown that fuel treatment effectiveness is diminished after 9–14 years (Collins *et al.*, 2009; Lydersen *et al.*, 2014). We explore the sensitivity of our estimates to different distances and time-since-fire in Section A6. Because mechanical fuel treatments are often conducted in a series of treatments that are followed up by a prescribed

recognises that fuel treatments incorporating both mechanical and prescribed fire treatments are considered best practice for reducing wildfire severity (Wimberly *et al.*, 2009; Prichard and Kennedy, 2014). Figure 3 provides an example of how we calculate fuel treatments for a particular fire. Using this definition of fuel treatments, 17.3% of the fires in our sample ignite near a fuel treatment.

We calculate the acres of fuel treatment near a fire's ignition point rather than those that intersect the fire's eventual footprint for several reasons. First, larger fires are mechanically more likely to intersect fuel treatments, regardless of whether treatments affected the fire's behaviour, creating a spurious correlation between fire size and exposure to fuel treatments. In contrast, measuring exposure near the ignition point better reflects the initial conditions a fire encountered when it started. Second, if fuel treatments serve as constructed fire lines and successfully stop the spread of a fire, then the fire will have little to no intersected area with those proximate treatments. Finally, perimeters of fires are only systematically recorded for large fires ($>$ 1000 acres), and hence any analysis using intersected areas would require restricting the sample to only large fires. 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.[33]

We include sets of socio-economic and environmental control variables, $X_{it}$, that influence a fire's size and its cost of suppression (Table A3). Environmental variables include

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.

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

topographic (e.g., slope, elevation, or aspect at ignition point), weather (e.g., temperature or vapour pressure deficit), vegetation (e.g., fuel type), and historic fire risk (e.g., mean fire return interval, a measure of how often an area typically burns) characteristics near the ignition point.[34] Socio-economic variables include the distance of a fire's ignition to the nearest WUI or Forest Service road. To account for the role of previous wildfires in influencing wildfire behaviour, we calculate the previous acres burned within the 100-acre circle surrounding an ignition point in the last 10 years.[35]

National forest fixed effects, $\mu_f$, control for time-invariant unobserved determinants of firefighting costs that are specific to a national forest. Year-month fixed effects, $\lambda_t$, control for unobserved changes in firefighting resources, conditions, and costs over time that are constant across national forests, as evident from the substantial year-to-year variation in suppression costs (Figure 1c). We cluster standard errors at the national forest level.[36]

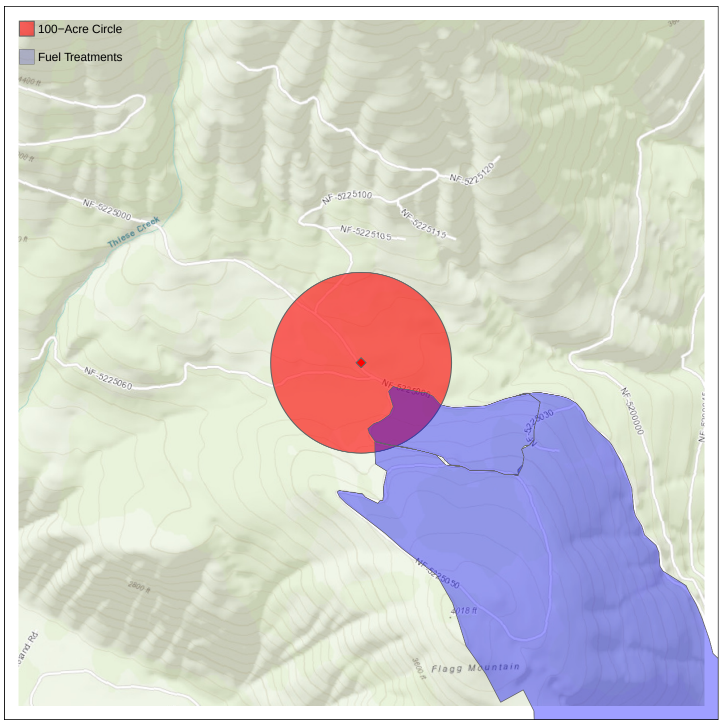
The identifying assumption in our baseline regression analysis is that unobserved determinants of fire cost and size, $\epsilon_{ift}$, are independent of $FT_{it}$, conditional on national-forest fixed effects and our other controls. Because both fuel treatments and fire suppression effort are jointly determined via socio-economic and environmental factors, we may expect estimates of $\phi$ 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,

[34] We do not control for vegetation characteristics that are influenced by fuel treatments in our sample, such as fuel load conditions at the time of fire, as this would condition on one of the mechanisms through which fuel treatments influence our outcomes of interest. Instead, we calculate all vegetation characteristics, like canopy base height, based on their 2001 levels so that they represent pre-treatment vegetation characteristics. See Table A3 in the Online Appendix for more details on such variables.

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

[36] Our primary estimates are robust to wild-cluster bootstrap inference, which yields nearly identical p-values to conventional cluster-robust inference (see footnote 41). We also find that our results remain robust when clustering standard errors at the Ranger District level (59 clusters) instead of the national forest level (15 clusters), mitigating concerns about the small number of clusters for cluster-robust inference (Table A11).

Figure 3: Example construction of $FT_{it}$ for the Flagg Mountain Fire (2020)




*Notes:* The above map visually demonstrates how $FT_{it}$ is calculated for a particular fire, the Flagg Mountain Fire, a 0.1 acre fire that occurred close to Mazama, WA, in 2020. The red star shows the ignition point location, and the red circle is the area in which fuel treatments are to be calculated (in this case, 100 acres surrounding the ignition point). The blue polygons indicate the locations of fuel treatments within this buffer. In this example, 10 acres of treatment footprint fall within the buffer. Within those 10 acres, there are three treatment activities: a mechanical thin in 2015, a machine pile in 2016, and a pile burn in 2019. Because our fuel treatment variable is defined as the sum of acres treated mechanically (no double-counting across years) plus the acres treated with prescribed fire, $FT_{it}$ for this fire equals 20 acres.

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.[37] Since we 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 and environmental factors that influence wildfire behaviour, $X_{it}$, confirms that fuel treatments highly correlate with such factors (Table 2). Specifically, fires that ignite closer to fuel treatments are, on average, closer in proximity to the WUI, housing units, and wealthier neighbourhoods. 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 address endogeneity concerns, we use spatial variation in late-successional reserves (LSRs) established under the NWFP within National Forests as an instrument for the extent of fuel treatment activity near a fire. The intuition behind this strategy is to compare fires igniting within the same National Forest during the same time of year but under different land designations—those igniting within LSRs (protected) versus those in Matrix (unprotected) areas (Figure 2b).

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

Table 2: Balance test regressions

**Economic Variables**

| | Distance to WUI (km) | Distance to FS Road (km) | Total Housing Value ($100,000s) | Population (persons) | No. Housing Units |
|---|---|---|---|---|---|
| $\log(FT_{it})$ | -0.531*** | -0.070*** | 43.351** | 164.677** | 94.791*** |
| | (0.084) | (0.013) | (17.929) | (61.759) | (29.990) |
| $LSR_i$ | 0.890* | 0.108 | -9.819 | -83.635 | -34.170 |
| | (0.460) | (0.063) | (20.522) | (122.272) | (65.423) |
| N | 9923 | | | | |

**Topography & Weather**

| | Slope (%) | Elevation (ft) | South Slope (0/1) | Wind Speed (m/s) | Energy Release Component |
|---|---|---|---|---|---|
| $\log(FT_{it})$ | -0.888*** | -39.930*** | 0.003 | 0.016 | 0.188 |
| | (0.181) | (7.615) | (0.006) | (0.011) | (0.141) |
| $LSR_i$ | 2.673*** | 41.181 | 0.015 | -0.032 | -0.548 |
| | (0.347) | (49.107) | (0.010) | (0.033) | (0.439) |
| N | 9923 | | | | |

**Historic Fire Risk Variables**

| | Mean Fire Return Interval (years) | Avg. 30-yr Precipitation (mm) | Avg. 30-yr Temperature (°C) | Max. 30-yr Temperature (°C) | Max. 30-yr Vapor Pressure Deficit (kPa) |
|---|---|---|---|---|---|
| $\log(FT_{it})$ | -0.343* | -0.462*** | 0.159*** | 0.266*** | 0.521*** |
| | (0.163) | (0.132) | (0.025) | (0.028) | (0.058) |
| $LSR_i$ | -0.138 | 0.529 | -0.219 | -0.484 | -1.375** |
| | (0.837) | (0.500) | (0.229) | (0.290) | (0.582) |
| N | 9923 | | | | |

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

*Notes:* This table reports the results of 30 separate regressions in which each economic, environmental, or fire risk covariate is regressed on either an indicator for whether the fire occurred within a late-successional reserve, $LSR_i$, or the natural log of fuel treatment acres at the ignition location, $\log(FT_{it})$. All regressions include National Forest and year-month fixed effects. The sample includes wildfires igniting inside Matrix and LSR lands within 15 National Forests comprising the NWFP (2006–2023). Economic variables are distance to the nearest wildland-urban interface (WUI) census block (km), distance to the nearest USFS road (km), and the total housing value ($100,000s), population (persons), and housing units within 10km of the ignition point. Topographic variables are the slope (%) and elevation (ft) at a fire's ignition point, and a dummy variable equal to one if the ignition point is on a south-facing slope aspect. Weather variables include the wind speed (m/s) and energy release component (ERC, unitless) on the day and point of ignition. Historic fire risk control variables include mean fire return interval (MFRI, yr) and the 30-year climate normals in August for precipitation (mm), temperature mean (°C), temperature max (°C), and max vapour pressure deficit (VPD, kPa) at the ignition point for a given fire. Standard errors are clustered at the national forest level.

As we discuss in Section 2, LSRs have inadvertently restricted fuel treatment activities due to the conservation-focused management constraints they impose. Consequently, we hypothesise that fires igniting within LSRs are surrounded by less extensive fuel treatments near their ignition points compared to those in Matrix lands. This variation in fuel treatments can be considered exogenous due to the idiosyncratic processes involved in delineating LSR and Matrix areas. While LSR boundaries were primarily motivated by ecological criteria, such as the nesting, foraging, and dispersal needs of the NSO, substantial portions of NSO critical habitat were left unprotected due to limited ecological understanding of the NSO at the time of designation (Gaines *et al.*, 2010; Johnson *et al.*, 2023). Indeed, most fires in our sample occur in dry forests, where scientists have noted the arbitrary ecological distinctions between LSRs and Matrix areas (Spies *et al.*, 2019). For this reason, LSR designations are unlikely to correlate with unobserved factors influencing wildfire behaviour, reinforcing the plausibility of our instrument.

More formally, our instrument is a binary variable equal to one if a fire ignites inside an LSR and zero otherwise.[38] Denoting our instrument as $LSR_i$, the first-stage equation relating fuel treatments and fires igniting in an LSR is:

$$\log(FT_{it}) = \delta LSR_i + X'_{ift}\Pi + \mu_f + \lambda_t + u_{ift}, \quad (5)$$

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

$$Y_{ift} = \eta LSR_i + X'_{ift}\Gamma + \mu_f + \lambda_t + v_{ift}. \quad (6)$$

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

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

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

## 4.4 Threats to identification

The identifying assumptions underlying our IV approach are i) relevance: $LSR_i$ has a strong correlation with fuel treatments; ii) independence: $LSR_i$ is (conditionally) uncorrelated with the unobservable determinants of fire size and suppression costs; iii) exclusion: LSR status has (conditionally) no direct impact on fire size and suppression costs; and iv) monotonicity:

LSR status should only reduce a fire's exposure to fuel treatments within LSRs or have no effect.

Our instrument would violate the first assumption if LSR status did not substantially hinder the Forest Service's ability to conduct fuel treatments. We confirm this assumption below by directly estimating Equation 5, finding a strong first-stage relationship between fuel treatments and a fire's LSR status.

Violations of the independence assumption could arise if LSR designations are correlated with factors other than fuel treatments that influence suppression costs—such as proximity to assets at risk, inherent wildfire risk, or differences in terrain and accessibility. We examine this possibility by regressing $LSR_i$ on the observable determinants of fire size and suppression costs with the inclusion of National Forest and year-month fixed effects. We find $LSR_i$ is generally balanced across observable characteristics and is a considerable improvement over $\log(FT_{it})$ (Table 2). We also conduct a series of falsification tests, discussed extensively in Section 5.1, to address remaining concerns that unobserved landscape features influencing suppression costs may also be related to a fire's LSR status.

Potential threats to the exclusion restriction include differences in forest management practices between Matrix and LSR areas, such as timber harvest activity or land-use restrictions that affect fire accessibility, which could affect suppression costs independently of fuel treatments. To address the first concern, we include controls for nearby timber harvests that are not categorised as fuel treatments. We calculate the acres of nearby timber harvests occurring within the 100-acre circle surrounding a fire's ignition point using the FACTS Timber Harvest database. While a fire's LSR status and timber harvests are negatively correlated ($p = 0.003$), the occurrence of nearby timber harvests is uncommon in our sample—only

5.9% of fires occur near any recorded harvest. Notably, nearby timber harvests have no predictive power for suppression costs, and their inclusion does not materially affect our estimates. To address the second concern, we conduct additional falsification tests, discussed in Section 5.1, to assess whether other land-use practices indirectly influence suppression costs through unobserved channels.

Finally, a remaining concern is that either suppression effort or treatment intensity within LSRs could differ systematically due to the presence of NSO habitat. If managers prioritised protecting old-growth forests or NSO habitat, they might devote more suppression effort to fires in LSRs, violating the exclusion restriction. Likewise, the monotonicity assumption would fail if the Forest Service conducted additional fuel treatments within LSRs to protect the NSO, contrary to our assumption that LSR status weakly decreases treatment exposure. Both possibilities appear unlikely. The Forest Service's fire management policies explicitly prioritise the protection of human life and structures over natural resources (USFS, 2000), and prior research finds no evidence of elevated suppression effort in ESA or sensitive habitat areas (Plantinga *et al.*, 2022). Similarly, agency guidance emphasizes minimizing the potential harm of fuel treatments to NSO habitat and other late-successional ecosystems (USFWS, 2008), consistent with the monotonicity assumption and our empirical findings.

# 5 The effect of fuel treatments on fire size and suppression costs

The first-stage estimate of the relationship between fuel treatments and a fire's LSR status indicates that, on average, fires igniting within LSRs have 11.3 percent fewer treated acres

(–0.120 log points; $p = 0.0001$) within 100 acres of their ignition point than fires igniting in Matrix areas (Table 3, column 1).[39] The Kleibergen–Paap F-statistic of 28.49 confirms that LSR status is a strong and relevant instrument. The reduced-form estimates reveal that, on average, fires igniting within LSRs are 6.6 percent larger (0.068 log points; $p = 0.24$) and 13.1 percent more expensive to suppress (0.141 log points; $p = 0.004$) than fires in Matrix areas (Table 3, columns 3 and 5). Taken together, these estimates imply that a one-percent increase in treated acreage within 100 acres of a fire's ignition reduces suppression costs by 0.96 percent (–1.17 log points; $p = 0.020$) and fire size by 0.46 percent (–0.56 log points; $p = 0.28$), on average (Table 4, columns 1 and 5).[40] These IV estimates are larger in magnitude than the corresponding fixed-effects OLS estimates (Table 4, columns 3 and 7), consistent with attenuation bias from endogenous treatment placement.

The IV estimate for suppression costs implies that fuel treatments and suppression effort are q-substitutes—that is, fire managers allocate less suppression effort to fires in close proximity to fuel treatments. This aligns with qualitative evidence suggesting that fuel treatments improve the effectiveness of hand crews conducting direct or indirect attacks, thereby reducing reliance on more costly aerial operations (Romero and Menakis, 2013). While this substitution lowers suppression costs, it can offset any direct reduction in fire size. Hence, fuel treatments are not guaranteed to shrink a fire's footprint, confirming insights from our conceptual model that fire size is an imperfect proxy for economic damages when evaluating the impact of treatments.

[39] Because we apply $\log(Y+1)$ and $\log(X+1)$ transformations in the cost regressions, we compute elasticities as $\epsilon_{xy} = \beta \cdot \frac{X}{X+1} \frac{Y+1}{Y}$, evaluated at sample means of $X$ and $Y$. For specifications with $\log(Y)$ and $\log(X+1)$ (e.g., fire size), the elasticity simplifies to $\epsilon_{xy} = \beta \cdot \frac{X}{X+1}$.

[40] To address concerns about the limited number of clusters (15 National Forests), we compute wild-cluster bootstrap p-values of 0.001 and 0.26 for suppression costs and fire size, respectively, using the `cluster.wild.ivreg` function from the `clusterSEs` R package. The bootstrapped p-values are very similar to conventional cluster-robust inference across all models in Tables 3 and 4.

Table 3: IV first-stage and reduced-form regression results

| | *First Stage* | | *Reduced Form* | | | |
|---|---|---|---|---|---|---|
| | $\log(FT_{it})$ | | $\log(Size_{it})$ | | $\log(Cost_{it})$ | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| $LSR_i$ | -0.120*** | -0.120*** | 0.068 | 0.047 | 0.141*** | 0.128*** |
| | (0.023) | (0.028) | (0.056) | (0.056) | (0.042) | (0.040) |
| No. Fires (×100) | | -0.006 | | 0.161*** | | 0.179*** |
| | | (0.025) | | (0.040) | | (0.050) |
| No. Fires FT > 0 | | -0.005 | | 0.014 | | 0.002 |
| | | (0.004) | | (0.011) | | (0.015) |
| 1st Stage F-Stat | 28.49 | 18.05 | | | | |
| $R^2$ | 0.20 | 0.20 | 0.19 | 0.19 | 0.69 | 0.73 |
| N | 9,797 | 8,297 | 9,797 | 8,297 | 9,797 | 8,297 |

∗ p < 0.1, ∗∗ p < 0.05, ∗ ∗ ∗ p < 0.01

*Notes:* The table reports the estimates of six separate regressions for the first-stage and reduced-form relationships in Equations 5 and 6. Columns (1) – (2) present the first-stage relationship between the natural log of fuel treatments, $\log(FT_{it})$, and an indicator of whether a fire occurs within a late-successional reserve, $LSR_i$. Columns (3) – (6) present the reduced-form relationships between the natural log of fire size, $\log(Size_{it})$, or suppression costs, $\log(Cost_{it})$, and $LSR_i$. Columns (1), (3), and (5) use the full sample of fires (2006–2023) across Matrix and LSR areas within the Northwest Forest Plan (NWFP) region. Columns (2), (4), and (6) restrict the sample to 2006–2020, the period for which ignition times and locations are comprehensively recorded in Short (2023). No. Fires (× 100) measures the number of contemporaneous fires (100s) in the same state, relative to the state-week average between 2000 and 2020. No. Fires FT > 0 counts the number of contemporaneous fires in the same state that have a fuel treatment within 100-acres of their ignition. Each regression includes a suite of additional economic and environmental control variables, described in Table A3. National Forest fixed effects include the 15 national forests comprising the NWFP. Standard errors are clustered at the national forest level. The first-stage Kleibergen-Paap F-statistic is calculated via cluster-robust standard errors using the `fixest` package in R (Laurent, 2018).

Table 4: IV and OLS regression results

| | $\log(Size_{it})$ | | | | $\log(Cost_{it})$ | | | |
|---|---|---|---|---|---|---|---|---|
| | IV | | OLS | | IV | | OLS | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| $\log(FT_{it})$ | -0.561 | -0.387 | -0.021 | -0.031 | -1.172** | -1.068** | 0.008 | -0.007 |
| | (0.502) | (0.502) | (0.020) | (0.019) | (0.450) | (0.483) | (0.029) | (0.021) |
| No. Fires (× 100) | | 0.159*** | | 0.162*** | | 0.172*** | | 0.179*** |
| | | (0.038) | | (0.040) | | (0.040) | | (0.051) |
| No. Fires FT > 0 | | 0.012 | | 0.014 | | -0.003 | | 0.002 |
| | | (0.011) | | (0.011) | | (0.015) | | (0.015) |
| 1st Stage F-Stat | 28.49 | 18.05 | | | 28.49 | 18.05 | | |
| $R^2$ | 0.13 | 0.16 | 0.19 | 0.19 | 0.62 | 0.67 | 0.69 | 0.73 |
| N | 9,797 | 8,297 | 9,797 | 8,297 | 9,797 | 8,297 | 9,797 | 8,297 |

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

*Notes:* The table reports the results of eight separate regressions for the IV and OLS estimates of the relationship between the natural log of fire size, $\log(Size_{it})$, or suppression costs, $\log(Costs_{it})$, and the natural log of of fuel treatments, $\log(FT_{it})$. Columns (1) – (2) and (5) – (6) present the IV regressions using an indicator for whether a fire occurs within a late-successional reserve, $LSR_i$, as an instrument for fuel treatments. Columns (3) – (4) and (7) – (8) show the corresponding OLS estimates. Columns (1), (3), (5), and (7) use the full sample of fires (2006–2023) across Matrix and LSR areas within the Northwest Forest Plan (NWFP) region. Columns (2), (4), (6), and (8) restrict the sample to 2006–2020, the period for which ignition times and locations are comprehensively recorded in Short (2023). No. Fires (× 100) measures the number of contemporaneous fires (100s) in the same state, relative to the state-week average (2000-2020). No. Fires FT > 0 counts the number of contemporaneous fires in the same state that have a fuel treatment within 100 acres of their ignition. Each regression includes a suite of economic and environmental control variables, described in Table A3. National Forest fixed effects include the 15 national forests comprising the NWFP. Standard errors are clustered at the national forest level. The first-stage Kleibergen-Paap F-statistic is calculated via cluster robust-standard errors using the `fixest` package in R (Laurent, 2018).

Following from our conceptual model, a negative direct effect of fuel treatments on fire size is a sufficient condition for the economic benefits of fuel treatments. While the direct effect cannot be empirically identified, we test for its existence indirectly by testing the null hypothesis that the effects of fuel treatments on fire size *or* cost are weakly positive. We find strong evidence to reject the null hypothesis ($p = 0.0001$) using an intersection-union hypothesis test (Casella and Berger, 2002).[41] This result supports the conclusion that fuel treatments are economically beneficial in our setting.

[41] The intersection-union hypothesis test considers the overall null hypothesis of the union of several individual null hypotheses, as we have here, to be true if at least one of the individual null hypotheses is true. Thus, to reject the overall null hypothesis, we must reject both of the individual null hypotheses. We test the overall null hypothesis using a bootstrap procedure described in detail in Section A5 in the Supplemental Appendix.

Our conceptual model also highlights the challenge of interpreting results when fire suppression resources are scarce. Under a binding resource constraint, effort may be disproportionately allocated away from fires with fuel treatments toward those without if effort and fuel treatments are q-substitutes. Such spillovers have two implications. First, they would violate SUTVA, resulting in an overestimation (underestimation) of the magnitude of fuel treatments' effect on fire suppression costs (fire size). Second, they would imply that reductions in suppression costs from nearby fuel treatments are not necessarily an accurate measure of the economic benefits of fuel treatments (Corollary 3).

To evaluate these possibilities, we re-estimate the first-stage, reduced-form, and structural equations, adding controls for potential spillovers and resource scarcity (Tables 3 and 4). First, we control for the number of concurrent fires within close proximity to fuel treatments ($FT_{it} > 0$) to capture potential spillover effects. Under q-substitutability, we expect this variable to be positively associated with suppression costs and negatively with fire size as resources shift toward other fires.[42] Second, we measure state-level resource scarcity as the difference between the weekly average number of fires in a state (2000–2020) and the observed number of fires during the week of a fire's ignition, capturing deviations from typical suppression resource availability (Gebert *et al.*, 2007).[43]

The IV estimates do not change meaningfully with the inclusion of controls for potential spillovers and resource scarcity (Table 4, columns 2 and 6). We find no evidence that spillovers from other treated fires affect fire size ($p = 0.28$) or suppression costs ($p = 0.83$). In contrast, the positive and significant effect of the number of concurrent fires on fire size ($p$

[42] Implicitly, we are assuming that fires are exchangeable and linear in their spillover effects on other fires so that a fire's potential size and cost only depend on the number of other treated fires (Vazquez-Bare, 2023).

[43] Because our main dataset lacks containment dates, we supplement it with the USFS wildfire ignition dataset (Short, 2023), which includes containment information through 2020, reducing the sample from 9,797 to 8,297 fires.

= 0.0008) and suppression costs ($p$ = 0.0006) indicates that resource scarcity may influence fire suppression outcomes. However, the magnitude of this effect is small: each additional concurrent fire (above a state's weekly average) increases fire size and suppression costs by only 0.16% and 0.17%, respectively. This effect likely reflects variation in general fire conditions within a state that is not fully captured by our fixed effects or other controls. Overall, we find limited evidence that resource constraints materially distort suppression effort allocation.[44] Hence, the estimated reduction in suppression costs due to fuel treatments remains a credible partial measure of their economic benefits, which we quantify below.

## 5.1 Falsification tests

To assess the validity of our instrumental variable, we implement a set of falsification tests following the framework of Danieli *et al.* (2023). These tests evaluate whether our instrument, a fire's LSR status, is correlated with unobserved factors that also affect suppression costs, thereby violating the independence or exclusion restriction assumptions.

We begin with falsification tests that assess whether unobserved factors known to influence suppression costs also determine a fire's LSR status (Figure A5, Panel A). For example, LSRs may be systematically located in areas where fires are inherently more difficult or expensive to suppress, due to rugged terrain, poor accessibility, or heavier fuel loads, thereby violating the independence assumption. Negative control outcome (NCO) tests detect such violations by identifying variables correlated with these unobserved factors but without a direct relationship to a fire's LSR status. A significant correlation between our instrument

[44] As further evidence, the addition of state-year-month fixed effects, which approximate the scale at which suppression resources are managed, also does not attenuate the estimated first-stage, reduced-form, or IV estimates for suppression costs (Table A11).

and the NCO variable would therefore indicate the existence of an alternative path between suppression costs and LSR status, undermining the validity of LSR as an instrument.

We consider two NCO tests. First, we estimate the reduced-form relationship between suppression costs and LSR status using fires that ignited on USFS land between 1980 and 1994, before the creation of the NWFP. Suppression costs for pre-NWFP fires should not depend on whether they occurred in areas later designated as LSRs. A significant correlation would suggest that LSR placement is correlated with unobserved features of the landscape that also affect suppression costs.[45] We find no such relationship (Table A6, column 1). Moreover, an event-study version of the reduced-form relationship using fires before and after 1994 shows that suppression costs in LSR and Matrix areas did not diverge until several years after the NWFP, consistent with the timing of restrictions on fuel treatments (Figure A4).

Second, we estimate the relationship between a fire's LSR status and its detection time—defined as the number of days between a fire's ignition and discovery. Intuitively, detection time should not depend on LSR status unless LSRs were located in more remote or difficult-to-access areas, which tend to have longer detection delays.[46] Using data on detection times for a subset of fires in our sample, we find no systematic difference in detection times between fires in LSR and Matrix areas (Table A6, column 2). Together, these NCO tests suggest that LSRs were not systematically placed in locations where suppression would have been inherently more costly.

[45]This falsification test is akin to a "zero-first-stage" test, in which the reduced-form equation is estimated on a subsample for which the first-stage effect is zero (Van Kippersluis and Rietveld, 2018).

[46]Detection time measures the number of days between the estimated ignition and when the fire was first detected (i.e., observed or recorded). For lightning-ignited fires, ignition times are inferred from lightning-detection networks, and detection occurs once the fire becomes visible to observers or sensors ("holdover" fires; Moris *et al.*, 2023). Although modern technologies have reduced detection time, there is considerable variation in our subsample of 5,074 fires that report both ignition and detection dates: mean = 1.9 days, SD = 15.1.

We then turn to falsification tests that assess whether unobserved factors known to be influenced by a fire's LSR status also determine suppression costs (Figure A5, Panel B). For example, land-use restrictions in LSR areas may increase the difficulty and cost of suppression by limiting road construction and maintenance, thereby violating the exclusion restriction. Negative control instrument (NCI) tests help detect such violations by identifying variables that are correlated with these unobserved factors but should not directly influence suppression costs. A correlation between suppression costs and an NCI variable would therefore indicate that LSRs are associated with unobserved confounding factors that affect suppression costs.

We consider two NCI tests. First, we test whether USFS grazing allotments and mineral rights near a fire's ignition are correlated with suppression costs. The amount of grazing or mineral-right allotments near a fire's ignition should depend on land-use restrictions in LSR areas, but should not be related to a fire's suppression costs unless LSR designation alters accessibility in ways that also raise suppression costs. Using data on USFS grazing allotments and mineral rights within 100 acres of fire ignitions, we find that fires igniting in LSRs are considerably less likely to be near such land uses, consistent with LSRs restricting land-use activity. However, neither variable explains suppression costs (Table A6, column 3).[47]

Second, we test whether LSR areas farther from a fire's ignition are correlated with suppression costs. Distant LSR areas are too far away to plausibly influence suppression costs through local fuel-treatment activity. However, if LSRs were placed in more remote or rugged

[47]This result is consistent with evidence that long-term budget constraints within the USFS have limited the overall scope of road maintenance, decommissioning, and other land-use activities on national forests, reducing their relevance for explaining contemporary suppression costs. For example, road activity and maintenance accounts for a large share of deferred maintenance reported by the USFS and other federal land agencies (U.S. Government Accountability Office (GAO), 2024).

terrain, or if their land-use restrictions reduce access to fires, then these distant LSR areas could still predict suppression costs, even after controlling for nearby LSRs. Using measures of LSR acreage located within different distances from a fire's ignition point (100-500, 500-1,000, and 1,000-1,500 acres), we find no measurable effect of distant LSR designations on suppression costs after controlling for LSR acreage within 100 acres (Table A7).

Taken together, these falsification tests provide suggestive evidence that the identifying variation induced by our instrument operates through local fuel-treatment exposure rather than alternative channels that could violate the independence or exclusion restriction assumptions.

Finally, we complement these falsification tests with a sensitivity analysis using the plausibly exogenous framework of Conley *et al.* (2012), which quantifies how sensitive our IV estimates are to small violations of the exclusion restriction by allowing LSR status to have a direct effect, $\gamma$, on suppression costs. We compute confidence-interval bounds for the IV estimate across a grid of possible $\gamma$ values. Our estimates remain statistically distinguishable from zero at the 5% significance level for direct effects smaller than 0.034 log-points and at the 10% level for effects up to 0.058 log-points. Since the reduced-form effect of LSR on suppression costs is approximately 0.14 log points, this implies that our IV estimate would remain statistically different from zero at the 5% level even if up to 24.3% of the reduced-form effect were attributable to a direct effect of LSR on suppression costs. Thus, our IV estimates would still reject the null of no treatment effect, even under moderate violations of the exclusion restriction.

### 5.2 Robustness Checks

We conduct a variety of robustness checks to evaluate the sensitivity of our results to alternative variable definitions, specifications, and samples. Below, we discuss a subset of these robustness checks; a full description is provided in Section A6 of the Online Appendix.

To address concerns that Matrix and LSR areas may be systematically different, even after controlling for observable determinants of fire suppression efforts, we implement a matching procedure to improve comparability between fires igniting in Matrix and LSR areas. This approach relaxes the parametric assumptions of our regression framework and avoids extrapolation when covariate overlap is limited. Each fire igniting in an LSR is matched exactly to a Matrix fire that occurs in the same National Forest, fuel type, and month. Fires are then inexactly matched using a genetic search algorithm to optimise covariate balance across the primary determinants of fire suppression costs and size, including distance to WUI and USFS roads, elevation, slope, vapour pressure deficit, and wind speed (Sekhon, 2011; Diamond and Sekhon, 2013). This procedure results in 3,225 matches and 6,450 fires in total. The matched IV yields estimates for suppression costs (-1.329 log points, $p = 0.0023$) and fire size (-0.823 log points, $p = 0.0136$) that are similar in magnitude and statistical significance with our baseline results (Table A5). While the matching procedure provides the strongest internal validity for our estimates, we prefer the estimates resulting from our IV regression specification because its estimation sample more closely represents the landscape encompassed by the NWFP and is, therefore, more externally valid for our counterfactual cost-benefit estimates in Section 5.3.

We also explore how our IV estimates change when using different specifications of our endogenous regressor and instrument: i) a linear specification of $FT_{it}$, ii) an inverse hyperbolic sine transformation of $FT_{it}$, iii) calculating fuel treatments that occur within the last five (instead of 10) years, and iv) using a continuous measure of LSR, analogous to our measurement of fuel treatments (Table A10). Across all specifications, the IV estimates for suppression costs remain statistically significant at the 5% or 10 % level, while estimates for fire size remain statistically insignificant.[48]

We also examine the robustness of our IV estimates to three alternative dependent variable specifications: i) excluding zero-cost fires, ii) imputing the cost of zero-cost fires by the median cost of suppressing a small fire, and iii) indicators for above-median fire size or cost (Table A9). Excluding zero-cost fires yields IV estimates that remain negative but become less precisely estimated, reflecting the smaller sample size and the removal of fires in which fuel treatments may have prevented low-cost ignitions from escalating into costly events. This conditioning likely attenuates the estimated effect toward zero and weakens the first-stage relationship (F-statistic declines from 28.5 to 10.6). For imputation (ii), small zero-cost fires (<100 acres) are assigned the median cost of small non-zero-cost fires, assuming they represent low-cost initial attacks. Large zero-cost fires (>100 acres) are excluded

[48]The log-level specification implies an elasticity of –0.38 when evaluated at the sample mean of fuel treatments, which is smaller than the elasticity of –0.96 observed in the log–log model. This difference is unsurprising since the two models capture nonlinearities in the relationship between fuel treatments and suppression costs that could differ at any given point. As a robustness check, we conduct the benefit-cost analysis in Section 5.3 using the estimate from the log-level model and find larger benefit-cost ratios—ranging from 8 to 11 (Table A12)—than those resulting from the log-log model. We prefer the log–log specification because the first-stage relationship between fuel treatments and a fire's LSR status is considerably stronger when fuel treatments are measured in logs rather than levels.

due to potential misreporting of cost.[49] Imputed results show no change in signs or magnitudes. For above-median indicators (iii), we find that fuel treatments significantly reduce the probability of a fire exceeding the median cost, with no significant effect on fire size.

We further investigate whether our results are influenced by the inclusion of zero-cost fires in our sample, as these fires may be more likely to occur during periods of low risk and low consequence. Focusing on periods of heightened wildfire risk, we re-estimate our IV model using only those fires that ignite when maximum vapor pressure deficit (VPD) and wind speed are above their respective sample medians, thereby isolating fires with the greatest potential to escalate into costly events (Table A9).[50] In both cases, the estimated effect of fuel treatments on suppression costs remains negative and statistically significant (–1.89 log points for high VPD; –1.14 log points for high wind speed), consistent with fuel treatments being most effective in reducing suppression costs during periods of elevated fire risk and behaviour.

We report four additional robustness exercises in Section A6. First, we test the sensitivity of our results to the size of the treatment buffer around a fire's ignition (50–150 acres) and the age of a treatment, finding consistent results across specifications (Figures A7 and A8). Second, we implement a randomisation-inference procedure that reassigns LSR status 1,000 times to assess design-based uncertainty, confirming that our estimates are highly unlikely to arise by chance (Figure A9). Third, we explore the sensitivity of our IV estimates to alternative estimation samples, including: fires ignited by lightning, all fires igniting in national forests intersecting the NWFP, fires that are within 2km of a Matrix-LSR border, fires that

[49] Fifty-one fires meet this criterion.

[50] Both variables are widely recognized as key determinants of wildfire risk and behavior, capturing the joint influence of atmospheric dryness and wind-driven spread on fire intensity and suppression difficulty (Abatzoglou and Williams, 2016; Jolly *et al.*, 2015).

are not associated with a complex, and fires that do not ignite in "checkerboard" ownership patterns (Table A8). Overall, suppression cost estimates remain robust across samples, while fire size estimates exhibit less consistency. Finally, we re-estimate our IV models under alternative fixed-effect structures (e.g., ranger-district and state-year specifications), finding negligible changes in magnitude or significance (Table A11).

### 5.3 Counterfactual costs and benefits of fuel treatments

Our test of the sufficient condition in Equation 2 suggests that marginal increases in fuel treatments are economically beneficial, and that fire suppression costs serve as a valid, yet incomplete, proxy for their welfare gains. However, this test does not quantify the value of such marginal increases, nor does it assess the economic benefits that could result from large, non-marginal increases in fuel treatments that might follow from changes in wildfire prevention policies.[51] To quantify the economic benefits of fuel treatments, we estimate the counterfactual reduction in suppression costs that would have resulted from a landscape-wide expansion of fuel treatments during our sample period, relative to the associated costs of expanding fuel treatments.

Suppose that all fuel treatments during our sample period increased proportionately by one percent. We assume this leads to a corresponding one-percent increase in fuel treatment costs, equal to $2.79 million (Table 1).[52] Given a one-percent increase in all fuel treatments, we then calculate the increase in 100-acre fuel treatment intersections for each fire (see

[51] As highlighted by Chetty (2009), the use of sufficient conditions derived from the envelope theorem can only be used for welfare analysis of marginal policy changes from the status quo.

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

Figure A6 for a demonstration), and predict the associated counterfactual suppression cost savings using our IV estimate (Table 4, column 5).[53] 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 $16 million and 7,470 fewer acres burned, corresponding to a benefit-cost ratio of 5.75.

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. Expanding treatment activity could exhibit either increasing or decreasing returns: our empirical model implies diminishing marginal benefits for fires already intersecting existing treatments, but expanding treatments may also create new treatment–fire intersections that generate additional benefits. Our analysis reveals that the cost-benefit ratio decreases from 5.75 to 5.24 and 4.84, respectively, suggesting decreasing returns to scale from expanding existing fuel treatments.

While our estimated benefit–cost ratio highlights the potential value of fuel treatments, several factors suggest it is an underestimate of their true economic benefits. First, our analysis only captures reductions in suppression costs, which account for less than 1% of the total annual economic cost of wildfires (JEC, 2023). Second, the relevant parameter for our counterfactual is the ATT—the average effect for fires that would intersect expanded treatments—but our IV strategy identifies a LATE for compliers, which we argue is likely

[53] Let $Y_i^C$ and $FT_i^C$ denote counterfactual suppression costs and fuel treatments for fire $i$. Given our log-log specification and "log-plus-one" transformation, we calculate suppression cost savings for fire $i$ as:

$$Y_i - Y_i^C = (Y_i + 1)\left[1 - \left(\frac{FT_i^C + 1}{FT_i + 1}\right)^{\theta}\right],$$

where $\theta$ is our IV estimate.

smaller in magnitude than the ATT (Section 4.3). Third, our fuel treatment cost data do not net out revenues from mechanical removal treatments.[54] Finally, fuel treatments likely reduce suppression costs through channels not captured by our design—for example, by influencing the behavior and costs of large fires that ignite outside our sample or intersect treatments further from the ignition point.[55] For these reasons, a comprehensive accounting of the benefits of fuel treatments would likely yield benefit–cost ratios that are higher than the estimates reported here.

Table 5: Counterfactual benefits of increasing fuel treatments

| | Cost of Treatment | Suppression Savings | Benefit-Cost Ratio | Reduction Acres Burned |
|---|---|---|---|---|
| 1% Increase | $2,796,182 | $16,074,536 | 5.75 | 7,470 |
| 5% Increase | $13,980,910 | $73,272,805 | 5.24 | 35,084 |
| 10% Increase | $27,961,820 | $135,445,150 | 4.84 | 66,398 |

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

# 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 challenge, expanding the pace and scale of fuel-reduction treatments—such as prescribed fires and mechanical thinning—has been proposed as a key strategy. Despite

[54] We also do not model potential smoke costs from prescribed burns; however, these burns are planned, localised, and generally reduce long-run smoke exposure (Kelp *et al.*, 2023).

[55] Many of the most costly fires ignite on private lands and spread onto federal lands (Levine *et al.*, 2022); our analysis does not account for potential cost reductions for such fires.

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 limited. Our study bridges this gap by quantifying the economic benefits of fuel treatments in reducing fire suppression costs and fire sizes, two primary drivers of wildfire costs.

To test whether fuel treatments reduce fire suppression costs and fire sizes, we employ an instrumental variable research design that leverages exogenous variation in the location of fuel treatments arising from spatial variation in late-successional reserves (LSR) from the Northwest Forest Plan (NWFP). We find that fires starting in LSRs receive significantly less fuel treatment acreage close to their ignition points 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 stylised 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, five to six are saved in fire suppression costs, depending on the level of increased treatment activity. Such fiscal savings have broader implications beyond simply reducing public expenditures: by lowering suppression costs, fuel treatments can ease budgetary pressures that often crowd out restoration and maintenance work, allowing agencies to reinvest in activities that enhance the long-term health, recreational value, and resilience of national forests.

Our results indicate that fuel treatments are a cost-effective means of addressing wildfire costs, despite identifying only one dimension through which fuel treatments can influence fire size and suppression costs. In particular, we do not identify the potential role that fuel treatments play in influencing fire ignitions, nor do we account for the impact that fuel treatments may have in mitigating the spread of large fires located further away from a fire's ignition point (Section A4). Further, our results do not capture how fuel treatments' impact on fire size and severity influences other significant contributors to the costs of wildfires, such as health effects, property damage, and labour market impacts (Bayham *et al.*, 2022; Borgschulte *et al.*, 2024; Heft-Neal *et al.*, 2023). Thus, our estimates of the economic benefits of fuel treatments are likely conservative and could be significantly larger once all potential sources are accounted for.

Our estimated benefit–cost ratio of 5–6 is higher than those reported in simulation studies focusing solely on suppression costs, which typically find ratios below one (Thompson *et al.*, 2013b; Thompson and Anderson, 2015; Hjerpe *et al.*, 2024). We believe our estimates are larger for two reasons. First, simulation analyses generally assume that fuel treatments reduce suppression costs exclusively through a reduction in fire size, but use empirical relationships that do not address the endogeneity between suppression effort and fire size, as we do here. This likely attenuates their estimates. Second, studies typically restrict their analysis to the effect of fuel treatments on the behaviour of large fires, whereas our estimates capture the benefits of fuel treatments near a fire's ignition—whether by preventing escalation into large, costly fires or by lowering the resources required to contain smaller ones. At the same time, our estimated benefit–cost ratio is lower than those reported in studies that account for the full range of economic and ecological benefits of fuel treatments, beyond just suppression cost savings. For example, a recent meta-analysis reports average benefit–cost ratios of approximately 7:1 when accounting for multiple sources of benefits (Hjerpe *et al.*, 2024).

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

In sum, our results provide strong evidence that fuel treatments are a cost-effective tool for mitigating wildfire costs, even when accounting for only a subset of their potential benefits.

By reducing suppression costs and potentially alleviating wildfire damages, fuel treatments provide a promising strategy for addressing growing wildfire risks on public lands in the western United States. However, realising 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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