Wildfires, Fuel Treatments & Endangered Species: Identifying the Economic Benefits of Fuel Treatments Through Endangered Species Protections

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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. 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 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 weather systems – hurricane-force winds and lightning that ignite more fires many miles away. This is just a glimmer of the frightening intensity and destructive capability of 21st-century mega-fires.

As the frequency of mega-fires has increased in recent decades, so too have the economic costs; with the estimated total annual cost in U.S. ranging from $394-893 billion USD (JEC, 2023). Wildfires incur economic costs through various channels: losses in human-made and natural assets, fire suppression costs, human health, and losses in ecosystem services.[1] Within the context of a warming climate, fuel load build-up due to fire exclusion, and increasing rural development in the wildland-urban interface (WUI) costs from wildfires are expected to rise across the globe (Abatzoglou and Williams, 2016; Radeloff et al., 2018).

Fuel loads have built up over time in response to current and historical fire suppression and are one of the leading causes of increasing wildfire severity (Miller et al., 2009). For example, in California, pre-1800, 5-12% of the state burned, a large portion occurred through cultural indigenous burning, and due to European settlement and fire suppression, fuel loads have increased far beyond their natural carrying capacity (Stephens et al., 2007; North et al., 2022). As a result, reducing fuel loads through fuel treatment activities, such as prescribed fires or mechanical tree removal (thinning), can significantly reduce the economic costs of wildfires. Despite widespread consensus in the forest ecology literature that fuel treatments are effective at reducing wildfire severity and restoring forest ecosystem health, fuel treatment activities have been strikingly underemployed in the Western U.S. (Agee and Skinner, 2005; Kolden, 2019).

An under-provision of fuel treatments on public lands may occur because public agencies are chronically underfunded and face contradicting expectations by the public. For example, the USFS employs 30,000 people despite owning more than 193 million acres of public land. Public pressure and risk aversion skew an already scarce resource base towards fire suppression at the expense of fuel treatments in order to avoid public lawsuits and condemnation. Regulatory constraints, based

[1] Examples of human-made assets are houses, power lines, school buildings, or any other human-made structures while natural assets include timber and recreation areas. Wildfires cause health damages through smoke emissions (Molitor et al., 2023) while examples of losses in ecosystem services are carbon sequestration and watershed protection (Smith et al., 2011).

on other environmental objectives, such as endangered species protections or smoke laws, also hinder the ability of public agencies to conduct fuel treatment activity (North et al., 2012, 2015).

The present paper explores the degree to which fuel treatments effectively reduce the economic costs of wildfires by measuring their impact on one of the most significant contributors to the cost of wildfires: fire suppression costs.[2] Investigating fires igniting on United States Forest Service (USFS) land in the Pacific Northwest (PNW) between 2006 and 2023, I find evidence that fuel treatments reduce the size and suppression costs of wildfires. In order to identify the average marginal effect of fuel treatment on fire suppression costs, I implement an instrumental variables strategy, using a major constraint to fuel treatment activity in the PNW, land-use designations designed to protect the Northern Spotted Owl (NSO), and old growth habitat, as an instrument for fuel treatment activity.

An instrumental variables approach is necessary to identify the causal effect of fuel treatments on fire suppression costs because the location and extent of fuel treatments and fire suppression efforts are jointly determined via 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). Hence, estimation strategies that compare fires receiving more fuel treatments to those that receive less will suffer from simultaneity bias. I find evidence that such estimates suffer from a downward bias as fuel treatments occur in locations where it is systematically easier to conduct fire suppression.

To address endogeneity concerns, I take advantage of spatial variation of land-use designations, such as Northwest Forest Plan (NWFP) reserves (LSRs) and Northern Spotted Owl (NSO) critical habitat. These protected areas have had the unintended consequence of restricting fuel treatment activity within such areas because of increased management restrictions and litigation potential from environmental groups (). Spatial variation in the above-mentioned protected areas creates quasi-random variation in the extent of fuel treatment activity because their boundaries were chosen based on the NSO's nesting, roosting, foraging habits, and dispersal ecology (Gaines et al., 2022). I find that protected areas, as compared to non-protected areas, do not systematically differ on observable determinants of fuel treatment activity and fire suppression effort. First-stage results confirm that the areas surrounding fire ignition points in protected areas receive significantly fewer acres of fuel treatment. Reduced-form results suggest that fires igniting in protected areas grow significantly larger, on average, than those igniting outside of protected areas, conditional on observable land characteristics. Together, these results demonstrate that fuel treatments significantly reduce the size and suppression costs of wildfires.

After deriving estimates of the average marginal effect of fuel treatments on fire suppression costs, I explore how the economic costs of wildfires would have changed in the last 15 years if more fuel treatment activity had occurred in protected areas. Counterfactual analyses suggest that substantial economic benefits would have been realized if more fuel treatments had occurred in protected areas in the PNW from 2006-2023. This suggests that fuel treatments may be a chronically underfunded public good, though future research is needed to analyze the costs and additional benefits of fuel

[2]From 1995-2014 $48 billion dollars were spent on fighting fires in the U.S. West (Baylis and Boomhower, 2023)

treatments in order to determine whether this is the case.

This paper provides the first empirical estimate of the effectiveness of fuel treatments in reducing fire suppression costs. Scientists have often argued for the widespread adoption of these practices (Agee and Skinner, 2005; Kolden, 2019) with little to no empirical analysis of their economic benefits. The economic research has focused on the determinants of fuel treatment activity and fire suppression effort but never the linkage between the two (Plantinga et al., 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer et al., 2019; Anderson et al., 2023). The lack of research linking fuel treatment activities' impact on economic outcomes is likely due to the empirical challenge in confronting the environmental and spatial-temporal complexities of wildfires, fuel treatments, and fire suppression efforts. By confronting these challenges, this paper provides an econometric framework for future studies to estimate the impact of fuel treatments on other economic outcomes.

Land managers and forest scientists have long acknowledged the unintended effects of the NWFP reserves and northern spotted owl critical habitat designations on fuel treatment and wildfire activity in the Pacific Northwest (Spies et al., 2019; Hessburg et al., 2021). Previous studies have shown that increasing areas of high-severity fire have been the leading cause of loss in northern spotted owl habitat (Davis et al., 2016) and old-growth forests (Davis et al., 2015) since the NWFP's inception. Others have pointed out the conflicting incentives of land managers under the ESA due to fuel treatments associated with short-term negative impacts on northern spotted owl habitat (Spies et al., 2018). The present study contributes to this literature by estimating the magnitude by which these policies have hampered fuel treatment activity in the region and how this has translated into increased economic costs of wildfires.

By exploring the impact of ancillary environmental policies on wildfire and fuel treatment activity occurring on public lands, this study underscores the importance of institutions and competing environmental policies in response to the impacts of climate change. The growing literature on climate adaptation has tended to emphasize private responses, (Barreca et al., 2016; Burke and Emerick, 2016; Auffhammer, 2022). However, many critical adaptive responses to climate change will likely occur through government investments in public goods like fuel treatments. By quantifying the counterfactual benefits of scaling up fuel treatments in protected areas in the last 15 years, this paper demonstrates the extent to which fuel treatments would have mitigated the economic costs of wildfires, underscoring the importance of rectifying the goals of alternative environmental policies in future climate change adaptation.

The paper is organized as follows: Section 2 provides a background of the NWFP and NSO critical habitat designations. Section 3 establishes a simple model of fuel treatment and fire suppression and explains how this model motivates our empirical approach and the interpretation of our estimates. Section 4 discusses the data and Section 5 provides an overview of our research design. Section 6 estimates the marginal effect of fuel treatment on fire suppression costs. Section 7 explores the counterfactual benefits of increased fuel treatment activity in protected areas and Section 8 concludes.

"Any big tree, for example, is a kind of time capsule, the accumulated biological memory of one hundred thousand days and nights, of snow and wind and rain. It is the rare person who remains unaffected by this aura of deep time, the wonder of things so big and so old. But trees are also mortal. They are inevitably dying in their core, succumbing to decay, ripe to be victimized by fire and storm. Each tree can be worth thousands of dollars, even tens of thousands, if harvested at its peak. To many who live in the dim woods, who work until their bodies ache, who sometimes see their friends and relatives killed by this forest, and who see it grow back up in riotous rankness in the cold rain, it is madness to ignore this economic gift. Yet it was not the trees themselves that finally brought this conflict to a political boil. It was of all things a bird, so rare that few in the Pacific Northwest have ever seen one, and so conveniently trusting in responding to human calls that it made it possible for scientists to count and quantify its decline. The northern spotted owl came to symbolize the struggle between conquering nature and worshiping it."

William Dietrich - The Final Forest

2 Institutional Background

2.1 NWFP Reserves & Northern Spotted Owl Critical Habitat Designations

It is said that when President Jimmy Carter was on his way to view the devastation caused by the eruption of Mt. St. Helens in 1980, he expressed horror at the sight of a shaven landscape. State officials had to gently explain that what Carter saw was clear-cut logging and not the aftermath of the explosion (Dietrich, 2010). The emotion brought about by the sight of clear-cuts and their deleterious effects on ecosystems led to one of the most hotly contested public debates: What should be the management objectives of federal forest owners? The northern spotted owl (NSO) was the centerpiece of this debate. It became not only a symbol for old-growth forest preservation but also the legal basis from which federal forest owner objectives changed through the Endangered Species Act (ESA).

The debate culminated in the early 1990s, and within only five years, federal forests in the Pacific Northwest underwent a sudden and tremendous shift in management focus from providing sustained yield timber to conserving biodiversity with emphasis on endangered species (Thomas et al., 2006). After listing the NSO as threatened by the U.S. Fish & Wildlife Service (USFWS), 6.9 million acres of federal forest were designated as critical habitat in 1992, spanning WA, OR, and northern CA. Shortly after that, in 1994 and spearheaded by then President Clinton, the Northwest Forest Plan (NWFP) was created that set up a system of reserves on 24.4 million acres of federal forest land in WA, OR, and CA designed to conserve old-growth forest, northern spotted owl and marbled murrelet habitat, along with key watersheds and riparian zones making it one of the largest reserve systems of any temperate forest in the world (Gaines et al., 2022; Spies et al., 2018).

During the creation of the NWFP, President Clinton was presented with a set of reserve options (created by scientists) that portrayed stark trade-offs between timber production and species conservation (Johnson et al., 2023). In each option presented, there were a different number of "working" forest lands protected under a late-successional reserve (LSR) status, with the remainder set aside as "Matrix" lands.[3] In the final plan, 7.4 million acres were designated LSR and around 4 million as "Matrix".

In LSRs, fuel treatment activity is possible, though more difficult to implement due to litigation potential from environmental groups and management restrictions from the NWFP. On the other hand, non-reserved "Matrix" areas have fewer management restrictions since they were designed to be areas where most timber harvest and other silvicultural activities would occur. It is worth noting that because the NWFP struck a middle ground between species conservation and timber production, Matrix areas also contained significant old-growth habitat at the time of designation, with around 2 million acres of late successional/old growth (LS/OG) compared to the 3.7 million acres of LS/OG in LSRs. Figure 1 plots the spatial distribution of LSR (purple) and Matrix (green) areas across the Pacific Northwest. See subsection A.1 for a description of the other land designation types for federal forests in the NWFP.

Although LSRs intended to protect old growth, NSO, and other sensitive habitat, they have had the unintended consequence of restricting fuel treatment activity within such areas because of increased management restrictions and litigation potential from environmental groups (Johnson et al., 2023). Managers & regulators have been oft-cited as making very conservative interpretations of NWFP rules, making it challenging to conduct fuel treatments in older forests within LSRs (Johnson et al., 2023).

Figure 2 explores how the regulatory constraints posed by LSRs have impacted fuel treatment activity by plotting the annual total acres of completed fuel treatments (normalized by area) across Matrix and LSR lands in the NWFP area. Matrix areas often receive significantly more acres of fuel treatment than LSR areas, suggesting constraints have led to significant differences in the spatial distribution of fuel treatments across national forests in the Pacific Northwest.

While then-President Clinton determined LSRs in NWFP, the critical habitat of the NSO is determined by the USFWS. When the USFWS lists a species as "threatened" or "endangered" under the Endangered Species Act (ESA), critical habitat is designated within the range of the species. Critical habitat designations affect management activities on federal lands through Section 7 of the ESA, where federal landowners must consult with the USFWS before engaging in any activities that may harm the critical habitat or current population of a listed species. Because fuel treatments are associated with a short-term negative impact on NSO habitat (Spies et al., 2018), conducting fuel treatments in critical habitat areas is more complex than in non-critical habitat areas under Section 7. Presumably, the lack of fuel treatments in critical habitat areas has contributed to high-severity fire, which has been the leading cause of loss in Northern Spotted Owl habitat since the NWFP inception (Davis et al., 2016).

While the NWFP land allocations have been static throughout time, critical habitat for the NSO

[3] "working" forest lands are those that were the 12 million of the 18 million forested acres in the NWFP area considered to be sufficiently productive for timber production (Johnson et al., 2023). These 12 million acres are the area from which "Matrix" and "LSR" lands were designated.

has been re-designated three separate times since 1992: in 2008, 2012, and 2021, and the total area has increased from 6.9 million acres in 1992 to 9.4 million in 2021. Unlike LSRs, critical habitat is determined solely by the ecology of the NSO. For example, critical habitat is based on historical range, current nesting sites, and dispersal ecology models.[4] Because ecological modeling techniques and survey results of the NSO change over time, critical habitat changes substantially when re-designated. See Table 11 for a description of all the relevant events.

Because NWFP LSRs and NSO critical habitat are determined via different means and at different times, these areas often do not overlap. Around 40 percent of historical nesting owl pairs resided in Matrix rather than LSR lands in eastern Washington State (Gaines et al., 2010). The discrepancies between NSO critical habitat and LSR status give credence to the arbitrariness through which LSRs and critical habitat are determined.

2.2 The 2011 Revised Recovery Plan

Management prescriptions and recommendations for federal actions concerning species listed under the ESA can change with “Recovery Plans" for a given species. Management prescriptions for the Northern Spotted Owl (NSO) dramatically changed with the 2011 Revised Recovery Plan, as the plan recognized and endorsed fuel treatment activity in critical habitat areas containing “dry" forests with historically low-mid fire severity regimes (regions most prone and susceptible to wildfire). The plan effectively encouraged and lowered barriers for federal agencies to engage in fuel treatments within critical habitat areas.

The Revised Recovery Plan came about as the public and land managers expressed a desire for a recovery plan that explicitly outlined and described management actions appropriate for the conservation of the NSO with special emphasis on actions that dealt with habitat loss due to wildfire (USFWS, 2011). The 2008 Recovery Plan endorsed the need for fuel treatment activities and was challenged in court due to controversy surrounding the recommendations. The 2011 Revised Recovery Plan addressed these concerns and became the final ruling of the USFWS. The following is a passage from the 2011 Revised Recovery Plan:

“In order to preserve the essential physical or biological features, these dynamic, disturbance-prone forests should be managed in a way that promotes northern spotted owl conservation, responds to climate change, and restores dry forest ecological structure, composition and processes, including wildfire and other disturbances (p. III–20)...The following restoration principles apply to the management that may be required in this dry forest region (pp. III–34 to III–35):

1. Conserve older stands that contain the conditions to support northern spotted owl occupancy or high-value northern spotted owl habitat as described in Recovery Actions 10 and 32.

2. Emphasize vegetation management treatments outside of northern spotted owl territories or highly suitable habitat;

3. Design and implement restoration treatments at the landscape level.

[4] See subsection A.2 for more details on how critical habitat is determined.

4. Retain and restore key structural components, including large and old trees, large snags, and downed logs.
5. Retain and restore heterogeneity within stands;
6. Retain and restore heterogeneity among stands;
7. Manage roads to address fire risk;
8. Consider vegetation management objectives when managing wildfires, where appropriate." (USFWS, 2011)

Under the ESA section 7, federal landowners must consult with the USFWS before engaging in any activities that may harm the critical habitat or current population of a listed species. By explicitly endorsing fuel treatments in fire prone regions the 2011 Revised Recovery Plan effectively made consultation under section 7 more streamlined for federal forest owners and provided them with confidence that they would not face future litigation.

2.3 Fighting Fire with Fire: Wildland Firefighting & Fuel Treatments in the Western U.S.

The Great Fire of 1910, an apocalyptic blaze that burned 3 million acres in 2 days in Washington, Idaho, and Montana, marked an important turning point in the management of U.S. national forests (Egan, 2011). At the time, the United States Forest Service (USFS), only five years after its founding, was severely underfunded and under political threat of dismantling.[5] However, the heroic deeds of forest service rangers like Ed Pulaski and the shock and terror from fire dramatically changed public perceptions of the USFS. This ultimately led to the USFS's expansion and a major shift in its mission statement: a shift from prioritizing conservation to fighting forest fires (while saving the trees from those fires to be logged by timber companies). Prioritizing wildfire suppression led to the "10 a.m." policy instituted by the USFS, which stated the goal to successfully contain any fires by 10 a.m. the day following its initial report.

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

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

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

Fuel treatments like prescribed fires or mechanical tree removal (thinning) aim to return forest ecosystems to their more natural state by emulating the natural processes of low-severity fires by reducing fuel loads, maintaining open stands of trees, and eliminating shade-tolerant species of trees that are more susceptible to wildfire. Because such ecosystems are adapted to frequent low-severity fires, the fire ecology literature has consistently shown that forests that receive such fuel treatments experience less high severity (stand-replacing) wildfire and hence enhance the ecosystem services associated with such forests such as reduced smoke exposure, increased nutrient cycling, water quality, and carbon sequestration post-wildfire, along with the promotion of biodiversity (Murphy et al., 2007; Converse et al., 2006; Boerner et al., 2009; Finkral and Evans, 2008; Yocom Kent et al., 2015). See Figure 3 for a demonstration of how fuel treatments influence fire behavior in frequent fire forests ubiquitous across the Western U.S.

Although no rigorous causal evidence exists of fuel treatments' impact on fire suppression costs, ample evidence suggests that fuel treatments should reduce the intensive and extensive margins of fire suppression costs. Wildfire simulation studies demonstrate how fuel treatments reduce fire suppression costs through its reduction in the size and frequency of large catastrophic wildfires (Thompson et al., 2013b; Finney et al., 2007). On the other hand, qualitative evidence suggests that fuel treatments reduce wildfire suppression costs by increasing the marginal productivity of "direct" and "indirect" attack efforts (Romero and Menakis, 2013).

Fuel treatments increase the marginal productivity of "direct" and "indirect" attack efforts by making it easier and safer to conduct such efforts. "Direct attack" consists of efforts by firefighters in close proximity to burning fuel by applying water or chemical retardant. However, a direct attack is only possible when a wildfire is of a sufficiently low flame length, which fuel treatments increase the likelihood of. Fuel treatments also enhance "indirect attack" efforts, firefighting activities that take place some distance from the perimeter of a burning fire, by creating/enhancing the ability of firefighters to take advantage of fuel breaks or create firelines, where burnable material is removed to stop a fire's spread. Another form of indirect attack is "back-burning," which is setting fire to fuel in the path of a fire's perimeter to slow down its spread, which requires favorable wind conditions. By proactively burning before the fire, fuel treatments reduce the need for favorable wind conditions during the fire, which is necessary for this form of indirect attack.

By enhancing the effectiveness of direct and indirect attack measures, fuel treatments also reduce the need for "aerial attack," where water or chemical fire retardant is applied by helicopters or fixed-wing aircraft. Because aerial attack incorporates large and expensive capital, it is significantly more expensive than indirect or direct attack measures (Calkin et al., 2014; Thompson et al., 2013a).

3 Conceptual Framework: Fuel Treatment & Fire Suppression Cost Model

When a public agency conducts a fuel treatment on a given plot of land, there are two main channels through which it can affect future fire suppression costs. The first is that fuel treatments will impact the probability of future ignitions, which are located close to the fuel treatment, from turning into large fires – I term this the "prevention effect". Because 98% of fire ignitions are successfully suppressed within a day, with the other 2% accounting for 95% of fire damages and effects (Calkin et al., 2005), whether and to what degree fuel treatments reduce the likelihood of ignitions turning into a large, uncontrollable fire, will likely to play a substantial role in how fuel treatments impact future fire suppression costs. The second channel through which fuel treatments will impact future fire suppression costs is that conditional on a fire becoming large, fuel treatments that intersect with the large fire will likely enhance fire suppression efforts in such locations – I term this the "landscape effect". Because fuel treatments often occur close to the wildland-urban interface (WUI), an area where fire suppression effort is greatest (because firefighters stated priorities are to save lives and man-made structures), fuel treatments may reduce the expected cost of fighting a fire conditional on it being a large fire.

To delineate these two different effects, assume for simplicity that there are two plots of identical land, $i = 1, 2$, that are at risk of fire and can receive a fuel treatment. Also for simplicity let's assume we have a one time period model. A fire can ignite in either of these plots of land denoted by the binary variable, I_i where the probability of ignition is the same for both plots of land. The expected suppression costs for fires starting in plot i can be written as:

$$E[SC_i] = P(I_i)E_I[SC_i]$$

Where I define fire suppression costs conditional on an ignition: $E_I[SC_i] \equiv E[SC_i|I_i = 1]$.

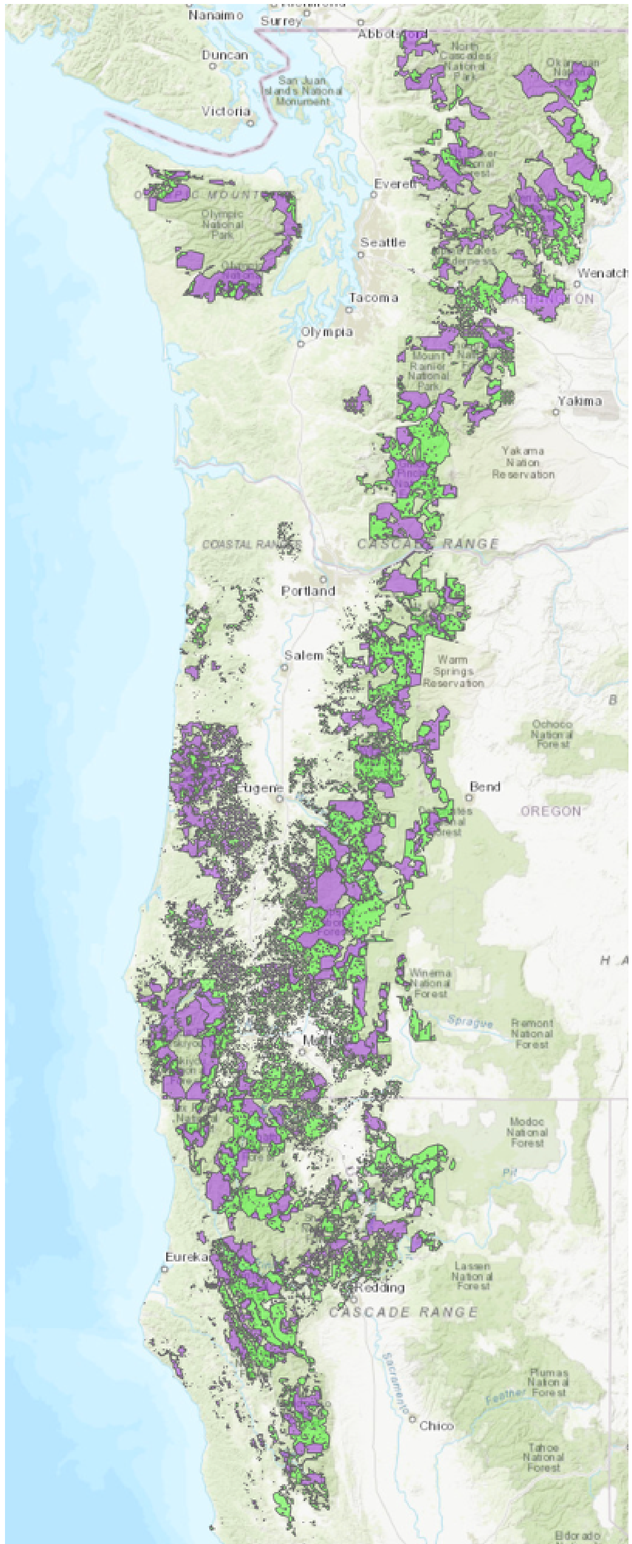
Let Π represent a transition probability matrix where, π_{ij} is the probability that a fire starting in plot i will spread to plot j. π_{ii} is the probability that a fire starting in plot i is contained within plot i. For the simple two plot case this is simplified to: $\pi_{ii} = 1 - \pi_{ij}$

$$\Pi = \begin{bmatrix} 1 - \pi_{12} & \pi_{12} \\ \pi_{21} & 1 - \pi_{21} \end{bmatrix}$$

Now let's assume that fires are either small, $S_i = 0$, if they are completely contained within their plot of land, or large, $S_i = 1$, if they spillover to an adjacent plot of land: $S_i \in \{0, 1\}$. Also assume that expected fire suppression costs are increasing with fire size. We can write the expected fire suppression costs conditional on a fire starting in plot i as:

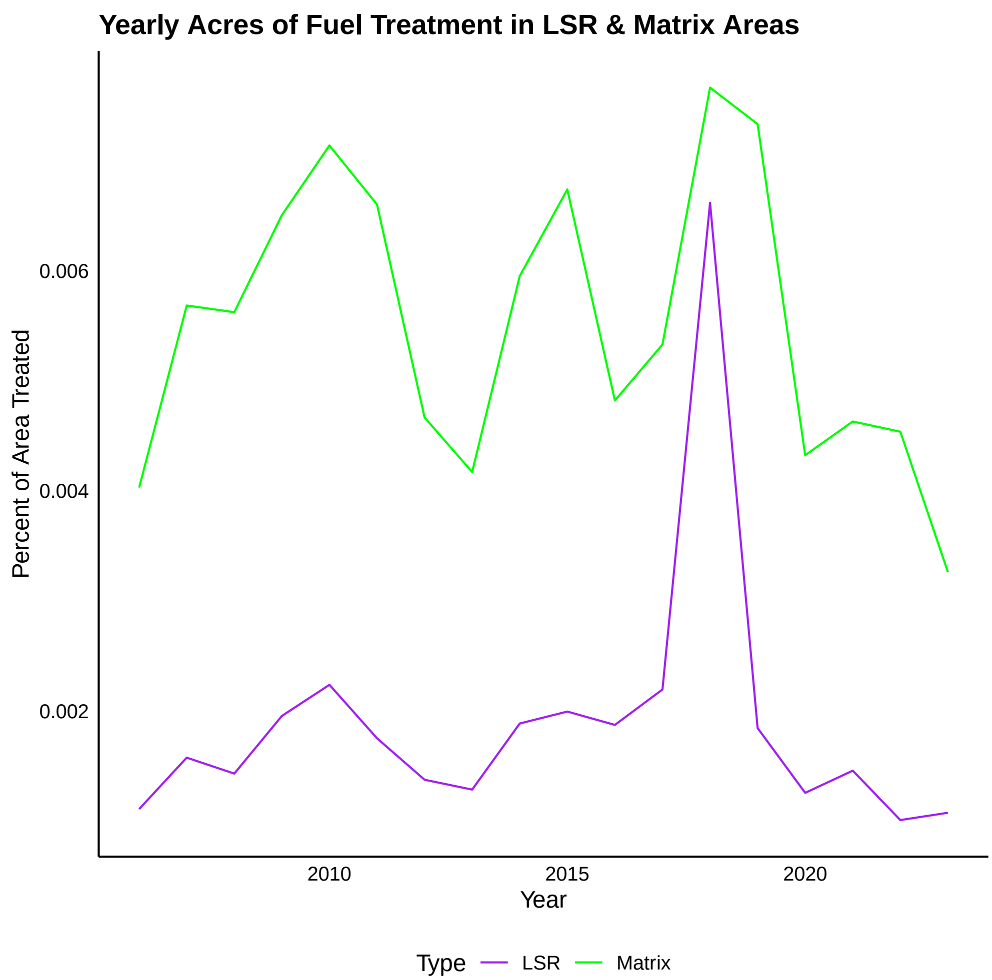
$$E_I[SC_i] = (1 - \pi_{ij})E_I[SC_i|S_i = 0] + \pi_{ij}E_I[SC_i|S_i = 1]$$

Figure 1: Distribution of Matrix & LSRs In The NWFP Area



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

Figure 2: Yearly Acres of Fuel Treatment - LSR v. Matrix



"Percent of Area Treated" is the total yearly acres of fuel treatment divided by the total area of Matrix or LSR areas. Total yearly acres are then calculated by taking the sum of total completed acres across all projects in a given land designation type. Total yearly acres of fuel treatments associated with any project is calculated by summing the total acres of a prescribed burn and the maximum acres of mechanical fuel treatment for a given project area. This definition ensures that multiple mechanical projects are not double-counted, which often occur in the same year.

Figure 3: Fire Suppressions' Effect on Wildfire Severity

FIRE-SUPPRESSED FOREST Fire in a ponderosa pine forest where fires have been repeatedly suppressed: Overcrowding can make the forest less healthy and resilient. When such a forest burns, the fire can extend into the crowns, killing large swaths of trees. © Erica Sloniker / TNC

FIRE-MAINTAINED FOREST Fire in a ponderosa pine forest using controlled burns with or without mechanical thinning: A fire burns low through the understory, maintaining gaps between some trees that help prevent future large crown fires. © Erica Sloniker / TNC

We can then write the expected total fire suppression costs conditional on an ignition starting in both plots as:

$$\sum_{i=1}^{2} E_I[SC_i] = (1-\pi_{12})E_I[SC_1|S_1=0] + \pi_{12}E_I[SC_1|S_1=1] \\ +(1-\pi_{21})E_I[SC_2|S_2=0] + \pi_{21}E_I[SC_2|S_2=1]$$

Now, suppose we are interested in the marginal impact of conducting fuel treatment on plot 1 on the total expected suppression costs of fires igniting on both plots of land. To derive this marginal impact lets first take the partial derivative of the above EQ with respect to an additional acre of fuel treatment conducted in plot 1:

$$\sum_i \frac{\partial E_I[\sum_i SC_i]}{\partial FT_1} = (1-\pi_{12})\frac{\partial E_I[SC_1|S_1=0]}{\partial FT_1} + \frac{\partial \pi_{12}}{\partial FT_1}\left(E_I[SC_{1t}|S_1=1] - E_I[SC_{1t}|S_1=0]\right) \\ +\pi_{12}\frac{\partial E_I[SC_1|S_1=1]}{\partial FT_1} + (1-\pi_{21})\frac{\partial E_I[SC_2|S_2=0]}{\partial FT_1} + \frac{\partial \pi_{21}}{\partial FT_1}\left(E_I[SC_2|S_2=1] - E_I[SC_2|S_2=0]\right) \\ +\pi_{21}\frac{\partial E_I[SC_2|S_2=1]}{\partial FT_2}$$

Now lets assume that:

1. If a fire spreads outside of the grid it starts in, fuel treatments that occurred within that grid have no impact on the suppression costs of that fire: e.g. $\dfrac{\partial E_I[SC_i|S_i=1]}{\partial FT_i} = 0$.

2. If a fire is completely contained within the grid it ignites in, any fuel treatments occurring in other grids have no impact on the cost of suppressing that fire: e.g. $\frac{\partial E_I[SC_j|S_j=0]}{\partial FT_i}=0$

3. A fuel treatment conducted in a given grid doesn't impact the probability that a fire starting in another grid will spread to that grid: e.g. $\frac{\partial \pi_{ji}}{\partial FT_i}=0$

4. Fuel treatments have no impact on the probability of ignition: e.g. $\frac{\partial P(I_i)}{\partial FT_i}=0$

With these assumptions, we can simplify the marginal impact of conducting fuel treatment on a given plot of land, say plot 1, on total expected suppression costs of fires starting on both plots of land to an expression of three terms:

$$
\begin{aligned}
\frac{\partial E[\sum_i SC_i]}{\partial FT_1} = & \underbrace{P(I)\frac{\partial \pi_{12}}{\partial FT_1}\left(E_I[SC_1|S_1=1]-E_I[SC_1|S_1=0]\right)+}_{\text{Prevention Effect}} \\
& \underbrace{P(I)(1-\pi_{12})\frac{\partial E_I[SC_1|S_1=0]}{\partial FT_1}+}_{\text{Small Fires Effect}} \\
& \underbrace{P(I)\pi_{21}\frac{\partial E_I[SC_2|S_2=1]}{\partial FT_1}}_{\text{Landscape Effect}}
\end{aligned}
$$

The first term I call the "prevention effect" is how fuel treatments reduce fire suppression costs through its influence on reducing the probability of fires spilling over to other plots of land. The second term I call the "small fires effect" is how fuel treatments reduce fire suppression costs for small fires. The last term I call the "Landscape Effect" which is how fuel treatments reduce suppression costs of fires that spill over onto plots of land that have received treatment.

Ex ante I expect the first term to be critical in understanding the influence of fuel treatments on fire suppression costs because large fires cause the majority of suppression costs. Hence, if fuel treatments reduce the incidence of these costly fires, there may be a subsequent large reduction in costs. This is why I believe having analyses that include small and large fires is critical. I expect the effect of the second term to be small because small fires constitute a smaller fraction of the costs of fire suppression, while the third term to be large because of its potential role in mitigating the costs of the largest, mostly costly fires.

These different effects motivate different estimation strategies on different samples. I estimate the prevention effect using my fixed effect strategy with a sample of all fires. My outcome here is fire size (my measure of fire spread). The "small fires effect" can be estimated by restricting my sample only to small fires and estimating the relationship between the proximity of fuel treatments and fire suppression costs. I can't estimate this parameter yet since I don't have cost information on small fires. Lastly, the "Landscape Effect" is estimated using a sample of large fires for which I have suppression costs and the perimeters of such fires.

4 Data & Descriptive Statistics

I construct a dataset that combines administrative data of NWFP reserves & NSO critical habitat areas with fuel treatment and wildfire outcomes in the Pacific Northwest (PNW) from 2006-2023. The cost, date, and location of wildfires come from two different sources comprising two different time periods. The National Fire and Aviation Management Web Applications (FAMWEB), used in Baylis and Boomhower (2023), comprises of wildfires igniting from 2006-2014 (FAMWEB, 2023). Because the FAMWEB collection system ended in 2014 and was replaced by the "Wildland Fire Incident Locations" data provided by National Interagency Fire Center (NIFC), we use this source for fires post 2014 (NIFC, 2024). For each fire we obtain the topographical conditions (elevation, slope, aspect, and vegetation characteristics) at the ignition point from LANDFIRE and weather conditions (temperature, precipitation, wind speed, and humidity) at the time of ignition from PRISM & GridMET.[6] We also estimate the distance between the ignition point of each fire and valuable nearby resources, including distance to nearest Census Block in the WUI, U.S. Forest Service roads, and the total housing value within 10/20 kilometers of an ignition point (Radeloff et al., 2022; USFS, 2023b).

Fuel treatment data come from the USFS' FACTS (Forest Service Activity Tracking System) Hazardous Fuel Treatment Reduction database (USFS, 2023a). 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 (e.g. tree removal (thinning), mastication of small trees and shrubs, and hand thinning or pruning followed by piling and burning), prescribed burning (e.g. intentional application of fire), and wildfire use (e.g. unplanned wildfires left to burn). We restrict our attention to the effectiveness of mechanical and prescribed burning fuel treatments since they are the types of treatment impacted by the NWFP and critical habitat designations.

Spatial data on NWFP LSRs and Matrix areas comes from the Regional Ecosystem Office (REO), which has the location of such reserves across the PNW (REO, 2013). The REO dataset has the exact location of LSRs, while Matrix areas are lumped in with Riparian Reserves. To account for the fact that Riparian Reserves have their own set of restrictions and regulations, we control for Exisiting Vegetation Group Type from LANDFIRE, which has Riparian Area as one of the groups.

Because NSO critical habitat has been designated 4 times: 1992, 2008, 2012, & 2021, our measures of critical habitat are incomplete as we only have the maps of 2021, 2012, & 2008 designations. For the 2021 designation we take publicly available data from the USFWS (USFWS, 2023). The 2012 designation map is taken from Ferris and Frank (2021). The 2008 critical habitat areas are manually created from UTM coordinate points provided in the 2008 Critical Habitat Federal Register Document (USFWS, 2008).

See Table 1 for a list of all data source, variables used, and coverage.

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

Because landownership across space is correlated with economic and environmental determinants of fire suppression efforts and fuel treatments, I restrict my sample to only those fires that ignite within National Forests to avoid apples-to-oranges comparisons.[7] To focus on the impact of NWFP reserves and NSO critical habitat, I further restrict my sample to fires that ignite within the NWFP boundary. In a less restrictive sample I include fires that ignite within any of the 17 National Forests lie within the NWFP boundary. This sample is less restrictive since some National Forests only lie partly within the NWFP boundary.

LSRs and critical habitat only occur within non-wilderness areas of national forests; hence, I also restrict my sample to include only fires that ignite outside of wilderness areas or national parks.[8] Restricting my sample to fires that ignite within non-wilderness portions of national forests is essential because fire behavior and suppression strategies are systematically different in wilderness areas (Gebert et al., 2007). In total, my two samples include 9,151 & 16,128 fires from 2006-2023.

Table 2 shows the number of observations, costs, total acreage, and coverage associated with my fuel treatment and fire cost data. There are major discrepancies between the median and averages in my fire dataset, consistent with previous literature showing that fire suppression costs are a right-tail-driven process. For example, the average cost of suppressing a fire is, $487,387, which is over one thousand times as large as the median cost of suppressing a fire, $307.8. We see a similar pattern for acres burned as the average is 543 and the median is 0.1. These results are consistent with the 10 a.m. fire suppression policy conducted by the Forest Service, where 98% of fires started are successfully suppressed within a day, while the other 2% account for 95% of fire damages and effects (Calkin et al., 2005). This suggests that fuel treatments will significantly reduce fire suppression costs if they can prevent fires from turning into large fires. Although fire suppression costs are a right-tailed process, after taking the natural log transformation, costs look to be approximately normally distributed [See **??** to see the distribution].[9]

In total $5.7 billion USD was spent on fire suppression throughout my sample period. As a reference the USFS spent $27.8 billion USD over the same time period ($35 billion including all federal agencies). Consistent with general trends in fire suppression costs, the majority of this spending has occurred during the second half of my sample period, 2015-2023. See Figure 5 for the trends in fire suppression costs across my sample period.

[7] For example, private forest lands are typically located near communities, along river bottoms, and around valley fringes, while National forests were created primarily from lands left after land grants and homesteading had privatized lower-elevation forests. BLM lands were created from former land grants that were reclaimed due to fraud (Johnson et al., 2023).

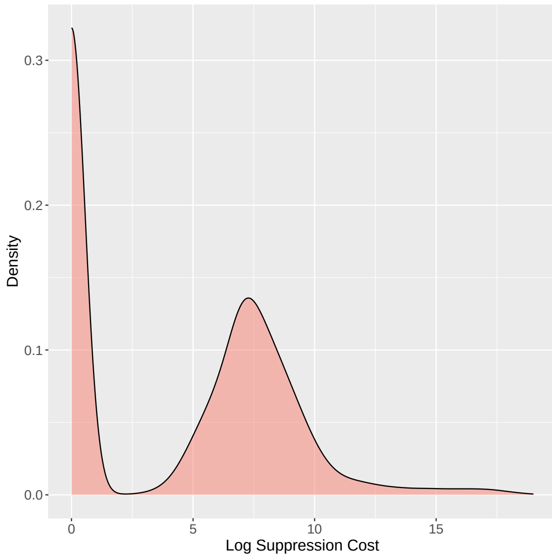
[8] Parks and wilderness areas were lobbied by the timber industry to high alpine areas and were mostly in areas with no development before designation.(Johnson et al., 2023)

[9] Technically this is the $\log(x + 1)$ transformation to account for fires that have 0 recorded cost.

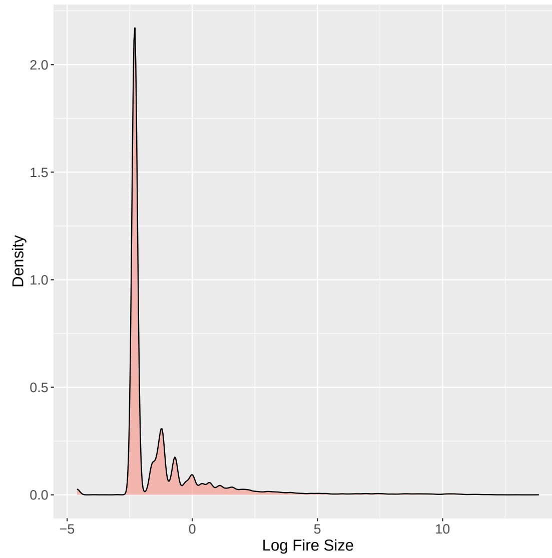
Table 1: Main Variables & Data Sources

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

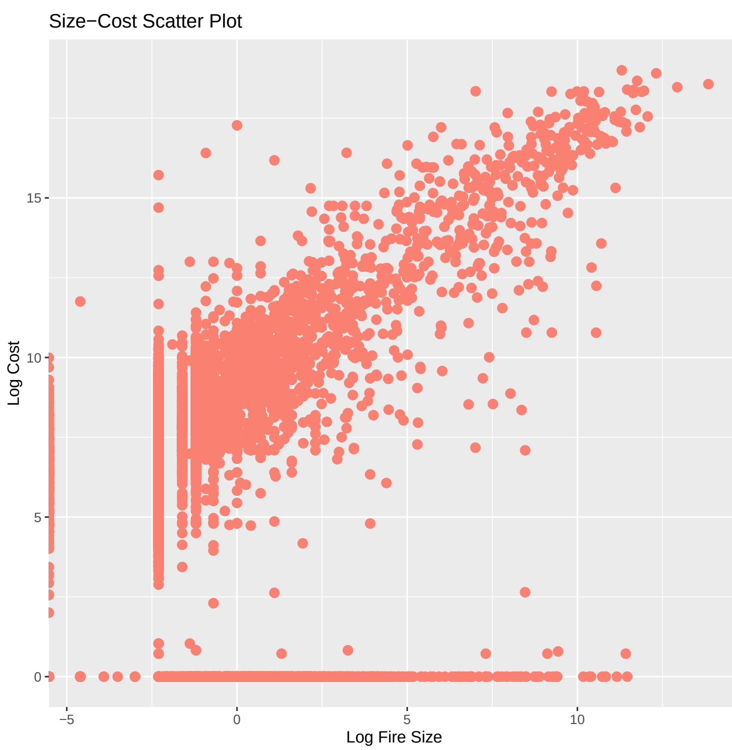
Figure 4: Distributions of Log Fire Size & Cost



(a) Distribution of Log Suppression Costs

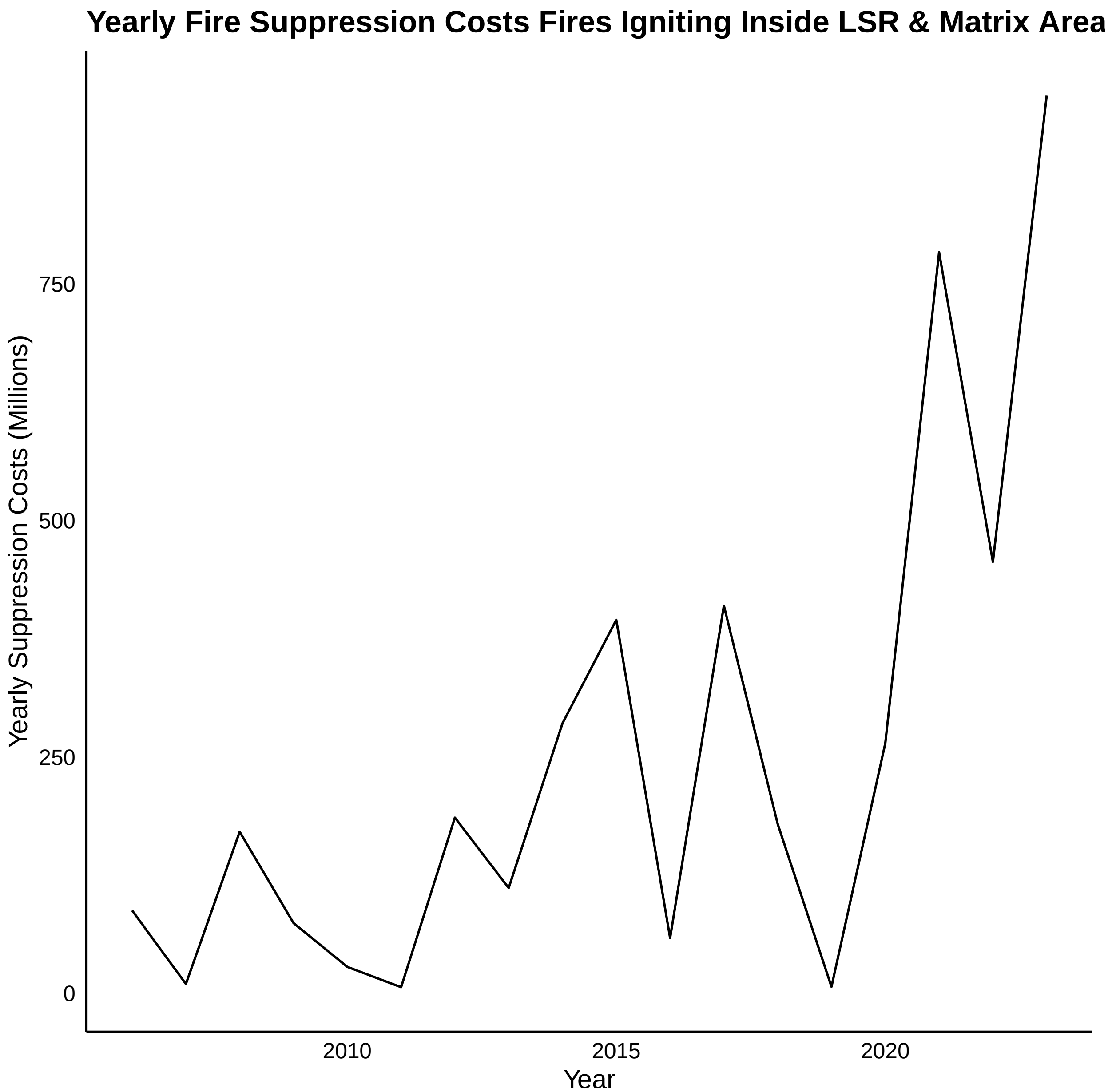


(b) Distribution of Log Fire Size



(c) Scatter Plot of Log Fire Size on Log Suppression Cost

Figure 5: Trends In Fire Suppression Costs



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

Table 2: Fuel Treatments & Wildfires Descriptive Statisticss

	Prescribed Fire	Mechanical	Total Treatments	Wildfires
Average Cost	$7,465	$8,793	$14,861	$353,985
Median Cost	$1,451.3	$970.7	$2,372	$240.5
Total Cost	$52,619,072	$217,665,873	$270,284,944	$5,706,238,674
Average Acres	55.8	27.6	38.5	438.3
Median Acres	18	15	16	0.1
Total Acres	393,476	307,426	700,903	7,065,595
Total Cost/Acre	$133.7	$708	$385.6	$807.6
No. Obs	7,049	11,139	18,188	16,120
Coverage	2006-2023	2006-2023	2006-2023	2006-2023

The first three columns show size and cost statistics for Prescribed Fires, Mechanical, and Total Fuel Treatments (Prescribed Fire + Mechanical) that occur in Matrix and LSR areas in USFS lands in the NWFP area. Cost data for fuel treatments should be interpreted cautiously because FACTS does not have a systematic way of recording cost data. For example, mechanical treatments do not record revenues from sold timber so some treatments will be recorded with 0 cost while others will not take into account revenues into their cost calculation. The fourth column shows size and cost statisitics for wildfires that ignite in Matrix and LSR areas in USFS lands in the NWFP area.

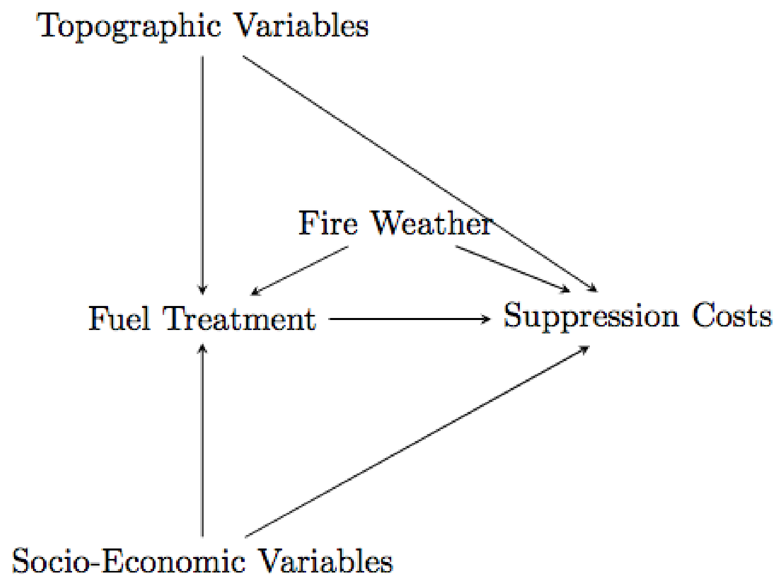
5 Empirical Framework

5.1 Estimation Strategy

This paper aims to identify the effect of fuel treatments on fire suppression costs. To identify this relationship, my research design takes advantage of both spatial and temporal variation in NWFP land allocations and critical habitat areas. By recovering a credible estimate of fuel treatment's effect on fire suppression costs, a major societal cost from wildfires, one can better understand how fuel treatments have reduced the economic costs of wildfires. Because this estimate will be a function of observable characteristics, one can conduct counterfactual analyses that answer questions such as what fire suppression costs would have been if the Forest Service had not been constrained by budgetary, regulatory, or political reasons in their ability to conduct fuel treatments.

Naively comparing fire suppression costs on plots of land that receive fuel treatments to those that do not will lead to biased estimates as both fuel treatments and fire suppression effort are jointly determined via socio-economic and environmental factors (Plantinga et al., 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer et al., 2019; Anderson et al., 2023). For example, fuel treatments are typically located closer to the WUI or homes, as one of the main goals of implementing fuel treatments is to protect communities in the WUI, while the closer a given fire is to a home, the more expensive it is on average (Schoennagel et al., 2009; Bayham and Yoder, 2020; Baylis and Boomhower, 2023). Additionally, fuel treatments correlate with both topographic (lower slopes & elevations) and fire weather variables that influence the fire suppression costs. See Figure 6 for a visual representation of the data generating process of fuel treatments and wildfires, where both are a function of topographic, fire weather, and socio-economic variables.

Figure 6: The Data generating process for Fuel Treatments & Fire Suppression Costs



Our baseline estimation strategy builds off the research design in Baylis and Boomhower (2023) by taking advantage of variations in ignition locations within national forests. Intuitively, this baseline strategy compares fire suppression costs of fires that start within the same national forest but experience more or less fuel treatments within a certain distance of the fire ignition location. Figure 8 shows this variation among ignition locations in our sample for a particular Ranger District.

More formally we can write our baseline regression EQ as:

$$Y_{ift} = FT'_{it}\phi + X'_{it}\beta + E'_{it}\Lambda + \mu_f + \lambda_t + \epsilon_{ift} \quad (1)$$

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.[10] We are interested in the impact of an additional acre of fuel treatment that occurs within a certain distance of fire i, FT_{it}, on the cost of suppressing a fire.

We begin by specifying FT_{it} as the acres of fuel treatment, both mechanical and prescribed fires, occurring within 1177 feet of ignition within the last 10 (or 5) years of the fire.[11] This is equivalent to calculating the acres of fuel treatments that occur within a 100-acre circle surrounding an ignition point of a fire. Because mechanical fuel treatments are typically conducted in a series of

[10]It's worth noting that we only observe fire i once, so we have a repeated cross-section model as opposed to a panel data setup.

[11]I choose 10 years to be the cutoff for counting previous fuel treatments as previous studies have shown that fuel treatment effectiveness is diminished after 9–14 years (Collins et al., 2009; van Wagtendonk et al., 2012; Lydersen et al., 2014)

treatments (Commerical Thin $\implies$ Pilling of fuels), I avoid double counting of such fuel treatments by only counting mechanical treatments once. By taking the sum of both mechanical and prescribed fire fuel treatments my measure of treatment takes into account that fuel treatments that incorporate both mechanical and prescribed fire treatments are the most effective at reducing wildfire severity (Wimberly et al., 2009; Prichard and Kennedy, 2014). See Figure 7 for an example how this is calculated for a particular fire.

We explore how our estimates change using different specified distances within an ignition's location, time weighting, and heterogeneous effects based on treatment type (e.g. prescribed burn v. mechanical) in Section 6.

I calculate the acres of fuel treatment "close" to a fire instead of the acres of fuel treatment that intersect with a fire to overcome reverse causation issues associated with using intersections and to account for the interaction between fire suppression and fuel treatments. Using fuel treatments that directly intersect with a fire as a treatment variable would lead to a spurious positive correlation between fire size and treatment exposure. Additionally, if fuel treatments are used to construct fire lines where the fire is to be stopped and contained, then fire the is unlikely to intersect with the proximate fuel treatments. Lastly, perimeters of fires are only systematically recorded for large fires (> 300 acres) by MTBS and hence any analysis using intersected areas would require restricting my sample only to large fires. Because my treatment variable calculates fuel treatments in close proximity to its ignition the results should be interpreted as fuel treatment's effect on preventing small fires, close to WUI, from turning into large uncontrollable and costly fires.

We include sets of socio-economic and environmental control variables: X_{it} & E_{ift} that influence the cost of suppressing a fire. Examples of environmental variables are topographic, weather, and vegetation type near the ignition point, while examples of socio-economic variables are the ignition's distance to the WUI or Forest Service Road. See Table X for a list of all the relevant control variables used in the analysis. Our national forest, μ_f, and time-fixed effects, λ_t, address various omitted variable bias concerns. μ_f is a national forest fixed effect that controls for time-invariant unobserved determinants of firefighting costs that are constant at the national forest level. λ_t is a year-month (or year) fixed effect that controls for unobserved changes in firefighting costs over time. Lastly, as in Baylis and Boomhower (2023), standard errors are clustered at the national forest level.

The identifying assumption in this analysis is that unobserved determinants of fire cost, ϵ_{ift}, are independent of FT_{it} conditional on national-forest fixed effects and our other controls.

Because both fuel treatments and fire suppression effort are jointly determined via socio-economic and environmental factors (Plantinga et al., 2022; Baylis and Boomhower, 2023; Bayham and Yoder, 2020; Wibbenmeyer et al., 2019; Anderson et al., 2023), we may expect estimates of ϕ to suffer from omitted variable bias. Ex-ante, one could expect estimates to suffer from either an upward or downward bias. Fuel treatments are typically placed closer to homes in the WUI, areas where fire suppression efforts and costs are the highest, and thus our estimate would understate the impact of fuel treatments on reducing fire suppression costs. On the other hand because of the economic and regulatory incentives for conducting fuel treatments, fuel treatments occur on plots of land with lower elevation, slope and closer proximity to Forest Service roads (North et al., 2015), the characteristics of which make it easier to conduct fire suppression, leading for such estimates to overstate fuel treatments effect on reducing fire suppression costs.

Table 3 show evidence of our estimates suffering from both forms of bias by regressing FT_{it} on the observable characteristics of fire suppression effort: X_{it} & E_{it} with the inclusion of National Forest and year-month fixed effects. We find evidence that fires which occur closer to more fuel treatments tend to occur closer to the WUI and wealthier neighborhoods, while also occurring in areas easier to conduct fire suppression with closer proximity to USFS roads, lower slopes and elevations. Lastly, we find evidence that fires with fuel treatments are positively correlated with inherent fire risk, as they occur in areas with low fire severity fire regimes, south facing slopes, and in areas that are historically drier and warmer in the summer. All this suggests that our estimate of ϕ could suffer from either upward or downward biases.

5.2 Instrumental Variables Approach - NWFP Reserves (LSRs) As An IV

To overcome endogeneity concerns, I take advantage of spatial variation in NWFP reserves as an instrument for the extent of fuel treatment activity occurring close to a fire. This variation is quasi-random because the NWFP was a compromise between timber production and species conservation, with a large portion of National Forest land having similar characteristics but for their reserve status. In my sample, I explore only fires that ignite within Late-successional reserve (LSR) or Matrix lands since these lands were the most similar prior to the policy change. Because LSR's have had the unintended consequence of restricting fuel treatment activity within such areas because of increased management restrictions and litigation potential from environmental groups we hypothesize that fires igniting within such areas will receive less fuel treatments close to such fires.

More formally the instruments I use are: i) a binary variable equal to 1 if a fire ignites inside a LSR and 0 if in Matrix & ii) the acres of land within a certain distance of the ignition point that is under a LSR status. I denote this variable as Z_{it}. We can write the first stage equation relating the extent of fuel treatment activity occurring within a fire and LSR status as:

$$FT_{it} = \delta Z_{it} + X'_{ift}\Pi + E'_{ift}\Psi + \mu_f + \lambda_t + u_{ift} \tag{2}$$

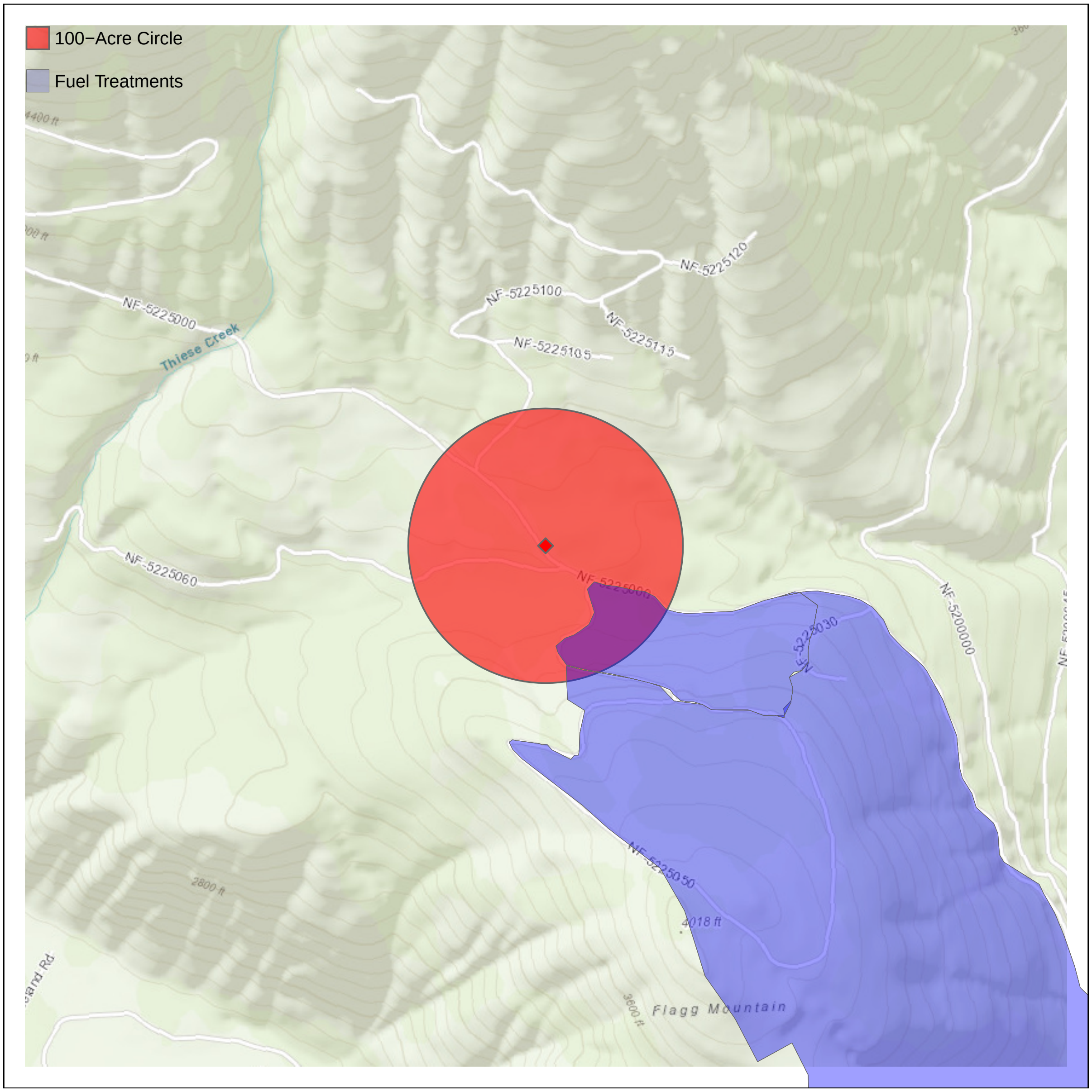
The reduced form equation relating fire suppression costs and LSR status is then:

$$Y_{ift} = \eta Z_{it} + X'_{ift}\Gamma + E'_{ift}\Omega + \mu_f + \lambda_t + v_{ift} \tag{3}$$

We can estimate equations (2) and (3) to garner an estimate of a one acre increase in fuel treatments within a certain distance of a fire's ignition on fire suppression costs by taking the ratio of the reduced form and first stage estimates: $\hat{\phi}_{IV} = \dfrac{\hat{\eta}}{\hat{\delta}}$.

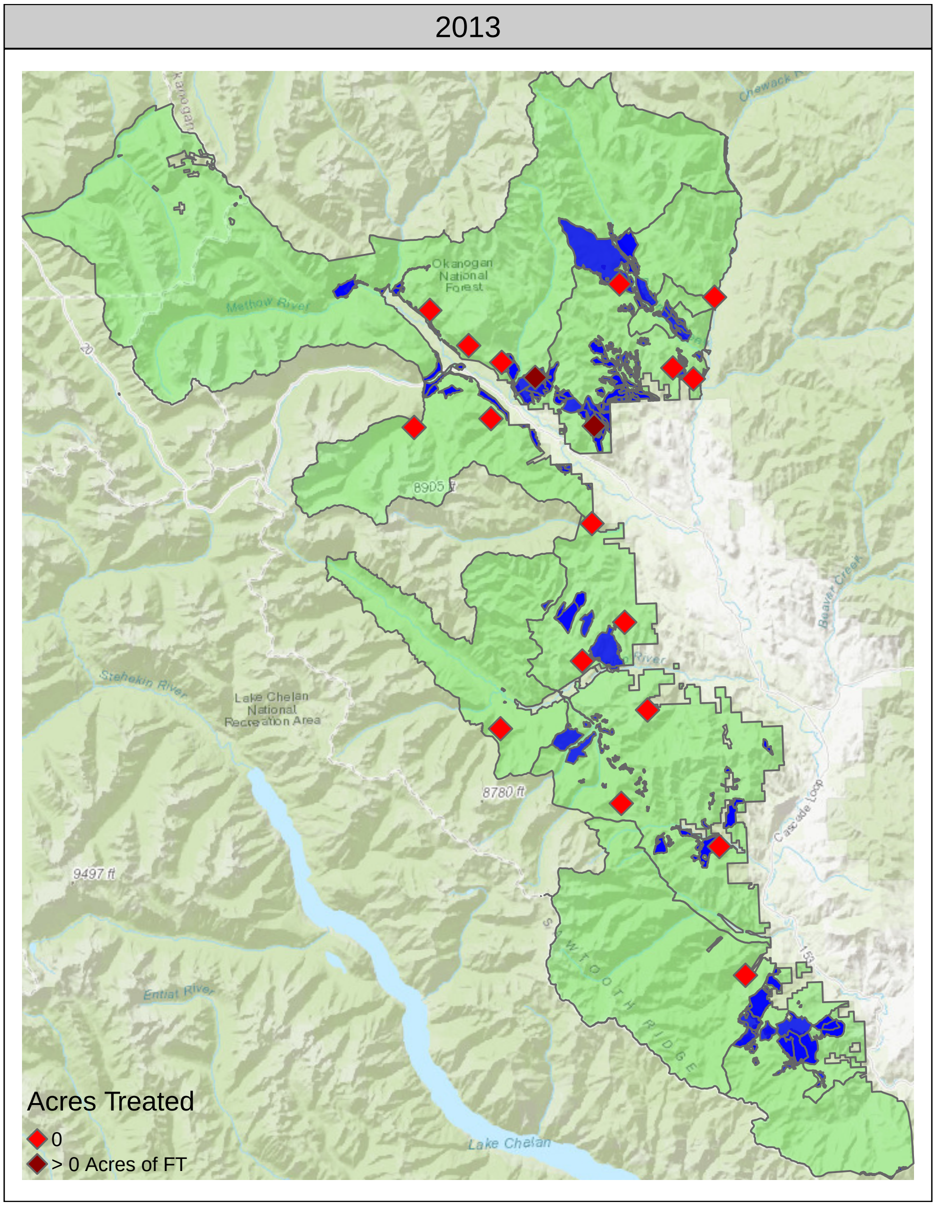
The intuition behind this IV estimation strategy is to compare fires that occur within the same national forest during the same time of year but differ on the acres of land within the ignition point

Figure 7: Example Construction of FT_{it} for Flagg Mountain Fire - 2020



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

Figure 8: Baseline Indentification Strategy Intuition



The above map shows fire ignition locations (in red) from 2013 that occur inside of the Matrix & LSR (in green) portions of the Methow Valley Ranger District, which is apart of the Okanogan-Wenatchee National Forest. Fuel treatment activity before the 2013 fire season is shown in blue.

Table 3: Balance Test Regressions - Acres Fuel Treatment

Economic Variables

	Distance WUI	Distance FS Road	Total Housing Value	Population	No. Housing Units
FT_{it}	-0.026**	-0.002***	16.786**	69.108**	27.251**
	(0.009)	(0.000)	(7.654)	(31.449)	(12.023)
LSR_{it}	0.669	0.056	-346.739	-1455.418	-547.415
	(0.490)	(0.060)	(290.478)	(1209.824)	(453.680)
N	16120	16120	16120	16120	16120

Environmental Variables

	Slope	Elevation	South Slope	Wind Speed	VPD
FT_{it}	-0.027***	-1.094***	0.000***	0.000	0.004
	(0.006)	(0.196)	(0.000)	(0.000)	(0.005)
LSR_{it}	3.261***	64.647	0.029*	-0.008	0.142
	(0.311)	(43.850)	(0.014)	(0.026)	(0.143)
N	16120	16120	16120	16120	16120

Historic Fire Risk Variables

	Percent Low Sev	VDI	Precip - CN	Temp Max - CN	VPD - CN
FT_{it}	0.059***	0.027*	-0.011***	0.008***	0.017***
	(0.012)	(0.014)	(0.003)	(0.001)	(0.002)
LSR_{it}	-2.350*	-0.424	1.094*	-0.768**	-2.057***
	(1.276)	(1.134)	(0.533)	(0.284)	(0.591)
N	15943	16128	16128	16128	16128

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

The table reports the results of five separate regressions regressing acres of total fuel treatment, FT_{it} on sets of economic, environmental, and historic fire risk variables with the inclusion of National Forest and year-month of sample fixed effects. The sample includes wildfires in 17 National Forests that are apart of the NWFP from 2006–2023. Economic variables are distance to WUI & USFS road and the total housing value, popular, and housing units within 10km of the ignition point. Environmental variables are the slope and elevation at a fires ignition point, a dummy variable equal to 1 is the slope at the ignition point is on a south facing slope aspect, along with wind speed and vapor pressure deficit (VPD) on day of ignition. Fire risk control variables include the percent low fire severity (PLS) and vegetation depature index (VDI), and the 30-year climate normals in August for precipitation, temperature max, and VPD for the ignition point for a given fire. Standard errors are clustered at the national-forest level.

that is under LSR status [See Figure 9 for a visual representation of this in an example National Forest].

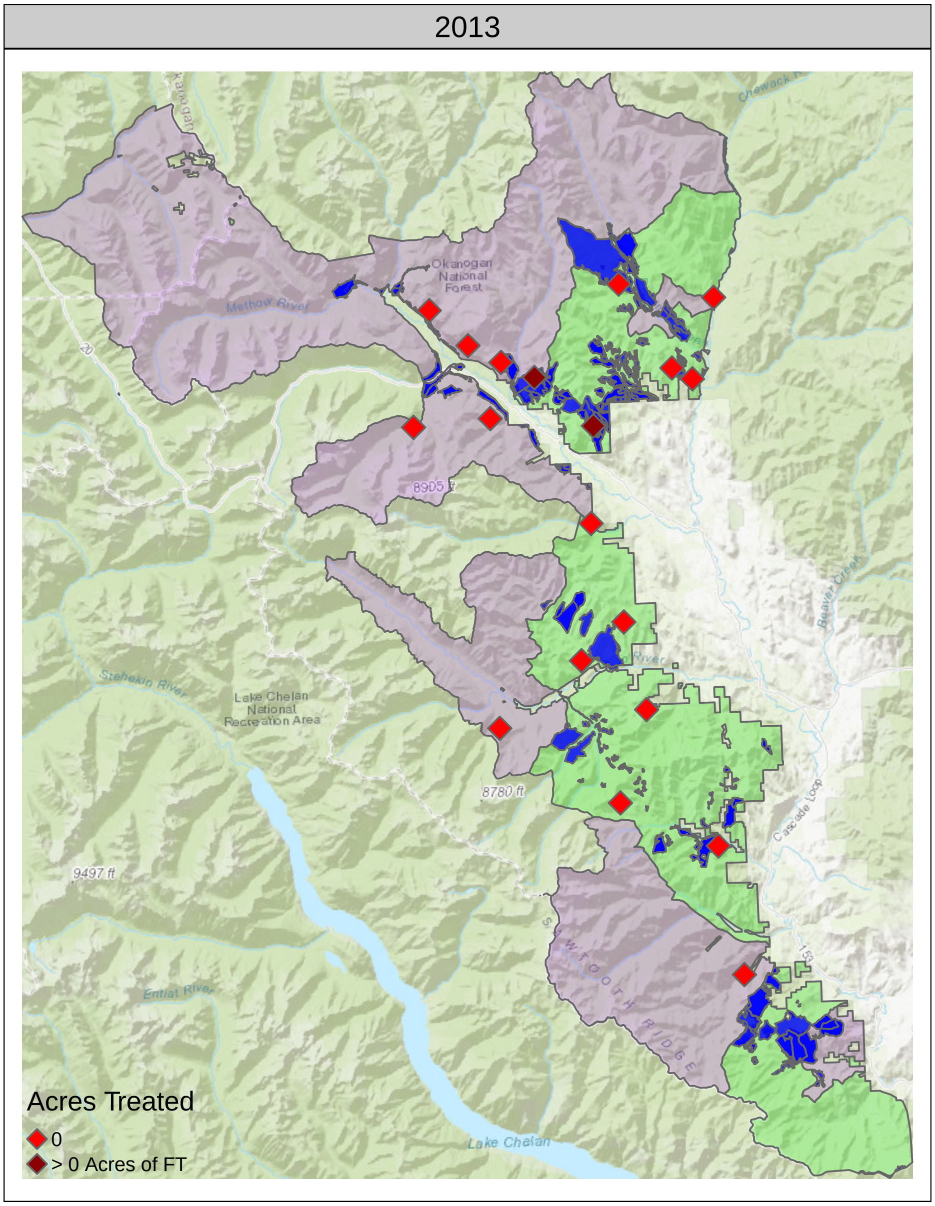
The identifying assumptions are i) relevance: e.g. Z_{it} has a strong correlation with fuel treatments, i.e. $\delta \neq 0$, ii) exogeneity: e.g. Z_{it} is uncorrelated with the unobservable determinants of fuel treatments, $E[Z_{it}u_{ift}] = 0$ and fire suppression costs, $E[Z_{it}v_{ift}] = 0$ and iii) the exclusion restriction: LSR status has no direct impact on fire suppression costs.

Our instrument would violate the first assumption if LSR status did not substantially hinder the Forest Service's ability to conduct fuel treatments. We test this assumption directly by estimating equation (2) in Section 6.

Table 4 tests the plausibility of the exogeneity assumption by regressing Z_{it} on the observable determinants of fire suppression costs with the inclusion of National Forest and year-month fixed effects. In general, we find a better balance on observable characteristics when using Z_{it} than FT_{it} as most of the variables show a statistically insignificant relationship with Z_{it}.

Lastly, the exclusion restriction would fail if fire suppression efforts generally increase in LSR areas due to a concern for saving old-growth forests. Although we cannot directly test this assumption we hypothesize this not to be the case because the USFS Cohesive Strategy points out the top priorities of the forest service in fire suppression. They first prioritize human life, then structures, and lastly natural resources (ESA habitat, watersheds, etc.) (USFS, 2000). Additionally, Plantinga et al. (2022) find no evidence of increased fire suppression effort in ESA or sensitive watershed habitats.

Figure 9: IV Indentification Strategy Intuition



The above map shows fire ignition locations (in red) that occur inside of either Matrix (light green) & LSR (purple) portions of the Methow Valley Ranger District, which is apart of the Okanogan-Wenatchee National Forest. Fuel treatment activity before the 2013 fire season is shown in blue.

Table 4: Balance Test Regressions - LSR IV

Economic Variables

	Distance WUI	Distance FS Road	Total Housing Value	Population	No. Housing Units
Z_{it}	0.669	0.056	-346.739	-1455.418	-547.415
	(0.490)	(0.060)	(290.478)	(1209.824)	(453.680)
R2	0.24	0.15	0.24	0.26	0.30
N	16120	16120	16120	16120	16120

Environmental Variables

	Slope	Elevation	South Slope	Wind Speed	VPD
Z_{it}	3.261***	64.647	0.029*	-0.008	0.142
	(0.311)	(43.850)	(0.014)	(0.026)	(0.143)
R2	0.31	0.45	0.04	0.05	0.08
N	16120	16120	16120	16120	16120

Historic Fire Risk Variables

	Percent Low Sev	VDI	Precip - CN	Temp Max - CN	VPD - CN
Z_{it}	-2.350*	-0.424	1.094*	-0.768**	-2.057***
	(1.276)	(1.134)	(0.533)	(0.284)	(0.591)
R2	0.39	0.08	0.74	0.49	0.54
N	15935	16120	16120	16120	16120

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

The table reports the results of five separate regressions regressing our instrument, a dummy on whether a fire ignites within a late-successional reserve, Z_{it}, on sets of economic, environmental, and inherent fire risk variables with the inclusion of National Forest and year-month of sample fixed effects. The sample includes wildfires in 17 National Forests that are apart of the NWFP from 2006–2023. Economic variables are distance to WUI & USFS road and the total housing value, popular, and housing units within 10km of the ignition point. Environmental variables are the slope and elevation at a fires ignition point, a dummy variable equal to 1 is the slope at the ignition point is on a south facing slope aspect, along with wind speed and vapor pressure deficit (VPD) on day of ignition. Fire risk control variables include the percent low fire severity (PLS) and vegetation depature index (VDI), and the 30-year climate normals in August for precipitation, temperature max, and VPD for the ignition point for a given fire. Standard errors are clustered at the national-forest level.

6 Estimating the Effect of Fuel Treatments on Fire Suppression Costs

6.1 Results

We begin by estimating Equation 1, the naive fixed effects regression approach, where we are interested in how fuel treatments "close" to a fire's ignition location influence fire size and suppression costs. Table 5 displays the regression results where the natural log of wildfire size and suppression costs is run on the total acres of fuel treatment within a 100-acre circle of the ignition point, FT_{it}, with the inclusion of economic, environmental, and historic fire risk control variables along with National Forest and year-month fixed effects. As more controls and fixed effects are included coefficient estimates of FT_{it} attenuate to zero for both size and cost, with a small and significant coefficient estimate for size and a positive, very small, and insignificant coefficient estimate for cost. Attenuation of coefficient estimates may be due to the fact that fuel treatments are located in areas that are systematically easier to conduct fire suppression (as we saw in Table 3) and as a result we see a reduction in the magnitude of the coefficient when controlling for such factors.

Table 6 shows the first stage, reduced form and full IV regression results using an indicator variable equal to one if a fire ignites inside of a LSR and the number of acres within the 100-acre circle surrounding a fires ignition point that is in LSR status as instruments for FT_{it}. We find a significant first stage relationship as fires that ignite inside of LSRs receive, on average, 1.26 acres less of fuel treatments "close" to their ignition point, FT_{it}, than fires igniting inside of matrix areas. For reference the average acres of fuel treatment in our sample is 6.83 acres, so this effect corresponds to around a 18% decrease relative to the sample mean. We also see positive coefficient reduced form results as fires igniting inside of LSRs are on average 7.9% larger and 16.8% more expensive. Though the effect on cost is highly significant, its impact on cost is insignificant. The full IV estimate is significant for cost (at the 10% significance level, p-value $\approx$ 0.06) and insignificant for size. We can interpret the coefficient as a one acre increase in fuel treatments "close" to a fire reduces fire suppression costs by 13.4% on average (6.5% for fire size). Another way of interpreting this is that for a 10% increase in fuel treatments across the fire prone landscape we will see a corresponding 134% decrease in fire suppression costs for fires that ignite. The first stage and reduced form estimates significance and full IV coefficients are similar when using acres in LSR status "close" to an ignition point as an instrument for FT_{it}.

6.2 Robustness Checks

Table 7 shows the IV estimation results when using a sample of matched fires.

Table 8 shows the IV estimation results when estimating on 4 different sub-samples of fires: i) lightning fires only, ii) fires in the NWFP area only, iii) fires from the FAMWEB cost source (2006-2014) and iv) fires that are not associated with a complex (2015-2023).

Table 5: Baseline Fire Size & Cost Regression Results

	(I)	(II)	(III)	(IV)	(V)
Log Size					
FT_{ift}	-0.006***	-0.003***	-0.002***	-0.001***	-0.001***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Econ Controls	No	No	Yes	Yes	Yes
Envir Controls	No	No	No	Yes	Yes
Fire Risk Controls	No	No	No	No	Yes
National Forest FE:		Yes	Yes	Yes	Yes
Year-Month FE:		Yes	Yes	Yes	Yes
R2	0.00	0.07	0.08	0.10	0.10
N	15935	15935	15935	15935	15935
Log Cost					
FT_{ift}	-0.021***	-0.002*	0.000	0.000	0.000
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
Econ Controls	No	No	Yes	Yes	Yes
Envir Controls	No	No	No	Yes	Yes
Fire Risk Controls	No	No	No	No	Yes
National Forest FE:		Yes	Yes	Yes	Yes
Year-Month FE:		Yes	Yes	Yes	Yes
R2	0.01	0.69	0.70	0.70	0.70
N	15935	15935	15935	15935	15935

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

The table reports the results of five separate regressions of the natural log of wildfire size and suppression cost on the total acres of fuel treatment within a 100-acre circle of a fire, FT_{it}. The sample includes wildfires in 17 National Forests that are apart of the NWFP from 2006–2023. The different columns report the coefficient estimates and with the inclusion of Economic, Environmental, and fire risk control variables. Economic controls include a cubic for distance to WUI & USFS road, the total population, housing units and housing value within 10km of the ignition point. Environmental controls include exisiting vegetation group type (EVT), topographic controls such slope, elevation, aspect class, and topographic ruggedness (TRI) at the ignition point, along with weather controls such as mean and max temperature, wind speed, precipitation, and vapor pressure deficit on day of ignition. Fire risk control variables include: percent low fire severity (PLS) and vegetation depature index (VDI). National forest fixed effects include the 17 national forests apart of the NWFP. Standard errors are clustered at the national-forest level.

Table 6: IV First Stage & Reduced Form Regression Results

	First Stage	Reduced Form		IV		OLS	
	FT_{it}	Size	Cost	Size	Cost	Size	Cost
LSR	-1.260***	0.079	0.168***				
	(0.420)	(0.059)	(0.047)				
FT_{it}				-0.065	-0.134*	-0.001***	0.000
				(0.062)	(0.076)	(0.000)	(0.001)
1st Stage F-Stat	15.05						
R2	0.21	0.11	0.70	-0.27	0.31	0.10	0.70
N	15935	15935	15935	15935	15935	15935	15935

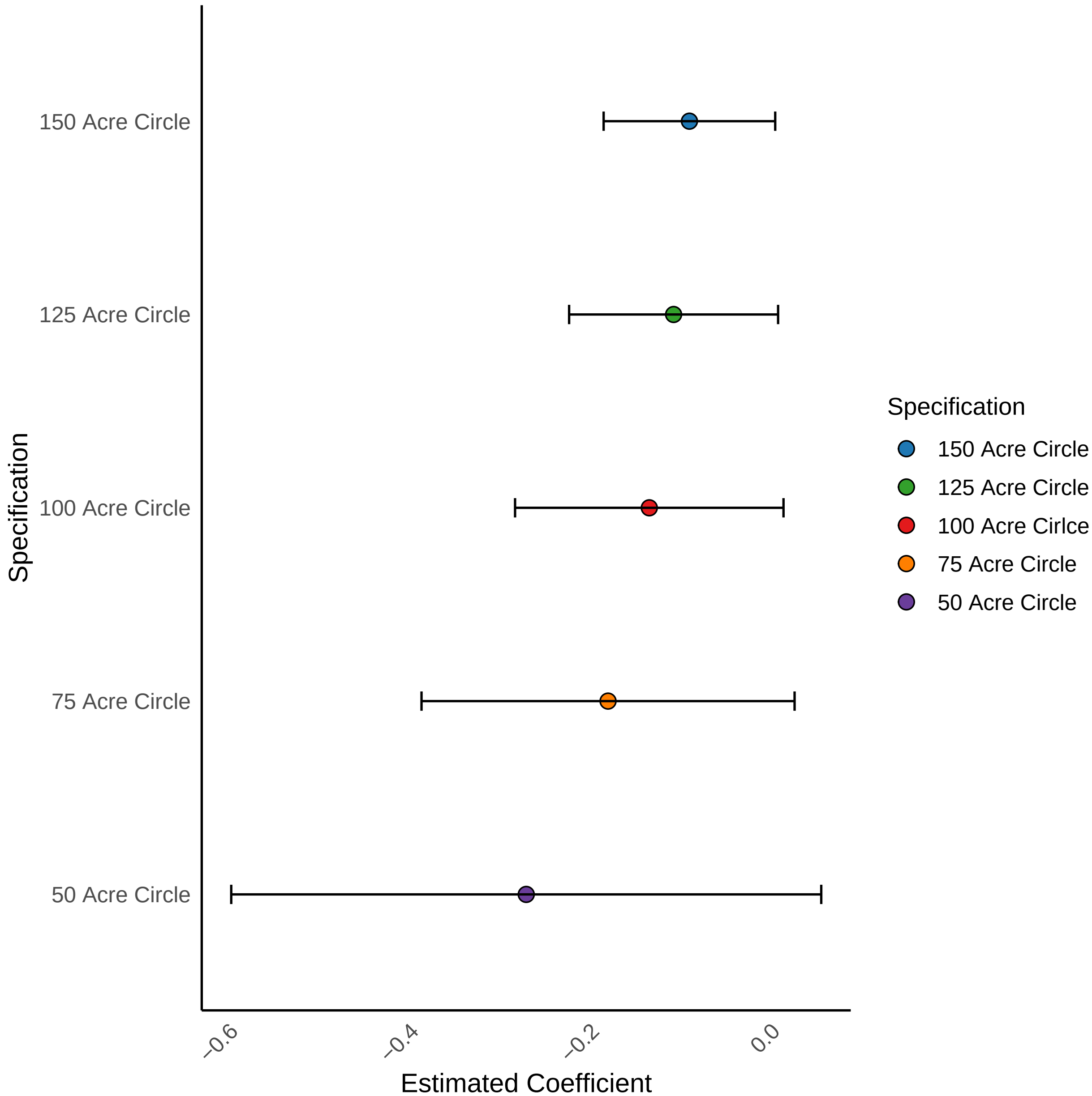
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The table reports the results of five separate regressions for the first stage, reduced form, and full IV estimate results using two instrumental variables: indicator for whether a fire occurs within a late-successional reserve or the acres of LSR within 1107 ft of a fire: LSR & $AcresLSR$. The sample includes wildfires in 17 National Forests that are apart of the NWFP from 2006–2023. The first column reports the coefficient estimates for the first stage, FT_{it}, while the second and third columns are the reduced form results on the natural log of fire size and suppression costs. The fourth and fifth columns are the full 2SLS regression results on the natural log of wildfire size and suppression cost. Each regression includes economic, environmental, and fire risk control variables. Economic controls include a cubic for distance to WUI & USFS road, the total population, housing units and housing value within 10km of the ignition point. Environmental controls include exisiting vegetation group type (EVT), topographic controls such slope, elevation, aspect class, and topographic ruggedness (TRI) at the ignition point, along with weather controls such as mean and max temperature, wind speed, precipitation, and vapor pressure deficit on day of ignition. Fire risk control variables include: percent low fire severity (PLS) and vegetation depature index (VDI). National forest fixed effects include the 17 national forests apart of the NWFP. Standard errors are clustered at the national-forest level. First stage F-statistics are calculated via cluster robust-standard errors from the Fixest package in R.

Table 9 shows the IV estimation results on different specifications of the independent and dependent variables: i) using log fuel treatments, ii) 50 acre FT_{it} circle (as opposed to 100), iii) a binary variable for whether a fire is large or not (>100 acres).

Figure 10 shows how the IV estimate on fire suppression cost varries by different specifications of the fire fuel treatment acre circle size: 50, 75, 100, 125, 150 acres.

Figure 10: IV Cost Estimate By Fire Fuel Treatment Acre Circle Size



The above figure plots the IV cost estimate based on different specifications of fire fuel treatment acre circle size.

Table 7: IV Matching Estimate Results

	Log Fire Size - LSR IV	Log Fire Cost - LSR IV
Point Estimate	-0.053	-0.134
95% CI	[-0.1,-0.006]	[-0.229,-0.04]
N	7190	7190

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

7 Counterfactual Costs & Benefits of Fuel Treatments

8 Conclusion

9 To Do List

1. **Improve Fire Cost/Zero Cost Problem**
   (a) Try matching 0 costs to ICS to get their cost.
   (b) Try to fill in zeros by predicting the cost.
   (c) Estimate using inverse hyperbolic sine transformation.
   (d) Use cost info from USFS (in process).
2. **Addressing Potential Spillovers**
   (a) Demonstrate potential for spillovers in theoretical model.
   (b) Add number of fires occurring at the same time in a region as a control.
3. **Quantile IV Estimation**
   (a) Estimate size through quantile regression approach.
4. **Finish Theoretical Model**
   (a) Put together model and write down sets of predictions from model
5. **Counterfactual Simulations**
   (a) Derive estimates savings from fuel treatments with i) proportional increase in all FT projects and ii) by completing proposed but incomplete projects.
6. **Robustness Checks**

(a) "Spatial RD": limit sample to fires that are within a certain proximity to Matrix/LSR boundaries.

(b) "Falsification Test": randomly assign Matrix & LSR polygons to either designation and keep the total area the same for both. Then re-run restimating EQs.

7. **Rewrite Introduction**

8. **Rewrite Background**

   (a) Explain argument that differences in LSRs and Matrix areas are much less pronounced on East side of Cascades as opposed to west side.

9. **Figures and Tables**

   (a) Tables 3 and 4: Estimate in one regression so these are conditional correlations. Try to condense them into one Table or Figure.

   (b) Alternatively, plot z-scores of coefficient estimates in a figure.

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Table 8: LSR IV - Robustness Checks - Estimation On Different Subsamples

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Lightning Only Fires					
LSR	-1.863**	0.134*	0.270***		
	(0.682)	(0.076)	(0.075)		
FT_{it}				-0.072	-0.145*
				(0.059)	(0.078)
1st Stage F-Stat	7.46	7.46	7.46	7.46	7.46
N	8567	8567	8567	8567	8567
NWFP Area Only Fires					
LSR	-1.608***	0.080	0.149**		
	(0.414)	(0.062)	(0.052)		
FT_{it}				-0.050	-0.093*
				(0.047)	(0.049)
1st Stage F-Stat	15.05	15.05	15.05	15.05	15.05
N	9011	9011	9011	9011	9011
FAMWEB Only Fires					
LSR	-1.253**	0.020	0.123		
	(0.454)	(0.050)	(0.071)		
FT_{it}				-0.016	-0.098
				(0.040)	(0.069)
1st Stage F-Stat	7.633	7.633	7.633	7.633	7.633
N	8513	8513	8513	8513	8513
No Complex Fires					
LSR	-1.694**	0.160	0.258**		
	(0.639)	(0.105)	(0.095)		
FT_{it}				-0.094	-0.152
				(0.087)	(0.097)
1st Stage F-Stat	7.032	7.032	7.032	7.032	7.032
N	7400	7400	7400	7400	7400

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

The above table explores the robustness of the main IV regression results using an indicator for whether a fire occurs within a late-successional reserve as an instrument on different samples of fires. Each regression includes the controls, National Forest, and month-year fixed effects used in Table 6 The first sample includes only fires started by lightning, the second fires that start inside of Matrix and LSRs within the NWFP area. The third sample uses only one source of fire cost data from FAMWEB (2006-2014). The fourth sample only includes fires that not apart of a complex from the NIFC fire cost data source (2015-2023).

Table 9: LSR IV - Robustness Checks - Different Specifications

	1st Stage	RF Size	RF Cost	IV Size	IV Cost
Log Fuel Treatment					
LSR	-0.096***	0.079	0.168***		
	(0.030)	(0.059)	(0.047)		
$\log(FT_{it})$				-0.829	-1.758**
				(0.709)	(0.806)
Controls	Yes	Yes	Yes	Yes	Yes
National Forest FE:	Yes	Yes	Yes	Yes	Yes
Year-Month FE:	Yes	Yes	Yes	Yes	Yes
1st Stage F-Stat	10.289	10.289	10.289	10.289	10.289
R2	0.26	0.11	0.70	-0.07	0.50
N	15935	15935	15935	15935	15935
Log Cost Per Acre					
LSR	-1.260***	-	0.089**		
	(0.420)	(0.037)	(0.037)		
FT_{it}				-	-0.071*
				(0.038)	(0.038)
National Forest FE:	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Year-Month FE:	Yes	Yes	Yes	Yes	Yes
1st Stage F-Stat	8.994	8.994	8.994	8.994	8.994
R2	0.21	0.82	0.82	0.68	0.68
N	15935	15935	15935	15935	15935
Above Median Size & Cost					
LSR	-1.260***	0.014	0.014***		
	(0.420)	(0.016)	(0.005)		
FT_{it}				-0.011	-0.011*
				(0.014)	(0.005)
National Forest FE:	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Year-Month FE:	Yes	Yes	Yes	Yes	Yes
1st Stage F-Stat	8.994	8.994	8.994	8.994	8.994
R2	0.21	0.10	0.76	-0.10	0.57
N	15935	15935	15935	15935	15935

A Appendix

A.1 Land-Use Allocations Under The NWFP

Thirty percent of the NWFP area comprises of a network of late-successional reserves (LSRs) designed to protect remaining old-growth forests and habitat for the NSO and marbled murrelet. Another thirty percent of NWFP area is comprised of “Congressionally Reserved" (CR) areas, areas such as National Parks or wilderness areas. Riparian reserves – areas designed to protect and restore salmonid habitat – comprise another 11 percent of the NWFP area. In both LSRs and riparian reserves fuel treatment activity is possible though limited due to potential for litigation's and management restrictions. However, in a good portion of CR areas, such as wilderness areas, fuel treatment is not allowed. Non-reserved “matrix” lands, are regions in which the majority of timber harvest and other silvicultural activities take place comprises 16 percent of NWFP area [See **??** for a map of NWFP areas and Table 10 for a list of and description of all land allocations under the plan].

A.2 Determination of Northern Spotted Owl Critical Habitat

USFWS determines blocks of critical habitat based on habitat that is representative of the birds historical distribution and current nesting sites (USFWS, 2007). The size of blocks, based on areas determined through ecological modeling, are large enough to support a given number of owls. Blocks are then spaced out to facilitate dispersal between blocks. Because nesting sites, modeling techniques, and suitable habitat for the NSO change over time, critical habitat has changed substantially when re-designated. These dynamics also explain why critical habitat and owl nesting sites don't always overlap with LSRs from the NWFP since LSRs were determined in 1994. In fact around 40 percent of historical nesting owl pairs resided in Matrix rather than LSR lands in eastern Washington State (Gaines et al., 2010).

Critical habitat designations can also occur for political reasons in addition to those described above (notice how re-designations take place right around presidential elections). The vast majority of critical habitat designations have occurred only on Federal lands despite State and private lands also being suitable. It was only until the 2012 designation that a small portion of State lands were designated while designating private land proved to be politically untenable. For example, the 2012 designation proposed designating 1.3 million acres of critical habitat in private lands but did not pass in the final ruling.

Table 10: **Land Allocations Under NWFP**

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

Table 11: **Main Policy Events & Descriptions**

Year	Event	Description
1990	NSO Declared Threatened	USFWS establishes the NSO as a **threatened** species under the ESA.
1992	1st NSO Critical Habitat Designation	6.9 million acres of **critical habitat** are designated on **federal** forest land in WA (2.2), OR (3.8), and CA (1.4).
1994	Northwest Forest Plan	Established a system of **reserves** on 24.4 million acres of **federal** forest land to conserve old growth forest, NSO, and marbled murrelet habitat.
2008	2nd NSO Critical Habitat Designation	Redesignated 5.3 million acres of **critical habitat** on **federal** forest land in WA (1.8), OR (2.2), and CA (1.3).
2011	NSO Revised Recovery Plan	**Endorsed fuel treatment** activity in **critical habitat** areas containing “dry" forests with historically low-mid severity fire regimes. Effectively encouraged and lowered barriers for federal agencies to engage in fuel treatments that protect the NSO from future wildfires.
2012	3rd NSO Critical Habitat Designation	Redesignated 9.5 million acres of **critical habitat** on **federal and state** forests in WA (2.9), OR (4.5), and CA (2.1). The designation proposed listing an additional 1.3 million acres of critical habitat on **private** land but this did not make the final designation.
2021	4th NSO Critical Habitat Designation	**Excluded** .2 million acres from the 2012 designation. **Revoked** a prior rule issued during the final days of the Trump administration, which would have excluded 3.4 million