DISSERTATION

ESSAYS ON NATURAL DISTURBANCES AND THE PROVISION OF ECOSYSTEM SERVICES: MONETIZING IMPACTS, ASSESSING MANAGEMENT TRADEOFFS, AND MEASURING VULNERABILITY

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ABSTRACT

ESSAYS ON NATURAL DISTURBANCES AND THE PROVISION OF ECOSYSTEM SERVICES: MONETIZING IMPACTS, ASSESSING MANAGEMENT TRADEOFFS, AND MEASURING VULNERABILITY

This dissertation evaluates the effect of natural disturbances on the provision of ecosystem services. The first chapter examines whether small and frequent wildfires affect drinking water prices, finding both short-run and long-run effects on downstream surface water resources and subsequent prices. The results indicate that water system variable cost rises immediately following a wildfire, encouraging capital investment to reduce variable cost and resulting in a significant effect of wildfire on fixed cost in the long run. The second chapter examines how increased Forest Service spending on fire management has affected non-fire management. The results indicate that spending on fire has increased in western regions, with spending cuts across non-fire and fire programs, and large impacts on eastern regions. In many cases it is a combination of direct and indirect effects that contribute to spending cuts in non-fire programs, and many programs experience additional cuts not associated with fire. The third chapter explores climate-induced changes in rangeland grazing services on National Forest land in the Intermountain West, measuring vulnerability based on environmental, economic, and social factors. Grazing on National Forest land is found to contribute to local economic conditions but is also associated with adverse effects on rangeland vegetation and water when the forage appropriation rate is high. Overall, the drivers of vulnerability are heterogeneous across the region, suggesting that management decisions and adaptive efforts may be best served at the local level.

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Introduction

Ecosystem services are broadly defined as benefits flowing from nature. These services reflect a crucial link between our economic, social, and environmental systems. Ecosystem services are varied and typically not traded in markets, making it challenging to assess changes in the provision of services. This dissertation aims to evaluate various effects of natural disturbances on the provision of ecosystem services, focusing particularly on wildfire and climatic changes. Each chapter assesses ecosystem services from a different but complementary dimension, utilizing an interdisciplinary approach that builds on previous economic and ecological literature. The first chapter examines whether small and frequent wildfires affect the cost of providing drinking water and subsequent water prices. The second chapter examines how increased spending on fire management has affected non-fire management on National Forest land. The third chapter explores climate-induced changes in rangeland grazing services on National Forest land in the Intermountain West, measuring vulnerability based on environmental, economic, and social factors.

Following a wildfire, changes in soil and vegetation conditions can adversely impact the quality and quantity of downstream water resources used by drinking water systems. Previous research has documented the negative impact of large extreme wildfires on water treatment cost, but small more frequent wildfires have been largely ignored, and the long-term capital response to wildfire remains unclear. The first chapter utilizes data for drinking water systems spanning the state of Utah to assess whether small more frequent wildfires that occur upstream from drinking water intakes impact water provisioning cost and subsequent consumer prices across time. Panel analysis is used to assess 25 years of wildfire and estimate water provisioning cost and demand

across water systems using a two-staged ordinary least squares (OLS) regression approach incorporating several lagged wildfire effects.

Permanent surface water intakes are found to be significantly influenced by small regular wildfire in both the short run (1 year after) and long run (10 years after). The results indicate that water system variable cost rises immediately following a wildfire, and that this encourages capital investment to reduce variable cost, resulting in a significant effect of wildfire on fixed cost in the long run. This is supported by testing the intertemporal relationship between water provisioning fixed cost and variable cost. The estimates show that the capital investment effect from wildfire is amplified for larger fires. The effect of wildfire in the medium run (5 years after) depends on fire characteristics as well as decisions to lower variable cost through investment. The impact of wildfire on water price is influenced by fire size, distance, and duration, as well as whether the affected water intake is permanent or seasonal. Post-fire management actions are also important, and the lack of detailed information on management likely dampens the effects identified in this analysis.

The U.S. Forest Service is charged with managing federal lands with a multiple-use agenda. This goal has becoming increasingly challenging over the years as the cost of fire management has consumed a growing share of the agency's budget. That said, it is unknown which programs have been affected the most by increased spending on fire, and it is unclear if this impact is evenly dispersed across Forest Service regions. It is also uncertain what portion of spending cuts stem from increased fire spending versus other sources and declines in the Forest Service's total budget, which has fallen in some years. The second chapter utilizes Forest Service regional funding allocation data for all fire and non-fire budget categories from FY2004-FY2016 to identify which non-fire programs and Forest Service regions have been affected by increased spending on fire. A

unique OLS regression model is used to separate the effect of increased fire spending into a permanent effect (operating directly through changes in annual appropriations and indirectly through carryover funds) and a temporary effect (operating through supplemental fire funds that are repaid in following years).

Over the sample, non-fire spending fell $817 million (USD 2016) and the results indicate that around 59% of this was attributed to permanent increases in fire spending, while the remainder came from other cuts equating to around $420 million (USD 2016). Restoration spending was found to increase with fire spending, so cuts in other non-fire programs exceed $817 million. Spending on fire has increased in western regions, with spending cuts across non-fire and fire programs, and large impacts on eastern regions. In some instances, declines in non-fire spending is directly linked with increased fire spending, while in other cases it is associated with increased carryover funds to support fire spending. In many cases it is a combination of direct and indirect effects that contribute to spending cuts in non-fire programs, and many programs experience additional cuts not associated with fire.

Climate change and associated disturbances are likely to alter the flow of future grazing services provided by rangelands in the western United States. Changes in temperature, precipitation, and evapotranspiration are expected to influence vegetation and hydrologic trends across rangelands in the region, potentially altering the flow of future grazing services for livestock beneficiaries. Rangelands managed by the U.S. Forest Service are an important source of forage for livestock operators in the Intermountain West and grazing on National Forest land supports employment and income in many local economies. The third chapter uses spatial data on projected climate-induced changes in vegetation and water to classify vulnerability to changes in rangeland grazing services from National Forest land in the Intermountain West. Vulnerability is categorized

across counties as a function of environmental, economic, and social conditions using standardized indicators of exposure to change, sensitivity to change, and ability to adapt to change. Several linear regressions are also tested to describe the economic impacts of grazing on National Forest land in the region, as well as environmental impacts associated with grazing.

For economic impacts, focus is placed on livestock employment (total employment and industry concentration) and livestock income (worker, firm, and industry concentration). For environmental impacts, attention is placed on vegetation conditions (rangeland vegetation and riparian vegetation), water conditions (quality and quantity), and soil conditions. The results suggest that stream runoff will come earlier, and summer water availability will decline in the northern part of the region, potentially reducing vegetation availability. Despite increased stress on water resources in parts of the region, vegetation productivity may actually increase in many areas due to warming temperatures and CO_2 fertilization effects at high elevations. This suggests that some areas of National Forest land, particularly those at higher elevations, may support adaptation needs on lower-elevation lands, public and private. Grazing on National Forest land is found to contribute to local economic conditions but is also associated with adverse effects on rangeland vegetation and water when the forage appropriation rate is high. Overall, the drivers of vulnerability are heterogeneous across the region, suggesting that management decisions and adaptive efforts may be best served at the local level.

Chapter 1

Do Regular Wildfires Heat up the Price of Drinking Water: A Utah Case Study

1.1 Introduction

Following a wildfire, changes in soil and vegetation conditions can adversely impact the quality and quantity of downstream source water before it is treated by drinking water systems. Previous research has documented the negative impacts of wildfire on water conditions, most often finding elevated turbidity and nutrient levels immediately following a wildfire (e.g. Emelko et al., 2011; Tecle and Neary 2015; Hohnor et al. 2016). Research has also found long-term effects on water quality, suggesting that effects can potentially persist for decades (Emelko et al., 2016). Reduced source water quality has been shown to significantly increase the cost of water treatment (Christiansson, 1979; Holmes, 1988; Dearmont et al., 1998; Davies and Mazumder, 2003; Emelko et al., 2011; Price et al., 2017). Since most water systems operate under average cost pricing, water prices are expected to change when there is a change in the cost of provision. Unfortunately, past research has primarily focused on large wildfires with unique features, ignoring potential impacts from small and more frequent wildfires. Furthermore, most studies only estimate the immediate impact on cost, failing to account for capital responses that might result over time (Price et al., 2017). This paper addresses these gaps by testing whether small regular wildfires impact the cost of water provision and subsequent drinking water prices, testing for both immediate and long-term effects. Cost is also separated into variable cost and fixed cost to test for potential capital investment responses associated with wildfire.

Previous estimates of average total cost (ATC) for water systems typically find economies of scale, with considerable declines in average cost as system size increases (Sauer, 2005). This makes water systems a classic example of a "natural monopoly." As a natural monopoly, many water systems are publicly operated and regulated to charge prices according to their average cost of water provision. The U.S. Environmental Protection Agency (EPA) also regulates and monitors water quality conditions with help from state and local governments. After a wildfire, changes in water conditions can result in a higher cost for water systems to treat raw water and meet the necessary water quality standards. Changes in treatment cost are then passed on to consumers through higher prices for water.

Water demand is typically very inelastic, with changes in price having minimal effect on the quantity consumed. Surveying 25 years of water demand estimates, Worthington and Hoffman (2008) find price elasticity estimates in the range of 0 to -0.5 in the short run, and -0.5 to -1 in the long run. Inelastic demand for water means that changes in water prices can heavily impact consumer welfare. For simplicity, most studies assume demand is perfectly inelastic and estimate changes in cost assuming it translates one-to-one into a change in price. For this study, cost and demand are simultaneously estimated, and price elasticity estimates for demand range from -0.422 to -0.629. When demand is not perfectly inelastic, the change in price is greater than the change in cost. This is due to water systems being a natural monopoly and operating at a higher cost when quantity falls from increased price. This suggests that previous studies understate the impact of wildfire on price by not accounting for demand responses to changes in price.

For this paper, a panel dataset is assembled to estimate water supply and demand for 144 drinking water systems across the state of Utah from 1999-2013. The impact of wildfire that occurs upstream from drinking water intakes is assessed across both space and time, accounting for

important wildfire and water system characteristics. Surface water and groundwater intakes are assessed separately, as are seasonal and permanent intakes. The model is intended to focus on small (1,000's of acres) and more recurrent wildfires, as opposed to large severe wildfires that are unique. Up to 10 years of lagged effects are tested, and cost is separated into variable cost and fixed cost to test for potential capital investment responses to regular wildfire. By simultaneously estimating water supply and demand, this study is able to directly link wildfire with potential changes in water price.

Water systems relying on forested water supplies are at risk as the frequency, size, and severity of wildfires have increased in recent decades (McKenzie et al., 2004; Westerling, 2006; Flannigan et al., 2009, 2013). Wildfire activity is expected to continue increasing, largely attributed to changing climate, weather, drought, and fuel load conditions (McKenzie et al., 2004; Westerling, 2006; Flannigan et al., 2009; Mooney, 2015). Fire seasons are now on average 78 days longer than in 1970, and the U.S. sees twice as many acres burned compared to three decades ago (Mooney, 2015). The acreage burned is expected to double again by mid-century (Mooney, 2015). These trends have led to increased attention surrounding the impact of wildfire on water resources (Sham et al., 2013; Bladon et al., 2014), and a greater urgency for water systems to understand and manage for wildfire effects on drinking water.

This paper proceeds as follows. First, the literature is reviewed to identify important linkages between wildfire and water conditions, and to determine how water supply and demand have been modeled in previous studies. Next, there is a discussion of the modeling framework used to link wildfire with changes in drinking water provisioning cost and subsequent consumer water prices. Following, there is an overview of the data utilized to empirically test for a causal relationship between wildfire and drinking water prices in the state of Utah. In the results section, water demand

is estimated using various specifications of price to test whether consumers respond to marginal price, average price, or another perception of price when facing block-pricing. Water supply is then modeled using a hedonic cost function approach, utilizing the estimate of water demand in a two-staged process. The supply and demand estimates are then used to assess the impact of wildfire on water price across time. The effect of wildfire is further separated for variable cost and fixed cost to examine intertemporal investment behavior and test for possible capital responses to wildfire. Finally, the model limitations are discussed along with concluding remarks.

1.2 Literature

1.2.1 Linking Wildfire with Water Conditions

Wildfire is generally defined as an unplanned fire occurring in an area of combustible vegetation. This includes any fire caused by lightning or other natural causes, by accidental (or arson-caused) human ignitions, or by an escaped prescribed fire. Wildfire is a natural disturbance that occurs in many terrestrial ecosystems across the United States. It can generate a range of effects on soils, water, riparian biota, and wetland components of ecosystems. Together, these effects can impact raw water quality and quantity conditions prior to treatment for human use. Increases in surface runoff following a wildfire can change the physical, chemical, and biological characteristics of water across a watershed, and can result in additional transport of solid and dissolved materials to stream channels, water bodies, and pipes. The most observable effects often stem from elevated suspended and bedload sediments, but there can also be changes in the chemical composition of source water both above and belowground.

Water quality refers to the physical, chemical, and biological characteristics of water. Physical characteristics of interest to water systems are sediment concentrations and turbidity. Increased

erosion following wildfire has been shown to elevate total suspended solids (TSS) and turbidity levels in surface waters (Dunne and Leopold, 1978; Satterlund and Adams, 1992; Brooks et al., 2003; Lane et al., 2006; Wilkinson et al., 2006: Malmon et al., 2007; Sheridan et al., 2007; Mast and Clow, 2008; Emelko et al., 2011; Rhoades et al., 2011; Oliver et al., 2011; Murphy et al., 2012; Writer et al., 2014; Tecle and Neary, 2015; Hohner et al., 2016). Post-fire sediment yields are generally the highest in the first year or so after burning, especially when the burned watershed has been exposed to large, high intensity rainfall events immediately after the fire has exposed the soil surface (Neary et al., 2009).

Large post-fire sediment fluxes impact drinking water systems in two important ways. First, there is the risk that reservoirs, infiltration basins, and treatment works will be filled, damaged, or otherwise disrupted by sediment. Second, high sediment loads increase pre-treatment processing needs (and cost) for suspended sediment removal. A typical water system is prepared to deal with normal levels of turbidity as well as spikes in turbidity. However, increased turbidity after a wildfire may require more treatment chemicals and can cause additional wear and tear on water treatment filters. These impacts are typically largest in areas adjacent to the wildfire, yet after the 2003 wildfires in Southern California, treatment works and reservoirs as far as 100 miles from fire were affected by increased sediment loads (Meixner and Wohlgemuth, 2004).

Dissolved chemical constituents of importance to water systems include nitrogen (N), phosphorus (P), chloride (Cl), and sulfate (SO4). Elevated nutrient concentrations are often observed in streams following a wildfire (Hauer and Spencer, 1998; Bladon et al., 2008; Lane et al., 2008; Mast and Clow, 2008; Emelko et al., 2011; Rhoades et al., 2011; Writer et al., 2012; Son et al., 2015; Tecle and Neary, 2015; Hohner et al., 2016). Wildfire characteristics determine the ecological impact on water, but the hydrologic cycle determines the magnitude of erosion and the

transport and deposition of sediment and nutrients. A major issue that water systems confront is whether wildfires create water conditions that are outside of the established water quality standards.

Drinking water quality standards have been established by the U.S. Environmental Protection Agency (EPA) and serve as the benchmark for water quality throughout the United States. Several chemical constituents that are regulated by water quality standards are potentially impacted by wildfire. The EPA sets both primary and secondary standards for quality. Primary standards are mandatory and are established to protect the public against health risks. Secondary standards are non-mandatory and are established as guidelines to assist public water systems in managing their drinking water for aesthetic considerations such as taste, color, and odor. Primary standards cover nitrate-nitrogen (NO3-N) and nitrite-nitrogen (NO2-N) which are both potentially affected by wildfire. Secondary standards apply to pH, sulfate (SO4-S), total dissolved solids (TDS), chloride (Cl), turbidity, and several constituents that influence the taste, color, and odor of water. Phosphate phosphorus (PO4-P) is not directly regulated but can also affect the color and odor of water by accelerating the eutrophication process. Wildfire has the potential to influence any or all these water quality parameters, depending on the ecological impact of the fire.

Nitrate-nitrogen (NO3-N), ammonium (NH4-N), and organic-nitrogen (N) are the nitrogen forms most commonly studied as indicators of fire disturbance. In a study conducted at the San Dimas Experimental Forest in California, researchers found an increase in nitrate export with an increase in fire severity (Riggan et al., 1994). Results three years after the fire indicated that fire increased nitrate concentrations in streams by as much as 10 times the EPA drinking water standard, and they found that elevated nitrate concentrations can persist for up to 10 years after a fire (Riggan et al., 1994). If soils on a particular site are close to nitrogen saturation, it is more

likely that nitrogen levels will exceed safe levels after a fire. It has also been shown that fertilizer application following a fire can result in higher concentrations of NO3-N in streams (Tiedemann et al., 1978). However, these post-fire effects are typically short lived, usually lasting only a few years (Kovacic et al., 1986; Monleon et al., 1997).

Phosphorus is present in several forms in soils and streams and can be concentrated in ash following a fire (Meixner and Wohlgemuth, 2004). Phosphorus is carried primarily in sediment loads, and post-fire erosion can deliver phosphorus downstream. Total phosphate (PO4-P) is reported as total P in most studies of post-fire phosphorus changes. Studies of soil leachates have reported increased levels of total phosphorous after fire (McColl and Grigal, 1975; Knighton, 1977). However, PO4-P is not as readily leached as NO3-N because it complexes with organic compounds in the soil (Black, 1968). There are no established standards for PO4-P in drinking water, only secondary standards set for water color and odor. This means that drinking water systems are not required to address phosphorus increases that result from a wildfire, unless the color and odor of the raw water is adversely impacted.

Sulfate (SO4-S) is relatively mobile in soil-water systems (Johnson and Cole, 1977). Although not as well studied as nitrogen, the mineralization process for sulfur is very similar (Neary et al., 2009). In one study, the post-fire SO4-S concentrations that were examined were found to be below the secondary water quality standard for drinking water (Landsberg and Tiedemann, 2000). Chloride (Cl) and total dissolved solids (TDS) levels are also set by secondary EPA water quality standards. Like nitrogen and sulfate, chloride is also relatively mobile. Chloride responses to fire have been documented in several studies, but all responses were significantly lower than standards set by the EPA (Landsberg and Tiedmann, 2000).

Few studies report concentrations of TDS, which serves as an aggregate measure of all dissolved substances and chemical constituents. For the studies that do exist, TDS values were found to be well below the secondary standards set by the EPA (Landsberg and Tiedmann, 2000). The pH of water is also important to water systems, as it affects the presence of chemical constituents. The pH of water can be affected by ash depositions immediately after a fire, and increased pH values of the soil can contribute to increased values of streamflow pH (Wells et al., 1979; DeBano et al., 1998; Landsberg and Tiedemann, 2000).

In a study of the 2002 Rodeo-Chediski wildfire (468,638 acres) in Arizona, the researchers measure water quality and quantity conditions downstream in the Salt River. Following the fire, total nitrogen and phosphorus rose approximately 22- and 390-times above EPA standards, respectively (Tecle and Neary, 2015). The EPA standards for lead, iron, copper, and arsenic were also found to be exceeded by about 460%, 3,000%, 300%, and 6,850%, respectively, while sulfur concentrations increased to about one half of the EPA standard (Tecle and Neary, 2015). The researchers also assess the physical properties of water, measuring flood magnitude, specific conductivity, turbidity, and temperature at the point where the Salt River enters Lake Roosevelt. Flood magnitude increased by 6,000% while specific conductivity and turbidity levels increased by 422% and 1,020,000% above EPA standards, respectively (Tecle and Neary, 2015). Fortunately, most of these impacts were short lived and dissipated within months as the continuously flowing water diluted the effects along the Salt River. On the other hand, where water is relatively stationary with little or no fresh water inputs, the authors contend that the adverse effects would likely be more persistent, especially during drought periods (Tecle and Neary, 2015).

Hohnor et al. (2016) assess the 2012 High Park wildfire (87,284 acres) in the Cache la Poudre watershed of Northern Colorado. A drinking water intake below a burned watershed and an

upstream, unburned reference site are monitored following the wildfire to address wildfire impacts on water treatment. Turbidity, nutrients, dissolved organic matter, coagulation treatability, and disinfection byproduct formation are evaluated and compared to pre-fire data. Post-fire differences for turbidity, nitrogen, and phosphorus increased by an order of magnitude (measured using a fluorescence index) compared to pre-fire differences (Hohnor et al., 2016).

Emelko et al. (2011) track source water quality following the 2003 Lost Creek Wildfire (17,300 acres) in Alberta, a Canadian province where most of the drinking water originates from forested land. The study finds elevated levels of turbidity, dissolved organic carbon, and chlorophyll for up to four years after the wildfire (Emelko et al., 2011). During this period, median turbidity levels in affected watersheds were 400% to 600% greater than in unaffected watersheds (Emelko et al., 2011). Emelko et al. (2016) later present the legacy of effects on water quality 10 years after the wildfire, particularly turbidity and phosphorus, and argue that these effects might persist for decades.

Though not frequently used for small wildfires, fire retardants are sometime used in the suppression of large wildfires. Although their effects on the soil-water environment are not a direct effect of fire, their use in the control of wildfires can produce adverse environmental impacts. Nitrogen-containing fire retardants have the potential to affect the quality of drinking water, though research on these retardants has largely focused on their impacts on aquatic environments (Norris and Webb, 1989). One study concluded that the most significant environmental impact of fire retardants is the toxic effect on aquatic organisms in streams (Gimenez et al., 2004). They noted that the amount of fire retardant used and its placement on the landscape are the two main factors determining the degree of environmental impact. Another study found that the application of fire retardant had minimal effects on surface water quality (Crouch et al., 2005). This suggests

that fire retardants can adversely impact aquatic organisms, but that retardants are not likely to significantly impact the cost of treating drinking water.

Most studies have only focused on surface water while ignoring the potential effects of wildfire on groundwater. This makes it unclear how fire might impact groundwater. That said, surface water and groundwater interact very closely. Streams interact with groundwater in three basic ways; (1) streams gain water from inflow of groundwater through the streambed, (2) streams lose water by outflow through the streambed, or (3) they do both depending upon the location along the stream. Groundwater contribution keeps streams flowing between precipitation events and after snowmelt. Surface-water bodies such as lakes and wetlands can receive groundwater inflow, recharge groundwater, or do both. The movement of water between groundwater and surface-water systems leads to the mixing of their water qualities. High quantities of nutrients or other dissolved chemicals in surface water can therefore be transferred to the connected groundwater system, especially near the surface. In particular, nitrogen, sulfate, and chloride tend to be relatively mobile, meaning that high concentrations can potentially leach into groundwater resources following a wildfire.

A key characteristic of groundwater is that it is hard to see and measure. Nevertheless, researchers have begun to study caves in order to observe the effects of wildfire on the subsurface. To do this, they investigate the chemical record of past fires preserved in cave stalagmites. Studies have found increased evaporation and decreased recharge in the years immediately after a wildfire (Nagra et al., 2016). Researchers also found nutrient flushes from the surface to the subsurface, moderated by vegetation uptake as regrowth occurs (Treble et al., 2016). Areas that are severely burned can develop water repellency, which impacts surface water runoff, but also influences the

recharge rate of groundwater in the area. Wildfire can also affect annual and seasonal water yield, peakflows and floods, baseflows, and the timing of flows (Baker, 1988).

Groundwater recharge was reduced after the 2002 McNally Fire in California, but recovered within six years (Berg and Azuma, 2008). Water flows are important for drinking water systems and influence water quality. This highlights that both water quality and quantity conditions can be affected by wildfire, and that both surface water and groundwater resources might be impacted. Recovery times after fires can range from years to decades, depending on fire characteristics and the rate of vegetation recovery, which are influenced by both natural conditions and measures taken by land managers.

The magnitude of wildfire effects on water resources is largely driven by fire severity. Fire severity is a qualitative term describing the amount of fuel consumed. The more severe the fire, the greater the amount of fuel consumed and nutrients released, and the more susceptible the site is to erosion and transport of soil and nutrients. Fire severity is considered a function of both fire intensity (energy released) and fire duration, which together determine the amount of fuel burned (Tecle and Neary, 2015). The distance of a wildfire from water intake is also important to consider. The further that water travels, the greater the ability for ecosystem services to purify and filter raw water before it is treated. Not all adverse changes in water conditions will therefore impact downstream water systems, especially if water passes through a healthy portion of the watershed before it is extracted for use. The impact of wildfire on water price thus depends on whether water provisioning cost is ultimately affected by adverse source water changes.

1.2.2 Linking Water Conditions with Water Prices

Price et al. (2017) estimate the relationship between source water quality and production costs in Canadian municipal water treatment facilities. Results show water quality, as measured by

turbidity, is a significant determinant of production costs. The findings highlight the potential costs to municipal water utilities of landscape disturbances and land use change (Price et al., 2017). Results from this analysis suggest that a landscape disturbance resulting in a 50% increase in median turbidity would increase short-term treatment cost by 4.95% in the average facility (Price et al., 2017). Unfortunately, these findings are specific to short-term variable costs and do not account for capital responses to higher turbidity. Furthermore, the effect of higher treatment costs on water prices and consumer welfare is difficult to determine without information on water demand (Price et al., 2017).

Estimation of water supply and demand is often done separately, and several model specifications have been tested in the literature. Previous estimates of water supply typically exhibit economies of scale, with considerable decreases in average cost as water plant size increases (Sauer 2005). This makes water systems a classic example of a "natural monopoly." As a natural monopoly, many water systems are publicly operated and regulated to charge prices according to their average cost of water provision. Estimating demand has proved more challenging than supply, however. This is due to the block-pricing structure commonly utilized by water systems. If the marginal price changes as consumers use more water, this creates a simultaneity issue when trying to estimate the relationship between price and quantity for consumers (Taylor, 1975).

Conventional treatment of source water consists of flocculation, sedimentation, filtration, and disinfection activities. High quality intake water with low levels of turbidity can be effectively treated by direct filtration, eliminating the sedimentation process and in some cases the flocculation process (Holmes, 1988). The cost savings of this include lower capital costs, along with lower chemical and maintenance costs. If water quality is very high, then some water systems

may omit the filtration processes altogether and simply disinfect their water (Holmes, 1988). Poor water quality is therefore associated with higher treatment costs and water prices. Organic material in runoff can also combine with chlorine to form trihalomehanes (THM's) in finished drinking water, which are suspected carcinogens and are regulated by mandatory drinking water standards. To address this issue, water systems can include the addition of ammonia, which obviates THM formation, change the point of chlorine application, or remove THM's after formation (Holmes, 1988). Each option nonetheless increases treatment costs for water systems.

Past research on water supply cost has often focused on the influence of new monitoring and treatment requirements (Clark and Goddard, 1977; Clark and Stevie, 1981; Bruggink 1982; and Feigenbaum and Teeples, 1983). National estimates for the costs of compliance have been estimated, but few models have examined individual system responses to various water quality and treatment concerns (Schmit, 1997). There has been some evaluation of treatment technologies used by small water systems (Logsdon et al., 1990; Goodrich, et al., 1992; and Malcolm Pirnie, 1993), providing a starting point for estimating changes in water treatment costs. As an alternative, others have used a hedonic approach whereby costs are assumed to be a function of overall water quality. In this setting, additional treatment costs are reflected in an index of water quality. The production technology does not require specification since a hedonic framework permits various technology combinations to reflect the same level of quality (Spady and Friedlaender, 1978).

In 1988, Holmes examined the relationship between soil erosion and water treatment costs by estimating a water production cost function which includes various water quality and economic variables. He presents a two-stage model where ambient water quality is a function of turbidity levels based on sediment loading, stream flow, and reservoir storage capacity. The second stage is then used to estimate treatment cost as a function of production, input prices, and ambient water

quality. He finds that erosion has a significant and positive effect on water treatment cost (Holmes, 1988). In his specification, environmental quality is viewed as a factor input where variations in quality induce changes in the cost of water.

Holmes estimates a Cobb-Douglas cost function, including a variable representing water quality. This framework uses engineering cost data to estimate changes in treatment costs. However, the Cobb-Douglas specification restricts the average cost estimation, so he also estimates a hedonic cost function using operating cost data. He concludes that the hedonic model fits the data well and provides reasonable estimates (Holmes. 1988). Hedonic cost analyses for water systems were also conducted by Bruggink (1982), Feigenbaum and Teeples (1983), and Teeples et al. (1986) where they focus on the effect of ownership on cost structure. The functional forms are adapted from Spady and Friedlaender's (1978) hedonic cost model for the regulated trucking industry. The hedonic specification is found to be superior to their non-hedonic specifications and costs are shown to increase significantly with the level of treatment.

In most of these frameworks, the researchers do not estimate water demand, and instead assume that it is perfectly inelastic so that changes in production cost reflect changes in water price. However, if demand is downward sloping then the estimates understate the true effect on price. When consumers reduce consumption due to a higher price, this generates a further increase in price as production declines and the average cost of provision increases. Also, when water demand is estimated, it is often estimated separate from water supply. Worthington and Hoffman (2008) provide an overview of empirical residential water demand analyses conducted in the 25 years prior, addressing both model specification and estimation. Price elasticity estimates are generally found in the range of 0 to -0.5 in the short run, and -0.5 to -1 in the long run (Worthington and Hoffman, 2008), suggesting that previous research understates the impact of wildfire on price.

Some demand models only include marginal price, while others only include a measure of average price. However, there is debate over whether consumers respond to marginal price, average price, or both when block pricing is used. To address this, Taylor (1975) introduced a decomposition of price that allows one to separate marginal and average price effects. Shortly after, Nordin (1976) argued that demand estimation should also include a 'difference' variable meant to address the income effect that arises when moving from one price block to the next. A modified Taylor-Nordin model was proposed by Opaluch (1982) to formally test whether consumers respond to either marginal price or average price. However, the model does not permit the consumer to react to a function of both marginal and average price, and the model implicitly assumes that consumers are fully knowledgeable about the rate structure, which there is little evidence to support (Chicoine et al., 1986; Brown et al., 1975).

To address these issues, Shin (1985) presented a demand model that estimates a 'price perception' parameter. Shin argued that the 'perceived price' specification is superior to Opaluch's model because the use of the perception parameter allows consistent estimation under any behavioral hypothesis. Even more important, Shin's specification allows consumers to respond to both marginal and average price, instead of one or the other as in Opaluch's model. When examining block-pricing used in electricity markets, Shin (1985) found that consumers respond to average price. Previous work typically estimates water supply and demand separately, under simplifying assumptions that water demand is exogenous from water provisioning cost. However, provisioning cost determines water price, price determines the quantity demanded, and the quantity demanded influences provisioning cost. This implies that water supply and demand are endogenous. To address this endogeneity, this study simultaneously estimates water supply and demand.

1.3 Model

For this assessment, four estimates of water demand are modeled using four different specifications of price. First, demand is modeled as a simple linear function of average price. Second, a Taylor-Nordin decomposition is tested using Opaluch's (1982) specification of price. Third, demand is modeled using the natural log of average price. Finally, a specification using Shin's price perception parameter is tested, requiring a logarithmic specification. The natural log of quantity is used for all estimates of demand. This implies that models (1) and (2) provide log-level estimates while (3) and (4) provide log-log estimates of water demand. The demand results are compared across the model specifications. This assessment contributes to the ongoing debate, while also utilizing novel water system data from Utah that has yet to be analyzed in any published studies of water demand.

As a natural monopoly, most water systems are regulated to charge prices according to their average total cost (ATC). In other words, most water systems are required to charge "breakeven" prices. This serves as an equilibrium condition, where the market price and quantity for water are simultaneously determined by the cost of providing water and the demand for water. Figure 1.1 illustrates the equilibrium between the average cost of water provision (*ATC*) and water demand (*Q(P)*), also depicting how water price changes from an increase in cost. Also shown is the difference in price when assuming demand is perfectly inelastic versus allowing demand to slope downward. When a wildfire impacts the cost of water treatment, water prices are expected to increase and the quantity of water consumed will fall. The quantity response depends on the price elasticity of demand. After a fire, *ATC* may shift upward, depending on the time it takes for the effects of fire to impact source water conditions. This is determined by the hydrologic cycle which governs precipitation and the delivery of adverse fire effects downstream, and also by behavioral

responses to manage a watershed following a wildfire. As vegetation and soil conditions improve over time, water treatment cost will return to the pre-fire level. This implies that the upward shift in *ATC* is likely temporary, and that cost will shift back down over time.

Although most water systems are regulated to charge a breakeven price, systems operate at a loss or with excess revenue in some years. This can be due to unexpected changes in the supply and/or demand of water, causing the price charged to be above or below average cost. Many water systems must also determine prices in advance, causing a lag between when price is set, and treatment cost is known. The typical rate setting process involves administrators and water district board members voting on price adjustments, generally reflecting changes in cost, both experienced and expected. Adjustments often occur annually, but in some instances water districts alter rates more or less frequently. This can cause the chosen price to be above or below average total cost in any given year. Table 1.1 shows the percent of Utah water systems assessed in this study that operate with a balanced budget (ATC=P), with excess revenue (ATC<P), or at a loss (ATC>P) across the sample period. Across the entire sample, about 80% of the time water systems ran a balanced budget, and when they didn't, they often had excess revenue. This suggests that *ATC=P* is a reasonable equilibrium assumption for a typical water system in Utah.

Water systems that don't operate with a balanced budget are still included in the sample, but their budget is controlled for using dummy variables in the model. This allows the equilibrium condition to remain valid even when a water system charges a price above or below average total cost in any given year. The frequency of balanced water system budgets suggests that systems typically charge prices according to their cost of providing water to consumers. However, many water systems do not charge a single price for water, and instead utilize a combination of base fees and variable fees. This implies that water systems are effectively setting their average cost equal

to the *average* price when they breakeven (*ATC=AP*). To determine the average price (*AP*) of water for a system, the total retail revenue is divided by the total quantity of water delivered. The first models of water demand test how consumers respond to average price. However, previous research suggests that water consumers may instead respond to marginal prices when block pricing is used. To address this, Opaluch's (1982) specification is used for model 2 and Shin's (1985) specification is used for model 4.

It is important to note some key differences between the specification used in this model and Opaluch (1982). First, his model focused on the household level on a monthly basis, while this assessment examines the water system level annually. Nonetheless, past research of aggregate and household level data has been shown to yield fairly similar results (Worthington and Hoffman, 2008). By measuring demand annually, one can also avoid concerns of seasonal variability which has been found to heavily influence demand. Second, Opaluch's framework only considers a two-block increasing rate structure, while this model generalizes the framework to include up to four price blocks. Third, Opaluch's specification does not include the base fee (i.e. a two-part tariff). A base fee is charged monthly and must be paid by consumers regardless of water use. Most water systems have an "allowance" associated with their base fee (roughly 82%), meaning that consumers can use a set amount of water before they are charged at the marginal price for water use. This model is designed to capture base fees, allowances, and variable fees.

Equation 1.1 shows how retail revenue is separated for each system (*j*) in each year (*t*). The marginal price (*MP*) of water is multiplied by the quantity of water used in each price block. For systems with an allowance, the base fee is separated into the amount paid per gallon (*BF*) and multiplied by the number of gallons allowed (Q_B). This is done in order to allow consumers to respond to base fees, which are an important component of average price. Note that if a system

does not have an allowance, then only the base fee enters equation 1.1, and if they do not have a base fee, then both terms drop out of the equation. After some simplification, equations 1.2 and 1.3 show how average price (*AP*) is separated into marginal price (*MP*) and a second term (*OP*) which captures the difference between average and marginal price.

$$AP_t^j = \frac{BF_t^j Q_{B_t}^j + MP_{1_t}^j Q_{1_t}^j + MP_{2_t}^j Q_{2_t}^j + MP_{3_t}^j Q_{3_t}^j + MP_{4_t}^j (Q_t^j - Q_{3_t}^j - Q_{2_t}^j - Q_{1_t}^j - Q_{B_t}^j)}{Q_t^j} \tag{1.1}$$

$$AP_t^j = MP_{1_t}^j + \frac{(BF_t^j - MP_{1_t}^j) Q_{B_t}^j + (MP_{2_t}^j - MP_{1_t}^j) Q_{2_t}^j + (MP_{3_t}^j - MP_{1_t}^j) Q_{3_t}^j}{Q_t^j} \tag{1.2}$$

$$AP_t^j = MP_t^j + OP_t^j \tag{1.3}$$

In this framework *MP* is captured by the price rate in the first block, while *OP* captures water used at other prices. *AP* is observed in the data based on total revenue and total quantity, and *MP* is given by the price structure of each system along with the quantity permitted for each block. This allows *OP* to be calculated as the difference between *AP* and *MP*. For the second estimate of demand, *MP* and *OP* are included as measures of water price. Opaluch argued that if the estimate on *MP* equaled the estimate on *OP* that consumers respond to average price, but if consumers respond to marginal price then the estimate on *OP* will equal zero. If estimates on *MP* and *OP* are different and nonzero, then it is indeterminate whether consumers respond to marginal or average price.

It is argued that this specification captures the 'spirit' of the block rate price schedule faced by consumers. However, Nordin (1976) suggests that a utility maximizing consumer would react not only to marginal price, but also to changes in consumer surplus resulting from movement from one block to the next in the price schedule. Nordin maintains that consumers translate this into a loss or gain in income and that this effect should be included in the demand equation. This income

effect is typically referred to as 'Nordin's difference variable' or the 'rate structure premium' and is sometimes included as a separate variable (Taylor et al., 1977). From here on it will be referred to as the rate structure premium (*RSP*). *RSP* is the difference between total expenditure on water less what the water bill would have been had the marginal price (MP_1) prevailed in all pricing blocks. This also captures base fees, which constitute a large portion of total expenditure on water. The coefficient on *RSP* is expected to be of opposite sign, but equal in magnitude to the coefficient on consumer income (Howe, 1982). However, this is rarely supported by empirical studies (Billings and Agthe, 1980; Agthe et al., 1986; Nieswiadomy and Molina, 1989; Hewitt and Hanemann, 1995; Arbues, et al., 2003). Shin (1985) argued that this may be due to incomplete information. Nonetheless, Opaluch (1982) and others simply subtract *RSP* from income to create an adjusted measure of income, which is the approach used in this model. It is worth noting that when *RSP* was tested as a separate variable, the coefficient was opposite in sign, but larger in magnitude than the coefficient on income. Equation 1.4 shows how the rate structure premium (*RSP*) was calculated for a system that uses up to four price blocks.

$$RSP_t^j = \left(BF_t^j - {MP_1}_t^j\right){Q_B}_t^j + \left({MP_2}_t^j - {MP_1}_t^j\right){Q_2}_t^j + \left({MP_3}_t^j - {MP_1}_t^j\right){Q_3}_t^j + \left({MP_4}_t^j - {MP_1}_t^j\right)\left(Q_t^j - {Q_3}_t^j - {Q_2}_t^j - {Q_1}_t^j - {Q_B}_t^j\right) \quad (1.4)$$

Keep in mind that a system may charge a uniform price or use an increasing price structure. For systems with a uniform price, only the first term capturing the base fee (*BF*) and allowance (Q_B) remains in the *RSP* calculation (when applicable), since effectively MP_1=MP_2=MP_3=MP_4. Since MP_1 captures the marginal price in this framework, systems with an increasing schedule will have a positive value for *RSP*, while systems with a decreasing schedule will have a negative value. However, with base fees also included in the framework, this may not hold true, depending on the base fee and allowance, which may lead those units of water to be priced above or below MP_1.

That said, by including base fees, *RSP* also captures the income effect associated with the "jump" from the base allowance to the first marginal rate in the price structure.

It is important to note that the data used for this study does not have information on the amount of water consumed in each block by consumers. At the household level, many studies approximate these values based on the final rate charged to consumers in each month. For this model and other aggregate models, the average quantity used per month per connection is utilized for each system to determine on average which price block consumers purchase water in for any given year. This is then used to determine the calculation of *RSP* for each system. *RSP* is also adjusted for systems that on average use less than the base fee allowance, implying that consumers on average don't purchase water at the marginal rate since the base fee and allowance cover their demand.

A major problem with Opaluch's (1982) specification of demand is that it only tests whether consumers respond to marginal price or average price, but it cannot test for a combination of both. To address this, Shin (1985) proposes a specification which allows one to estimate whether consumers respond to marginal price, average price, or a combination of both. Shin argues that obtaining information regarding rate structures and marginal prices may be costly for consumers, so if the expected gain from the determination of true marginal price is less than its cost, then the consumer may determine his consumption based on other price information. This is tested by generating a 'perceived price' ($P*$) variable as shown in equation 1.5 where the parameter (k) is intended to capture price perception.

$$P*_t^j = MP_t^j \left(\frac{AP_t^j}{MP_t^j}\right)^k \tag{1.5}$$

The price perception parameter (k) is expected to be nonnegative. If consumers only respond to *MP*, then $k = 0$. If consumers only respond to *AP*, then $k = 1$. If the perceived price is between

AP and MP, then $0 < k < 1$. With an increasing block rate schedule, $k > 1$ implies that $P* > AP > MP$, and $k < 0$ implies that $P* < MP < AP$. To estimate the price perception perimeter (k), a natural log transformation is used as shown in equation 1.6.

$$\ln P{*}_t^j = \ln MP_t^j + k\ln\left(\frac{AP_t^j}{MP_t^j}\right) \tag{1.6}$$

To empirically estimate each model of demand, it is important to control for various economic, housing, demographic, and weather characteristics which influence water consumption. For this assessment, the demand variables are chosen based on key findings from previous work as well as data availability. Equations 1.7-1.10 provide the four demand models that are estimated. All models include the same control variables, and differ only in the specification of price. The control variables are shown for the first specification, but muted for the remaining equations. Note that *RSP* is subtracted from income in each model. Estimate (1) of demand (equation 1.7) is a log-level specification with average price (*AP*) entering linearly. Estimate (2) (equation 1.8) is a log-level specification separating average price into *MP* and *OP* as done by Opaluch (1982). Estimate (3) of demand (equation 1.9) is a log-log specification using the natural log of *AP*. Estimate (4) (equation 1.10) is a log-log specification that estimates the 'perceived price' that consumers respond to, as done by Shin (1985). If consumers respond to average price only, then the estimates for (1) and (2) will be identical, and the estimates for (3) and (4) will be identical. If consumers respond to something other than average price, then model (4) is the preferred specification, as it allows consumers to respond to any perception of price. All models are estimated using OLS and include a fixed effect for both year (t) and water system (j).

$$
\begin{aligned}
lnQ_t^j \; &= \beta_0 + \beta_1 AP^{*}{}_t^j + \beta_2 PDSI_t^j + \beta_3 lnPop_t^j \\
&+ \beta_4 Persons\ per\ Connection_t^j + \beta_5 (Household\ Income_t^j - RSP_t^j) \\
&+ \beta_6 Rooms_t^j + \beta_7 Renters_t^j + \beta_8 Yard_t^j + \beta_9 Home\ Age_t^j + \beta_{10} Age_t^j \\
&+ \ \beta_{11} Race_t^j + \beta_{12} Edu_t^j + \alpha_j + \delta_t + u_t^j
\end{aligned}
\tag{1.7}
$$

$$
lnQ_t^j = \beta_0 + \beta_1 MP_t^j + \beta_2 OP_t^j + Controls_t^j + u_t^j \tag{1.8}
$$

$$
lnQ_t^j = \beta_0 + \beta_1 lnAP_t^j + Controls_t^j + u_t^j \tag{1.9}
$$

$$
lnQ_t^j = \beta_0 + \beta_1 lnMP^{*}{}_t^j + \beta_1 kln\left(\frac{AP_t^j}{MP_t^j}\right) + Controls_t^j + u_t^j \tag{1.10}
$$

When estimating water demand, variation in weather is crucial to control for. This is typically done by including variables for precipitation, temperature, and/or drought. For this model, drought conditions are measured, since drought is highly correlated with wildfire. Drought is measured using an annual average of the Palmer Drought Severity Index (*PDSI*), which is directly linked with precipitation, and indirectly linked with temperature. Drought is expected to increase the demand for water. Next, the natural log of population (*lnPop*) is included to account for differences in the number of consumers served by each water system. Population is generally a key determinant of water use. The population served by each water connection is also included (*Persons per Connection*), as done by Carver and Boland (1980). More people per connection often means more water use. However, when holding population constant, more people per connection typically means less water use, since fewer connections are being used to service an equivalent number of people. This variable is very similar to average household size, which is commonly used in the literature.

The next variable measures median household income (*Household Income*) which is adjusted to account for income effects that stem from moving along a block-price schedule (*RSP*). Estimates of income elasticity are often smaller in magnitude than price elasticity. The estimate is also

typically positive, suggesting that water is a normal good. The next few variables in the model address housing characteristics. First, the average number of rooms per house (*Rooms*) is included, as done by Dandy et al. (1997). More rooms correspond with more water use. This is similar to house size, which is commonly included in demand estimates. Typically, the number of bathrooms is a preferable measure, but this data is not available. The next variable in the model accounts for the fraction of homes that are occupied by renters versus homeowners (*Renters*). Nieswiadomy and Cobb (1993) include the fraction of homes that are owner-occupied in their model. Renters are often expected to use more water since they typically have less water-efficient appliances, while homeowners have more incentive to upgrade their appliances.

The next housing variable accounts for the fraction of homes with a yard (*Yard*). Homes with a yard are expected to use more water in order to maintain lawns. This variable is intended to capture demand for secondary (untreated) water and is approximated by measuring the fraction of homes classified as one-unit detached. These homes have space between them and neighboring homes, implying that they have a yard. Unfortunately, data on yard size was not available. The final housing variable captures the age of housing (*Home Age*). To capture home age, the fraction of homes built before 1939 is used, as done by Nieswiadomy and Cobb (1993). Older homes often have outdated and leaky pipes and are therefore expected to use more water. The remaining variables in the model are intended to capture key demographic characteristics that vary across Utah. Median age (*Age*), the fraction of population identifying as White (*Race*), and the fraction of the population with a high school degree or better (*Edu*) are included. There are no expectations for the impact of these demographic characteristics on water use, but they are nonetheless included to control for potential variation across water consumers.

After demand is estimated, the results are then used for a two-staged estimation of average total cost (*ATC*) for water provision. For this assessment, water treatment and delivery costs are estimated using a hedonic cost approach similar to Feigenbaum and Teeples (1983). The hedonic indirect cost function for water systems is derived from a production function of the form:

$$Q(Q_D; z_1, z_2, \ldots, z_s) = f(L, E, D, W) \tag{1.11}$$

where

$Q(\ )$ = an index of firm output,
Q_D = average annual flow of water delivered,
z_s = water system characteristics associated with Q_D,
L = labor input,
E = energy input,
D = service area population density, and
W = water input.

Water output is represented by the hedonic output Q, reflecting both the water production of the system measured in gallons per year (Q_D) and system treatment and delivery characteristics (z_s). The production technology applicable to the firm is represented by $f(\ )$ and does not require further specification, as a hedonic specification permits various technology combinations to reflect the same level of quality (Spady and Friedlaender, 1978). Since a typical water system is legally obligated to supply all output that is demanded at regulated rates, it is assumed that systems operate to minimize cost subject to their demand. Under these conditions, duality implies that there exists an indirect cost function $C(\ )$ which depends on both endogenous and exogenous factors. The regulatory constraints imposed on the water systems make the quality dimensions of output exogenous to the firm, and hence assure that the parameter estimates are free of simultaneity bias (Feigenbaum and Teeples, 1983). The hedonic cost function is given in equation 1.12 where annual costs (C) are a function of the hedonic output (Q) and fixed factors (F_r), and output is determined by the estimates for water demand (Q_D) and system characteristics (z_s).

$$C = C(Q(Q_D; z_1, z_2, \ldots, z_s); F_1, F_2, \ldots, F_m) \tag{1.12}$$

Unfortunately, factor prices and shares are not known, so they are excluded from the estimation in this study. This leaves system characteristics (z_s) which are endogenous to water systems, and fixed factors (F_m) which are exogenous to systems. The quantity of water demanded (Q_D) is typically assumed to be exogenous, but here is modeled as endogenous by utilizing the water demand function estimates. For this assessment, system characteristics are captured by water system financial condition, leak condition, and physical condition. Fixed factors for water systems are captured by drought, the number of connections, persons per connection, and wildfire.

In this model, the occurrence of wildfire is primarily captured by the number of acres burned upstream from water intakes. Acres burned enters as a quadratic variable to allow for nonlinearity between fire size and the impact on water cost. It is important to note that the acreage burnt is weighted by the fraction of water system intakes affected (*wAcres*) (for more discussion refer to the data section). Lagged variables are included to measure the impact of wildfire in the short run (1 year after), medium run (5 years after), and long run (10 years after). Note that various other lagged forms were also tested. Lags are included for fire size (*wAcres*), as well as fire duration (*Duration*), fire distance (*Distance*), and whether or not the fire impacts a permanent or seasonal water intake (*Permanent*). The impact of wildfire is estimated separately for surface water intakes, groundwater well intakes, and groundwater spring intakes. This is done using interaction variables. Estimating differences in a single model using interaction variables is preferable to estimating separate models, since many water systems use a combination of intake types, and a wildfire may impact multiple intakes. This makes it challenging to separate wildfire impacts by water intake type without modeling the impacts simultaneously.

Equation 1.13 provides the ordinary least squares (OLS) specification used to estimate average total cost (*ATC*) while controlling for both endogenous and exogenous factors (recall that it is

assumed that *AP=ATC*). The equation is estimated utilizing the estimates of water demand ($ln\hat{Q}$) using a two-staged OLS process. To simplify notation, the lagged time intervals are denoted by (*l=1, 2, 3*) to reflect the short-run (*t -1*), medium-run (*t - 5*), and long-run (*t - 10*), respectively.

$$ATC_t^j = \beta_0 + \beta_1 ln\hat{Q}_t^j + \sum_{i=2}^{46}\sum_{l=1}^{3}[\beta_{il}^j(1 + Spring_{il}^j + SW_{il}^j)(wAcres_{il}^j + wAcres\ Sq_{il}^j + Distance_{il}^j + Duration_{il}^j + Permanent_{il}^j)] + \beta_{47} lnConnections_t^j + \beta_{48} Excess\ Rev_t^j + \beta_{49} Loss\ Rev_t^j + \beta_{50} Some\ Leaks_t^j + \beta_{51} Many\ Leaks_t^j + \beta_{52} Phys\ Cond_t^j + \beta_{53} PDSI_t^j + \alpha_j + \delta_t + u_t^j \quad (1.13)$$

The impact of wildfire is estimated separately for groundwater wells (reference group), groundwater springs, and surface water using interactions and controlling for additional determinants. Wildfire is assumed to impact costs through changes in water quality and quantity conditions. The first control variable captures the number of water connections (*lnConnections*) served by each water system, measured as a natural log. Adding additional connections is often expensive, adding to a system's fixed cost and therefore overall costs. The next two variables account for whether a system charges water prices above *ATC* (*Excess Rev*) or below *ATC* (*Loss Rev*) in any given year. This is captured using dummy variables, while systems with a balanced budget serve as the reference group. This permits the equilibrium assumption *AP=ATC* to remain valid. Next, system leak condition is accounted for using dummy variables for systems with leaks (*Some Leaks* and *Many Leaks*), while systems with no leaks serve as the reference group.

The next variable in the model measures the physical condition (*Phys Cond*) of water systems. Systems responded based on the number of years before major repairs are expected to be needed, in 5-year increments. Next, drought conditions are captured in the model using an annual measure of the Palmer Drought Severity Index (*PDSI*). Drought is essential to include in order to avoid an

omitted variable bias when looking at the relationship between wildfire and water provision costs, since drought is highly correlated with both wildfire and the cost of providing water.

The model also includes both a system (j) and year (t) fixed effect. The system fixed effect picks up all time-invariant features of each water system that may explain some of the differences between costs. For example, the elevation of each water system is an important fixed factor of provisioning cost, but this does not change from year to year and is therefore captured by the system fixed effect. The time fixed effect accounts for the year and therefore captures aggregate time-series trends not explicitly included in the model. Note that the demand estimates also include a system and year fixed effect to capture time-invariant features and aggregate time-series trends associated with water demand. After water demand and *ATC* are estimated, the results are then used to see how wildfire impacts the cost of water provision, which then impacts the price of water for consumers. Although assessing effects across time, it is important to note that this framework is static in nature. Rather than using fixed effects, one could look at first differences in a dynamic framework. However, assuming homoskedasticity and no serial correlation in the errors, a fixed-effect estimator is more efficient than a first-difference estimator (Wooldridge, 2001).

1.4 Data

Limited data on drinking water systems has prevented researchers from systematically assessing how wildfire might impact drinking water markets. Few datasets provide information that is consistent across water systems and available across time. Detailed facility level characteristics are also sometimes proprietary and only available for specific use. That said, Utah's Department of Environmental Quality conducts an annual *Survey of Community Drinking Water Systems* across the state. The survey is used to gather information on the population served, water quantity

used, revenues received, and prices charged by each water system across Utah. Additional information on budget condition, system physical condition, and system leak condition is also collected. This data was provided for 1999-2013 and used to empirically estimate the average cost of water treatment and water demand for a typical drinking water system in Utah. This data has not been empirically tested in any known published work. However, the data is regularly utilized by Utah's state government and others for research purposes. For example, in 2012 Utah's state legislature published a briefing paper titled, *"How Utah Water Works: An Overview of Sources, Uses, Funding, and Pricing"* utilizing this data to help assess water systems across the state.

Water systems that are flagged for questionable data by Utah's Department of Environmental Quality are dropped. Some systems only replied to the survey in intermittent years. For those systems, a linear interpolation is used to fill gaps in the data. Systems missing observations at either the start or end of the sample (1999 or 2013) are dropped to avoid the use of extrapolation. Survey data is not available for 2003-2005, so a linear interpolation is used for this period. Survey questions differed before 1999 and after 2013, restricting the sample to this period. The number of systems surveyed in each year is not published, making the survey response unknown. That said, based on the population served by each water system, reliable data is provided for systems that together served approximately 87% of Utah's total population across the entire sample period.

For this assessment, the sample is restricted to residential water systems, focusing on water systems that provide culinary (treated) water. Water systems which receive any of their revenues from taxes are removed. These systems receive a portion of their funding through a combination of general taxes, property taxes, and sales taxes. Estimating water demand for these systems is challenging because consumers do not directly pay for the water they use, and instead indirectly pay for water through taxes. This creates a disconnect between the price of water and the amount

of water used. Indirectly paying for water can therefore dramatically alter consumption behavior, and tax subsidies can also distort prices and incentivize overconsumption.

Water systems that receive revenues from taxes are typically unique from other systems. For example, water conservation districts (WCD), water improvement districts (WID), special service districts (SSD), and irrigation districts (ID) are specially defined political subdivisions which provide water for specific purposes. These water systems often span numerous political boundaries and are usually funded partially through various taxes. That said, many of these systems focus on providing secondary water (untreated) or water for wholesale. By removing systems that receive any funding from taxes, many of the non-residential and non-culinary water systems are dropped from the data.

Any remaining water conservation districts (WCD) and irrigation districts (ID) are removed. Irrigation districts provide untreated water which is used to irrigate land. Water conservation districts primarily provide water at wholesale, and therefore focus on storing and transporting water, not treating water for drinking. Any systems classified as a pipeline are also removed. This leaves only municipal drinking water systems in the sample, along with a handful of special service districts (SSD) and water improvement districts (WID) which do not receive any funding from taxes. Special service districts are a separate legal entity created and controlled by a municipality or a county, which typically serve culinary water for residential use. Water improvement districts primarily provide culinary water to residents within the improvement district, but also may provide some secondary water for outdoor use. The systems kept in the sample therefore provide only residential water, some of which is treated, some of which is untreated.

Unfortunately, it is not known how much water is delivered to residents as treated versus untreated. Homes with a yard sometimes have the option to water their lawns with untreated water,

meaning that they consume both treated and untreated water. In the early years of the drinking water survey (1999-2002) systems reported the percent of culinary connections that have a secondary irrigation system, along with the fraction delivered by ditch versus pipe. However, this question was no longer asked in later years, so the water quantity observed in the data encompasses both treated and untreated water delivered to residents. The Utah Legislature (2012) estimates that about 28% of residential water is untreated, while the remaining 72% is treated. In order to account for water use coming from secondary irrigation, a variable is included in the model to capture the percent of homes with a yard. That said, wildfire is primarily expected to impact culinary water, which must be treated before delivery to consumers.

In order to capture a typical water system, the sample is further restricted to water systems that served at least 100 connections throughout the entire sample period. It is worth noting that the EPA only regulates water systems serving at least 25 connections. A handful of water systems with a price per thousand gallons above $10 (2010 real dollars) in any year are also dropped. This brings the final sample to 144 drinking water systems from 1999-2013 which serve approximately 55% of Utah's total population across the sample period. Table 1.2 provides the descriptive statistics for water systems used in the sample.

Note that most water systems charge a base fee every month, which often has an allowance of water use before consumers are charged per gallon of use. Beyond the monthly allowance, some systems charge a uniform price per gallon, while many systems utilize an increasing block-price structure to incentivize conservation. Two systems in the sample utilize a decreasing block-price structure for a few years and are removed to focus on systems with a uniform or increasing price structure. For systems with an increasing block-price, no more than four blocks are used in any year. Note that many water systems adjust their price structures across the sample period, with

many systems changing from a uniform price to an increasing price structure. In 1999 about 68% of water systems charged a uniform price, but by 2013 only 30% of systems still used a uniform price, with the remaining systems utilizing increasing price structures. This variation in price structure helps strengthen the empirical estimation. Figure 1.2 plots the average increasing block price structure and uniform price used by water systems in 1999 and 2013, also highlighting the switch from uniform to increasing prices across the sample period. Prices have increased about 44% on average from 1999 to 2013 and about 38% of systems switch from using a uniform price structure to an increasing price structure.

The Utah water system survey data provides crucial information at the facility level; however, it does not include crucial demand characteristics for each system, other than the population served and persons per connection. County data was used to capture other key demand information such as economic, housing, and demographic characteristics. Data from the American Community Survey (ACS) was used in order to get annual estimates. The 5-year estimates were used to be consistent across water systems, since the 1-year and 3-year ACS estimates are only available for larger counties (population greater than 65,000 and 20,000 respectively). The ACS data starts in 2005 and so the 2000 census is used for a linear interpolation from 2001-2004 and a linear extrapolation for 1999. Given that water system data is linearly interpolated for 2003-2005, the models are tested with a restricted sample (2006-2013) to determine whether the results are affected by linearly filling missing values.

County data is associated with each water system based on the location of their water intakes. This assumes that a water system serves the county in which their water intakes are located. According to the Utah Legislature (2012), water in Utah is often used within a relatively short distance from its source, and does not usually require costly, long distance transportation. This

assumption is therefore reasonable. However, water systems located in the same county will share some of the same demand data, such as median income. Some of the demand data is available at a finer resolution, for example the census block level, but it does not sufficiently cover the sample period, and could therefore not be used. Table 1.3 provides the descriptive statistics for water demand characteristics.

The location of water intakes used by each system also comes from the Utah Department of Environmental Quality is only available for 2010. Only active water intakes are assessed. This data provides information on whether an intake is seasonal or permanent and whether it is used to extract surface water or groundwater. This information is not available for other years, so it must be assumed that the intake features apply to each water system across the sample period. Since time-invariant effects are already captured by a fixed-effect in the modeling process, these intake features are only utilized during the occurrence of wildfire. For example, intake locations are used to identify which wildfires occur upstream from water intakes, and to measure the linear distance from the wildfire centroid to each intake downstream. Information on intake type (seasonal or permanent) and water type (surface water, groundwater well, or groundwater spring) are only employed when a wildfire occurs upstream from a water intake and used to see how the impact of wildfire differs by the type of water intake used.

All wildfires five acres or larger and upstream from a water intake are assessed. Information on wildfire location comes from the *Federal Wildland Fire Occurrence Data* which includes all fires recorded since 1980 by the Bureau of Indian Affairs, Bureau of Land Management, Bureau of Reclamation, Forest Service, Fish and Wildlife Services, the National Park Service, and state-level agencies. Prescribed fires are excluded since they typically are managed to have minimal impacts on water conditions. All wildfires from 1989-2013 are assessed, allowing for up to 10

years of lagged effects to be tested. Across the sample, there are 1,047 occurrences of wildfire upstream from a water system, but some wildfires are counted multiple times if they impact multiple systems. For example, a single fire that impacts two systems is considered two occurrences of wildfire impacting a water system. Figure 1.3 provides the location of all water system intakes and upstream wildfires in Utah from 1989-2013.

Information for acres burned and wildfire duration (measured by the days between the fire start and end date) are used to assess the influence of wildfire size and duration. Distance is captured using the predefined fire centroids to measure the linear distance to downstream intakes. Each wildfire is individually identified as upstream using ArcGIS based on topography, stream lines, and sub-watershed (12-digit hydrologic unit code) boundaries. An automation process could not be used given the diversity of topography and uniqueness of each sub-watershed across the landscape. See Equations 1.14-1.18 for information on the method used to aggregate data across wildfires occurring in the same year. Since many water systems utilize multiple water intakes, a weighted measure of acres burned is created to account for the fraction of intakes impacted (*wAcres*). For example, a 200-acre fire that impacts half the intakes used by a system is weighted to be equivalent to a 100-acre fire that impacts all the intakes used by a system. Table 1.4 provides annual descriptive statistics for upstream wildfires in Utah from 1989-2013.

Many water systems utilize multiple water intakes and, in some years, may experience multiple wildfires upstream. It is therefore crucial to aggregate wildfire information in a meaningful way when several wildfires impact several water intakes. Each water system is individually assessed in order to compile wildfire information appropriately. For multiple upstream wildfires occurring in the same year, the acres burned is added together while the distance and duration of each fire is weighted by the acres burned. For example, if a 200-acre fire burned for 1 day 4 miles upstream

and a 100-acre fire burned for 4 days 1 mile upstream, then the combined average would be a 300-acre fire that burned for 2 days 3 miles upstream. When a wildfire impacts multiple intakes, the acres burned is weighted by the fraction of intakes impacted, the distance is averaged across intakes, and duration is unchanged. For example, if both fires in the previous example only impact 50% of the intakes used by a system, then the wildfire would be entered as a 150-acre fire that burned for 2 days 3 miles upstream, where 3 miles upstream captures the average distance from each intake affected. Figure 1.4 illustrates this hypothetical example.

Equations 1.14-1.18 show how data for each wildfire and water intake is aggregated to provide annual estimates for each water system. The information is aggregated for all upstream wildfires (*i = 1,…,n*) across each water system (*j*) in each year (*t*).

$$Acres_t^j = \sum_{i=1}^{n} Acres_{it}^j \tag{1.14}$$

$$wAcres_t^j = \sum_{i=1}^{n} \frac{Intakes_{it}^j}{Intakes_t^j} Acres_{it}^j \tag{1.15}$$

$$Distance_t^j = \sum_{i=1}^{n} \frac{wAcres_{it}^j}{wAcres_t^j} Distance_{it}^j \tag{1.16}$$

$$Duration_t^j = \sum_{i=1}^{n} \frac{wAcres_{it}^j}{wAcres_t^j} Duration_{it}^j \qquad (1.16)$$

Next, intake type (permanent or seasonal) and water type (surface water, groundwater well, or groundwater spring) is measured according to the intakes impacted by wildfire. For example, if wildfire impacts a permanent surface water intake, a permanent groundwater intake, and two seasonal groundwater intakes, then it is entered as impacting intakes that are 50% permanent and 25% surface water. For multiple wildfires, intake and water type are weighted by acres burned as is done with fire distance and duration. Equation 1.17 shows how the fraction of permanent intakes

is calculated, with the remaining intakes only getting used seasonally. Equation 1.18 shows how the fraction of surface water intakes is calculated, while the same is done for groundwater well intakes and groundwater spring intakes.

$$\%\ Permanent_t^j = \sum_{i=1}^{n} \frac{wAcres_{it}^j}{wAcres_t^j} \frac{Permanent\ Intakes_{it}^j}{Intakes_{it}^j} \tag{1.17}$$

$$\%\ Surface\ Water_t^j = \sum_{i=1}^{n} \frac{wAcres_{it}^j}{wAcres_t^j} \frac{Surface\ Water\ Intakes_{it}^j}{Intakes_{it}^j} \tag{1.18}$$

These equations are used to generate annual estimates of upstream wildfire characteristics and information on the water intakes affected. While fire size, distance, and duration are crucial fire characteristics, it is important to note that burn severity is not explicitly captured. Burn severity corresponds with the loss of organic matter aboveground and belowground and can be captured using various metrics. Severity is a function of both fire intensity and duration. For this study, fire duration is used to approximate severity. Burn severity information is gathered by the USGS using remote sensing, but this data is not utilized since it is only available for large wildfires (300+ acres) and only for public lands. In this analysis, many of the upstream wildfires are less than 300 acres in size, and many arise on private lands. Restricting the sample to only larger wildfires on public lands could bias the estimated effect for an average wildfire.

Figure 1.5 plots acres burned, and weighted acres burned by wildfires that occurred upstream from drinking water intakes in Utah. The time-series highlights that upstream wildfires in Utah trend closely with the national trend of wildfire. Overall, there is an upward trend of wildfire across the United States, which is closely linked with drought conditions that have negatively impacted the West. Figure 1.6 plots the annual Palmer Drought Severity Index relative to upstream wildfires in Utah. An annual average is created by averaging index values across all months of the year.

There appears to be a strong relationship between acres burned and dryness in any given year. Given that drought negatively impacts water conditions, it is crucial to control for drought conditions when looking at the relationship between wildfire and water prices in order to avoid omitted variable bias. Both drought and wildfire have gotten worse over the sample period.

Water prices have also been trending upward across the sample period, but at an even quicker rate than wildfire. Figure 1.7 shows the average monthly water bill for Utah relative to inflation. Water prices have been continuously rising, outpacing inflation and unaffected by the 2008 recession. This trend is common across the country. One recent study analyzed the 50 largest metropolitan areas in the U.S. and found that residential water bills have steadily increased by approximately 5.7% annually from 2012-2017, outpacing average annual income growth (5%) and inflation (1.9%) (Bluefield Research, 2017). Another study examined water bills for six different states across the U.S. and found the same trend, with water bills rising faster than regional inflation (Eskaf, 2013). Overall prices in the economy fell after the 2008 recession, but water prices appear to have continued upward unaffected. This trend is found in Utah and across the country, suggesting that the 2008 recession had minimal impact on drinking water markets. This is not too surprising given that water is a necessity and often found to be income inelastic, implying that changes in income minimally influence water demand. A meta-analysis of 307 income elasticity estimates across 62 studies found a mean income elasticity for water of 0.26 and median elasticity of 0.16, with 3% of the estimates above 1 and 94% of the estimates above 0 (Havraneka et al., 2017). This suggests that water demand was largely unaffected by income effects during the 2008 recession, allowing water prices to continue upward due to pressure from both water demand and supply.

It is important to realize that monthly water bill captures changes in both water prices and quantities. The upward trend of water bills across the U.S. could therefore be due to changing prices, quantities, or both. It is essential to separate price and quantity effects in order to model water provisioning cost and water demand. To determine the average price (*AP*) of water for system (*j*) in year (*t*), total retail revenue is divided by the total quantity of water delivered (*Q*), as shown in equation 1.19. Equations 1.20 and 1.21 then show how average price (*AP*) is separated into an average base fee (*ABF*) and an average variable fee (*AVF*) for each system (*j*) in each year (*t*) under the assumption that $AP = ABF + AVF$.

$$AP_t^j = \frac{Retail\ Revenue_t^j}{Q_t^j} \tag{1.19}$$

$$ABF_t^j = \frac{Connections_t^j * Monthly\ Base\ Fee_t^j * 12}{Q_t^j} \tag{1.20}$$

$$AVF_t^j = AP_t^j - ABF_t^j \tag{1.21}$$

Figure 1.8 plots the real price (2010 CPI adjusted) of water in Utah from 1999-2013, separating payments going towards base fees versus variable fees. Water systems typically charge base fees according to the fixed cost of water provision and variable fees according to the variable cost of provision. Under this assumption the impact of wildfire can be separated between impacts on variable cost verses impacts on fixed cost across time. This also allows one to test the relationship between variable cost and fixed cost for different periods. In this study the intertemporal relationship between current fixed cost and past variable cost is explored to identify potential investment behavior. Across the sample, base fees regularly account for about two-thirds of average water price and variable fees account for the other one-third. This is consistent with the fact that water systems often face a high fixed cost, typically constituting much of their total cost.

As figure 1.8 shows, the average price of water has been consistently rising in Utah, driven by increases in both base fees and variable fees.

1.5 Results

The OLS estimates for water demand are shown in Table 1.5., highlighting the estimates for each specification of price. The relationship between price and quantity is highly significant in all models tested. Estimates for the price-elasticity of demand range from -0.442 (model 2) to -0.629 (model 3), indicating that consumers have an inelastic response to changes in water prices. If consumers respond to average price only, then the log-level estimates (1) and (2) should be equivalent and the log-log estimates (3) and (4) should be equivalent. This is not the case. The estimates are very similar, but they are statistically different from one another. This implies that consumers respond to other price factors besides just the average price of water. The estimates of elasticity are larger in magnitude (more elastic) in models 1 and 3 which measure average price, while demand is more inelastic in models 2 and 4 when block pricing is modeled.

Model 2 uses Opaluch's (1982) specification of price to test whether consumers respond to average price or marginal price (but not both). If the estimate on *MP* equals the estimate on *OP* than consumers respond to average price, and if consumers respond to marginal price then the estimate on *OP* will equal zero. The model 2 estimates on *MP* and *OP* are statistically different from one another and the estimate on *OP* is nonzero. This implies that it is indeterminate whether consumers respond to marginal or average price but suggests that consumers do not respond only to average price. The estimate on *MP* would equal the estimate on *OP* and model 1 and 2 would be identical if consumers respond only to average price.

To test the 'perceived' price (P^*) that consumers actually respond to, model 4 uses Shin's (1985) price specification to estimate a price perception parameter (k). If consumers only respond to marginal price, then $k = 0$, and if consumers only respond to average price, then $k = 1$. Furthermore, if consumers respond only to average price, then models 3 and 4 should be identical. That said, the estimate of k is slightly above one (1.156) with a standard error of 0.084 which means that $P^* > AP > MP$. The standard error for k is calculated as a function of the robust standard errors from the coefficient estimates on AP and MP. A hypothesis test for whether k is different from 1 yields a t-statistic of 1.86 indicating that k is statistically different from 1 at the 10% level. The estimate for k has a 90% confidence interval of (1.018, 1.293). Since it appears that consumers actually respond to a perceived price above both marginal price and average price, model 4 is the preferred specification of water demand, as the perception parameter allows consistent estimation under any behavioral hypothesis (Shin, 1985). Model 4 is therefore used for the two-staged estimation of water cost in the final model (note that all demand models were tested, with minimal variation across two-staged estimates for cost).

All four models of water demand include the same control variables. The estimates on the control variables are very similar across each model, with almost identical coefficients between models 1 and 2, and between models 3 and 4. This suggests that the specification of price has minimal influence on these estimates. Population, persons per connection, drought, and the year fixed effect are determinants of water demand that are statistically significant across all models. Interestingly, education is also statistically significant in all models.

The estimate on the year fixed effect captures aggregate time-series trends in water quantity not captured explicitly in the model. The coefficient suggests that these aggregate trends are increasing water demand by roughly 1.3% each year. The coefficient on the Palmer Drought

Severity Index is not immediately interpretable since it is capturing changes in index values which range from -4.85 to 7.03. That said, the estimate suggests that moving up one value in the index reduces water demand by about 0.23%. Since positive values represent wetness and negative values represent dryness, the negative estimate implies that increased wetness reduces water demand (or increased dryness increases water demand). As expected, the population served by each system is one of the strongest predictors of water demand. The estimates suggest that a 1% increase in population increases water demand by about 0.6%. Persons served per connection is also an important determinant. Holding population constant, the estimate suggests that fewer connections (additional people per connection) reduces water demand, with an additional person per connection lowering water demand by about 0.16%.

The remaining variables in the model are not statistically significant, aside from education, which is likely associated with coarse data resolution (the variables come from county data, not system data). The estimate on education suggests that a 1% increase in the fraction of the population holding a high school degree or better corresponds with a 2% decrease in water demand. Keep in mind that income, housing, and demographic characteristics are held constant, suggesting that perhaps more education reduces wasteful water use. Across all models, the estimate on median household income less the rate structure premium (*RSP*) is not statistically different from zero, and the coefficients are negative. This suggests that water demand in Utah is not heavily driven by income, although household level data is needed in order to make any such conclusion. Previous studies have found that income elasticity is typically low, but often not negative (Havraneka et al., 2017), which would imply that water is an inferior good.

Housing characteristics such as the median number of rooms, the fraction of homes with a yard, home age, and the fraction of homes occupied by renters are not statistically different from

zero in any of the models. Demographic variables such as median age and race are also not statistically different from zero. This is again likely due to coarse demand data, as some water systems share data if they are in the same county. Nevertheless, when estimating water demand, the key relationship of interest is that between price and quantity, as it is vital for the estimation of wildfire impacts on water provisioning costs and subsequent water prices.

Table 1.6 provides the estimates of average total cost (*ATC*) for water provision. *ATC* is estimated using the preferred model of demand (model 4) with a two-staged OLS process. The elasticity for ATC is -1.47 in the model, implying a downward sloping *ATC* which is more elastic than demand, as expected of a natural monopoly. The response is elastic, meaning that increasing the quantity of water provided by 1% reduces ATC by more than 1% (1.47%). The data used to estimate *ATC* is unique to each water system, so many of the coefficient estimates are highly significant. Table 1.6 highlights the estimates for the impact of wildfire, divided by intake type. The results are used to assess the impact of wildfire in the short run (1 year after), medium run (5 years after), and long run (10 years after). Only the estimates for surface water are statistically significant. Keep in mind that the coefficients are simultaneously estimated in a single model using interaction variables.

Given the equilibrium assumption that *AP=ATC*, the estimated coefficients for *ATC* can be directly interpreted as changes in *AP*. That said, the consumer response to changes in price is determined by the demand estimates. Since demand is inelastic, changes in price have minimal influence on the quantity demanded. However, given that demand is not perfectly inelastic, the change in *AP* reflects both changes in cost and the demand response to changing price. This means that the estimate more accurately captures the effect of wildfire on price than previous studies that only estimate cost and assume no change in quantity demanded when price changes. This is

supported by the fact that when *ATC* is estimated without utilizing the estimate of demand (i.e. assuming demand is exogenous and perfectly inelastic), there is a statistically significant, but smaller coefficient for the effect of wildfire on surface water.

The estimate on the year fixed effect is statistically significant and shows that aggregate time-series trends not captured in the model are increasing provisioning costs by roughly 1.5% each year. Drought is also a key contributor to water provisioning cost, as suggested by the statistically significant estimate on the Palmer Drought Severity Index. The estimate suggests that moving up one value in the index reduces water provisioning cost by about 0.5%. Since positive values represent wetness and negative values represent dryness, the negative estimate implies that increased wetness reduces water provisioning cost (or increased dryness increases cost). The next variable in the model captures the number of connections served by a water system. The estimates show that increasing system connections by 1% increases cost by about 0.8%. Keep in mind that this is while holding the quantity of water delivered constant.

The next two variables in the model control for systems that charge an average water price above or below *ATC*, with systems operating under a balanced budget serving as the reference group. This allows the equilibrium assumption *ATC=AP* to remain valid. The estimates are not statistically significant in the model, but the sign of the estimates suggest that systems generating excess revenue or operating at a loss charge water prices that are higher than systems operating with a balanced budget. The next two variables capture the leak condition of water systems, with systems that have no leaks serving as the reference group. The estimates are statistically significant for the effect of having many leaks, suggesting that systems with many leaks charge a price for water that is about 3% higher. This suggests that water systems can meaningfully lower provisioning cost and the subsequent price for water by fixing leaks in their infrastructure.

The final control variable in the model captures the overall physical condition of water systems. The estimate is statistically significant and shows that systems in better condition (more years before major repair is needed) have lower costs. The estimate indicates that systems needing major repair in the next 5 years charge prices that are about 3% higher than systems that don't need major repairs for at least 25 years. Keep in mind that leak condition is held constant, so this captures other conditions of a system's infrastructure besides leaks.

Looking at the estimates for the impact of wildfire on surface water intakes, the results suggest that a 1,000-acre wildfire increases water prices by about 4% in the short run, and that this impact dissipates in the medium run, but then price rises again by about 2% in the long run. Figure 1.9 plots the estimated effect of a 1,000-acre wildfire on surface water intakes across time. The estimates are shown for permanent intakes at the mean values of fire distance and duration. Accounting for fire distance and duration proved to be essential to get an accurate picture of wildfire effects across time, as the results indicate that distance and duration may influence the effect of wildfire differently across time. Figure 1.10 plots the estimated impact of an average wildfire (748.7 acres, 15 days burning, 7.6 miles upstream) on a typical water system (67.6% permanent intakes and 9.9% surface water intakes). Only the estimates for surface water intakes are statistically different from zero, in the short-run (1-year) and long-run (10-years). Due to the use of surface water intakes, a typical wildfire increases water prices by about 0.2% in the short run and 0.1% in the long run. Recall that per year there is an average of 42 wildfire occurrences upstream from water systems across the sample (table 1.4).

For the effect of wildfire on surface water, it is not immediately apparent why price increases in the short run and then again in the long run. Table 1.7 separates the estimate for *ATC* into effects on average variable fee (AVF) versus average base fee (ABF) under the assumption that

AP=ATC=AVF+ABF. This allows one to examine how wildfire affects these average price components individually across time. Under the assumption that the base fee is set according to fixed cost and variable fee is set according to variable cost, this separation allows one to test how wildfire affects average variable cost versus average fixed cost. Table 1.8 translates the estimated coefficients into percent changes in *AP* to make the estimates immediately comparable.

The results indicate that water system average variable cost rises immediately following a wildfire, and that this encourages capital investment to reduce variable cost, resulting in a significant effect of wildfire on average fixed cost in the long run. This is supported by testing the intertemporal relationship between water provisioning fixed cost and variable cost. Table 1.9 provides estimates for the relationship between current *ABF* and past *AVF*. Assuming base fee is a proxy for fixed cost and variable fee is a proxy for variable cost, I find a positive relationship between fixed cost and past variable cost, while there is an inverse relationship in any given year. This suggests that elevated variable cost encourages future capital investment which increases fixed cost, and that increased fixed cost correlates with lower variable cost in a given period.

Various lags are tested, and the lagged relationship appears strongest for *t-2*, implying a strong positive relationship between variable cost in one period and fixed cost 2 years later. This relationship explains why average price increases immediately following a wildfire, but then again in the long run as elevated variable cost encourages capital investment. Note that the relationship between fixed and variable cost is estimated without the inclusion of wildfire, permitting wildfire to be one of many potential drivers of the relationship between *AVF* and *ABF*. Figures 1.9 and 1.10 include the estimates for *AVF* and *ABF* along with *AP* to highlight how price increases in the short run due to elevated variable cost, and again in the long run due to elevated fixed cost.

Looking at the impact of wildfire by fire size (acres burned), I find that the long-run investment effect only exists for moderately sized fires, and that the larger the fire, the stronger the effect on investment behavior and fixed cost in the long run. Figure 1.11 shows the impact of wildfire on surface water by fire size, indicating that a small wildfire (100 acres) impacts variable cost, and therefore price, only in the short run. Meanwhile, a moderate sized fire (1,000 acres) is found to increase price in both the short run and long run, operating through elevated variable cost and elevated fixed cost, respectively (as previously discussed). That said, when the wildfire is even larger (2,000 acres) the impact is amplified on investment and fixed cost in the long run. This indicates that larger wildfires encourage more capital investment in the long run, and that relatively small fires only have an immediate impact on cost and price since they don't encourage a change in future investment behavior.

Looking at the medium run (5 years after wildfire), the results indicate that the impact of wildfire depends heavily on fire duration. Wildfire duration is only found to have a statistically significant effect in the medium run. The estimate shows that the impact of wildfire in the short run carries into the medium run when a wildfire burns longer. Figure 1.12 shows the impact of wildfire on price in the medium run, highlighting that the impact depends heavily on wildfire duration. In general, the longer a wildfire burns the more damage it does, explaining why the impact is likely to persist beyond the short run when a wildfire burns for a long time. All else equal, the impact of a wildfire that burns for about 20 days or less dissipates by the medium run, while a fire that burns for more than 20 days impacts price in both the short and medium run.

Looking at the influence of wildfire distance, the estimates are statistically significant for the short run and long run. Figure 1.13 shows how the impact of wildfire varies by distance upstream. It is important to note that the measure of distance used in this assessment is very simplistic, as it

only captures a linear distance from the fire centroid to each water intake. A preferable measure of distance would consider the actual flow of water across the surface of the landscape. That said, the sign on distance interestingly switches over time, with a positive estimate in the short run and a negative estimate in the long run. A priori, a negative estimate is expected for distance, indicating that the further a wildfire is from a drinking water intake, the smaller the impact is expected to be. The positive and significant estimate in the short run is potentially associated with an omitted variable bias, as close wildfires are likely to encourage post-fire management actions. This would imply a reduced impact on price due to nearby wildfires receiving more post-fire management attention than further fires.

By omitting post-fire management actions, the estimates provided in this study are expected to be dampened. This is because post-fire management is expected to positively correlate with fire size and duration, but negatively correlate with price, dampening the positive estimates on fire size and duration when omitted. For distance, post-fire management is likely to be inversely related, meaning closer fires receive greater management attention. This is supported by the fact that wildfire distance is positively correlated with wildfire size (cc = 0.38) and wildfire duration (cc = 0.35), suggesting that nearby fires get put out quicker and burn fewer acres. The omission of post-fire management actions is therefore likely to dampen the estimates on wildfire size and duration in this study and is a possible explanation for the positive and significant sign on distance in the short run.

Unfortunately, data on post-fire management actions is sparse, especially for this study which analyzes over 1,000 instances of wildfire. Furthermore, data that does exist is typically only publicly available for large wildfires, making it difficult to assess smaller fires which are the focus of this paper. That said, future work examining the role of post-fire management actions could

provide a valuable contribution towards better understanding the link between wildfire and water price. The a priori expectation is that including information on management actions will amplify the relationship between wildfire and price found in this study. The estimates found here should therefore be interpreted as low-end estimates that are potentially dampened from an omitted variable bias associated with post-fire management actions.

Although not statistically significant, the estimates suggest that only permanent water intakes are affected by wildfire, while seasonal intakes are not significantly influenced. This difference could be associated with the flexibility that water systems have over the use of seasonal intakes. If a wildfire occurs near a seasonal intake, water systems may stop utilizing the intake for a few years until water conditions improve, while they likely do not have this flexibility with permanent intakes. Figure 1.14 shows the impact of wildfire on permanent intakes versus seasonal intakes for surface water. It is worth noting that the difference is statistically significant when utilizing models (1) and (2) of demand, but not when utilizing the preferred estimate of demand (model 4). Nonetheless, the magnitudes of the coefficients are comparable across all models of demand, suggesting that permanent intakes are impacted more than seasonal intakes.

To determine whether linearly filling missing values at the start of the sample affects these estimates, the models are rerun with a restricted sample (2006-2013). The results suggest that the estimates are robust and not substantially affected by using the full sample (1999-2013) that contains some data elements that are linearly interpolated (demand data for 2001-2004 and water system data for 2003-2005) and linearly extrapolated (demand data for 1999). For model 4 of demand (preferred specification), the sign for all estimates remains the same and the magnitude of coefficients only differs slightly with the restricted sample. The estimate on education is no longer statistically significant, and the estimate on the Palmer Drought Severity Index and year fixed

effect go from a 1% significance level to a 5% significance level. That said, the other estimates remain highly significant including the estimate for the price perception parameter (*k*) which only slightly changes from 1.156 to 1.151 in the restricted sample.

For *ATC* under the restricted sample the effects on surface water slightly decline along with the statistical significance of the estimates. The short-run impact is slightly lower and statistical significance goes from 1% on both the level and quadratic term to 10% significance and 5% significance, respectively. The magnitude for the long-run effect also declines slightly and statistical significance on the level term goes from the 1% level to the 5% level while the quadratic term goes from the 5% level to a 10% level. In the restricted sample the estimate for the medium-run impact is slightly positive and statistically significant, which was not the case in the full sample. Furthermore, the medium-run estimate for duration increases slightly in magnitude and goes from 5% significance to 1% significance. The short-run and long-run estimates for distance are no longer statistically significant in the restricted sample, but they remain the same in sign and similar in magnitude. Meanwhile, the medium-run estimate for distance is negative and gets slightly larger in magnitude and becomes statistically significant at the 10% level in the restricted sample. Lastly, the estimate for the short-run effect on seasonal intakes becomes statistically significant at the 5% level and slightly larger in magnitude. These estimates indicate that the key findings hold in both the full and restricted sample and that the full sample is not drastically affected by linearly filling missing observations, other than the statistical significance on coefficient estimates.

It is important to realize that figure 1.9 reflects a wildfire impacting a system that uses only permanent surface water intakes, and that all intakes are affected. The effect is therefore dampened when this is not the case, as shown in figure 1.10 reflecting a typical water system using a mix of

intake types. For the average water system in Utah, about 10% of intakes are surface water, about 68% of intakes are permanent, and when a wildfire occurs upstream about 69% of a system's intakes are affected (table 1.4). It is also important to note that wildfire characteristics are unique for surface water intakes, differing a bit from those shown in table 1.4 which reflect wildfires upstream from all intake types. Across the sample, there are 159 occurrences of wildfire upstream from a surface water intake. About 88% of the surface water intakes affected are permanent, with a mean fire distance of 3.9 miles and a mean fire duration of 9.2 days. Most notably, wildfires upstream from surface water intakes are on average closer, but also smaller than wildfires upstream from groundwater intakes. This is potentially associated with behavioral responses from land managers. For surface water, mean *wAcres* = 578 and max *wAcres* = 6,661, again highlighting that this model is only intended to measure the effect of small wildfires.

To understand the policy relevance of these findings, the estimated effect of regular wildfire is linked with consumer welfare in the market for drinking water. To do so, the change in consumer surplus is calculated for a typical wildfire (748.7 acres, 15 days burning, 7.6 miles upstream) and a typical water system (67.6% permanent intakes and 9.9% surface water intakes) in Utah. This is done by calculating the definite integral under the model 4 estimate of demand for changes in the price of water associated with wildfire. Only the short-run (1 year) and long-run (10 year) effects are used, meaning this measure of welfare change reflects a low-end estimate. The change in welfare would be larger if accounting for effects in the intermediate years (2-9 years after a fire) and effects beyond 10 years. However, the final model in this analysis focuses on 1-year, 5-year, and 10-year lags, and only the 1-year and 10-year lagged effects are statistically significant, so only these effects are used to calculate impacts on consumer welfare. The change in consumer surplus for a typical system is translated into an annual amount using the average number of

wildfires occurring upstream from water systems in a given year. This amount is then divided by the average population served to get a final measure of annual consumer welfare change per person. Across the sample, consumer welfare in Utah is found to decline by about $8.86 per person per year due to the short-run and long-run effects of regular wildfires. Discounting these effects to account for the 1-year and 10-year lags results in a welfare change of $7.60, $6.95, and $5.75 per person per year, assuming a discount rate of 3%, 5%, and 10% respectively. For reference, the average person in Utah from 1999-2013 annually paid around $124.56 for drinking water. This means that managing regular wildfires to prevent adverse effects on drinking water resources can help keep water prices down and prevent losses in consumer welfare. Policy makers can utilize the estimates from this work as a benefit measure for drinking water, helping to inform cost-benefit analysis for wildfire and land management decisions.

1.6 Conclusion

For this paper, a panel dataset is assembled to examine 144 drinking water systems from 1999-2013 across the state of Utah. The impact of wildfire that occurs upstream from drinking water intakes is assessed across both space and time, accounting for important wildfire and water system characteristics. Surface water and groundwater intakes are assessed separately, as are seasonal and permanent intakes. The model is intended to focus on small (1,000's of acres) and more recurrent wildfires, as opposed to large severe wildfires that are unique. Small regular wildfires are found to significantly impact downstream drinking water prices for water systems that utilize surface water intakes. The results show that a 1,000-acre wildfire temporarily increases water prices by about 4% in the short run, and then again by 2% in the long run.

I find that water system variable cost rises immediately following a wildfire, and that this encourages capital investment to reduce variable cost, resulting in a significant effect of wildfire on fixed cost in the long run. This is supported by testing the intertemporal relationship between water provisioning fixed cost and variable cost. The results show a positive relationship between fixed cost and past variable cost, while there is an inverse relationship in any given year. The capital investment effect from wildfire is amplified for larger fires. The effect of wildfire in the medium run (5 years after) depends on fire characteristics as well as decisions to lower variable cost through investment. The impact of wildfire is influenced by fire size, distance, and duration, as well as whether the water intake is permanent or seasonal. Post-fire management actions are also important, and the omission of information on management likely dampens the estimates in this study. Estimates for the impact of regular wildfire on groundwater well and spring intakes are not statistically different from zero in this study, signifying that groundwater is insulated from the adverse effects of regular wildfire.

One major limitation of this model is that it cannot identify the specific changes in water quality and quantity conditions that are driving the results. For example, changes in water quality may stem from changes in the physical properties of water, changes in chemical properties, or both. These specific mechanisms are not identified in this model. However, one major benefit of the model is that it allows for any changes to water quality and quantity conditions to be picked up by the estimates. This framework thus permits any changes to water conditions associated with wildfire to affect water provisioning cost and subsequent water price. This is desirable since wildfires often impact numerous water conditions simultaneously, sometimes with synergistic or cancelling effects, and the impacts may be short or long lived. The model also avoids measurement complications that come with deciding the specific water indicators to adopt and how to measure

them. For example, water quality measures such as turbidity can be highly transient, variable, inconsistent, and vary by the instrument used (Neary et al., 2009). So, while this model does not identify specific impacts on water conditions, the trade-off is that it is general enough to pick up any and all impacts that wildfire has on downstream water systems across time.

For surface water, suspended and deposited sediment is often the biggest concern. Turbidity is regulated under secondary EPA standards since high levels of suspended sediment are associated with high levels of disease-causing microorganisms such as viruses, parasites, and bacteria which attach to suspended solids. Increased turbidity after a wildfire may require more treatment chemicals and can cause additional wear and tear on water treatment filters. Deposited sediment can clog water intakes, pipes, stream channels, and storage basins, requiring costly removal. Therefore, sediment is a key focus of studies investigating the impact of fire on water. Sediment is much less of an issue for groundwater, suggesting that sediment is a key reason for the difference between surface water and groundwater effects.

Part of the impact identified in this study could also be associated with nutrient delivery. Highly mobile nutrients such as nitrate-nitrogen (NO3-N) can travel downstream quickly following a wildfire, as can other mobile nutrients like sulfur and chloride. Phosphorus levels can also be elevated after a fire, but phosphorus is often less mobile. Changes in water quantity conditions such as runoff timing and volume may also be driving some of the results. That said, water quantity conditions are closely linked with water quality conditions, making it difficult for researchers to separate their effects. For example, more rapid surface flows are associated with increased sediment and nutrient delivery but can also affect the quantity of water brought in by a system.

Another limitation of this work has to do with using annual system-level data rather than monthly household-level data for water consumption. Worthington and Hoffman (2008) mention

some potential biases from annual aggregate data versus monthly household data. They note that where consumption from the population of households is summed, or whole-of-utility consumption is used, there could be influence (and possible bias) from the presence of non-residential water consumption (i.e. agricultural, commercial, and industrial). The sample for this work excludes wholly non-residential and non-culinary water systems, but the remaining systems may still provide a portion of water supply for non-residential consumption, and the proportion of treated versus untreated water is unknown. Homes with a yard is used to proxy for untreated water, but this is imperfect and there may be different prices and demand elasticities for treated and untreated water that are not observed here. Wildfire should only impact water that is treated, so the estimated elasticities in this work could be biased by consumption of untreated water. If the elasticity of demand for untreated water is greater than for treated water, then these estimates are biased upward and overstate the effect on price. If the elasticity for untreated water is less than for treated water, than these estimates are biased downward and understate the effect on price.

Intuitively, one might expect the demand for untreated water to be more elastic than for treated water, as it largely reflects use such as watering one's lawn, while treated water is used more for necessities such as consumption, bathing, and cleaning. This suggests that the elasticity estimates in this work may be biased upward, insomuch that including homes with a yard does not fully capture demand differences for untreated water. Worthington and Hoffman (2008) also mention potential biases in elasticities when there is less variation in the sample, for example when using annual consumption data versus monthly data that varies across seasons. Monthly variation and observable differences in water demand in winter and summer seasons is desirable and allows for a more precise measure of elasticity. Unfortunately, the sample used for this analysis is only available annually, meaning the estimates for elasticity of demand in this work may be biased. In

general, Worthington and Hoffman (2008) argue that more variation is likely to increase measures of elasticity, meaning the estimates in this work may be biased downward due to less variation. This implies that the estimates for elasticity of demand in this work could potentially be biased upward due to demand differences for untreated water and biased downward due to using annual consumption data rather than monthly.

Not every wildfire necessarily has an adverse impact on water quality and quantity conditions. The factors that influence the type and severity of post-fire water issues are complex and differ from place to place depending on precipitation, soils, vegetation, geology, topography, wildfire features, and post-fire management decisions. The results of this model are meant to be interpreted as only an average effect, recognizing that the actual impact of any single fire could be below or above the estimated effect. The model also focuses on small more regular wildfires and should therefore not be generalized to large severe wildfires which are often unique. Past research has primarily focused on large wildfires, ignoring potential impacts from small and more frequent wildfires. Furthermore, most studies only estimate the immediate impact on cost, failing to account for capital responses that might result over time (Price et al., 2017). This study finds that small regular wildfires impact the price for surface water, both immediately and in the long run due to capital responses. Severe weather conditions and increased drought are expected to fuel the wildfire problem that already exists across the West. These findings highlight the importance of managing wildfire and watershed conditions upstream from surface water intakes and emphasize the vital link between environmental conditions and drinking water prices.

1.7 Chapter 1 Tables

Table 1.1 Water System Budgets

Year	% Balanced (ATC=P)	% Excess (ATC<P)	% Loss (ATC>P)
1999	88.2	11.1	0.7
2000	87.5	11.8	0.7
2001	82.6	16.0	1.4
2002	81.9	16.7	1.4
2003	82.6	15.9	1.4
2004	82.6	15.3	2.1
2005	81.9	15.3	2.8
2006	71.5	25.0	3.5
2007	82.6	13.9	3.5
2008	82.6	13.9	3.5
2009	74.3	20.8	4.9
2010	75.7	20.8	3.5
2011	75.0	18.8	6.2
2012	77.7	18.8	3.5
2013	73.6	23.6	2.8
Average	80.0	17.2	2.8

n=2,160 and systems=144.

Table 1.2 Annual Water System Descriptive Statistics, 1999-2013

	Average	Minimum	Maximum	Std. Dev.
Price per thousand gallons	2.02	0.23	9.23	1.22
Base fee per thousand gallons	4.69	0	16.94	1.76
Block price 1 per thousand gallons	1.14	0.15	5.5	0.75
Block price 2 per thousand gallons	1.63	0.3	10.5	1.34
Block price 3 per thousand gallons	2.17	0.35	12	1.73
Block price 4 per thousand gallons	2.78	0.4	15	2.42
Monthly quantity per connection, thousands of gallons	56.43	0.68	811.6	114.2
Base allowance per month, thousands of gallons	10.67	0	100	11.08
Block 1 quantity per month, thousands of gallons	20.38	2	188	24.21
Block 2 quantity per month, thousands of gallons	25.43	2	200	30.72
Block 3 quantity per month, thousands of gallons	31.18	2	200	36.09
Connections	2,696	100	28,000	4,483.6
Balanced budget, percent	80.05	0	100	39.98
Some leaks, percent	30.0	0	100	45.84
Many leaks, percent	13.24	0	100	33.9
Years before major repair, 5-year	3.03	0	5	1.34
Major improvement, percent	5.0	0	100	21.8
Palmer Drought Severity Index	-0.18	-4.85	7.03	2.45

n=2,160 and systems=144. Prices are CPI adjusted to 2010 dollars.

Table 1.3	Annual Water Demand Descriptive Statistics, 1999-2013			
	Average	Minimum	Maximum	Std. Dev.
Population served	9,789	135	126,250	18,332
Persons per connection	2.99	0.33	6.71	0.96
Median household income, 2010	52,713	35,400	87,464	9,935
Median rooms	6.04	4	7.4	0.58
Renters, percent	25.6	9.93	39.1	6.35
Home with yard, percent	71.7	49.48	93.3	8.1
Home built before 1939, percent	12.2	1.8	37.8	8.0
Median age	29.3	22.9	48.2	4.1
White, percent	92.1	40.7	98.9	6.4
High school or better, percent	89.63	68.5	97.6	3.57

n=2,160 and systems=144. Population served and persons per connection are unique to each water system, while the remaining characteristics are only available at the county level and therefore shared by water systems in the same county.

Table 1.4	Annual Wildfire and Water Intake Descriptive Statistics, 1989-2013			
	Average	Minimum	Maximum	Std. Dev.
Occurrences of wildfire upstream from water systems	41.88	16	90	19.43
Water systems downstream from a wildfire, percent	17.92	7.64	30.56	6.47
Water system intakes downstream from a wildfire, percent	69.11	6.9	100	30.32
Surface water intakes, percent	9.92	0	100	25.01
Groundwater spring intakes, percent	22.24	0	100	36.43
Groundwater well intakes, percent	67.84	0	100	38.97
Permanent intakes, percent	67.56	0	100	38.29
Seasonal intakes, percent	32.44	0	100	38.29
Acres burned per downstream water system	831.68	5	47,588	2,906.66
Weighted acres burned per downstream water system	748.73	0.35	23,707	1,970.24
Wildfire distance upstream, miles	7.63	0.06	24.57	5.1
Wildfire Duration, Days	15.03	1	165	20.11

Only wildfires occurring upstream from water intakes are assessed. There are 1,047 occurrences of wildfire upstream from a water system, but note that some wildfires are counted multiple times if they impact multiple systems. Acres burned per downstream water system encompasses all wildfire occurrences in a given year. Weighted acres burned per downstream system accounts for the fraction of water intakes affected.

Table 1.5	Water Demand Price Estimates, 1999-2013 Dependent Variable: lnQuantity, thousands of gallons			
	(1)	(2)	(3)	(4)
AP	-0.2465***			
	(0.032)			
MP_1		-0.1932***		
		(0.036)		
OP		-0.2583***		
		(0.032)		
lnAP			-0.6288***	
			(0.042)	
$lnMP_1$				-0.5635***
				(0.046)
$ln(AP/MP_1)$				-0.6512***
				(0.043)
k				1.156***
				(0.084)
Price elasticity	-0.498	-0.442	-0.629	-0.524
Controls: Year, System, Palmer Drought Severity Index, lnPopulation, Persons per Connection, lnMedian Income less RSP, Median Rooms, percent Renters, percent Homes with Yard, percent Homes Built Before 1939, Median Age, percent White, percent High School or Better				
Within R^2	0.484	0.492	0.614	0.622
Between R^2	0.866	0.861	0.919	0.919

n=2,160, systems=144, robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. Prices are CPI adjusted to 2010 dollars. For model 2 price elasticity is shown for average price (*AP*). For model 4 price elasticity is shown for perceived price (*P**).

Table 1.6	ATC Estimates for a 1,000 Acre Wildfire by Intake Type, 1999-2013 Dependent Variable: lnATC per thousand gallons, 2010 dollars		
	Groundwater Well	Groundwater Spring	Surface Water
wAcres burned$_{t-1}$	-0.0028	0.0089	0.0374***
	(0.003)	(0.008)	(0.112)
wAcres burned squared$_{t-1}$	0.0001	-0.0005	-0.005***
	(0.0002)	(0.0004)	(0.001)
wAcres burned$_{t-5}$	0.001	0.0053	-0.0096
	(0.005)	(0.01)	(0.013)
wAcres burned squared$_{t-5}$	0.00004	-0.0005	-0.0001
	(0.0003)	(0.001)	(0.001)
wAcres burned$_{t-10}$	-0.0029	0.0209	0.0602***
	(0.007)	(0.017)	(0.023)
wAcres burned squared$_{t-10}$	0.0006	-0.0016	-0.0062***
	(0.001)	(0.001)	(0.003)
Seasonal intake$_{t-1}$, (0-1)	-0.0067	0.0185	-0.0281
	(0.005)	(0.02)	(0.022)
Seasonal intake$_{t-5}$, (0-1)	-0.0063	0.0162	0.0046
	(0.006)	(0.028)	(0.026)
Seasonal intake$_{t-10}$, (0-1)	-0.0106	-0.0172	-0.016
	(0.009)	(0.025)	(0.029)
Distance$_{t-1}$, miles	-0.0003	0.0013	0.0046*
	(0.001)	(0.001)	(0.003)
Distance$_{t-5}$, miles	-0.0002	-0.0008	-0.0035
	(0.001)	(0.001)	(0.003)
Distance$_{t-10}$, miles	-0.0001	-0.0017	-0.0042**
	(0.001)	(0.002)	(0.002)
Duration$_{t-1}$, days	-0.0001	0.0001	-0.0006
	(0.0002)	(0.0004)	(0.001)
Duration$_{t-5}$, days	-0.0002	0.0001	0.0012**
	(0.0002)	(0.0003)	(0.001)
Duration$_{t-10}$, days	0.0002	-0.0007	-0.0019
	(0.0002)	(0.001)	(0.001)

Controls: Predicted lnQuantity (-***), Year (+***), System, Palmer Drought Severity Index (-***), lnConnections (+***), Excess Revenue (+), Operate at Loss (+), Some Leaks (+), Many Leaks (+***), Years Before Repair (-*)

For wildfire estimates the robust standard errors are in parenthesis and for control estimates the sign and statistical significance are in parenthesis. ***1% significance, ** 5% significance, *10% significance. n=2,160, systems=144, within R^2=0.946, between R^2=0.806. The elasticity for *ATC* is -1.47.

Table 1.7 Surface Water Estimates for a 1,000 Acre Wildfire by Fee Type, 1999-2013			
	lnAP	lnAVF	lnABF
SW*wAcres burned$_{t-1}$	0.0374***	0.2912*	-0.096
	(0.112)	(0.171)	(0.079)
SW*wAcres burned squared$_{t-1}$	-0.005***	-0.0305**	0.0098
	(0.001)	(0.016)	(0.009)
SW*wAcres burned$_{t-5}$	-0.0096	0.0311	-0.0779*
	(0.013)	(0.118)	(0.045)
SW*wAcres burned squared$_{t-5}$	-0.0001	-0.0126	0.0094*
	(0.001)	(0.009)	(0.005)
SW*wAcres burned$_{t-10}$	0.0602***	-0.1133	0.1476**
	(0.023)	(0.22)	(0.06)
SW*wAcres burned squared$_{t-10}$	-0.0062***	0.0246	-0.026***
	(0.003)	(0.028)	(0.009)
Number of Observations	2,160	2,160	2,140
Number of Water Systems	144	144	144
Within R^2	0.946	0.216	0.646
Between R^2	0.806	0.089	0.054

Robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. Prices are CPI adjusted to 2010 dollars. This table separates the estimates for *ATC* into changes in variable fees (*AVF*) and changes in base fees (*ABF*) assuming that *AP=ATC=AVF+ABF*. Note that some observations are dropped for occurrences where water systems do not charge a base fee, prohibiting the use of a natural log transformation.

Table 1.8 Surface Water Price Effects for a 1,000 Acre Wildfire Across Time			
Time	AP	AVF	ABF
Short run (1 year)	**3.74%**	**7.36%**	-4.34%
Medium run (5 years)	-1.15%	5.67%	**-4.30%**
Long run (10 years)	**2.14%**	-3.46%	**5.65%**

These estimates are for the impact of a 1,000 acre wildfire on permanent surface water intakes at the mean values of fire distance and duration. The surface water estimates for *AVF* and *ABF* are converted into percent changes in *AP* assuming *AP=ATC=AVF+ABF*. Note that *AVF* and *ABF* don't exactly sum to *ATC* since the number of observations differs slightly for the *ABF* estimation. Bold numbers represent estimates that are statistically significant at the 10% level or better for both the level and quadratic coefficients on fire size.

Table 1.9	Estimates for Intertemporal Investment Dependent Variable: ABF_t per thousand gallons, 2010 dollars			
	(1)	(2)	(3)	(4)
AVF_t	-0.2571*** (0.053)	-0.234*** (0.052)	-.0221*** (0.053)	-0.246*** (0.059)
AVF_{t-1}	0.0912** (0.045)	0.0245 (0.031)	0.0327 (0.038)	0.0629 (0.047)
AVF_{t-2}		0.0925*** (0.031)	0.1047*** (0.037)	0.0932*** (0.035)
AVF_{t-3}			-0.005 (0.035)	0.0222 (0.022)
AVF_{t-4}				-0.004 (0.044)
Controls: Year, System, Physical Condition, Excess Revenue, Operate at a Loss, Some Leaks, Many Leaks				
Number of Observations	2,016	1,872	1,728	1,584
Number of Water Systems	144	144	144	144
Within R^2	0.546	0.546	0.540	0.543
Between R^2	0.447	0.448	0.447	0.444

Robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. It is assumed that average variable fee (AVF) is a proxy for average variable cost and average base fee (ABF) is a proxy for fixed cost. The estimates show an inverse relationship between *ABF* and *AVF* in a given year, but a positive relationship between *ABF* in one year and *AVF* in previous years. The lagged relationship is strongest for t-2. The estimates indicate that high *AVF* in one year is linked with increased *ABF* in future years, and that greater *ABF* correlates with reduced *AVF* in a given year.

1.8 Chapter 1 Figures

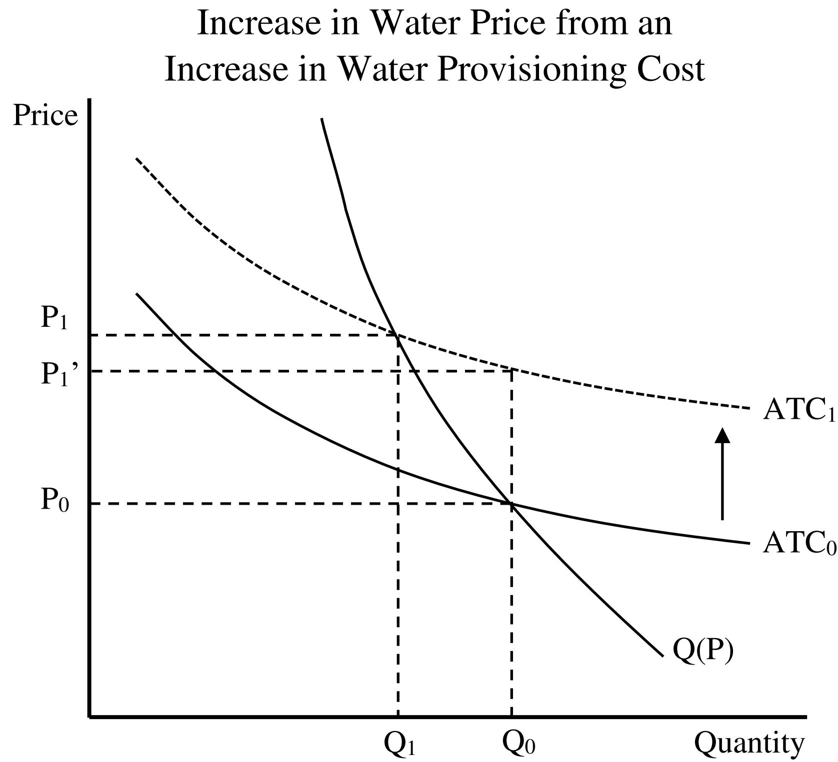


Figure 1.1

An increase in average total cost (ATC) increases price. If demand is assumed to be perfectly inelastic, then the change in price is less (P_1') than when consumers reduce quantity due to a higher price (P_1). Previous studies that assume demand is perfectly inelastic are therefore likely to understate effects on price.

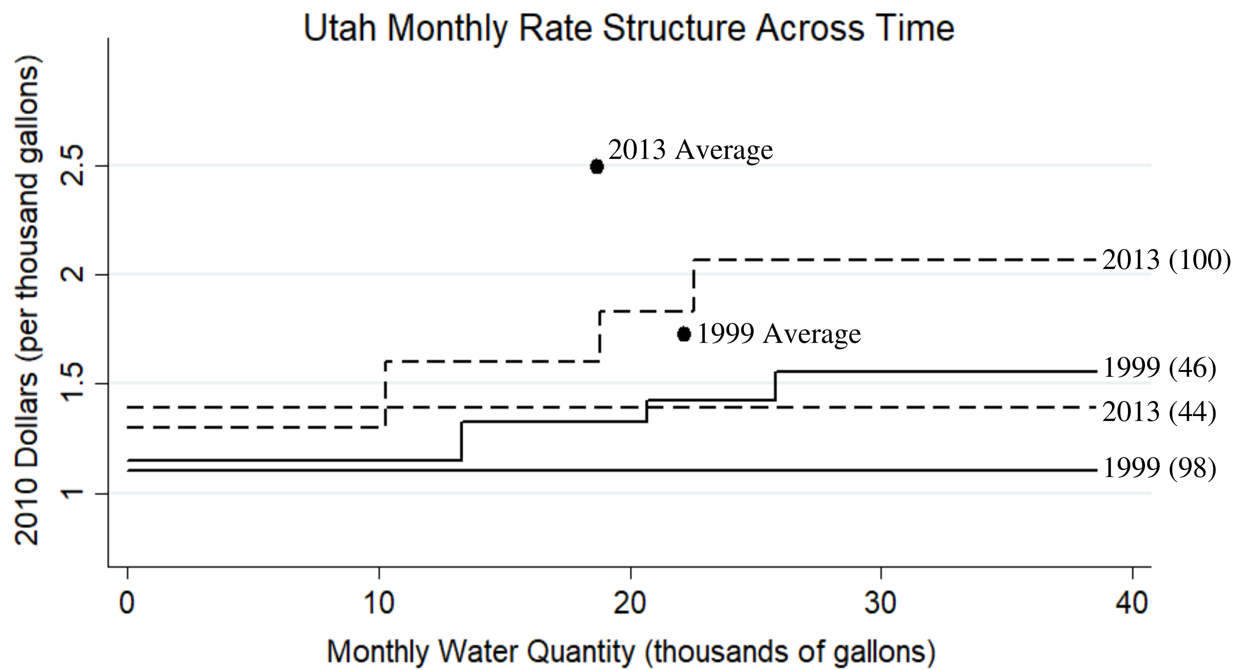


Figure 1.2

Systems=144 and the numbers in parentheses show how many water systems used a constant versus increasing block-price structure in each year. Average base fee (per thousand gallons of allowance) is $2.58 in 1999 and $7.10 in 2013. Prices have increased on average from 1999 to 2013 and about 38% of systems (54) switched from using a uniform price structure to an increasing structure. By 2013 over two-thirds of water systems (100) used an increasing structure.

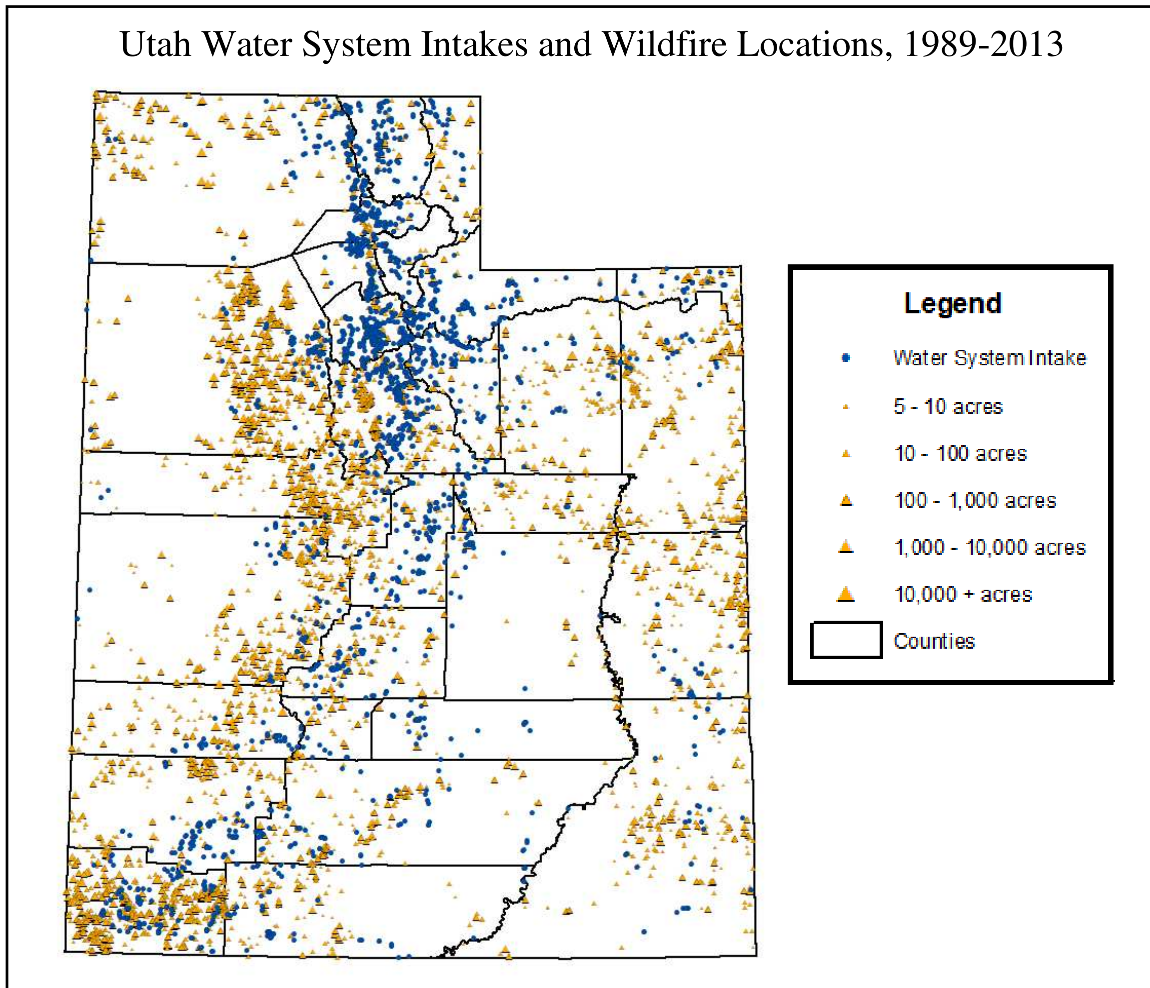


Figure 1.3

These locations reflect water intakes used by drinking water systems (n=144) from 1999-2013 and all upstream wildfires 5 acres or larger (1,047 occurrences) from 1989-2013.

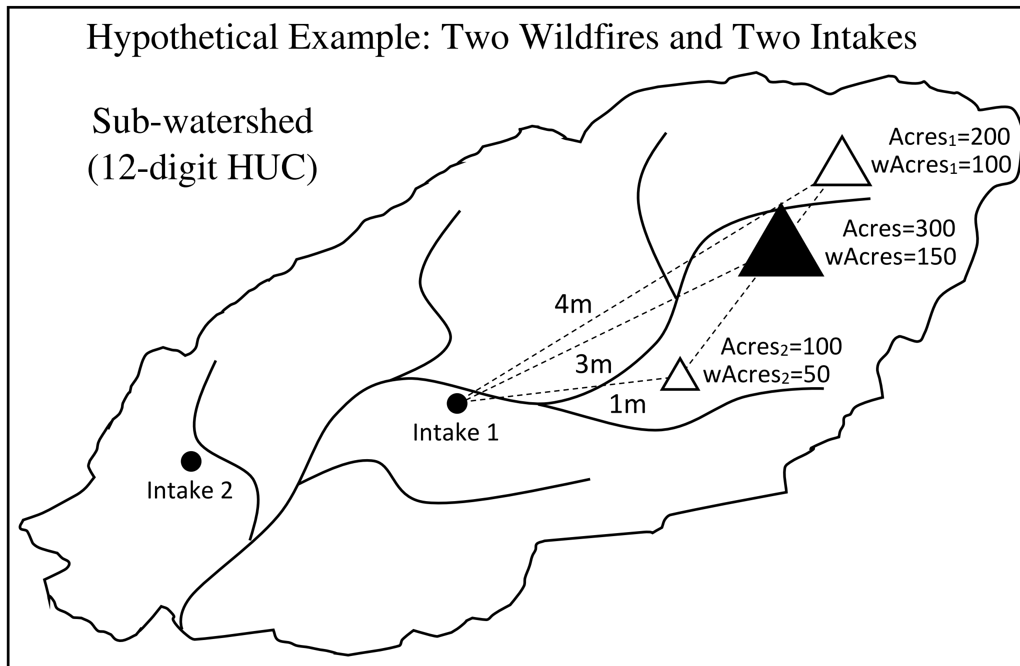


Figure 1.4

In this hypothetical example, two wildfires occur in the same year, but only one of a system's two intakes are affected. The acres burned is weighted (*wAcres*) to account for the fraction of intakes affected. To get an annual estimate of burned acres, *wAcres* is then added across fires. Fire distance from the water intake is measured as a linear distance. Fire distance and duration are averaged across fires, weighted by *wAcres*, to get annual estimates.

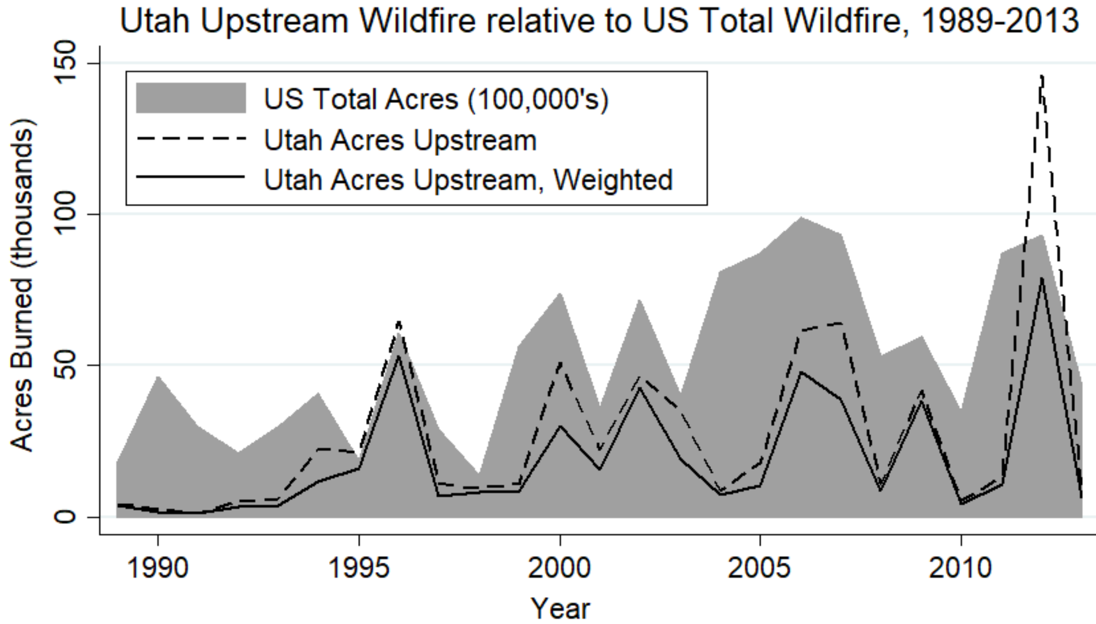


Figure 1.5

Weighted acres burned accounts for the fraction of water system intakes impacted by a wildfire and is used for all model estimates.

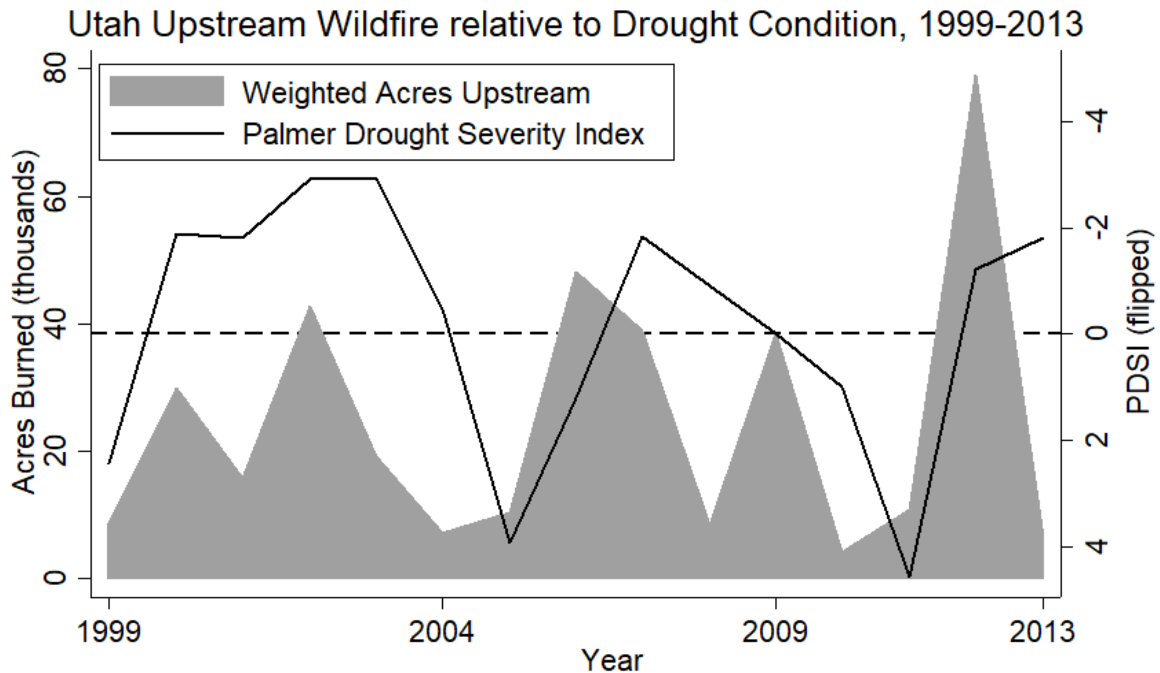


Figure 1.6

The Palmer Drought Severity Index is flipped since negative values represent dryness. The index represents the annual average across all months. Weighted acres accounts for the fraction of water system intakes impacted by a wildfire and is used for all model estimates.

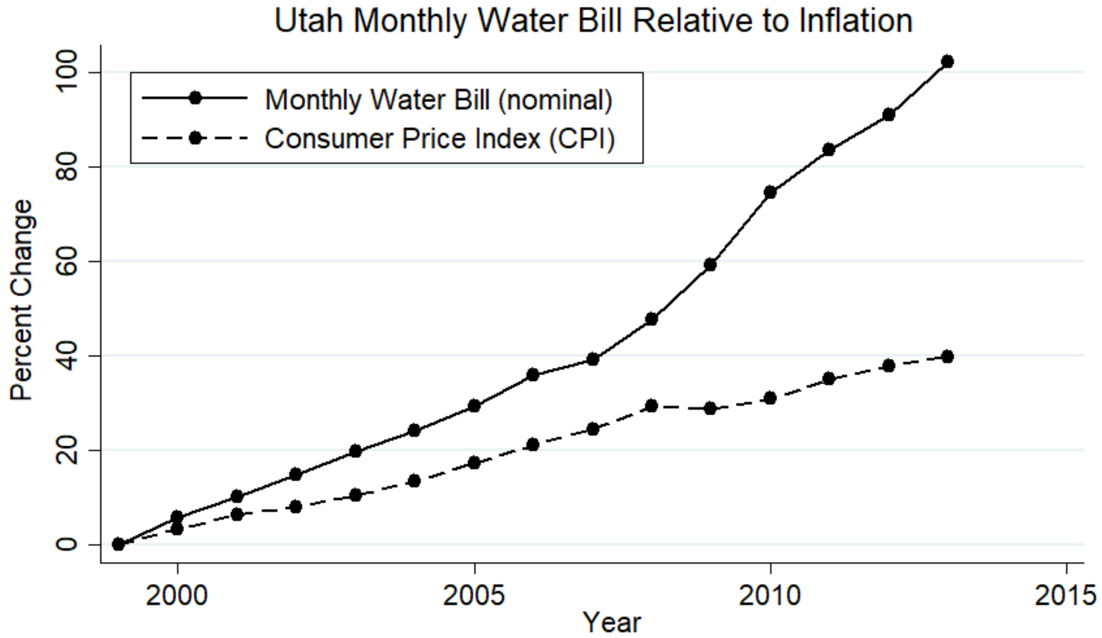


Figure 1.7

Water bills were unaffected by the 2008 recession. Monthly water bill captures changes in both water prices and quantities. The upward trend could be driven by changing prices, quantities, or both.

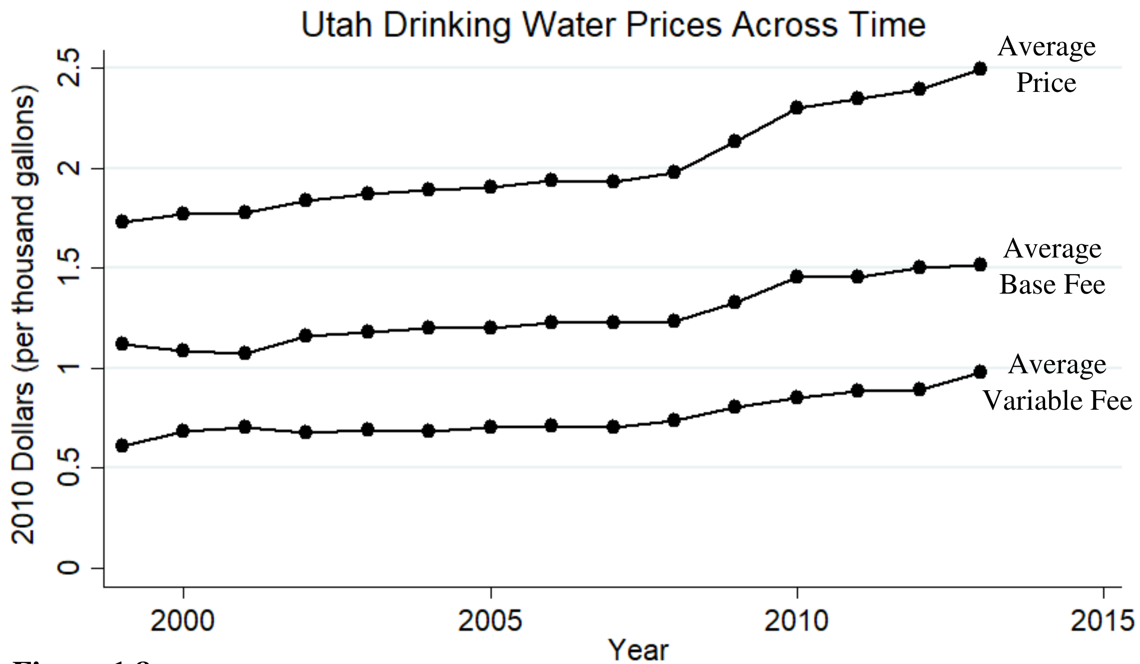


Figure 1.8

Prices are adjusted based on the U.S. National Consumer Price Index (CPI). Real water prices have been rising steadily in Utah. Base fees consistently account for about two-thirds of average water price and variable fees account for the other one-third.

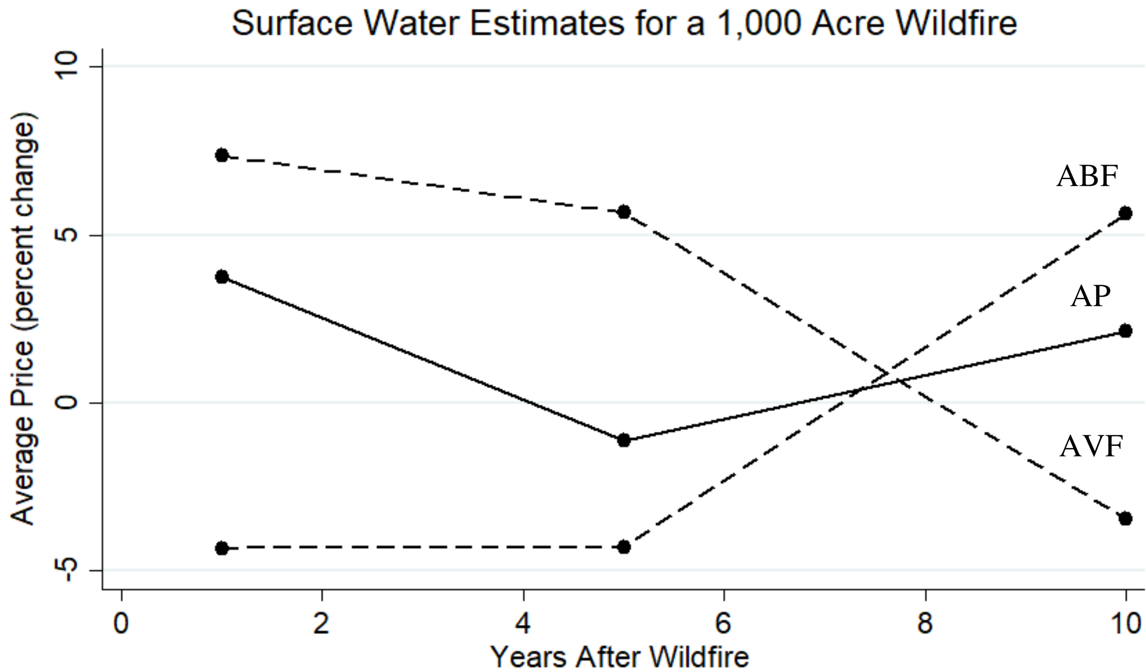


Figure 1.9

Estimates represent the impact of a 1,000-acre wildfire on permanent surface water intakes at the mean values of fire distance and duration. It is assumed that *AP=ATC=AVF+ABF*. Note that *AVF* and *ABF* don't exactly sum to *ATC* since the number of observations differs slightly for the *ABF* estimation. In the short run *AP* rises due to increased *AVF* and in the long run *AP* rises again due to increased *ABF*. Once *ABF* begins to rise, *AVF* falls rapidly.

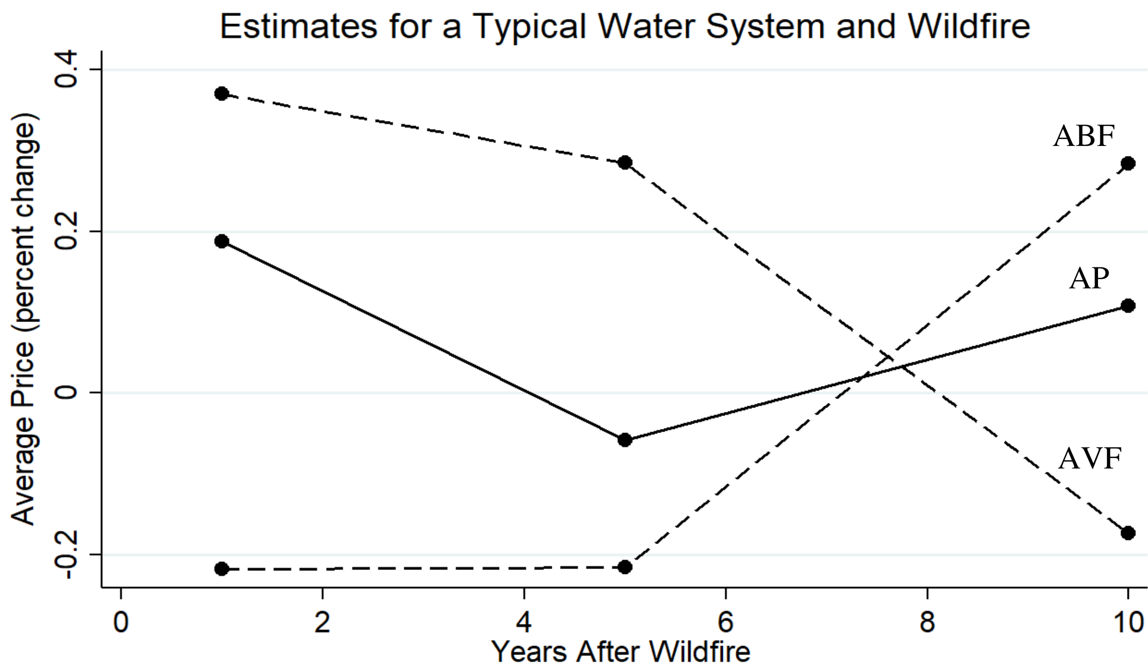


Figure 1.10

Estimates represent the impact of an average wildfire (748.7 acres, 15 days burning, 7.6 miles upstream) on a typical water system (67.6% permanent intakes and 9.9% surface water intakes). Only the estimates for surface water intakes are statistically different from zero, in the short-run (1-year) and long-run (10-years).

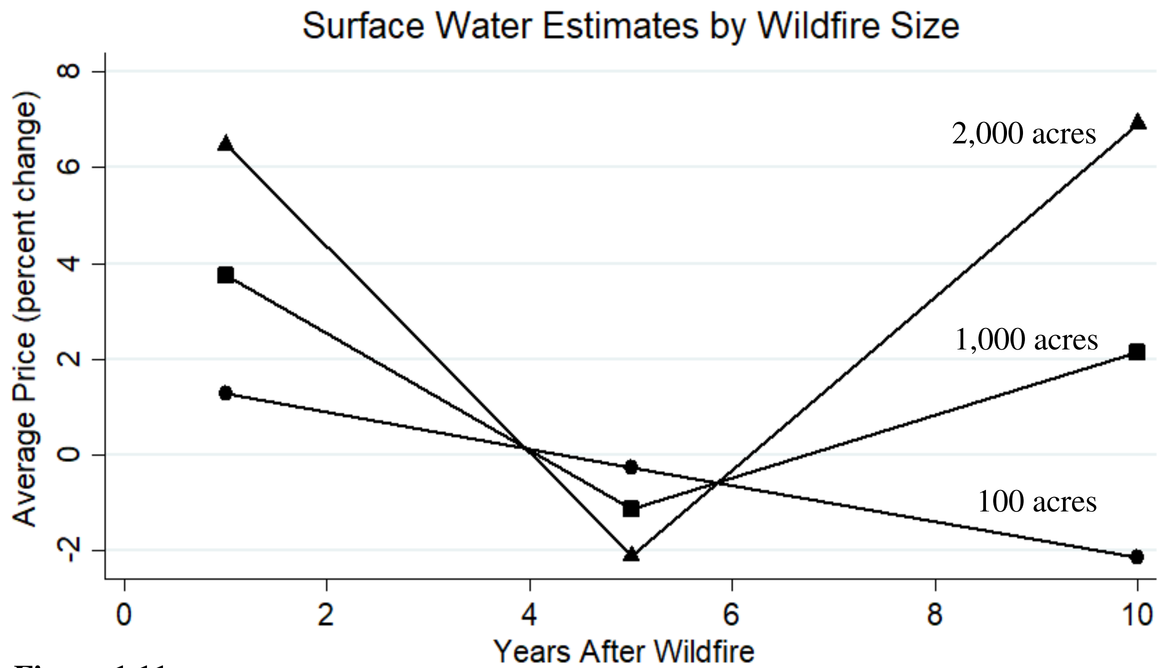


Figure 1.11

Estimates represent the impact of wildfire on permanent surface water intakes at the mean values of fire distance and duration. For small wildfires there is only a short run impact on price, while the long run impact is amplified for large wildfires. This suggests that large wildfires encourage more investment in the long run, resulting in higher prices.

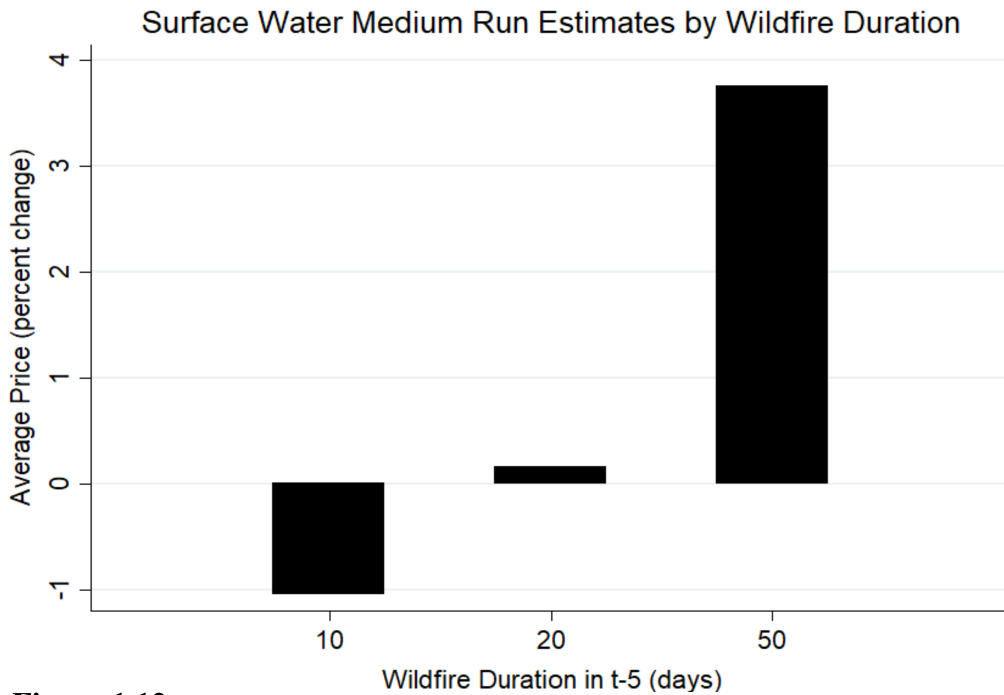


Figure 1.12

Estimates represent the impact of a 1,000-acre wildfire on permanent surface water intakes at the mean value of fire distance. For an average wildfire the short run increase in price dissipates by the medium run, but when wildfire duration is high, the impact carries into the medium run.

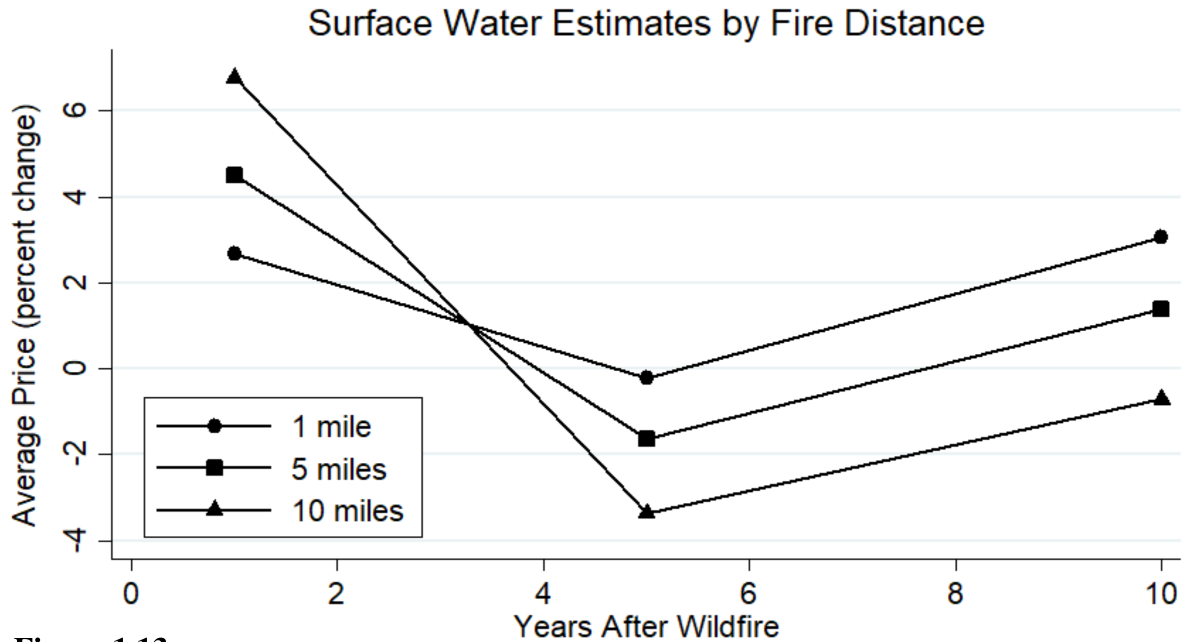


Figure 1.13

Estimates represent the impact of a 1,000-acre wildfire on permanent surface water intakes at the mean value of fire duration. In the short run, wildfires that are closer have a smaller impact on price. This is likely associated with an omitted variable bias, as close wildfires are likely to encourage post-fire management actions, implying a reduced impact on price. In the long run, wildfires that are closer have a larger impact on price, suggesting increased investment.

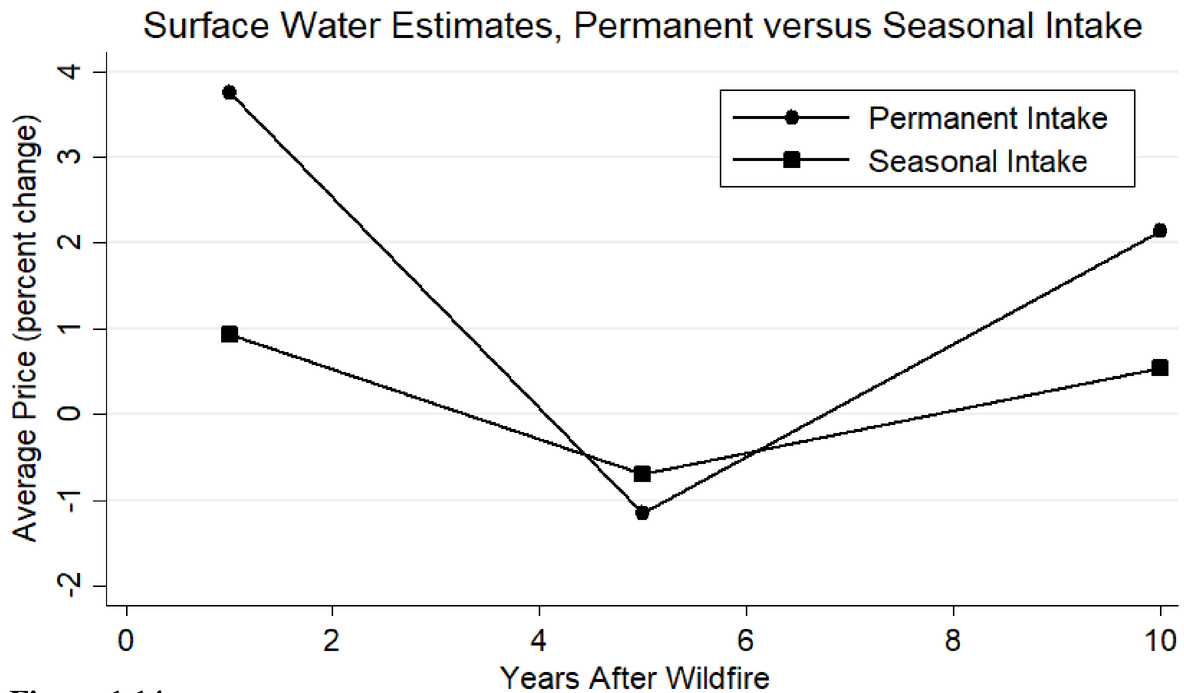


Figure 1.14

Estimates represent the impact of a 1,000-acre wildfire on surface water intakes at the mean values of fire distance and duration. The impact of wildfire is much lower for seasonal intakes than permanent intakes. This is likely due to greater flexibility over the use of seasonal intakes versus permanent intakes following a wildfire.

Chapter 2

Burning Through the Budget: How Has Increased U.S. Forest Service Spending on Fire-Management Affected Spending on Non-Fire Management?

2.1 Introduction

The mission of the U.S. Forest Service is “to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations." Given this mission, their goal is “to achieve quality land management under a sustainable multiple use concept that meets the diverse needs of the public.” Over the years this goal has become increasingly challenging for the Forest Service to achieve, as the cost of fire management has consumed a growing share of the agency’s budget. In 2015 the agency released a report documenting the growth of their budget that is dedicated to fire, highlighting the debilitating impact that rising wildfire costs have on recreation, restoration, planning, and other Forest Service activities on public land (USDA, 2015). Historically, Congressional appropriations fund the agency using a 10-year average for wildfire suppression costs. If suppression costs exceed the 10-year average, the agency must use reserve funds, and when those are depleted, they must execute “fire transfers” from other program accounts.

Although fire transfers are often repaid in subsequent years through congressional appropriations, increases in fire appropriations and carryover funds to support fire transfers can permanently reduce the amount of funding available for non-fire programs. Continuously exhausting fire appropriations and executing fire transfers has led to a slow migration of non-fire

funding to fire programs at the beginning of each fiscal year (HFHC, 2018). This arises from constraints in the agency's total budget, and subsequent internal appropriation decisions across Forest Service regions.

In 1995, fire spending made up only 16 percent of the Forest Service's annual appropriated budget, while in 2015 they had expected more than 50 percent of the budget to be dedicated to wildfire (USDA, 2015). In 2015 wildfire spending did in-fact surpass half of the agency's total budget (costing $1.7 billion, USD 2016), and in 2017 spending was even greater ($2.4 billion, USD 2016), requiring $515.5 million (USD 2016) in fire transfers. These transfers were repaid in full through supplemental appropriations the following year, but this trend has prompted various legislative proposals to address future wildfire funding (H.R. 2862, S. 1842, H.R. 2936, and S. 1571). The Consolidated Appropriations Act of 2018 was the first legislation passed, aimed at providing federal agencies additional funding and new policy tools to support fuels reduction and prevent fire borrowing. The changes are set to go into effect in FY2020, so it is yet to be seen how effective this change will be.

Over the past few decades, the Forest Service's budget has been consumed by spending on fire management. The agency predicts that the share devoted to fire in 2021 could exceed 67 percent, equating to reductions of nearly $700 million from non-fire programs compared to 2015 funding levels (USDA, 2015). The cost of fire suppression alone is predicted to increases to about $1.8 billion in 2021 (USDA, 2015). Changes in climatic conditions have led to fire seasons that are now on average 78 days longer than in 1970 and burn twice as many acres, and Forest Service scientists expect the acreage burned to double again by mid-century (USDA, 2015). The six worst fire seasons since 1960 have all occurred since 2000, and since 2000 many western states have experienced the largest wildfires in their state's history (USDA, 2015). Without an increase in total

appropriations, this wildfire trend adversely affects the Forest Service's non-fire programs and hinders their ability to achieve sustainable multiple use land management.

For decades the Forest Service has experienced rising costs associated with fire operations. Meanwhile, the agency's total real annual appropriated budget has not risen accordingly, and has instead slightly fallen over time. This has caused increased fire spending to adversely affect non-fire activities. Past work has coarsely looked at the effect of fire spending on non-fire spending, looking only at trends of broad spending categories over time. It is unclear which particular non-fire programs have been affected the most by increased spending on fire, and it has yet to be explored how this impact is dispersed across Forest Service regions. Previous research has also looked at declines in fire programs due to suppression needs, which can create a "positive feedback" in spending on fire management (Calkin et al., 2015). That said, previous assessments focusing on the Forest Service do not account for the portion of spending cuts stemming from increased fire spending versus other sources of declines. Many often make the simplifying assumption that aggregate spending declines mostly, if not fully, reflect impacts associated with fire spending.

This study seeks to identify which non-fire and fire programs have been affected by increased spending on fire. This is further explored spatially by looking across Forest Service regions utilizing Forest Service regional funding allocation data for all fire and non-fire budget line items from FY2004 to FY2016. A unique OLS model is used to separate the effect of increased fire spending into a permanent effect (operating directly through changes in annual fire appropriations and indirectly through carryover funds) and a temporary effect (operating through supplemental fire funds that are repaid in following years). Changes in total appropriations are also included in the model to account for changes stemming from sources other than fire spending. The model

therefore identifies which programs are temporarily affected across regions by fire transfers, as well as which programs are permanently affected by appropriations migrating to fire spending over time. This analysis also explores where fire spending is going across fire programs and regions.

This paper proceeds as follows. First, the literature is reviewed to assess previous work looking at fire management, particularly adverse effects from Forest Service spending on fire. Background is provided on the budgeting process and mechanisms for allocating funds to Forest Service spending programs across regions, along with discussion of reform attempts. Next, is an overview of the modeling framework used to identify the impact of fire spending on both non-fire and fire programs across Forest Service regions. Following, there is a discussion of the data utilized to empirically test various regression models. In the results section, the findings are reported and used to assess how increased fire spending has affected non-fire and fire programs across regions. Finally, limitations are discussed along with some policy implications and concluding remarks.

2.2 Literature

Over the past few decades, both the magnitude and the variability of wildfire have increased substantially (Calkin et al., 2005; Gebert et al., 2007; Westerling et al., 2006). The causal factors have been largely attributed to past suppression efforts (Arno and Brown, 1991), drought conditions (Collins et al., 2006; Crimmins and Comrie, 2004; Gedalof et al., 2005; Westerling et al., 2002, 2003), and climate change (Flannigan et al., 2000; Westerling et al., 2006). Rapid population growth in the wildland-urban interface (WUI) also generates suppression challenges (Cardille et al., 2001; Liang et al., 2008; Gill and Stephens, 2009; Mozumder et al., 2009). Congress mandates that the federal government is responsible for managing wildfires that begin

on federal lands, such as National Forests and National Parks, while states are responsible for managing wildfires that originate on all other lands.

Although more wildfires occur annually on nonfederal lands, fires on federal lands tend to be much larger, particularly in the western United States (Hoover and Lindsay, 2017). From 2004-2016, an average of 71,749 wildfires burned an average of 7 million acres annually, including both federal and non-federal lands (NIFC, 2019). On Forest Service Lands, an average of 7,412 wildfires burned an average of 1.4 million acres annually (NIFC, 2019). The federal government's wildfire management responsibilities are carried out by the Forest Service and the Department of the Interior, managing for fire preparedness, prevention, detection, response, suppression, and recovery. From FY2004-FY2016, the Forest Service and the Department of the Interior spent $20.8 billion (USD 2016) on fire suppression alone, with about 76 percent coming from the Forest Service's budget and 24 percent from the Interior Department's budget (NIFC, 2019). The Federal Emergency Management Agency also provides disaster relief on occasion, but primarily for non-federal wildfires. This paper focuses on federal lands and the Forest Service, in particular, the effect that increased spending on fire management has had on the agency's non-fire management responsibilities.

Wildfire suppression activities on and around National Forest lands are generally funded entirely within the Forest Service's budget, based on a 10-year rolling average. This method originated in the 1990s from an agreement between the House and Senate Committees on the Budget, the Congressional Budget Office, and The Office of Management and Budget (U.S. Congress House Report, 2008). This means that the agency's annual fire suppression appropriations are limited by the average cost of fire operations in the past years. When the average was stable, the agency was able to use this model to budget consistently for the annual costs

associated with fire suppression. However, over the last few decades the cost of fire suppression has increased as fire seasons have grown longer and the frequency, size, and severity of wildfires has increased (USDA, 2015). Changing climatic conditions across the United States are driving increased temperatures and drought conditions, particularly in regions where fire has not been historically prominent (USDA, 2015). This change is causing variations and unpredictability in precipitation and is amplifying the effects and costs of wildfire (USDA, 2015).

As long as the 10-year average serves as the Forest Service's funding model for fire suppression, this wildfire trend presents a significant threat to the quality of all services that the agency supports across National Forests. The 115th Congress considered legislation to address this issue (H.R. 2862, H.R. 2936, S. 1842, and S. 1571), but none of those bills were passed. Many of these proposals would have allowed for some wildfire suppression funds to be provided outside the statutory limits on discretionary spending, either through the annual appropriations process or through supplemental appropriations. Under those proposals, varying levels of wildfire funding would not need to compete with other programs and activities that are subject to the statutory limits (Hoover and Lindsay, 2017). In 2018, the Consolidated Appropriations Act was passed which gave federal agencies additional funding and new policy tools to support fuels reduction and prevent fire borrowing. This included a new fire suppression funding mechanism that adjusts federal spending caps to accommodate firefighting needs. The legislation provided a new "disaster cap allocation" for wildfires starting in FY2020 at $2.25 billion, which increases to $2.95 billion in FY2027. However, the legislation freezes the wildfire suppression budget line item (BLI) at the FY2015 level in an attempt to stop the slow migration of non-fire funding to the fire programs at the beginning of each fiscal year (HFHC, 2018). The new budget cap is set to go into effect in FY2020.

The Forest Service has two accounts for wildfire; Wildland Fire Management (WFM) appropriations, and a reserve fund known as the Federal Land Assistance, Management, and Enhancement (FLAME) appropriations. WFM appropriations primarily go towards preparedness and suppression. FLAME was implemented in 2010 (U.S. Code §1748a) and serves as a supplemental source for funding fire suppression. Nonetheless, suppression costs frequently exceed annual appropriations for both WFM and FLAME, requiring mid-season transfers of additional funds from non-suppression accounts, or "fire transfers." Before a fire transfer can be executed the agency must first exhaust all fire reserve funds, then the agency may get authorization to transfer unobligated funds from other program accounts. Congress typically repays fire transfers with supplemental appropriations the following year. Spending on fire in any given year can therefore come from fire appropriations, fire reserve funds, or fire transfers.

Federal wildfire suppression spending is influenced by several factors, including the size and intensity of the fire and the proximity of the fire to the WUI and associated valuable resources (Cardille et al., 2001; Liang et al., 2008; Gill and Stephens, 2009; Mozumder et al., 2009). Development in the WUI has resulted in more people and homes within or closer to fire-prone areas, particularly in the western United States. This trend has been cited as a primary factor that increases suppression expenditures (USDA OIG 2004). Federal suppression costs tend to be higher as the number and value of homes near a fire increase (Gebert et al., 2007; Yoder and Gebert, 2012; Gude et al., 2013) or when private land is a greater share of the burned area (Liang et al. 2008). It is estimated that from 1970 to 2000 the WUI expanded more than 52 percent to 179,775 square miles, and it is expected to increase to 198,333 square miles by 2030, with the greatest expansion occurring in the states of the intermountain West (Theobald and Romme, 2007). Some have pointed out that this WUI development also makes it difficult to identify a causal relationship

between acres burned and spending on fire, as more spending on fire can encourage development in fire-prone areas and contribute to large wildfires (Kousky et al., 2012).

Suppression expenditures reflect management decisions at multiple levels to assign resources to a fire incident, and the choice of overall suppression strategy can influence those expenditures. Strategies vary from aggressive direct suppression efforts meant to contain a fire quickly and limit damage, to monitoring efforts that largely allow the fire to take its natural course when few highly valued resources are at risk (Hand et al., 2014). These types of strategies will call for different time-paths of resource allocation as managers weigh tradeoffs over fire size, duration, intensity, ecological impact, and damage to valued assets (Hand et al., 2014). Gebert and Black (2012) examine suppression strategies ranging from direct full suppression to strategies that seek to allow the fire to achieve resource benefits. They find that using the most aggressive strategies tends to result in shorter duration fires with smaller burned areas, but with higher expenditures per acre and per day (due to more intensive suppression effort over a shorter time and smaller area). However, total suppression expenditures were roughly the same when using the least aggressive suppression strategy relative to the full suppression strategy, as the longer duration of less aggressive suppression offset the per acre and daily expenditures savings (Gebert and Black, 2012).

Rehabilitation and restoration projects can also be funded with fire suppression dollars. Project work is accomplished in conjunction with emergency stabilization work authorized through Burned-Area Emergency Response (BAER). Funding authority for the Forest Service to conduct emergency stabilization through BAER provides for the use of Wildland Fire Management funds for necessary expenses related to “emergency rehabilitation of burned-over National Forest System lands and water.” BAER gives authority to enter into watershed restoration and enhancement agreements and expend appropriated funds on non-Federal lands, when there is a clear benefit to

the National Forest System lands in the watershed. Information collected by the BAER teams is shared with other Federal, State and local agencies so they can aid communities and private landowners who may also be affected by potential post-fire damage.

Even after accounting for many of the biophysical factors and landscape characteristics that are related to fire expenditures, much variation in expenditures remains unexplained (Hand et al., 2014). This suggests that human factors including the characteristics of the local land managers and assigned incident management team as well as social and political influences may play a substantial role in determining fire expenditures (Hand et al., 2014). Donovan and Brown (2005) argue that manager incentives are a contributing factor resulting in the build-up of hazardous fuels that cause larger, more dangerous, and more costly fires. A budgeting process whereby expenditures are paid largely from national accounts rather than from local accounts may encourage overuse of suppression resources on a given fire and over the course of a fire season (Hand et al., 2014). This limits the amount of fire on the landscape that can naturally treat and reduce hazardous fuels, which leads to larger and more expensive fires in the future. Donovan and Brown (2005) identify two factors that create an incentive for overuse of suppression resources. First, budgets for suppression are paid out of national funds rather than from budgets at the local level, which means a manager in a local unit does not bear any of the opportunity cost for using additional suppression resources. Second, management decisions tend to discount beneficial effects of fire for treating the build-up of fuels, meaning managers may only consider the potential damages of additional fire on the landscape and not the potential future benefits of a less aggressive suppression response.

The disincentives faced by managers to contain expenditures have been recognized as a potential barrier to more efficient risk management of wildland fire (Calkin et al., 2011).

Thompson et al. (2013) suggest that risk management for wildland fires could benefit from the application of actuarial principles to fire program funding, which could encourage both suppression expenditure containment and efficient management of risk. Managerial incentives (Donovan and Brown, 2005; Thompson et al., 2013) and managerial biases and risk perception may be important in the budget allocation process (Wilson et al. 2011; Wibbenmeyer et al. 2013), yet the role of such factors in decision making and strategic choices are only beginning to be understood in a wildfire management context (Hand et al., 2014).

The general response to wildfire is to prioritize the safety of the firefighters first, then the ecological, social, and legal consequences of the fire. While attention has focused on protecting life, property, and communities in the WUI, opinions vary over if and how much the Forest Service should pay to protect those resources. Protecting these resources often increases firefighter risks as well as suppression costs as more personnel and assets are deployed to provide protection (USDA OIG, 2006). The cost of managing wildfire generally reflects the values being protected (human, natural, historical, or cultural), and consideration of economic efficiency is not necessarily required (Hoover and Lindsay, 2017). In other words, fire management priorities may include managing costs, but only so much as it does not compromise safety. Some believe this approach allows the Forest Service flexibility to provide a high-quality emergency response, while others believe this is analogous to a "blank check" policy and that it has removed any incentive for the agency to control suppression costs (see for example, NAPA, 2002; O'Toole, 2002; Ingalsbee, 2010; Lueck, 2012).

When wildfire expenditures began to increase in the 2000s, many were concerned that the federal government was bearing too much of the cost of wildfires and that state, local, and private landowners lacked incentive to mitigate future fire risk to offset suppression costs (O'Toole, 2002;

GAO, 2006; USDA OIG, 2006; Headwaters Economics, 2009). The agencies have since modified their cost share agreements with many of the states to provide more consistent arrangements, although these still may vary by state and by fire (GAO, 2007). The Forest Service has also initiated several technical and financial assistance programs to increase WUI community preparedness and homeowner protections. Given this, the debate in more recent years has focused less on the federal share of rising suppression costs and more on budgetary constraints on discretionary spending (Hoover and Lindsay, 2017).

Appropriations for preparedness are used to support efforts that assist with fire prevention and detection, equipment, training, and baseline personnel. Suppression appropriations are primarily used for wildfire response. Suppression operations fund firefighter salaries, equipment, aviation asset operations, and incident support functions in direct support of wildfire response. Funds are also used for hazardous fuels reduction and fire assistance programs, as well as other activities that are focused on decreasing the risk of future catastrophic wildfires. The FLAME account is a reserve fund for wildfire suppression and is intended to prevent the need for fire transfers and supplemental appropriations. Despite this intent, the Forest Service has had to borrow funds 4 times since the establishment of the FLAME account in 2010.

In 2017, Congress designated the appropriations to the FLAME account as emergency requirements and not subject to certain limits on discretionary spending (Hoover and Lindsay, 2017). This meant the Forest Service had more funds in FY2017 than they had requested for suppression activities, and the FLAME account consisted of additional suppression funds that were provided outside of discretionary spending caps. In this sense, FY2017 was the first year that the FLAME account actually functioned as a reserve account with funding in excess of the 10-year suppression average (Hoover and Lindsay, 2017). However, the FY2017 change appears to have

still been insufficient, as the Forest Service notified Congress in late August 2017 that suppression and FLAME accounts were within 30 days of depletion and that the FS was going to transfer funds from other accounts (Hoover and Lindsay, 2017). The reserve amount was therefore unable to cover the agency's full suppression needs in FY2017, which was another record-breaking year for wildfire.

Even when suppression and FLAME funds are depleted, the Forest Service must continue to respond to wildfire. Once funds are drained from both WFM and FLAME, continued suppression needs force the agency to transfer appropriations from non-fire accounts, known as a fire transfer or "fire borrowing." The authority to transfer funds for WFM related activities was first granted in the 1980 appropriations law, which allowed transfers for the emergency rehabilitation of lands affected by wildfire (Hoover and Lindsay, 2017). This authority was continued annually, and funds may be transferred from non-fire discretionary accounts, mandatory accounts, permanent accounts, and trust funds. In this sense, funding for suppression is partially reactive, and not entirely proactive.

Typically, the Forest Service develops an internal fire borrowing plan prior to the start of the wildfire season (Hoover and Lindsay, 2017). The plans identify accounts and programs that may be targeted if transfers are needed, based on unobligated balances and a strategy that minimizes potential impacts to agency programs (Hoover and Lindsay, 2017). Historically, the Forest Service borrowed funds primarily from its trust fund accounts (considered mandatory accounts), particularly the Knutson-Vandenberg (K-V) Fund (Hoover and Lindsay, 2017). This account accumulates deposits from timber purchasers and is used to reforest and improve conditions in timber sale areas. Because of the lag between timber payments and reforestation, the K-V Fund often had a balance of around $500 million; much more than was needed for annual tree planting

efforts. However, the K-V Fund has had a limited balance since 2000 due to lower timber sales (Hoover and Lindsay, 2017). From the 1960's-1980's around 11 billion board feet of timber was sold per year, while the amount sold plummeted to about 2 billion board feet per year by 2000 (USDA, 2019). Meanwhile, emergency fire suppression costs have risen, and the Forest Service has had to borrow funds from other programs that support recreation, wildlife, vegetation, watersheds, and several other ecosystem services that benefit local businesses and communities along with visitors from all over. Funds are also sometimes transferred from other fire operations, such as hazardous fuels management, which can create a "positive feedback" in fire management (Calkin et al., 2015). Diverting mitigation funds to spend on immediate suppression needs can exacerbate future suppression needs and lead fire management costs to be higher over time.

When considering fire transfer, the Forest Service often targets programs that have relatively large unobligated balances (GAO, 2004). These programs are often funded in one year, but the funds may not be obligated for several years, potentially allowing for transfers to be made with minimal immediate impact so long as the funds are reimbursed (Hoover and Lindsay, 2017). The agency may then make a request to Congress to provide additional funding to replenish the FLAME account and to repay any transferred funds. Congress often provides a supplemental appropriation to repay those accounts, and from FY2001-FY2017 Congress has had to provide supplemental appropriations for wildfire suppression in 12 of the 16 years from FY2001-FY2016 (Hoover and Lindsay, 2017). Although Congress typically provides supplemental funds to replenish the agency's budget, they can be problematic by disrupting seasonal work, frustrating partners, and delaying vital work (see for example GAO 2004, 2007, and 2009; USDA, 2015).

The authority to access additional funds for suppression is intended to provide flexibility and quick response in emergency situations. However, some argue that it also effectively provides the

agency with an open-ended transfer authority, which provides little incentive to manage suppression costs (NAPA, 2002; O'Toole, 2002; Ingalsbee, 2010; Lueck, 2012). Meanwhile, the Forest Service has argued that the fire transfers are disruptive to their non-fire operations and hinder their ability to carry out their statutory mission (GAO, 2014). Even when funds are repaid, fire transfers can create uncertainty and affect non-fire programs. Some programs are also time sensitive (e.g. land sales) and may suffer adverse impacts (e.g., changing land prices) if delayed by fire transfers (GAO, 2004).

Due to the timing of the budget process, the suppression budget request for any given year is based on the rolling 10-year suppression obligation average calculated two fiscal years previously. For example, the FY2016 suppression budget request was formulated using the FY2014 rolling obligation average. This means that suppression spending from FY2005 through FY2014 was used to formulate the suppression budget request for FY2016. Because this method is based on past spending, estimates have not been accurate for predicting future suppression spending needs. This method has underestimated suppression spending in 8 of the 10 fiscal years from FY2007-FY2016, and over this time period, the rolling 10-year suppression obligation average has been about 50% below the necessary obligations (Hoover and Lindsay, 2017). An earlier proposed version of the FLAME Act would have required the agency to use a rolling 5-year suppression obligation average to formulate their budget request, which would have potentially been a bit more accurate since the lower values from earlier years would drop out of the calculation.

The enacted version of the FLAME Act requires the Forest Service to develop an estimate of future suppression costs based on the best available science, but it does not direct that these estimates be used to formulate budget requests. The agency is supposed to predict suppression spending during a wildfire season to ensure the availability of funds and to determine if and how

much additional funding is going to be necessary. Although the FLAME forecasts generally have not been the basis used for funding requests, the agencies have used the forecasts to inform congressional decisionmakers about potential spending levels throughout a wildfire season or during budget hearings. Since the passage of the FLAME Act, the agency began using regression models that incorporate weather and climate data, among other data, to forecast spending. The models are based on methods developed by Prestemon, Abt, and Gebert (2008) and used to predict a range of suppression spending within a 90% confidence interval (CI) and they are published four times per year. The estimate for the upper 90% CI ranged from $1.6 billion in the March 2014 forecast to $2.0 billion in the May 2014 forecast three months later (Hoover and Lindsay, 2017). This highlights the inherent uncertainty in predicting future costs for fire operations. In the six years (2011-2016) for which data are available, suppression obligations exceeded the annual average FLAME median forecast 5 times and the average upper 90% CI 3 times (Hoover and Lindsay, 2017). Future spending on wildfire has thus proved difficult to predict, and the current funding methods have not been adequate to prevent spending on fire management from adversely affecting non-fire management.

2.3 Research Focus

When it comes to the rising cost of managing wildfire, past work has analyzed several inefficiencies and problems associated with wildfire management. For example, research has focused on matters such as increasing hazardous fuel reduction to reduce suppression spending (GAO, 2007 and 2009); increasing wildfire prevention education and prescribed fire to minimize management costs (Butry et al., 2009); pre-positioning suppression resources to minimize damage from wildfires and constrain suppression expenditures (Fried et al., 2006); cost sharing with private

landowners to reduce social losses from forest fires (Amacher et al, 2006; Shafran, 2008; Crowley et al., 2009); discouraging development near the WUI (Kousky et al., 2012); altering incentives and restricting access to additional funds to help contain fire management spending (NAPA, 2002; O'Toole, 2002; Ingalsbee, 2010; Lueck, 2012); reducing "positive feedbacks" in fire management from fire transfers across fire accounts (Calkin et al., 2015); and minimizing project cancellations and delays from fire transfers (GAO, 2004, 2007, and 2009). Amid increased public scrutiny and a highly variable wildland fire environment, a substantial body of research has studied factors affecting the cost-effectiveness of fire management activities (Hand et al., 2014).That said, little work has looked at how increased spending on fire management adversely affects the funds available for non-fire management activities, and subsequent work is needed to measure potential impacts from budget cuts to programs that support important economic values such as recreation, grazing, wildlife, and freshwater.

This paper focuses on the effect of fire management spending on non-fire programs managed by the U.S. Forest Service – the agency with the largest wildfire management responsibility in the country. The effect of fire spending on non-fire programs is an important question concerning several government agencies, especially the U.S. Forest Service which annually spends billions on land management and managing wildfire. The Forest Service is mandated to manage land with a multiple-use agenda and thus regularly faces trade-offs as fire management consumes a growing share of their budget. The work that has looked at the effect of increased fire spending on non-fire programs has only looked at time-series trends (USDA, 2015; Hoover and Lindsay, 2017), concluding that increased spending on fire has adversely affected the funds available for non-fire programs. However, these studies do not control for changes in total appropriations, which may reflect declines that are unrelated to increases in fire spending. They do nevertheless make note

that considering changes in annual appropriations could be important. Given that the Forest Service's real total appropriated budget has declined in recent years, past work likely overstates adverse effects on non-fire programs by focusing only on time-series trends. This paper formally models changes in Forest Service non-fire spending that come from various sources, using a unique econometric model that separates the effect of increased fire spending into a permanent effect (operating directly through changes in annual appropriations and indirectly through carryover funds) and a temporary effect (operating through supplemental fire funds that are repaid in following years). By including changes in total appropriations to control for changes unrelated to fire spending, and changes in carryover funds to support future fire spending, the models serve to identify a causal relationship between permanent increases in fire spending and declines in non-fire spending.

Past work has not clearly identified the particular non-fire programs that are most affected by increased spending on fire, and they have not looked at whether funding might be cut in some Forest Service regions to fund fire-related costs in other regions. Hand et al. (2014) assess the regional and temporal trends in wildfire suppression expenditures, evaluating whether differences in fire characteristics and management responses to wildfire explain expenditure differences. They find that expenditures in the western regions tend to move together and coincide with fire activity and climate patterns that affect a broad geographic area in the western United States (Hand et al., 2014). For per-unit expenditures of managing Forest Service fires they conclude that the overall trend in aggregate suppression expenditures may largely be due to factors outside the control of the agency (Hand et al. 2014). That said, they do not link regional differences in fire spending to the potential adverse effects on other regions and programs. Spending is likely cut from non-fire programs in some regions to support fire spending in other regions. Spending cuts could also occur

for fire programs in some regions to fund fire spending in other regions, such as cuts in spending on hazardous fuels management and preparedness in the East to fund fire suppression in the West. This might then generate a "positive feedback" in fire management costs as found by Calkin et al. (2015). This paper utilizes Forest Service regional spending data and a unique OLS regression model to address these hypotheses and test the following research question; *Which Forest Service programs are cut to fund additional fire spending, and how are spending cuts distributed across regions?*

It is important to distinguish between the actors that determine how annual appropriations are allocated across programs and across regions. Total appropriations for each budget line item (BLI) reflect discretionary funds largely determined by Congress, although the agency may request increases or decreases in particular BLIs through their annual Budget Justification (funding request for Congress). Once appropriations are determined across BLIs, the Forest Service then decides how to allocate those appropriations across regions. This distinction implies that shifts in spending across BLIs is largely linked with congressional decisions, while shifts across regions is largely linked with the agency's decisions (though of course there is a link between congressional and agency decision-making). This has important implications when considering solutions to address shifts in spending across programs versus shifts across regions, and a comprehensive fix would likely require addressing decision-making at both levels. That said, for this analysis attention is placed on identifying where appropriations are going, regardless of who determines the allocation of that spending. It is nevertheless important to keep in mind that the allocation of appropriations across BLIs is driven by both Congress and the agency, while appropriations across Forest Service regions is primarily determined by the agency's internal decision-making.

2.4 Model

Given that Forest Service discretionary fire appropriations are based on a 10-year average of past spending, increased spending on fire-related activities permanently reduces non-fire appropriations unless total appropriations rise to fund wildfire spending, or carryover funds are used. Changes in non-fire spending can therefore come from four key sources; changes in (1) total appropriations, (2) carryover funds, (3) discretionary fire appropriations, or (4) supplemental fire spending. It is assumed that changes stemming from discretionary fire appropriations cause a direct permanent effect since appropriations are designed to rise when the 10-year average rises, causing budget allocations to migrate from non-fire to fire programs over time. Changes due to supplemental fire funding are assumed to only be temporary so long as they are repaid, as they often are the following year (although additional costs such as project delays and cancelations are possible, as previous work has found). Changes in carryover are assumed to reflect permanent changes that are indirectly linked with fire spending, since carryover funds are an important funding source when annual fire appropriations and fire reserve funds run out. These assumptions are used to separate direct from indirect effects as well as permanent versus temporary impacts when looking at the relationship between fire spending and non-fire spending.

The 10-year rolling-average funding design for fire suppression implies that suppression appropriations can affect non-fire appropriations, but non-fire appropriations do not affect suppression appropriations. The same applies for supplemental fire funding, which can affect non-fire appropriations, but is unaffected by non-fire appropriations and instead largely determined by fire conditions in a given year. This means that causality primarily goes in one direction, with fire spending able to affect non-fire spending, while fire spending is largely independent from non-fire

spending and instead based on fire conditions. This feature is exploited in the empirical analysis to isolate the effect that increased spending on fire has on non-fire programs.

The total Forest Service annual budget (*Total*) can be divided between mandatory appropriations (*Mand Appr*), discretionary non-fire appropriations (*NonFire Appr*), discretionary fire appropriations (*Fire Appr*), supplemental fire funds (*Fire Suppl*), and carryover funds (*CO*) as shown in Equation 2.1.

$$Total_t = Mand\ Appr_t + NonFire\ Appr_t + Fire\ Appr_t + Fire\ Suppl_t + CO_t \qquad (2.1)$$

Only non-fire and fire appropriations are discretionary. Mandatory funds are set by law and cannot be adjusted through the appropriation process (e.g. the K-V Trust Fund). These funds are assumed to remain relatively fixed across the sample. Supplemental fire funds are those used to fund fire operations (suppression) once discretionary fire appropriations run out (i.e. the use of reserve funds and fire transfers from other accounts). These funds are generally repaid in the following years through congressional appropriations (reserve funds through the annual appropriation process and fire transfers through supplemental appropriations). This category also includes emergency disaster-relief appropriations which do not need to be repaid. Supplemental fire appropriations are thus assumed to only have a temporary impact on non-fire appropriations. Carryover funds are those not appropriated for a particular use and available for use in future years (i.e. unobligated funds that don't get used in a given year and can be used for fire transfers in future years).

The first few models are intended to identify a causal relationship between fire spending and non-fire spending. Model 1 (equation 2.2) uses a univariate ordinary least squares (OLS) regression to examine the relationship between total fire spending (appropriations and supplemental funds) and non-fire spending in a given year (*t*). Model 2 (equation 2.3) separates fire spending between fire appropriations and supplemental fire funding to separate a permanent

effect (through appropriations) from a temporary effect (through supplemental funds that are repaid). Models 3 and 4 (equations 2.4 and 2.5) include total appropriations as an independent variable, which past work has not formally accounted for when looking at the relationship between fire spending and non-fire spending. This is crucial for identifying a causal relationship since total appropriations are closely linked with both fire and non-fire spending, and not all reductions in non-fire programs come from spending on fire. Accounting for total appropriations serves as a control for changes in non-fire spending that are not associated with spending on fire.

$$NonFire_t = \alpha + \beta(Fire_t) + u_t \tag{2.2}$$

$$NonFire_t = \alpha + \beta_1(Fire\ Appr_t) + \beta_2(Fire\ Suppl_t) + u_t \tag{2.3}$$

$$NonFire_t = \alpha + \beta_1(Fire_t) + \beta_2(Total_t) + u_t \tag{2.4}$$

$$NonFire_t = \alpha + \beta_1(Fire\ Appr_t) + \beta_2(Fire\ Suppl_t) + \beta_3(Total_t) + u_t \tag{2.5}$$

Model 5 (equation 2.6) includes carryover funds, which accounts for an indirect effect of fire spending on non-fire spending, since carryover is an important source for funding fire once appropriations run out. Model 5 therefore includes all variables shown in equation 2.1, aside from mandatory appropriations which are excluded as the base group. This means that model 5 is "collectively exhaustive" in the independent variables which implies that any change in non-fire spending must stem from one of the independent variables. This serves as the baseline specification for the remaining models, which separate the effects identified in model 5 by spending programs and Forest Service regions. Model 5 also serves to separate direct from indirect effects as well as permanent versus temporary impacts. This is done by measuring how changes in fire appropriations (*PermEffect*), supplemental fire spending (*TempEffect*), carryover funds (*IndEffect*), and total appropriations (*Total*) affect non-fire spending (*NonFire*) in a given year (*t*).

$$NonFire_t = \alpha + \beta(PermEffect_t) + \delta(TempEffect_t) + \gamma(IndEffect_t) + \rho(Total_t) + u_t \quad (2.6)$$

This approach allows the effect of increased spending on fire to be separated into a direct permanent effect (β) that persists, a direct temporary effect (δ) that lasts until the supplemental funding is repaid, and an indirect effect (γ) that operates through an increased need for carryover funds. The combination ($\beta + \delta + \gamma$) reflects the immediate effect in a given year, and ($\beta + \gamma$) is the persisting impact on non-fire appropriations. It is important to also account for the fact that non-fire spending can change due to changes in total appropriations (ρ).

Model 6 (equation 2.7) is used to split non-fire spending into stratified categories (*Cat*: *i=1,…,I*), such as spending on recreation, and Model 7 (equation 2.8) is used to further split those categories into their underlying budget line items (*BLI*: *j=1,…,J*), such as spending on trails and spending on facilities.

$$NonFire_{it} = \alpha + \sum_{i=1}^{I} \beta_i(Cat_i * PermEffect_t) + \sum_{i=1}^{I} \delta_i(Cat_i * TempEffect_t) + \sum_{i=1}^{I} \gamma_i(Cat_i * IndEffect_t) + \sum_{i=1}^{I} \rho_i(Cat_i * Total_t) + u_{it} \quad (2.7)$$

$$NonFire_{jt} = \alpha + \sum_{j=1}^{J} \beta_j(BLI_j * PermEffect_t) + \sum_{j=1}^{J} \delta_j(BLI_j * TempEffect_t) + \sum_{j=1}^{J} \gamma_j(BLI_j * IndEffect_t) + \sum_{j=1}^{J} \rho_j(BLI_j * Total_t) + u_{jt} \quad (2.8)$$

For easier interpretation of Models 6 and 7, dummy variables are used for each non-fire spending category (*Cat*) and non-fire budget line item (*BLI*) and then interacted with the variables as shown. In model 6, this allows for β_i to be interpreted as the direct permanent effect on category i, δ_i the

direct temporary effect on category i, and γ_i the indirect permanent effect on category i. In model 7, this allows for β_j to be interpreted as the direct permanent effect on BLI j, δ_j the direct temporary effect on BLI j, and γ_i the indirect permanent effect on category i. To separate effects spatially by Forest Service region, model 8 (equation 2.9) uses the same specification as model 7, but is estimated for each region separately (*Region*: *r=1,…,R*).

$$NonFire_{jrt} = \alpha + \sum_{j=1}^{J} \beta_{jr}\left(BLI_{jr} * PermEffect_{rt}\right) + \sum_{j=1}^{J} \delta_{jr}\left(BLI_{jr} * TempEffect_{rt}\right) + \sum_{j=1}^{J} \gamma_{jr}\left(BLI_{jr} * IndEffect_{rt}\right) + \sum_{j=1}^{J} \rho_{jr}\left(BLI_{jr} * Total_{rt}\right) + u_{jrt} \qquad (2.9)$$

This allows for β_{jr} to be interpreted as the direct permanent effect on BLI j in region r, δ_{jr} the direct temporary effect on BLI j in region r, and γ_i the indirect permanent effect on category i in region r. Model 8 is run separately for each region to simplify the empirical estimation. This analysis uses dummy variables for non-fire spending categories (*Cat*: *i=1,…,I*) and non-fire budget line items (*BLI*: *j=1,…,J*) to provide a straightforward interpretation of the estimated coefficients in each region (*Region*: *r=1,…,R*). Note that *PermEffect*, *TempEffect*, *IndEffect*, and *Total* are measured at the national level, while non-fire spending is separated across categories and regions to identify where funds come from to support fire spending nationally. This allows for estimates of how changes in aggregate fire spending affects each non-fire program and region.

While measured nationally in the empirical estimation, changes in discretionary fire spending and supplemental fire spending can be separated by region, and across several budget line items related to fire management (e.g. preparedness, suppression, hazardous fuels, and fire research and development). However, suppression expenditures are not readily available for each region, so this analysis uses the acres burned on Forest Service land to approximate where spending on fire

suppression occurs across regions. To determine where spending on fire is going, national fire spending is divided across each fire-related BLI j in each region r and the summary statistics are analyzed. This identifies where fire funding is going, across both fire programs and regions, while Models 7 and 8 identify where increased fire funding comes from, across both non-fire programs and regions. This framework informs whether Forest Service regions have had declines in non-fire spending to aide fire spending in other regions across the country, while also identifying which particular fire and non-fire programs have been affected.

2.5 Data

This assessment uses Forest Service budget justifications (budget requests for Congress) from FY2006-FY2018, which provide actual allocations by Forest Service region and budget line item (BLI) from FY2004-FY2016 (i.e. each budget justification has the actual spending amounts from two years prior). This sample period was chosen due to data availability and due to BLI's remaining relatively consistent across this period (several changes occurred in FY2017). The budget justifications for these years are readily available on the agency's website and include data on total spending required for fire suppression from all sources. For estimation purposes, supplemental fire spending is the difference between fire appropriations and the total amount needed for fire suppression in a given year. Supplemental fire spending therefore captures fire reserve funds (replenished through appropriations each year) and fire transfers (from various accounts and repaid through supplemental appropriations in the following year). This category also captures emergency disaster-relief appropriations which do not need to be repaid. When supplemental fire funding is appropriated, it may include repaying past fire transfers as well as providing emergency funds for that year. When summarizing the data, emergency funds are

combined with FLAME reserve funds that began in 2010, as FLAME was intended to prevent the need for emergency funds (this has no consequence for the empirical models).

There are nine Forest Service regions (labeled *R1-R10*, with no Region 7), and Region 9 is combined with the Northeastern Area State and Private Forestry (a separate entity within Region 9). Research stations are combined into a single category (*ReStat*) which also includes the Forest Service Forest Products Lab and the International Institute of Tropical Forestry. These entities constitute the majority of spending on the BLI "Forest and Rangeland Research." The Albuquerque Service Center (started in 2005) and Washington D.C. Headquarters are combined into a single category (*Admin*). This allows the effects of increased fire spending to be separated across regions, while also treating research stations and administrative offices as separate entities to further analyze spending changes associated with fire spending. Figure 2.1 shows the Forest Service regional boundaries as well as offices across the nation. Table 2.1 provides the number of acres of Forest Service land in each region, along with the number of National Forests and Grasslands.

Each BLI is available by region, other than fire suppression appropriations and supplemental fire funding, which are only available at the national level. To identify which regions fire suppression appropriations and supplemental fire funding are used in, the number of acres burned on Forest Service land is used as a proxy. For example, if 15% of the acres burned in a given year occurred in a region, then 15% of national suppression appropriations and 15% of supplemental fire funding are attributed to that region in that year (funds are not attributed to research stations and administrative offices, but suppression allocations do happen to be provided for these entities). Data for acres burned on Forest Service land is readily available by state and year from the National Interagency Fire Center (NIFC). Given that Regions 1, 2, and 4 do not perfectly align with state

boundaries, acreage data for South Dakota, Wyoming, and Idaho is attributed to the regions they overlap based on the fraction of Forest Service lands falling within each region. Table 2.2 provides the acres burned by Forest Service region across the sample, which is used to divide national fire suppression appropriations and supplemental fire funding across regions. From 2004-2016, the acres burned increased in the Northern Region (Region 1) by 878.2%, in the Rocky Mountain Region (Region 2) by 1,459.1%, in the Intermountain Region (Region 4) by 370.2%, and in the Pacific Southwest Region (Region 5) by 622%. The acres burned decreased in all other regions. Across all Forest Service regions combined, the acres burned increased from 753,448 acres to 1,247,906 acres (65.6%) from 2004-2016. Figure 2.2 shows the relationship between acres burned and spending on fire from 2004-2016, which move together and trend upward over the period.

Supplemental fire funding comes first from fire reserve funds (FLAME) and then from fire transfers from other programs. Funds are generally replenished through appropriations the following year. Across the sample period (FY2004-FY2016), fire transfers totaled over $2 billion (USD 2016) and were fully repaid in subsequent years, except for $90,273 (USD 2016) used for transfers between FY2006-FY2008. It is therefore assumed that changes in non-fire allocations associated with supplemental fire funding are only temporary, while permanent effects stem from increases in fire appropriations and unobligated carryover funds. That said, the Forest Service may experience project delays and cancellations due to fire transfers, generating various costs such as increased capital improvement and maintenance costs. These costs are not captured in this assessment, meaning that the estimates represent a lower bound for the effect of increased fire spending on non-fire programs. This analysis only measures changes in budget allocations, and not secondary costs associated with those budget changes (such as project delays).

Figure 2.3 shows Forest Service non-fire appropriations, fire appropriations, supplemental fire funding, carryover funds, and mandatory appropriations from FY2004-FY2016. After adjusting for inflation (USD 2016), total appropriations fell $420 million (-6.1%), with non-fire spending falling $817 million (-27%), fire appropriations increasing $240 million (12.1%), carryover funds increasing $258 million (118.8%), mandatory funds falling $50 million (-6.5%), and supplemental fire spending falling $51 million (-5.8%) over the sample period. Across this period, the proportion of total appropriations going to fire appropriations, supplemental fire spending, and carryover funds increased from 45 percent to 55 percent, while the proportion going to non-fire spending decreased from 44 percent to 34 percent. Mandatory appropriations constitute the remining share and stayed constant at 11 percent of total appropriations across the sample. Changes in fire appropriations, supplemental fire spending, carryover funds, and total appropriations are therefore to blame for declines in non-fire spending. That said, it is not clear how this impact is divided between these sources, and it is unclear which non-fire programs and Forest Service regions are most affected.

Across the sample period, supplemental fire spending is negatively correlated with non-fire appropriations (CC = -0.31) as one would expect. This is likely associated with fire transfers and a temporary effect on non-fire funds. However, the correlation between fire appropriations and non-fire appropriations happens to be slightly positive (CC = 0.07), which goes against a priori expectations, and highlights why looking only at correlation like past work could be misleading. This positive relationship may indicate that both fire and non-fire appropriations go up or down in some years, depending on total appropriations. This is supported by the fact that both fire and non-fire appropriations are positively correlated with total appropriations (CC = 0.44 and CC = 0.71, respectively). This indicates that changes in total appropriations are crucial to control for in order

to get closer to a causal relationship between fire spending and non-fire spending. Carryover funds are also positively correlated with non-fire spending (CC = 0.19), although once controlling for other factors one would expect a negative relationship given that carryover funds often stem from reducing allocations to non-fire programs. This is supported by a negative correlation between carryover and supplemental fire spending (CC = -0.46), which is likely due to fire transfers and carryover funds being used as a source of supplemental funding when fire appropriations run out.

Table 2.3 provides the correlation coefficients between these variables of interest. Also included, is the acres burned on Forest Service land (*Acres*). Acres burned is negatively correlated with non-fire appropriations (CC = -0.33) as well as total appropriations (CC = -0.38). Acres burned is also negatively correlated with fire appropriations (CC = -0.41). This highlights the inadequate job of the 10-year average for fire suppression to provide fire funding when it is most needed, and the need to control for changes in total appropriations which have been trending downward while fire spending trends upward (though not in the years needed). On the other hand, acres burned and supplemental fire funding are positively correlated (CC = 0.54), indicating the need for supplemental funds during extreme fire years. Given that carryover is also an important source for funding fire, there appears to be an inverse relationship with acres burned (CC = -0.41). While these correlations shed some light on the possible effects of increased fire spending on non-fire programs, they more importantly suggest that all of these factors need to be addressed simultaneously when looking for a relationship. For this study, several spending categories are created using various BLI that are available by Forest Service region.

Table 2.4 provides a description of each BLI that is used to generate each spending category. The categories created are; (1) Fire Appropriations, (2) Fire Supplemental, (3) Infrastructure and Recreation, (4) Non-Fire Land and Resource Management, (5) Non-Fire Cooperative Work, (6)

Non-Fire Research, (7) Restoration, (8) Mandatory Appropriations, (9) Carryover, and (10) Unidentified. Each of these categories is made up of 1-6 BLIs that are closely related. Table 2.5 provides the spending in each category and BLI for FY2004 and FY2016, along with the percent change over this period. As shown, fire appropriations increased due to increases in fire suppression, fire preparedness, and hazardous fuel treatments, while spending decreased for most non-fire categories and underlying BLIs. Separating the non-fire categories, Infrastructure and Recreation fell 46.3%, Non-Fire Land and Resource Management fell 29.5%, Non-Fire Cooperative Work fell 32.8%, Non-Fire Research fell 13.7%, and Restoration increased 5.1%. This suggests that Infrastructure and Recreation may be affected most by increased spending on fire, while Non-Fire Research may be relatively unaffected. Increased spending on restoration is likely associated with increased wildfire.

Table 2.6 shows how non-fire funding has declined across regions, as well as research stations and administrative offices. Looking across regions, the Northern Region (Region 1) had the lowest decline in non-fire funds (-24.1%), while the Alaska Region (Region 10) experienced the greatest decline (-48.2%). Research stations experienced a decline of about 27.5% in non-fire funds, while non-fire funding for administrative offices actually increased 50% across the sample period. This suggests that non-fire spending at the regional offices and research stations may be adversely affected by increased spending on fire, with variation across regions and stations, while administrative offices appear to have increased non-fire and fire spending across the sample period. Fire spending at administrative offices may in part reflect a shift in spending from regional offices to administrative offices.

Table 2.7 shows how fire spending (fire appropriations and supplemental fire funds) has changed across regions, as well as research stations and administrative offices. Recall that fire

spending is available for each region, other than suppression appropriations and supplemental fire funds, which are only available at the national level (except for research stations and administrative offices). These amounts are separated amongst the regions based on the acres burned on Forest Service land in each region. From FY2004-FY2016, fire spending increased in the Northern Region (Region 1) by 70.2%, in the Rocky Mountain Region (Region 2) by 95.4%, in the Intermountain Region (Region 4) by 63.2%, and in the Pacific Southwest Region (Region 5) by 60.7%. Fire spending also increased 555.7% for Administrative Offices, while decreasing 26.5% for Research Stations. Fire spending decreased in the Southwestern Region (Region 3) by 44.9%, in the Pacific Northwest Region (Region 6) by 42%, in the Southern Region (Region 8) by 64.4%, in the Eastern Region (Region 9) by 19.2%, and in the Alaska Region (Region 10) by 26.5%. This highlights that funding for fire may not only get diverted from non-fire accounts across regions, but also shifted across regional fire accounts. In general, fire spending has decreased in the Eastern and Southern United States, while significantly increasing in the West and Rocky Mountains.

While these summary statistics strongly suggest that fire spending is causing spending cuts in non-fire programs and even fire programs in some regions, it is not immediately obvious how this impact is spread across programs and across regions. For example, these statistics cannot reveal if recreation in the eastern regions is being adversely affected by fire spending in the western regions. Answering this sort of question requires going beyond correlation and using an empirical approach that identifies where fire spending comes from, across both non-fire programs and regions, and where that funding is going, across both fire programs and regions. The empirical models in the previous section are tested using Forest Service funding allocations by BLI and region from FY2004-FY2016, allowing for a detailed breakdown of the relationship between fire and non-fire spending across regions.

2.6 Results

The first few empirical models (1-5) are intended to identify a causal relationship between fire spending and non-fire spending. The OLS estimates are provided in Table 2.8 along with robust standard errors to account for heteroskedasticity. In model 1 a univariate regression is tested with total fire spending (appropriations and supplemental funds) as the independent variable and non-fire spending as the dependent variable. The estimated coefficient is -0.468, meaning non-fire spending decreases about $0.47 for every $1 increase in fire spending. However, the estimate is not statistically significant and the model R-squared is 0.124. Model 2 separates the effect for fire appropriations, which permanently affects non-fire appropriations, and supplemental fire funding, which is typically repaid. The coefficient on fire appropriations is -0.385 and on supplemental funding is -0.463, but again neither are statistically significant. The model R-squared for model 2 is 0.126.

Models 3 and 4 include changes in total appropriations, which accounts for other changes in non-fire spending that are not associated with fire spending. The estimate on total appropriations is 0.46 and 0.55, respectively, and statistically significant at the 1% level in both models. This implies that for every additional $1 appropriated, about $0.46-0.55 goes to non-fire spending, or conversely, for every $1 cut, about $0.46-0.55 comes from non-fire appropriations. The inclusion of total appropriations makes the coefficients on fire (model 3) and on fire appropriations and supplemental fire funding (model 4) statistically significant, and the model R-squared jumps to 0.586 and 0.667, respectively. Looking at model 3, the coefficient on fire (appropriations and supplemental together) is -0.375 and statistically significant at the 10% level. Looking at model 4, the coefficient on fire appropriations is -0.928 and statistically significant at the 5% level. This suggests that when accounting for changes in total appropriations, every additional $1 on fire

spending permanently decreases non-fire spending by about $0.93. The coefficient on supplemental fire spending is -0.389 and statistically significant at the 10% level, implying that every $1 of supplemental fire spending temporarily reduces non-fire spending by about $0.39.

Model 5 adds carryover funds to account for indirect changes in non-fire funds to support fire spending, as carryover is an important source of funds for supplemental fire spending. The inclusion of carryover funds makes the model "collectively exhaustive" in the variables and all coefficient estimates become statistically significant at the 1% level. The coefficient on carryover is -0.951, meaning that for every $1 saved for carryover, about $0.95 comes from non-fire programs. The coefficient on total appropriations is 0.88, on fire appropriations is -0.975, and on supplemental fire funding is -0.595. The model R-squared is 0.932, reflecting that most of the variation in non-fire spending is accounted for. The unexplained variation comes from changes in mandatory appropriations, which are excluded as the base group. Model 5 serves as the baseline specification for the remaining models, which separate the effects by spending programs and Forest Service regions. This specification also serves to separate direct from indirect effects as well as permanent versus temporary impacts.

Over the sample period, non-fire spending fell $817 million (USD 2016). The results from Model 5 in Table 2.9 indicate that 28.6% of this was attributed to increases in fire appropriations, 30% to increases in carryover funds, and 45.1% to declines in total appropriations (other sources). The remaining 3.7% comes from increases in non-fire spending due to a slight decline in supplemental fire spending over this period. The coefficient estimates indicate that there is roughly a 1-for-1 trade-off between fire appropriations and non-fire appropriations, meaning that a $1 increase in fire appropriations decreases non-fire appropriations by about $1. The same 1-for-1 trade-off is found for increases in carryover funds. This of course does not necessarily mean that

this applies equally to each non-fire category and BLI. For supplemental fire funding, every additional $1 used for fire suppression corresponds with roughly a $0.60 decline in non-fire appropriations, with the remaining $0.40 coming from fire appropriations other than suppression (e.g. fire research and development, which declined 28% across the sample period). Recall that the effect from fire transfers is assumed to be only temporary given that funds are typically repaid the following year. For total appropriations, every additional $1 increases non-fire appropriations by roughly $0.88, with the remaining $0.12 going to fire appropriations. That said, given that total appropriations fell about $420 million across the sample, this was a key source of declines in non-fire appropriations. Assuming changes in carryover funds are associated with fire spending, the permanent effect of increased fire spending (fire appropriations + carryover funds) explains around 58.6% of the declines in non-fire spending. This indicates that only a bit over half of the observed decline in non-fire spending across the sample is attributed to increased fire spending, while the remaining decline comes from other sources.

Model 6 separates these effects for each non-fire spending category. Table 2.10 reports the estimates for model 6 as well as model 7. The results of model 6 indicate that the non-fire category most affected by fire and other cuts is Infrastructure and Recreation with declines of $323.8 million (-29.8%) due to fire and $193.4 million (-17.8%) due to other cuts from FY2004-FY2016. Non-Fire Land and Resource Management experienced declines of $133.9 million (-21.4%) and $88.2 million (-14.1%); Non-Fire Cooperative work declined $53.9 million (-23.7%) and $35.9 million (-15.8%) due to other cuts; and Non-Fire Research decline $19.6 million (-6.1%) due to fire and $27 million (-8.4%) due to other cuts. Spending on Restoration increased about $38.6 million (5.3%) due to fire and decreased $2 million (-0.3%) due to cuts from other sources. Most of these

effects are statistically significant, as shown in Table 2.10. That said, separating these categories into individual BLIs allows for more precise and detailed estimation.

Model 7 separates non-fire spending categories into their underlying BLIs and model 8 further separates those effects across regions. Table 2.11 provides the estimates for models 7 and 8. Although the use of supplemental spending slightly declined from FY2004-FY2016, many programs and regions experienced a temporary impact across this period. Spending on facilities on average declined $0.2 for every dollar of supplemental fire spending. Over half of this came from spending in Region 2, Region 5, Region 8, and Research Stations, with the remaining spread across other regions and no impact on administrative offices. Spending on roads declined about $0.13 for every dollar of supplemental fire spending, with the largest impact on Region 5, Region 8, and Region 10, though effects were observed across all regions. Land management planning, assessment, and monitoring declined about $0.09 for every dollar of supplemental fire spending. This hit Region 6 and Region 9 the hardest, followed by Region 4 and Region 2. Region 3 was the only region unaffected.

Spending on recreation, heritage, and wilderness declined about $0.04 for every dollar of supplemental fire spending, with Region 5 getting hit 2-4 times harder than any other regions, and Region 3 and Region 6 were not affected. Spending on landownership management also declined about $0.04 for every dollar of supplemental fire spending, with about 20 percent from Region 5 and the remainder spread across regions. Spending on forest and rangeland research declined around $0.03 for every dollar of supplemental fire spending, with only Research Stations getting adversely impacted. Forest health management on federal lands declined about $0.03 for every dollar, with Region 2 affected most and Region 5, Region 8, Region 9, and Region 10 unaffected. Infrastructure improvement declined $0.02 for every dollar, with Region 6 affected most and

Region 1, Region 5, and Region 9 unaffected. Spending on trails decreased $0.01 for every dollar, with Region 1 and Region 6 experiences the largest effects, and Region 5 actually receiving additional spending on trails associated with supplemental spending. Spending on forest stewardship also declined about $0.01 for every dollar, with only Region 8 and Region 9 being affected. The Undefined category declined about $0.03 for every dollar, suggesting that programs that started or ended across the sample period were also important for supplemental funding. This appeared to only impact Region 3 and Region 10. The remaining estimates for temporary changes in spending programs were not statistically significant. Spending on integrated resource restoration was found to increase $0.09 for every dollar of supplemental fire spending, suggesting that temporary shifts have helped support restoration. This primarily went to Region 1, Region 2, Region 3, and Region 9. It is important to keep in mind that these effects are only considered temporary, so long as the funds are repaid in following years.

Figure 2.4 shows the permanent changes (i.e. supplemental fire spending is excluded) in Non-fire BLIs from FY2004-FY2016 by the source of change (Fire Appropriations, Carryover Funds, or Other) that are associated with model 7. Figure 2.5 displays the breakdown of changes in each non-fire BLI across regions along with the sources of change. The results show that there is tremendous heterogeneity across BLIs and across regions. In some instances, declines in non-fire spending was linked with increased fire appropriations (direct effect), while in other cases it was associated with increased carryover funds to support fire spending (indirect effect). In many instances it was a combination of direct and indirect effects associated with fire spending that contributed to declines in non-fire programs, and most programs also experienced additional cuts for other reasons than fire.

Looking at the BLI's underlying the Infrastructure and Recreation category, spending on Facilities declined the most (in dollars, but not percentage) falling $193.4 million (-74%) with about $80.6 million going to fire appropriations, $48.6 million going to carryover funds, and the remainder due to the other factors. Looking across regions, spending on facilities in Region 8 declined the most at -$34 million (-82%) with about $22 million related to spending on fire (fire appropriations and carryover). In percentage terms however, regions experienced declines in spending on facilities ranging from -64% to -82%, with about two-thirds of cuts due to spending on fire. This means facilities across all regions have been significantly impacted by spending on fire, aside from administrative offices which had a 63% increase ($5 million) in spending.

The next biggest decline underlying the Infrastructure and Recreation category came from appropriations going to roads. Spending on roads declined $120.9 million (-42%) with about $51.8 million going to fire appropriations, $32 million going to carryover funds, and the remainder due to the other factors. Region 6 had the largest decline of about $28 million (-57%) while Regions 2 and 9 only declined about $7 million (-29%). Regions 5 and 10 experienced declines of $18 million (-54%) and 17 million (-67%), respectively, while administrative offices had a 66% increase ($9 million) in spending. Law enforcement operations declined $80.9 million (-81%) with about $37.9 million going to fire appropriations, $16 million going to carryover funds, and the remainder due to the other factors. However, the estimates for the sources of changes in spending on law enforcement were not statistically significant in the models.

Spending on recreation, heritage and wilderness declined $57.6 million (-19%) with about $9.5 million going to fire appropriations, $19.5 million going to carryover funds, and the remainder due to the other factors. Region 5 had the largest decline of $21 million (-45%) with about $8 million going to fire appropriations and $5 million to carryover funds that help support supplemental fire

spending. Regions 2 and 3 only experienced declines of around $5 million (-18%), with each losing about $1 million to fire appropriations and $2 million to carryover funds. Around half of the declines in recreation, heritage and wilderness spending stem from other sources than fire appropriations or carryover and spending in this category at administrative offices increased $29 million (110%), suggesting a major shift in appropriations from regional offices to administrative offices.

Spending on infrastructure improvement declined $35.9 million (-92%) with about $11 million going to fire appropriations, $9.8 million going to carryover funds, and the remainder due to the other factors. For many regions, spending on infrastructure improvement declined 100%, meaning there was no spending on this program in FY2016. This has contributed to a growing deferred maintenance backlog, along with declines in several other programs such as facilities and roads. Spending on trails declined $14 million (-16%) with about $0.5 million going to fire appropriations, $5.6 million (-6%) going to carryover funds, and the remainder due to the other factors. There was wide variation across regions, with a decline of $5 million (-42%) coming from Region 5 and only $1 million (-2%) coming from Region 2. Spending on trails in Regions 2 and 4 actually increased with fire appropriations, but overall declined due to increases in carryover and other sources of change. For administrative offices, spending on trails increased about $7 million (151%), again suggesting a shift in appropriations from regional offices to administrative offices, as with the BLI for recreation, heritage, and wilderness.

Looking at the BLIs underlying the Non-Fire Land and Resource Management category, land management planning, assessment, and monitoring fell the most with a decline of about $111.9 million (-39%) and about one-third going to each source. This heavily affected Region 6 and Region 9, but also affected other regions, aside from Region 3 and Region 10. Landownership

management declined $36.7 million (-33%) with about $11.2 million (-10%) going to fire appropriations, $10.4 million (-9%) to carryover, and the rest to other sources of change. Region 5 was affected the most with a decline of about $8.6 million (-53%), followed by Region 6 which declined about $6.3 million (-48%). Region 8 was the least affected with a decline of $2.8 million (-27%), and over half of this decline was attributed to other sources than fire. Forest health management on federal lands declined $29.8 million (-36%) with about one-third going to each source. Region 8 had a decline of about $7 million (-47%), Region 5 a decline of $6 million (-60%), and Region 2 a decline of about $5 million (-61%). Region 10 declined the least at $1 million (-33%), with most of this going to carryover funds. Together, spending at research stations and administrative offices increased about $6 million, suggesting that some of the appropriations for forest health management on federal lands has shifted away from the regional offices.

Land acquisition fell $11.6 million (-57%) with about one-third going to each source. Region 8 was hit the hardest with a decline of $3.8 million (-71%), with $1.1 million to fire appropriations and $1.3 million to carryover funds. Region 3 and Region 4 had the smallest impacts, and Region 10 had an increase in spending on land acquisition. Spending at administrative offices also fell about $1.6 million (-48%), which was associated with fire appropriations and would have fallen more if it were not for the use of carryover funds and other increases. The estimates for grazing management were not statistically significant, other than a decline of $1.3 million associated with a decrease in total appropriations. There was however a shift in appropriations, with declines in spending in Region 1, Region 3, and Region 4 that were roughly offset by an increase in spending at administrative offices. Spending on minerals and geology management increased about $7 million (11%) across the sample period, and the estimates were only statistically significant for a few regions. Spending fell in Region 5 by $2.6 million (-34%), in Region 6 by $1.8 million (-

28%), and in Region 8 by $0.7 million (-14%). Much of this shifted to spending at administrative offices, which increased $9.9 million (174%).

Looking at the Non-Fire Cooperative Work category, forest health management on cooperative lands fell the most, decreasing $25.6 million (-42%), with around one-third going to each source. Region 1 fell the most in percentage terms, declining $3.8 million (-78%). Region 8 also declined $8.4 million (-54%) and Region 9 fell $9 million (-40%). Spending increased about $0.6 million in Region 4. Spending on the forest legacy program declined $18.2 million (-23%), with no funds going to carryover, only fire spending and changes in total appropriations. Spending fell $4 million (96%) in Region 3, with about half going to fire appropriations. Spending in Region 8 declined $7.5 million (32%) and Region 9 fell $12.6 million (39%), while Region 1 and Region 6 had increased spending, largely coming from carryover funds. Spending on forest stewardship fell $16.8 million (-44%), affecting most regions similarly in percentage terms, but coming primarily from Region 8 and Region 9 which previously had the most spending in this program. Spending at administrative offices increased, coming from carryover funds and other sources, such as shifts from regional offices. The estimates for fire appropriations were not statistically significant.

Urban and community forestry fell $14.7 million (-36%), with about a quarter associated with fire spending, and the rest going to carryover funds or other sources. Region 8 and Region had the most spending in this category, which fell about $6.2 million (-53%) in Region 8 and $7 million (-44%) in Region 9. As with forest stewardship, spending at administrative offices increased from carryover funds and other sources, some of which likely reflects a shift from regional offices. There was no statistically significant effect found on international forestry, which increased about $0.5 million across the sample. Looking at the Non-Fire Research category, only research stations were affected and spending on forest and rangeland research fell $44.1 million (-14%), but most

of this was not associated with increases in fire appropriations. Instead, it appears that fire spending may have led to a shift in appropriations from research stations to administrative offices, while carryover funds and other cuts are responsible for the decline in spending.

Spending on Restoration increased $36.6 (5%) million across the sample period and was attributed entirely to fire spending, meaning spending was cut from other programs to support spending on rehabilitation and restoration. Spending on restoration increased in Region 1, Region 3, and Region 9, with a decline of $23.2 million (-41%) in Region 10. The remining regions experienced increases in spending associated with fire, but total spending fell due to funds going to carryover and other cuts. Spending increased $54.4 million (88%) at administrative offices, primarily due to fire, reflecting additional shifts in spending associated with fire, beyond going directly to fire programs. The undefined category that captures programs that started or ended across the sample period declined nearly 100% for all regions, reflecting the fact that by 2016 most of these programs had ended. A large share of these funds appear to have gone to spending on fire.

Shifting the focus from where funds are coming from to where funds are going, Figure 2.6 shows changes in fire spending by region and fire program. Spending increased in Region 1, Region 2, Region 4, and Region 5, going almost entirely to fire preparedness and suppression. Spending increased in Region 1 by $90.6 million (70%), in Region 2 by $100 million (95%), in Region 4 by $123.1 million (63%) and in Region 5 by $269.3 million (61%). Spending on fire was cut $332.9 million (-45%) in Region 3, $128.7 million (42%) in Region 6, $449 million (64%) in Region 8, $15.7 million (19%) in Region 9, and $9.6 million (64%) in Region 10. Much of this shifted to spending at administrative offices, which increased $552.5 million (556%), while some of this likely went to fire spending in other regions. This suggests that increased fire spending is adversely affecting non-fire programs, as well as fire programs, in some regions. Figure 2.7 shows

changes in both non-fire and fire appropriations by region. The source of change in non-fire appropriations from Model 8 are included. The figure highlights that fire spending in Region 1, Region 2, Region 4, and Region 5 has led to declines in non-fire and fire spending across all other regions, with disparate impacts across programs and regions. In general, increased fire spending has gone to western regions and spending cuts have been the largest in the East (Region 8 and Region 9) as well as the south (Region 3). That said, the regions spending heavily on fire have also had major cuts in non-fire spending, especially Region 5.

The results of this analysis show that fire spending has led to a movement of non-fire funding to fire programs. The estimates are highly statistically significant and show that the impact of fire spending is heterogeneous across programs and regions. This arises from constraints in the agency's total budget, and subsequent internal appropriation decisions across Forest Service regions. The programs with the largest spending cuts (in dollars) from 2004 to 2016 were facilities, roads, and land management planning, assessment, and monitoring. In some instances, such as spending on infrastructure improvement, the impact was uniformly spread across regions and the source of changes was evenly split between the different sources. In other cases, such as spending on urban and community forestry, only a handful of regions were affected. In some cases, spending increased across the sample period and appeared unaffected by fire, such as with minerals and geology management. Several programs appear to have had a shift in appropriations from regional offices to administrative offices. It is not clear what may be driving this and whether it might affect the implementation of these programs. This could be a potential topic for further research.

2.7 Conclusion

The U.S. Forest Service is charged with managing federal lands with a multiple-use agenda. This goal has becoming increasingly challenging over the years as the cost of fire operations have consumed a growing share of the agency's budget. This paper utilizes Forest Service regional funding allocation data for all fire and non-fire budget categories from FY2004-FY2016 to identify which non-fire programs and Forest Service regions have been affected by increased spending on fire. In particular, this paper exams which programs are cut to fund additional fire spending, and whether spending is cut in some regions to fund fire spending in other regions. A unique OLS specification is developed to separate direct from indirect effects as well as permanent versus temporary impacts. The results show that there is tremendous heterogeneity across both fire and non-fire programs, as well as across regions. In some instances, declines in non-fire spending was linked with increased fire appropriations, while in other cases it was associated with increased carryover funds to support fire spending. In many cases it was a combination of these direct and indirect effects associated with fire spending that contributed to declines in non-fire programs, and most programs also experienced additional cuts for other reasons than fire. In general, there has a been a shift in spending from eastern regions (Region 8 and Region 9) to fund fire management in western regions.

One key limitation of this analysis is that it does not measure secondary costs associated with fire-transfers, such as project delays. In this study, only changes in budget amounts are captured, and fire transfers are therefore considered temporary if repaid through supplemental appropriations in following years. That said, previous work suggests that there are various costs associated with fire transfers, such as project cancellations and delays, strained relationships, and management disruptions (GAO, 2004, 2007, and 2009). Without data on these outcomes of interest, it is difficult

to measure these impacts. Given that these sorts of costs are not captured in this assessment, these estimates represent a lower bound for the effect of increased fire spending on non-fire programs. This provides an opportunity for further research into the effects of fire spending on non-fire activities, looking at both the effect of total funds available and the timing of when those funds are available for use.

Recall that total appropriations for each BLI reflect discretionary funds set by Congress, while the Forest Service then decides how to allocate those appropriations across regions (recognizing there is a link between congressional and agency decision-making). This distinction has important implications when considering solutions to address shifts in spending across programs versus shifts across regions, and a comprehensive fix will likely require addressing decision-making at both levels. That said, for this analysis attention is placed on identifying where appropriations are going, regardless of who determines the allocation of that spending. Future research could add value by distinguishing between these levels of decision-making to determine the role of congressional decisions versus the agency's internal decisions to allocate funds. On the surface, based on the historical budgeting process, this work suggests that Congress may be responsible, at least in part, for shifts from non-fire spending to fire spending, while the agency may be most at blame for spending shifts across regions. There are however several exogenous factors, such as fire conditions, as well as a degree of endogeneity between congressional and agency decision-making, that must be accounted for to precisely assess the mechanisms underlying spending shifts.

There have been several attempts to change budgeting tools and spending priorities to prevent fire transfers and a shift of non-fire appropriations towards fire spending. The Forest Service and others have argued that increasing current investments in hazardous fuel reduction projects may potentially reduce long term suppression spending (e.g. GAO, 2007 and 2009). However, some

debate this idea, such as Reinhardt et al. (2008) arguing “It is a natural mistake to assume that a successful fuel treatment program will result in reduced suppression expenditures. Suppression expenditures rarely depend directly on fuel conditions, but rather on fire location and on what resources are allocated to suppression. The only certain way to reduce suppression expenditures is to decide to spend less money suppressing fires”. This notion is further supported by recent work from Loomis et al. (2019) that finds little evidence of fire mitigation expenditures affecting suppression costs, although they do find that mitigation influences fire damages. Rideout and Ziesler (2008) suggest that wildland fire suppression and fuels treatments are not necessarily substitutes with clear tradeoffs, and that investments in both treatment and suppression reduce fire damages and have complementary effects in reducing damages and expenditures.

Some argue that the agencies should place a higher priority on cost containment efforts, perhaps by reducing agency budgets or restricting access to additional funds under certain conditions (Ingalsbee, 2009). It has also been shown that cost sharing of fuel reduction and fire suppression between the government and private landowners along the WUI can reduce social losses from forest fires (Amacher et al, 2006). This is because private landowners may underinvest in fuel treatments and generate externalities on others (e.g. Shafran, 2008; Crowley et al., 2009). Others have also found that wildfire prevention education and prescribed fire can help minimize management costs (Butry et al., 2009). Other options include providing incentives for non-federal entities to mitigate their risk of wildfire damages or discourage future WUI development.

Knowing the reasons for increasing expenditures can help land management agencies focus expenditure-containment efforts in ways likely to be most effective. If the increases are largely due to factors outside the control of the agencies (like climate and weather), management efforts should be more focused on when and where to fight fires, rather than on hazardous fuel

manipulation or specific strategies and tactics (Hand et al., 2014). If increasing expenditures are due to changes in vegetation (like increased fuel loads, insect infestations, etc.), then some type of vegetative manipulation may also be helpful. However, if increasing expenditures are likely due to human factors such as social and political pressures, risk aversion leading to overuse of resources, or increasing populations in the WUI, then the answer may lie more in how to change the behavior and incentives facing fire managers and landowners than in changing the biophysical environment (Hand et al., 2014).

Changes by Congress could also help address this issue, such as implementing legislation similar to the proposals in the 115th Congress (H.R. 2862, H.R. 2936, S. 1842, and S. 1571) that would have allowed for some wildfire suppression funds to be provided outside the statutory limits on discretionary spending, either through the annual appropriations process or through supplemental appropriations. This would mean that wildfire funding would not need to compete with other programs and activities that are subject to the statutory limits. Some have proposed simply allowing agencies to access emergency disaster funds when suppression funds are exhausted, but the idea has faced resistance from members of Congress (HFHC, 2018). Projections used for FLAME could also be formally incorporated into the budget process, as the FLAME Act directed that the Forest Service develop a formula to forecast suppression spending, but it did not mandate that the agency use that formula to formulate budget requests (although that was debated). In 2018, legislative progress was made on these fronts.

The Consolidated Appropriations Act of 2018 gave federal agencies additional funding and new policy tools to support fuels reduction and prevent fire borrowing. This included a new fire suppression funding mechanism that adjusts federal spending caps to accommodate firefighting needs. The legislation provided a new "disaster cap allocation" for wildfires starting in FY2020 at

$2.25 billion, which increases to $2.95 billion in FY2027. However, the legislation freezes the wildfire suppression BLI at the FY2015 level in attempt to stop the slow migration of non-fire funding to the fire programs at the beginning of each fiscal year (HFHC, 2018). The new budget cap is set to go into effect in FY2020. As of September 26, 2019, the Senate bill for FY2020 would provide $2.25 billion for wildfire suppression activities and allocate a total of $3.64 billion for fire suppression across the Department of the Interior and Forest Service (Lunney and Bogardus, 2019). The Act also required mapping of wildfire risks to prioritize fuels management needs and identify potential wildfires that could be difficult for suppression resources to contain and that could cause ignitions to structures (HFHC, 2018).

The Forest Service is responsible for maintaining 370,000 miles of roads, 158,000 miles of trails, and 13,000 bridges. However, the agency's deferred maintenance backlog is around $5.5 billion, compared with an annual maintenance and improvement budget of around $499 million (Heller, 2019). This spending category includes the Facilities, Roads, Trails, and Infrastructure Improvement BLIs. In the Forest Service's FY2020 budget justification they developed a capital improvement program to help reduce the backlog and requested $1.23 billion for buildings. However, $3 billion is backlogged for roads and bridges, and so officials are launching an infrastructure strategy at the request of the Department of Agriculture's Inspector General (Heller, 2019). The agency also faces a backlog of 5,000 special use permits and renewals of special use permits awaiting environmental analysis (Heller, 2019). The agency therefore continues to be challenged by limited funding, and it is yet to be seen if the Consolidated Appropriations Act of 2018, which goes into effect in FY2020, will be effective at preventing short-term impacts from fire transfers and long-term impacts from the permanent migration of non-fire appropriations to fire spending.

2.8 Chapter 2 Tables

Table 2.1 Forest Service Land Area by Region

Region	Acres, millions	National Forests	National Grasslands
Region 1 – Northern Region	25.6	15	4
Region 2 – Rocky Mountain Region	22.1	17	7
Region 3 – Southwestern Region	20.8	12	4
Region 4 – Intermountain Region	32.0	18	1
Region 5 – Pacific Southwest Region	20.2	19	1
Region 6 – Pacific Northwest Region	24.8	21	1
Region 8 – Southern Region	13.4	35	2
Region 9 – Eastern Region	12.1	17	0
Region 10 – Alaska Region	22.0	2	0
Total	192.9	156	20

Data from USDA (2011): *https://www.fs.fed.us/land/staff/lar/LAR2011/LAR2011_Book_A5.pdf*

Table 2.2 Acres Burned on Forest Service Land by Region, 2004-2016

Region	2004	2016	Change
Region 1 – Northern Region	11,965	117,044	878.2%
Region 2 – Rocky Mountain Region	7,919	123,464	1,459.1%
Region 3 – Southwestern Region	283,415	262,311	-7.4%
Region 4 – Intermountain Region	42,701	200,762	370.2%
Region 5 – Pacific Southwest Region	49,437	356,951	622.0%
Region 6 – Pacific Northwest Region	74,783	48,386	-35.3%
Region 8 – Southern Region	275,838	129,807	-52.9%
Region 9 – Eastern Region[1]	7,374	9,176	24.4%
Region 10 – Alaska Region	16	5	-68.8%
Total Acres	753,448	1,247,906	65.6%

[1]Region 9 includes the Northeastern Area State and Private Forestry.
Data from NIFC (2019): *https://www.nifc.gov/fireInfo/fireInfo_statistics.html*

Table 2.3 Correlation Coefficients for Variables of Interest, 2004-2016

	Fire Appr	*Fire Suppl*	*NonFire Appr*	*CO*	*Total*	*Acres*
Fire Appr	1					
Fire Suppl	-0.65	1				
NonFire Appr	0.07	-0.31	1			
CO	0.42	-0.46	0.19	1		
Total	0.44	-0.34	0.71	0.71	1	
Acres	-0.41	0.54	-0.33	-0.41	-0.38	1

Table 2.4 Spending Categories and Descriptions of Forest Service Budget Line Items

Budget Line Item	Description
Category: Wildfire Appropriations	
Coop Fire Protection - State Fire Assistance	Provides financial assistance through partnerships with state agencies for the prevention, mitigation, control, and suppression of fires on non-federal lands.
Coop Fire Protection - Volunteer Fire Assistance	Provides technical and financial assistance to local volunteer fire departments that protect communities with populations of 10,000 or fewer. The program supports local fire preparedness and suppression efforts to protect state and private forestlands.
Fire Suppression	Used to fund firefighters, equipment, aviation operations, and incident support functions that support wildfire response. Also supports post-fire rehabilitation and restoration through BAER. (In 2012 there was a realignment of aviation assets to fall under preparedness rather than suppression.)
Fire Preparedness	Supports fire planning, prevention, detection, information and education, training, equipment, advancement of technology, program analysis and reviews, and other fire management activities. (In 2012 there was a realignment of aviation assets to fall under preparedness rather than suppression.)
Fire Research and Development	Provides research to inform management and reduce the negative impacts of fire on human communities and ecological benefits.
Hazardous Fuels	Supports vegetation removal to reduce fire hazards, lower the risk of catastrophic fire, and make fire management easier.
Category: Wildfire Supplemental Funds	
Fire Transfers for Suppression	Money transferred from non-fire programs for the use of fire suppression. Transfers only occur when the agency has exhausted suppression appropriations. This money is generally repaid the following year.
Reserve Funds (FLAME) for Suppression	Secondary appropriations for fire suppression. The Federal Land Assistance, Management, and Enhancement (FLAME) Act of 2009 started a reserve fund in 2010. Prior to this any form of emergency funds are included in this category, as FLAME was intended to prevent the need for future emergency funds.

Category: Infrastructure and Recreation	
Facilities	Supports maintenance and capital improvement on recreation sites as well as research and administrative buildings.
Infrastructure Improvement	Supports the maintenance, repairs, and restoration of infrastructure.
Law Enforcement Operations	Used for enforcing laws and regulations and investigating crimes and illegal occupancy.
Recreation, Heritage, and Wilderness	Supports a range of recreational opportunities for the public across National Forest lands.
Roads	Supports maintenance of the National Forest Road System that provides access for recreational, resource management, administrative, and commercial purposes.
Trails	Used to maintain the National Forest Trail System used for recreation and management access.
Category: Non-Fire Land and Resource Management	
Forest Health Management – Federal Lands	Supports insect and disease surveys; supports forest insect and disease prevention, suppression, restoration, and eradication projects; provides technical assistance; and monitors forest health on all federal lands (including those of other agencies).
Grazing Management	Maintains and restores rangelands while also supporting rural ranchers and farmers who rely on those lands.
Land Acquisition	Used to purchase new land to add to the National Forest System.
Land Management Planning, Assessment, and Monitoring	Used to keep forests and grasslands healthy and resilient. Monitoring and assessment activities provide information to inform resource management and projects are adjusted based on information acquired through inventory and monitoring activities. Prior to 2012 this category was divided between Land Management Planning and Inventory and Monitoring.
Landownership Management	The program secures and protects National Forest lands and land interests and lays the foundation for all land and natural resource management activities.
Minerals and Geology Management	Used to manage energy and mineral development on National Forest lands, and to secure and protect unique resources, such as fossils, caves, groundwater, wildlife habitat,

	and places of scientific, cultural, and recreational interest, and to protect people and the environment by monitoring and mitigating geologic and mining hazards.
Category: Non-Fire Cooperative Work	
Forest Health Management – Cooperative Lands	Provides technical and financial assistance to States to monitor, assess, and mitigate forest health threats on non-Federal lands.
Forest Legacy Program	Protects critical forest landscapes threatened by land conversion. The agency protects these lands through conservation easements and fee-simple purchases with partners, including State agencies, private landowners, and other conservation partners.
Forest Stewardship Program	Assists private forestland management and conservation and address private resource management concerns.
International Forestry Program	Promotes sustainable forest management globally and brings technologies and innovations back to the United States. Also addresses several domestic natural resource conservation issues.
Urban and Community Forestry Program	Delivered in cooperation with State forestry agencies and other national and local partners to provide funding and technical assistance to help communities conserve, protect, and enhance urban forests.
Category: Non-Fire Research	
Forest and Rangeland Research	Provides research to improve the health and use of forests and grasslands, looking at biological, physical, and social aspects of sustainable management.
Category: Restoration	
Integrated Resource Restoration	Used to improve watershed conditions, vegetation conditions, habitat conditions, and wildlife conditions. This budget line item started in 2012 and prior was separated into Fire Rehabilitation and Restoration; Collaborative Forest Landscape Restoration; Legacy Roads and Trails; Forest Products; Vegetation and Watershed Management; and Wildlife and Fisheries Habitat Management.
Category: Mandatory Appropriations	
Payments to States and Counties	Funds paid to states and counties for use on roads and schools where National Forest lands are located.

Permanent Working Funds	Funds used for brush disposal, timber salvage sales, and other permanent work.
Trust Funds	Funds held as a reserve for various purposes such as reforestation after timber sales (e.g. Knutson-Vandenberg account).
Category: Carryover Funds	
Unobligated funds	Funds left for future years after appropriations and supplemental funding for fire suppression. Programs with the most unobligated funds are generally the first to be used for fire transfers.
Category: Unidentified	
Unidentified	Includes all budget line items and programs that were only present in a few years across the sample, capturing items that started or ended across the period that are not included elsewhere.

This information comes from Forest Service Budget Justifications. All funds are Discretionary other than those under Mandatory Appropriations.

Table 2.5 Forest Service Appropriations, FY2004-FY2016 (thousands, USD 2016)

Budget Line Item	FY2004	FY2016	Change
Wildfire Appropriations	1,978,427	2,218,442	12.1%
Coop Fire Protection - State Fire Assistance	104,611	69,569	-33.5%
Coop Fire Protection - Volunteer Fire Assistance	16,464	13,000	-21.0%
Fire Suppression[1]	746,128	811,000	8.7%
Fire Preparedness[1]	809,189	1,017,302	25.7%
Fire Research and Development	26,926	19,380	-28.0%
Hazardous Fuels	275,109	288,191	4.8%
Wildfire Supplemental Funds	873,697	823,000	-5.8%
Fire Transfers for Suppression[2]	-	-	-
Reserve Funds (FLAME) for Suppression[3]	873,697	823,000	-5.8%
Infrastructure and Recreation	1,085,356	582,694	-46.3%
Facilities	261,764	68,410	-73.9%
Infrastructure Improvement	39,035	3,150	-91.9%
Law Enforcement Operations	100,194	19,252	-80.8%
Recreation, Heritage, and Wilderness	308,350	250,796	-18.7%
Roads	287,362	166,462	-42.1%
Trails	88,651	74,624	-15.8%
Non-Fire Land and Resource Management	624,195	439,936	-29.5%
Forest Health Management – Federal Lands	82,072	52,295	-36.3%
Grazing Management	55,709	54,434	-2.3%
Land Acquisition	20,610	8,964	-56.5%
Land Management Planning, Assessment, and Monitoring	290,346	178,465	-38.5%
Landownership Management	110,788	74,120	-33.1%
Minerals and Geology Management	64,670	71,658	10.8%
Non-Fire Cooperative Work	227,721	152,924	-32.8%
Forest Health Management – Cooperative Lands	61,144	35,528	-41.9%
Forest Legacy Program	79,967	61,706	-22.8%
Forest Stewardship Program	38,579	21,797	-43.5%
International Forestry Program	7,218	7,750	7.4%
Urban and Community Forestry Program	40,812	26,143	-35.9%
Non-Fire Research	321,432	277,311	-13.7%
Forest and Rangeland Research	321,432	277,311	-13.7%
Restoration	723,739	760,306	5.1%
Integrated Resource Restoration	723,739	760,306	5.1%
Mandatory Appropriations	761,026	711,210	-6.5%
Payments to States and Counties	494,403	292,105	-40.9%
Permanent Working Funds	117,560	226,511	92.7%
Trust Funds	149,063	192,594	29.2%
Carryover Funds	216,935	474,719	118.8%
Unidentified	50,823	3,062	-94%
Grand Total	6,863,351	6,443,604	-6.1%

[1]In 2012 there was a realignment of aviation assets to fall under Fire Preparedness rather than Fire Suppression.
[2]Fire Transfers were not required for fire suppression in FY2004 or FY2016, but across this time period $2,242,378 (USD 2016) was transferred to fund fire suppression.
[3]FLAME includes emergency appropriations.

Table 2.6	Forest Service Non-Fire Spending by Region, FY2004-FY2016 (millions, USD 2016)		
Region	2004	2016	Change
Region 1 – Northern Region	228.28	173.36	-24.1%
Region 2 – Rocky Mountain Region	232.65	159.03	-31.6%
Region 3 – Southwestern Region	203.50	145.80	-28.4%
Region 4 – Intermountain Region	238.61	160.43	-32.8%
Region 5 – Pacific Southwest Region	316.87	172.23	-45.6%
Region 6 – Pacific Northwest Region	353.45	227.96	-35.5%
Region 8 – Southern Region	358.20	210.38	-41.3%
Region 9 – Eastern Region[1]	326.71	219.77	-32.7%
Region 10 – Alaska Region	164.41	85.18	-48.2%
Research Stations[2]	327.60	237.49	-27.5%
Administrative Offices[3]	282.99	424.61	50.0%
Total Non-Fire Spending	3,033.27	2,216.23	-26.9%

Non-Fire spending excludes Mandatory Appropriations and Carryover.
[1]Region 9 includes the Northeastern Area State and Private Forestry.
[2]Research Stations includes the Forest Products Lab and the International Institute of Tropical Forestry.
[3]Administrative Offices includes the Washington Office and the Albuquerque Service Center.

Table 2.7	Forest Service Fire Spending by Region[1], FY2004-FY2016 (millions, USD 2016)		
Region	2004	2016	Change
Region 1 – Northern Region	129.03	219.65	70.2%
Region 2 – Rocky Mountain Region	104.77	204.74	95.4%
Region 3 – Southwestern Region	740.65	407.75	-44.9%
Region 4 – Intermountain Region	194.88	317.97	63.2%
Region 5 – Pacific Southwest Region	444.00	713.29	60.7%
Region 6 – Pacific Northwest Region	306.42	177.75	-42.0%
Region 8 – Southern Region	697.40	248.35	-64.4%
Region 9 – Eastern Region[2]	82.06	66.32	-19.2%
Region 10 – Alaska Region	14.91	5.35	-64.1%
Research Stations[2]	38.58	28.35	-26.5%
Administrative Offices[4]	99.43	651.92	555.7%
Total Fire Spending	2,852.12	3,041.44	6.6%

[1]These amounts reflect wildfire appropriations and wildfire supplemental funds. Suppression appropriations and supplemental fire funds are divided across regions based on the acres burned on Forest Service land in each region. All other fire accounts are available by region.
[2]Region 9 includes the Northeastern Area State and Private Forestry.
[3]Research Stations includes the Forest Products Lab and the International Institute of Tropical Forestry.
[4]Administrative Offices includes the Washington Office and the Albuquerque Service Center.

Table 2.8	Models 1-5 Estimates Dependent Variable: Non-Fire Appropriations, USD 2016				
	Model 1	Model 2	Model 3	Model 4	Model 5
Fire (Appr & Suppl)	-0.468 (0.294)		-0.375* (0.213)		
Fire Appr		-0.385 (0.653)		-0.928** (0.41)	-0.975*** (0.214)
Fire Suppl		-0.463 (0.323)		-0.389* (0.183)	-0.595*** (0.131)
Total			0.457*** (0.122)	0.55*** (0.144)	0.88*** (0.101)
CO					-0.951*** (0.19)
R^2	0.124	0.126	0.586	0.667	0.932

Robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. n=13.

Table 2.9	Model 5 Estimated Sources of Declines in Non-Fire Spending, FY2004-FY2016 (millions, USD 2016)		
	Change, FY2004-FY2016	Estimated Effect	Percent Attributed
PermEffect (*Fire Appr*)	$240.0	-$233.7	28.6%
TempEffect (*Fire Suppl*)	-$50.7	$30.2	-3.7%
IndEffect (*CO*)	$257.8	-$245.1	30.0%
Total	-$419.7	-$368.5	45.1%

Estimated Effect captures Model 5 coefficients multiplied by the changes from FY2004-FY2016 (shown in the first column). Percent Attributed captures the proportion of declines in Non-Fire Spending ($817 million) attributed to each source. The percentages sum to 100%.

Table 2.10	Models 6 and 7 Estimates Dependent Variable: Non-Fire Appropriations, USD 2016			
	PermEffect	*TempEffect*	*IndEffect*	*Total*
Infrastructure and Recreation	-0.807*** (0.193)	-0.465*** (0.087)	-0.505*** (0.144)	0.462*** (0.079)
Facilities	-0.336*** (0.099)	-0.196*** (0.048)	-0.188*** (0.07)	0.162*** (0.039)
Infrastructure Improvement	-0.046*** (0.018)	-0.02** (0.008)	-0.038** (0.017)	0.024*** (0.008)
Law Enforcement Operations	-0.158** (0.068)	-0.054* (0.03)	-0.062 (0.045)	0.068*** (0.026)
Recreation, Heritage, and Wilderness	-0.039*** (0.013)	-0.043*** (0.012)	-0.076*** (0.015)	0.067*** (0.006)
Roads	-0.216*** (0.042)	-0.134*** (0.022)	-0.124*** (0.025)	0.126*** (0.016)
Trails	-0.002 (0.008)	-0.013** (0.005)	-0.022*** (0.007)	0.019*** (0.003)
Non-Fire Land and Resource Management	-0.270*** (0.058)	-0.158*** (0.036)	-0.268*** (0.039)	0.211*** (0.023)
Forest Health Management - Federal Lands	-0.037*** (0.011)	-0.026*** (0.009)	-0.04*** (0.014)	0.03*** (0.004)
Grazing Management	0.011 (0.008)	0.008* (0.004)	-0.006 (0.006)	0.007** (0.003)
Land Acquisition	-0.036* (0.021)	-0.009 (0.013)	-0.035 (0.023)	0.02** (0.009)
Land Management Planning, Assessment, and Monitoring	-0.176*** (0.024)	-0.094*** (0.013)	-0.138*** (0.015)	0.112*** (0.009)
Landownership Management	-0.053*** (0.008)	-0.036*** (0.005)	-0.045*** (0.005)	0.041*** (0.003)
Minerals and Geology Management	0.029 (0.036)	0.001 (0.017)	-0.008 (0.025)	0.007 (0.014)
Non-Fire Cooperative Work	-0.131** (0.053)	-0.018 (0.053)	-0.089* (0.045)	0.087*** (0.017)
Forest Health Management - Cooperative Lands	-0.041** (0.017)	-0.018 (0.012)	-0.039*** (0.014)	0.028*** (0.006)
Forest Legacy Program	-0.041 (0.031)	0.019 (0.033)	-0.0003 (0.033)	0.023** (0.011)
Forest Stewardship	-0.034*** (0.011)	-0.013** (0.007)	-0.03*** (0.009)	0.022*** (0.005)
International Forestry	0.009 (0.006)	0.002 (0.003)	-0.001 (0.003)	0.001 (0.003)
Urban and Community Forestry	-0.017** (0.008)	-0.006 (0.005)	-0.022*** (0.006)	0.015*** (0.004)
Non-Fire Research	0.001 (0.030)	-0.023 (0.016)	-0.075*** (0.023)	0.064*** (0.014)
Forest and Rangeland Research	-0.009 (0.018)	-0.028*** (0.01)	-0.069*** (0.016)	0.059*** (0.007)
Restoration	0.318*** (0.069)	0.093** (0.037)	0.023 (0.038)	0.01 (0.027)
Integrated Resource Restoration	0.309*** (0.066)	0.089** (0.035)	0.029 (0.038)	0.006 (0.023)
Undefined	-0.086** (0.034)	-0.024 (0.017)	-0.038* (0.023)	0.046*** (0.014)
Undefined	-0.095*** (0.026)	-0.029** (0.014)	0.033* (0.019)	0.04*** (0.01)

Robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. Model 6 estimates the effects for categories, n=78, R^2=0.988. Model 7 estimates effects for underlying BLIs, n=273, R^2=0.994.

Table 2.11	Models 7 and 8 Estimates Dependent Variable: Non-Fire Appropriations, USD 2016			
	PermEffect	*TempEffect*	*IndEffect*	*Total*
Facilities	-0.336*** (0.099)	-0.196*** (0.048)	-0.188*** (0.07)	0.162*** (0.039)
Region 1	-0.017*** (0.006)	-0.009*** (0.003)	-0.011** (0.005)	0.009*** (0.003
Region 2	-0.039*** (0.012)	-0.022*** (0.006)	-0.025** (0.011)	0.019*** (0.005)
Region 3	-0.035*** (0.012)	-0.017*** (0.006)	-0.02** (0.01)	0.16*** (0.005)
Region 4	-0.021*** (0.007)	-0.014*** (0.004)	-0.014** (0.006)	0.01*** (0.003)
Region 5	-0.054*** (0.021)	-0.027*** (0.01)	-0.023* (0.013)	0.025*** (0.008)
Region 6	-0.035*** (0.012)	-0.017*** (0.006)	-0.018 (0.011)	0.016*** (0.005)
Region 8	-0.061*** (0.017)	-0.03*** (0.008)	-0.033*** (0.011)	0.03*** (0.007)
Region 9	-0.031*** (0.009)	-0.018*** (0.005)	-0.016*** (0.005)	0.015*** (0.003)
Region 10	-0.019*** (0.006)	-0.012*** (0.003)	-0.011*** (0.004)	0.01*** (0.002)
Research Stations	-0.023** (0.011)	-0.03*** (0.006)	-0.022*** (0.008)	0.014*** (0.004)
Administrative Offices	0.001 (0.007)	-0.002 (0.003)	0.004 (0.005)	-0.002 (0.003)
Infrastructure Improvement	-0.046*** (0.018)	-0.02** (0.008)	-0.038** (0.017)	0.024*** (0.008)
Region 1	-0.003** (0.001)	-0.001 (0.001)	-0.003** (0.001)	0.002*** (0.0006)
Region 2	-0.003** (0.001)	-0.002** (0.001)	-0.003*** (0.001)	0.002*** (0.0006)
Region 3	-0.003*** (0.001)	-0.001*** (0.0005)	-0.002** (0.001)	0.0015*** (0.0005)
Region 4	-0.004** (0.001)	-0.002** (0.001)	-0.004*** (0.001)	0.0025*** (0.001)
Region 5	-0.005 (0.004)	-0.002 (0.002)	-0.006* (0.004)	0.003** (0.002)
Region 6	-0.015** (0.006)	-0.006** (0.003)	-0.009* (0.005)	0.007*** (0.002)
Region 8	-0.001 (0.001)	-0.002** (0.001)	-0.005*** (0.001)	0.003*** (0.001)
Region 9	-0.003** (0.001)	-0.001 (0.001)	-0.002** (0.001)	0.002*** (0.001)
Region 10	-0.003** (0.001)	-0.002** (0.001)	-0.003*** (0.001)	0.002*** (0.0006)
Research Stations	0.0003 (0.003)	-0.0003 (0.001)	-0.002* (0.001)	0.001 (0.001)
Administrative Offices	-0.005* (0.003)	-0.003* (0.002)	0.002 (0.002)	-0.002 (0.002)
Law Enforcement Operations	-0.158** (0.068)	-0.054* (0.03)	-0.062 (0.045)	0.068*** (0.026)
Region 1	-0.006 (0.004)	-0.002 (0.002)	-0.006 (0.004)	0.003 (0.002)
Region 2	-0.006 (0.005)	-0.002 (0.002)	-0.007 (0.005)	0.003 (0.002)
Region 3	-0.007 (0.005)	-0.003 (0.002)	-0.007 (0.005)	0.003 (0.002)
Region 4	-0.006 (0.005)	-0.002 (0.002)	-0.007 (0.005)	0.003 (0.002)
Region 5	-0.014 (0.011)	-0.005 (0.004)	-0.016 (0.011)	0.007 (0.005)
Region 6	-0.013	-0.004	-0.013	0.006

	(0.01)	(0.004)	(0.009)	(0.004)
Region 8	-0.017 (0.013)	-0.006 (0.005)	-0.02 (0.013)	0.009 (0.006)
Region 9	-0.008 (0.006)	-0.003 (0.003)	-0.009 (0.006)	0.004 (0.003)
Region 10	-0.003 (0.003)	-0.001 (0.001)	-0.004 (0.003)	0.002* (0.001)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Administrative Offices	-0.078 (0.061)	-0.027 (0.025)	0.028 (0.044)	0.026 (0.021)
Recreation, Heritage, and Wilderness	-0.039*** (0.013)	-0.043*** (0.012)	-0.076*** (0.015)	0.067*** (0.006)
Region 1	-0.009*** (0.002)	-0.004*** (0.001)	-0.007*** (0.002)	0.007*** (0.001)
Region 2	-0.006** (0.002)	-0.004*** (0.001)	-0.006*** (0.002)	0.006*** (0.001)
Region 3	-0.002 (0.002)	-0.002 (0.001)	-0.005** (0.002)	0.005*** (0.001)
Region 4	-0.02*** (0.005)	-0.008*** (0.002)	-0.015*** (0.004)	0.013*** (0.002)
Region 5	-0.035*** (0.007)	-0.016*** (0.003)	-0.022*** (0.005)	0.02*** (0.003)
Region 6	-0.006 (0.006)	-0.003 (0.003)	-0.009 (0.006)	0.007*** (0.003)
Region 8	-0.008*** (0.003)	-0.006*** (0.002)	-0.01*** (0.003)	0.01*** (0.001)
Region 9	-0.014*** (0.003)	-0.007*** (0.002)	-0.011*** (0.003)	0.011*** (0.001)
Region 10	-0.006*** (0.002)	-0.003** (0.001)	-0.006** (0.002)	0.005*** (0.001)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0003 (0.001)
Administrative Offices	0.063** (0.027)	0.008 (0.014)	0.014 (0.021)	-0.017 (0.011)
Roads	-0.216*** (0.042)	-0.134*** (0.022)	-0.124*** (0.025)	0.126*** (0.016)
Region 1	-0.022*** (0.005)	-0.011*** (0.003)	-0.012*** (0.003)	0.012*** (0.002)
Region 2	-0.006 (0.005)	-0.008*** (0.003)	-0.007 (0.005)	0.007*** (0.002)
Region 3	-0.015*** (0.005)	-0.011*** (0.002)	-0.008** (0.004)	0.009*** (0.002)
Region 4	-0.022*** (0.003)	-0.009*** (0.002)	-0.013*** (0.002)	0.012*** (0.001)
Region 5	-0.029*** (0.008)	-0.019*** (0.004)	-0.02*** (0.006)	0.017*** (0.003)
Region 6	-0.05*** (0.011)	-0.03*** (0.005)	-0.028*** (0.008)	0.026*** (0.004)
Region 8	-0.031*** (0.007)	-0.017*** (0.004)	-0.016*** (0.005)	0.018*** (0.003)
Region 9	-0.016*** (0.006)	-0.01*** (0.003)	-0.008** (0.003)	0.01*** (0.002)
Region 10	-0.04*** (0.011)	-0.014** (0.006)	-0.017** (0.007)	0.018*** (0.004)
Research Stations	0.001 (0.001)	0.0003 (0.001)	-0.001 (0.001)	0.001 (0.001)
Administrative Offices	0.013 (0.02)	-0.004 (0.009)	0.005 (0.014)	-0.004 (0.008)
Trails	-0.002 (0.008)	-0.013** (0.005)	-0.022*** (0.007)	0.019*** (0.003)
Region 1	-0.001 (0.002)	-0.003*** (0.001)	-0.004*** (0.001)	0.003*** (0.001)
Region 2	0.005* (0.002)	0.0007 (0.001)	-0.0004 (0.002)	0.0002 (0.0001)
Region 3	-0.003*	-0.001*	-0.002	0.002***

	(0.002)	(0.001)	(0.001)	(0.001)
Region 4	0.003* (0.002)	0.001 (0.002)	-0.0003 (0.002)	0.001 (0.001)
Region 5	-0.006*** (0.002)	0.004*** (0.001)	-0.006*** (0.002)	0.005*** (0.001)
Region 6	-0.005* (0.003)	-0.003** (0.001)	-0.005** (0.002)	0.004*** (0.001)
Region 8	-0.001 (0.002)	-0.001* (0.001)	-0.004*** (0.002)	0.004*** (0.001)
Region 9	0.001 (0.002)	-0.0001 (0.001)	-0.002 (0.001)	0.002*** (0.0006)
Region 10	-0.004** (0.002)	-0.002** (0.001)	-0.004** (0.002)	0.003*** (0.001)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Administrative Offices	0.01 (0.009)	-0.001 (0.004)	0.006 (0.006)	-0.005 (0.003)
Forest Health Management - Federal Lands	-0.037*** (0.011)	-0.026*** (0.009)	-0.04*** (0.014)	0.03*** (0.004)
Region 1	-0.003** (0.001)	-0.003*** (0.001)	-0.0026* (0.0014)	0.003*** (0.001)
Region 2	-0.007*** (0.002)	-0.005*** (0.001)	-0.005** (0.002)	0.004*** (0.001)
Region 3	-0.004*** (0.001)	-0.002*** (0.001)	-0.003*** (0.001)	0.002*** (0.001)
Region 4	-0.002* (0.001)	-0.003*** (0.001)	-0.003** (0.001)	0.003*** (0.001)
Region 5	-0.01*** (0.004)	-0.0003 (0.001)	-0.006** (0.002)	0.006*** (0.001)
Region 6	-0.006** (0.003)	-0.003** (0.001)	-0.004** (0.002)	0.004*** (0.001)
Region 8	-0.015*** (0.004)	-0.004 (0.003)	-0.01*** (0.003)	0.009*** (0.002)
Region 9	-0.002 (0.004)	-0.003 (0.003)	-0.007* (0.004)	0.004*** (0.001)
Region 10	-0.001 (0.001)	-0.001 (0.001)	-0.003** (0.001)	0.001*** (0.0004)
Research Stations	0.002 (0.003)	0.001 (0.001)	-0.0004 (0.002)	0.0002 (0.001)
Administrative Offices	0.009 (0.006)	0.004 (0.003)	0.003 (0.004)	-0.005** (0.002)
Grazing Management	0.011 (0.008)	0.008* (0.004)	-0.006 (0.006)	0.007** (0.003)
Region 1	-0.002 (0.002)	0.0002 (0.001)	-0.002 (0.002)	0.002** (0.001)
Region 2	0.003* (0.002)	0.002** (0.001)	0.0002 (0.001)	0.001 (0.001)
Region 3	-0.004* (0.002)	-0.0002 (0.001)	-0.004** (0.002)	0.003*** (0.001)
Region 4	-0.002 (0.002)	-0.0001 (0.001)	-0.004** (0.002)	0.013*** (0.002)
Region 5	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001* (0.0006)
Region 6	0.002* (0.001)	0.001* (0.0006)	-0.0004 (0.001)	0.0003 (0.0006)
Region 8	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001** (0.001)
Region 9	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Region 10	0.001 (0.001)	0.0003 (0.0003)	-0.0004 (0.0004)	0.0003 (0.0003)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Administrative Offices	0.009 (0.006)	0.001 (0.00	0.008* (0.004)	-0.006** (0.003)
Land Acquisition	-0.036*	-0.009	-0.035	0.02**

	(0.021)	(0.013)	(0.023)	(0.009)
Region 1	-0.005 (0.004)	0.0001 (0.002)	-0.004 (0.004)	0.002 (0.002)
Region 2	-0.002 (0.002)	-0.001 (0.001)	-0.003 (0.002)	0.002* (0.001)
Region 3	-0.003 (0.002)	-0.0003 (0.001)	-0.001 (0.002)	0.001 (0.001)
Region 4	-0.001 (0.002)	0.0003 (0.001)	-0.003 (0.003)	0.001 (0.001)
Region 5	-0.003 (0.003)	-0.002 (0.002)	-0.005 (0.004)	0.003** (0.001)
Region 6	-0.005** (0.002)	-0.001 (0.001)	-0.003* (0.002)	0.002*** (0.001)
Region 8	-0.008** (0.004)	-0.001 (0.003)	-0.008*** (0.001)	0.005*** (0.001)
Region 9	-0.006 (0.005)	-0.002 (0.003)	-0.008 (0.006)	0.004* (0.002)
Region 10	0.001 (0.001)	0.0004 (0.0004)	-0.001 (0.001)	0.0003 (0.0004)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Administrative Offices	-0.006 (0.004)	-0.002 (0.002)	0.003 (0.003)	-0.002 (0.002)
Land Management Planning, Assessment, and Monitoring	-0.176*** (0.024)	-0.094*** (0.013)	-0.138*** (0.015)	0.112*** (0.009)
Region 1	-0.011** (0.004)	-0.006** (0.002)	-0.01*** (0.003)	0.008*** (0.002)
Region 2	-0.014*** (0.003)	-0.009*** (0.001)	-0.011*** (0.002)	0.009*** (0.001)
Region 3	0.002 (0.002)	-0.002 (0.001)	-0.005*** (0.002)	0.002*** (0.001)
Region 4	-0.019*** (0.005)	-0.011*** (0.002	-0.014*** (0.003)	0.011*** (0.002)
Region 5	-0.016** (0.006)	-0.008*** (0.003)	-0.017*** (0.005)	0.01*** (0.003)
Region 6	-0.004*** (0.01)	-0.016*** (0.005)	-0.023*** (0.007)	0.019*** (0.004)
Region 8	-0.017*** (0.005)	-0.008*** (0.002)	-0.014*** (0.003)	0.011*** (0.002)
Region 9	-0.037*** (0.01)	-0.016*** (0.005)	-0.018*** (0.007)	0.018*** (0.004)
Region 10	-0.005** (0.002)	-0.002** (0.001)	-0.004*** (0.001)	0.004*** (0.001)
Research Stations	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Administrative Offices	-0.022 (0.025)	-0.018 (0.013)	-0.022 (0.019)	0.019* (0.01)
Landownership Management	-0.053*** (0.008)	-0.036*** (0.005)	-0.045*** (0.005)	0.041*** (0.003)
Region 1	-0.005*** (0.001)	-0.003*** (0.001)	-0.004*** (.001)	0.003*** (0.001)
Region 2	-0.005 (0.002)	-0.003*** (0.001)	-0.004*** (0.001)	0.004*** (0.001)
Region 3	-0.005*** (0.002)	-0.002*** (0.001)	-0.003** (0.001)	0.003*** (0.001)
Region 4	-0.006*** (0.001)	-0.004*** (0.001)	-0.006*** (0.001)	0.005*** (0.001)
Region 5	-0.013*** (0.002)	-0.007*** (0.001)	-0.01*** (0.002)	0.008*** (0.001)
Region 6	-0.01*** (0.002)	-0.006*** (0.001)	-0.007*** (0.001)	0.006*** (0.001)
Region 8	-0.002 (0.001)	-0.003*** (0.001)	-0.004*** (0.001)	0.004*** (0.001)
Region 9	-0.004*** (0.001)	-0.003*** (0.001)	-0.004*** (0.001)	0.004*** (0.001)
Region 10	-0.004**	-0.002**	-0.003**	0.003***

	(0.002)	(0.001)	(0.001)	(0.001)
Research Stations	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Administrative Offices	-0.001 (0.01)	-0.005 (0.005)	-0.0003 (0.007)	0.0001 (0.004)
Minerals and Geology Management	0.029 (0.036)	0.001 (0.017)	-0.008 (0.025)	0.007 (0.014)
Region 1	-0.001 (0.004)	-0.001 (0.002)	-0.003 (0.003)	0.003* (0.002)
Region 2	0.003 (0.004)	-0.00001 (0.002)	-0.001 (0.003)	0.001 (0.002)
Region 3	0.004 (0.004)	-0.0001 (0.002)	0.001 (0.003)	-0.0001 (0.002)
Region 4	0.001 (0.006)	-0.002 (0.003)	-0.004 (0.004)	0.003 (0.002)
Region 5	-0.003 (0.003)	-0.002 (0.001)	-0.005*** (0.002)	0.004*** (0.001)
Region 6	-0.003 (0.002)	-0.002 (0.001)	-0.003** (0.001)	0.003*** (0.001)
Region 8	0.001 (0.002)	0.001 (0.001)	-0.002 (0.002)	0.002*** (0.001)
Region 9	0.002 (0.003)	0.001 (0.002)	-0.002 (0.002)	0.001 (0.001)
Region 10	0.002 (0.002)	0.0004 (0.001)	-0.0002 (0.001)	0.0003 (0.001)
Research Stations	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.001 (0.001)
Administrative Offices	0.023* (0.012)	0.006 (0.006)	0.012 (0.009)	-0.01** (0.004)
Forest Health Management - Cooperative Lands	-0.041** (0.017)	-0.018 (0.012)	-0.039*** (0.014)	0.028*** (0.006)
Region 1	-0.006*** (0.002)	-0.002*** (0.001)	-0.005*** (0.001)	0.003*** (0.001)
Region 2	0.001 (0.002)	0.0004 (0.003)	-0.001 (0.001)	0.001 (0.001)
Region 3	-0.002** (0.001)	-0.001 (0.0005)	-0.00004 (0.001)	0.001* (0.0004)
Region 4	-0.003 (0.002)	0.0002 (0.001)	-0.001 (0.002)	0.0001 (0.001)
Region 5	-0.0002 (0.003)	-0.0003 (0.001)	-0.004 (0.002)	0.002* (0.001)
Region 6	-0.001 (0.002)	-0.0004 (0.001)	-0.002 (0.001)	0.0014** (0.001)
Region 8	-0.018** (0.07)	-0.013*** (0.004)	-0.013** (0.005)	0.012*** (0.002)
Region 9	-0.013** (0.006)	0.001 (0.006)	-0.013*** (0.005)	0.008*** (0.001)
Region 10	0.002 (0.001)	0.001* (0.0006)	0.001* (0.001)	-0.0001 (0.001)
Research Stations	0.003 (0.002)	0.002 (0.001)	0.0003 (0.002)	-0.0002 (0.001)
Administrative Offices	0.009*** (0.004	-0.005*** (0.002)	-0.002 (0.002)	-0.005** (0.002)
Forest Legacy Program	-0.041 (0.031)	0.019 (0.033)	-0.0003 (0.033)	0.023** (0.011)
Region 1	0.005 (0.008)	0.011* (0.006)	0.01* (0.006)	-0.002 (0.002)
Region 2	-0.001 (0.004)	0.0005 (0.003)	-0.001 (0.004)	0.009*** (0.001)
Region 3	-0.005* (0.003)	-0.001 (0.002)	-0.002 (0.002)	0.002* (0.001)
Region 4	-0.001 (0.002)	0.004*** (0.001)	0.001 (0.001)	0.001 (0.001)
Region 5	-0.003 (0.005)	0.005 (0.005)	0.001 (0.005)	0.002 (0.002)
Region 6	0.006	0.007**	0.008**	-0.002

	(0.005)	(0.003)	(0.003)	(0.002)
Region 8	-0.016 (0.014)	-0.002 (0.01)	-0.006 (0.012)	0.009* (0.006)
Region 9	-0.021 (0.014)	-0.003 (0.015)	-0.013 (0.016)	0.012** (0.005)
Region 10	-0.0003 (0.001)	-0.0001 (0.001)	-0.001 (0.001)	0.001* (0.0004)
Research Stations	0.0001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
Administrative Offices	-0.004 (0.003)	-0.002 (0.002)	0.002 (0.002)	-0.002 (0.002)
Forest Stewardship	-0.034*** (0.011)	-0.013** (0.007)	-0.03*** (0.009)	0.022*** (0.005)
Region 1	-0.0005 (0.001)	-0.0003 (0.0004)	-0.0014** (0.0006)	0.001** (0.0004)
Region 2	-0.0003 (0.001)	-0.001 (0.001)	-0.002** (0.001)	0.001** (0.0004)
Region 3	-0.0003 (0.001)	-0.0001 (0.0003)	-0.0004 (0.0004)	0.0002 (0.0003)
Region 4	0.0001 (0.001)	0.0004 (0.0004)	-0.001** (0.0005)	0.0008** (0.0003)
Region 5	0.001 (0.001)	0.001 (0.001)	-0.002 (0.001)	0.001 (0.001)
Region 6	-0.001 (0.001)	-0.001 (0.001)	-0.002*** (0.0006)	0.001** (0.0005)
Region 8	-0.014*** (0.004)	-0.005** (0.002)	-0.011*** (0.003)	0.009*** (0.001)
Region 9	-0.018*** (0.004)	-0.006** (0.003)	-0.011*** (0.003)	0.009*** (0.002)
Region 10	0.0001 (0.001)	0.00002 (0.0004)	-0.001** (0.001)	0.001* (0.0004)
Research Stations	-0.001 (0.001)	-0.001 (0.001)	-0.002** (0.001)	0.002*** (0.0005)
Administrative Offices	0.0002 (0.003)	-0.001 (0.002)	0.004* (0.002)	-0.003** (0.001)
International Forestry	0.009 (0.006)	0.002 (0.003)	-0.001 (0.003)	0.001 (0.003)
Region 1	0.001 (0.001)	0.0002 (0.0004)	-0.0003 (0.0004)	0.0002 (0.0003)
Region 2	0.001 (0.001)	0.0003 (0.0003)	-0.0003 (0.001)	0.0003 (0.0004)
Region 3	-0.0001 (0.001)	-0.00003 (0.0003)	0.00004 (0.0004)	-0.00003 (0.0003)
Region 4	0.001 (0.001)	0.0004 (0.0004)	-0.0005 (0.0005)	0.0004 (0.0003)
Region 5	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Region 6	0.0005 (0.001)	0.0002 (0.0005)	-0.0003 (0.001)	0.0002 (0.0005)
Region 8	0.002 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001* (0.0006)
Region 9	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Region 10	0.001 (0.001)	0.0003 (0.0003)	-0.0004 (0.0004)	0.0003 (0.0003)
Research Stations	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Administrative Offices	0.0004 (0.004)	-0.002 (0.002)	0.004 (0.004)	-0.003 (0.002)
Urban and Community Forestry	-0.017** (0.008)	-0.006 (0.005)	-0.022*** (0.006)	0.015*** (0.004)
Region 1	0.0002 (0.001)	0.0003 (0.0004)	-0.001 (0.001)	0.0006* (0.0004)
Region 2	-0.0006 (0.001)	0.0001 (0.0001)	-0.002** (0.001)	0.001** (0.0004)
Region 3	0.00004	-0.0001	-0.0004	0.0001

	(0.0007)	(0.0004)	(0.001)	(0.0003)
Region 4	0.001 (0.0001)	0.001 (0.001)	-0.001 (0.001)	0.0005 (0.0004)
Region 5	0.001 (0.001)	0.0003 (0.001)	-0.002** (.001)	0.001** (0.0005)
Region 6	0.0001 (0.001)	-0.0002 (0.001)	-0.0002 (0.001)	0.0006 (0.0005)
Region 8	0.003 (0.005)	-0.004*** (0.002)	-0.009*** (0.002)	0.007*** (0.001)
Region 9	-0.009** (0.004)	-0.003 (0.002)	-0.009*** (0.003)	0.006*** (0.001)
Region 10	0.001 (0.001)	0.0003 (0.0003)	-0.0004 (0.001)	0.0004 (0.0003)
Research Stations	0.0002 (0.001)	-0.0001 (0.001)	-0.001 (0.001)	0.001* (0.0005)
Administrative Offices	-0.001 (0.003)	-0.0004 (0.002)	0.004* (0.002)	-0.003** (0.001)
Forest and Rangeland Research	-0.009 (0.018)	-0.028*** (0.01)	-0.069*** (0.016)	0.059*** (0.007)
Region 1	0.001 (0.001)	0.0002 (0.0004)	-0.0003 (0.0004)	0.0002 (0.0003)
Region 2	0.0006 (0.001)	0.0003 (0.0004)	-0.0003 (0.0005)	0.0002 (0.0004)
Region 3	-0.0001 (0.001)	-0.00003 (0.0003)	0.00003 (0.0004)	-0.0003 (0.0003)
Region 4	0.001 (0.001)	0.0004 (0.0004)	-0.001 (0.001)	0.0004 (0.0003)
Region 5	0.001 (0.001)	0.001 (0.001)	-0.001 (0.001)	0.001 (0.001)
Region 6	0.001 (0.001)	0.0004 (0.001)	-0.0001 (0.001)	0.0001 (0.001)
Region 8	0.002* (0.001)	0.001* (0.001)	-0.001 (0.001)	0.001* (0.0006)
Region 9	0.001 (0.001)	0.0004 (0.001)	-0.001 (0.001)	0.0004 (0.001)
Region 10	0.001 (0.001)	0.0004 (0.0003)	-0.0003 (0.0004)	0.0002 (0.0003)
Research Stations	-0.07*** (0.02)	-0.051*** (0.011)	-0.084*** (0.016)	0.073*** (0.007)
Administrative Offices	0.057** (0.025)	0.019* (0.012)	0.018 (0.016)	-0.017* (0.01)
Integrated Resource Restoration	0.309*** (0.066)	0.089** (0.035)	0.029 (0.038)	0.006 (0.023)
Region 1	0.053*** (0.012)	0.021*** (0.007)	0.014* (0.008)	-0.008* (0.004)
Region 2	0.006 (0.009)	0.009*** (0.003)	-0.004 (0.006)	0.007** (0.003)
Region 3	0.034*** (0.009)	0.027*** (0.005)	0.01 (0.008)	-0.007* (0.004)
Region 4	0.008 (0.012)	0.004 (0.007)	-0.001 (0.009)	0.0059 (0.005)
Region 5	0.016 (0.016)	-0.01 (0.007)	-0.017* (0.009)	0.01* (0.006)
Region 6	0.047*** (0.018)	0.002 (0.01)	-0.003 (0.01)	0.003 (0.006)
Region 8	0.026* (0.016)	0.01 (0.007)	0.002 (0.011)	0.004 (0.006)
Region 9	0.048*** (0.014)	0.021*** (0.006)	0.013 (0.009)	-0.006 (0.005)
Region 10	-0.045** (0.019)	-0.006 (0.009)	-0.009 (0.015)	0.021*** (0.007)
Research Stations	0.001 (0.001)	-0.0002 (0.001)	-0.0004 (0.001)	0.001 (0.001)
Administrative Offices	0.115 (0.07)	0.012 (0.038)	0.024 (0.055)	-0.025 (0.029)
Undefined	-0.095***	-0.029**	0.033*	0.04***

	(0.026)	(0.014)	(0.019)	(0.01)
Region 1	-0.008*** (0.003)	-0.001 (0.001)	-0.002 (0.002)	0.003*** (0.001)
Region 2	-0.003 (0.002)	0.001 (0.001)	-0.0001 (0.002)	0.0013* (0.0007)
Region 3	-0.011** (0.004)	-0.006** (0.003)	-0.003 (0.004)	0.004*** (0.002)
Region 4	-0.004** (0.002)	0.0001 (0.001)	-0.001 (0.001)	0.0021*** (0.0006)
Region 5	-0.005** (0.002)	-0.002 (0.001)	-0.001 (0.002)	0.003*** (0.001)
Region 6	-0.007*** (0.002)	-0.001 (0.001)	-0.003* (0.002)	0.003*** (0.001)
Region 8	-0.01* (0.006)	0.001 (0.003)	-0.002 (0.004)	0.005** (0.002)
Region 9	-0.012*** (0.004)	-0.002 (0.003)	-0.005 (0.004)	0.005*** (0.002)
Region 10	-0.018*** (0.006)	-0.007** (0.003)	-0.007* (0.004)	0.008*** (0.002)
Research Stations	-0.011*** (0.003)	-0.008*** (0.002)	-0.01*** (0.003)	0.007*** (0.001)
Administrative Offices	-0.007** (0.003)	-0.004** (0.002)	0.001 (0.003)	-0.001 (0.002)

Robust standard errors in parenthesis. ***1% significance, ** 5% significance, *10% significance. Model 7 estimates the effects for BLIs, n=273, R^2=0.994. Model 8 is estimated separately for each Region (1-10 as well as Research Stations and Administrative Offices), n=273, R^2= {0.988, 0.985, 0.978, 0.983, 0.98, 0.989, 0.975, 0.971, 0.967, 0.999, 0.94}.

Table 2.12 Changes in Fire Program Appropriations by Region, FY2004-FY2016			
	Change thousands (USD 2016)	Change, percent	Percent Attributed
Coop Fire Protection – State Fire Assistance	-$35,042.4	-33.5%	-14.6%
Region 1	-$3,071.1	-31.7%	-1.3%
Region 2	-$3,577.9	-35.5%	-1.5%
Region 3	-$829.0	-21.1%	-0.3%
Region 4	-$1,738.1	-34.1%	-0.7%
Region 5	-$5,236.1	-43.0%	-2.2%
Region 6	-$1,054.4	-16.8%	-0.4%
Region 8	-$8,279.0	-32.5%	-3.4%
Region 9	-$6,034.6	-31.1%	-2.5%
Region 10	-$8,057.7	-87.5%	-3.4%
Research Stations	-$106.0	-15.6%	0.0%
Administrative Offices	$2,941.5	112.4%	1.2%
Coop Fire Protection – Volunteer Fire Assistance	-$3,463.7	-21.0%	-1.4%
Region 1	-$377.8	-31.5%	-0.2%
Region 2	-$248.9	-15.1%	-0.1%
Region 3	-$51.2	-6.3%	0.0%
Region 4	-$186.8	-38.9%	-0.1%
Region 5	-$419.7	-29.2%	-0.2%
Region 6	-$84.9	-8.4%	0.0%
Region 8	-$586.9	-13.7%	-0.2%
Region 9	-$1,010.9	-20.3%	-0.4%
Region 10	-$382.3	-78.5%	-0.2%
Research Stations	-$114.4	-80.3%	0.0%
Administrative Offices	NA	NA	NA
Fire Operations – Suppression[1,2]	$64,872.0	8.7%	27.0%
Region 1	$44,156.5	372.7%	18.4%
Region 2	$51,235.2	653.3%	21.3%
Region 3	-$155,146.4	-55.3%	-64.6%
Region 4	$53,778.0	127.2%	22.4%
Region 5	$121,843.5	248.9%	50.8%
Region 6	-$50,903.9	-68.7%	-21.2%
Region 8	-$211,045.8	-77.3%	-87.9%
Region 9	-$2,911.7	-39.9%	-1.2%
Region 10	-$13.5	-84.9%	0.0%
Research Stations	$1,266.0	NA	0.5%
Administrative Offices	$212,614.0	NA	88.6%
Fire Preparedness[2]	$208,113.0	25.7%	86.7%
Region 1	-$12,475.5	-16.6%	-5.2%
Region 2	-$11,632.2	-27.7%	-4.8%
Region 3	-$17,195.1	-20.7%	-7.2%
Region 4	-$13,630.7	-17.8%	-5.7%
Region 5	-$13,790.4	-5.3%	-5.7%
Region 6	-$25,966.6	-23.8%	-10.8%
Region 8	-$7,535.2	-16.2%	-3.1%
Region 9	-$3,674.2	-12.7%	-1.5%
Region 10	-$1,006.7	-24.9%	-0.4%
Research Stations	$1,712.1	174.6%	0.7%
Administrative Offices	$313,307.7	385.7%	130.5%
Fire Research and Development	-$7,546.0	-28.0%	-3.1%

Region 1	NA	NA	NA
Region 2	NA	NA	NA
Region 3	NA	NA	NA
Region 4	NA	NA	NA
Region 5	NA	NA	NA
Region 6	NA	NA	NA
Region 8	NA	NA	NA
Region 9	NA	NA	NA
Region 10	NA	NA	NA
Research Stations	-$6,487.6	-25.1%	-2.7%
Administrative Offices	-$1,058.3	-97.7%	-0.4%
Hazardous Fuels	$13,082.1	4.8%	5.5%
Region 1	-$927.7	-5.4%	-0.4%
Region 2	-$8,044.3	-23.7%	-3.4%
Region 3	-$4,024.1	-9.2%	-1.7%
Region 4	$1,987.1	9.6%	0.8%
Region 5	-$11,197.3	-17.8%	-4.7%
Region 6	$4,151.2	14.2%	1.7%
Region 8	$12,647.2	45.1%	5.3%
Region 9	$393.2	3.0%	0.2%
Region 10	-$92.8	-8.1%	0.0%
Research Stations	-$6,500.3	-59.5%	-2.7%
Administrative Offices	$24,690.0	170.4%	10.3%

These represent the proportion of fire appropriations going to each fire program and region from FY2004-FY2016. Percent Attributed captures the proportion of increases in Fire Appropriations ($240 million) attributed to each source and sums to 100% across categories and 100% across Regions. Negative percentages reflect decreased spending, so total increases alone actually exceed $240 million.

[1]Suppression appropriations are divided across regions based on the acres burned on Forest Service land in each region.

[2]In 2012 there was a realignment of aviation assets to fall under Preparedness rather than Suppression.

2.9 Chapter 2 Figures

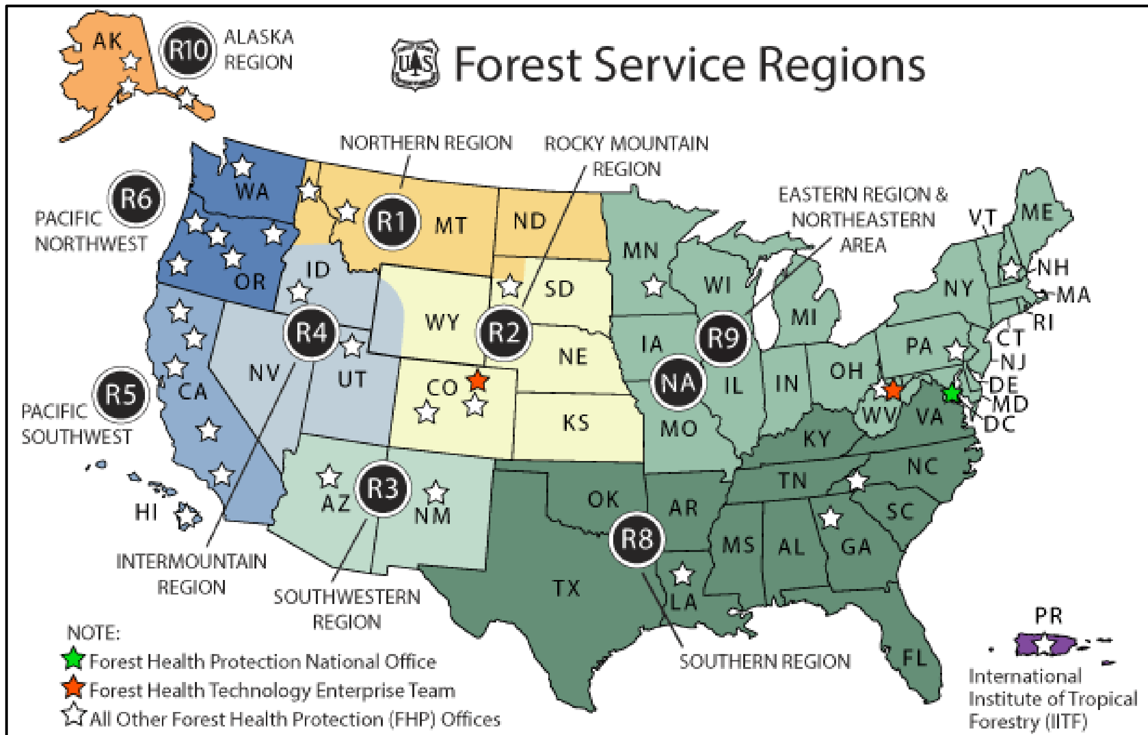


Figure 2.1
Graphic from USDA (2019): *https://www.fs.usda.gov/Internet/FSE_MEDIA/fsbdev2_040657.gif*

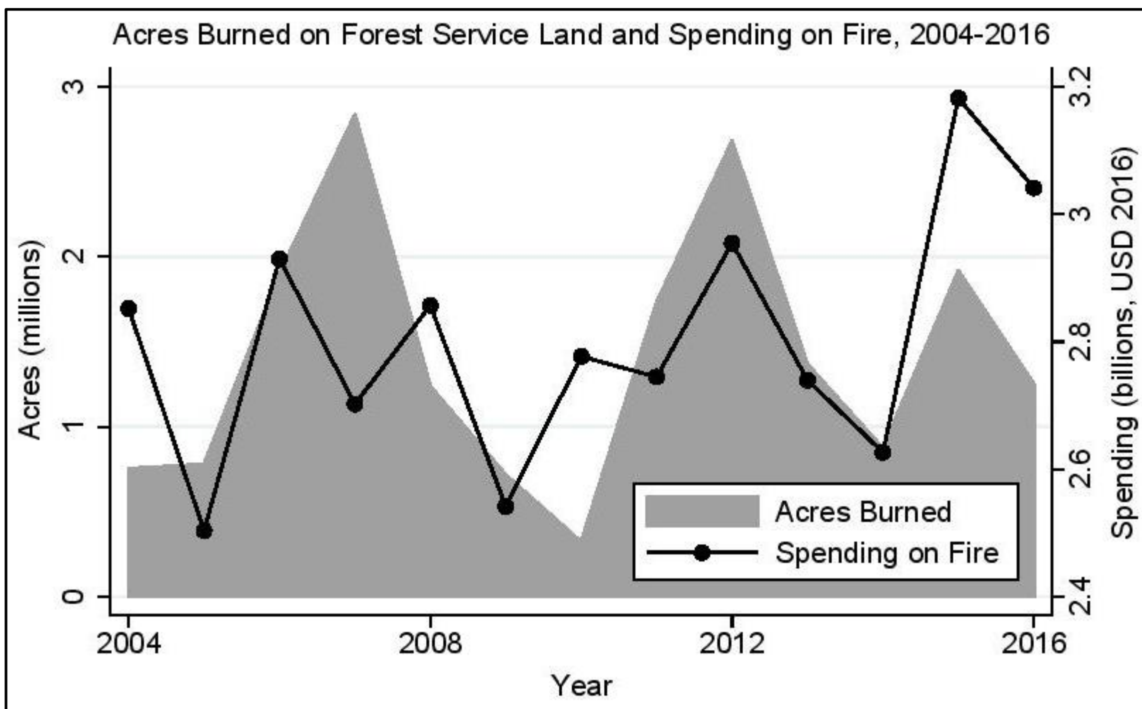
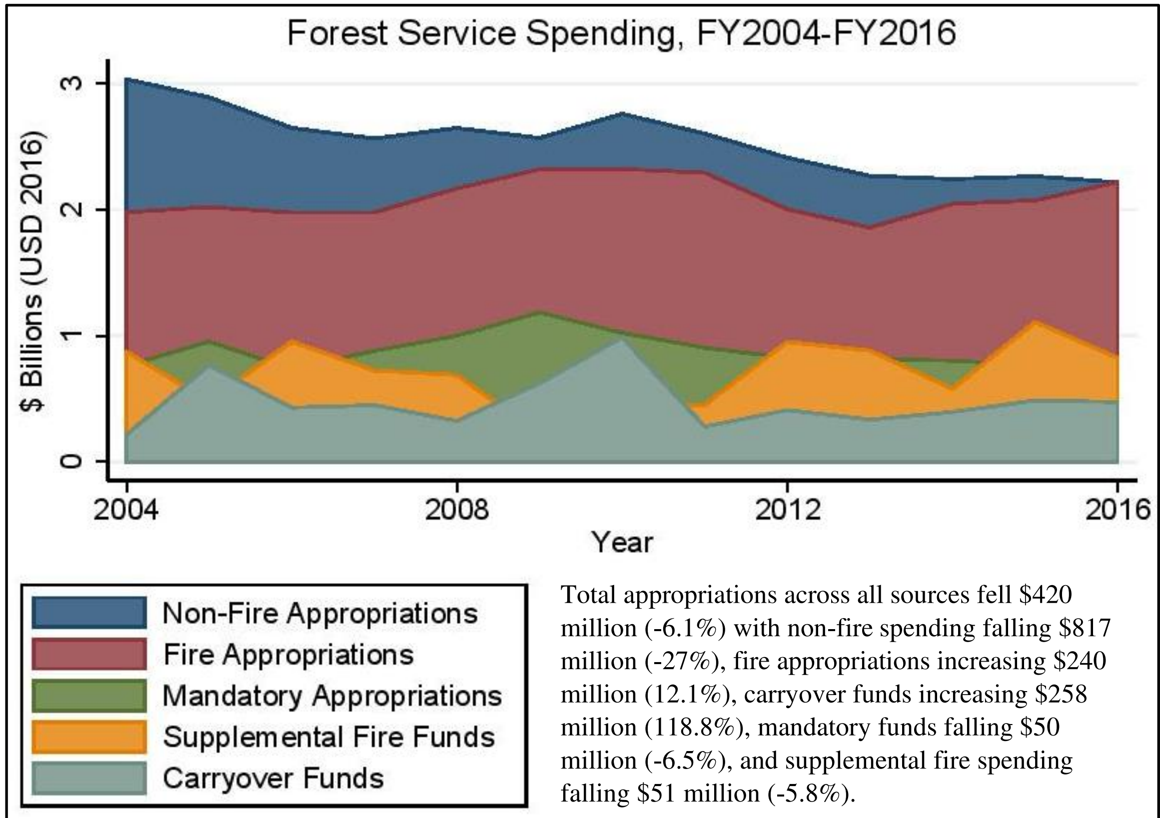


Figure 2.2
Fire spending includes fire appropriations and supplemental fire funding.



Total appropriations across all sources fell $420 million (-6.1%) with non-fire spending falling $817 million (-27%), fire appropriations increasing $240 million (12.1%), carryover funds increasing $258 million (118.8%), mandatory funds falling $50 million (-6.5%), and supplemental fire spending falling $51 million (-5.8%).

Figure 2.3

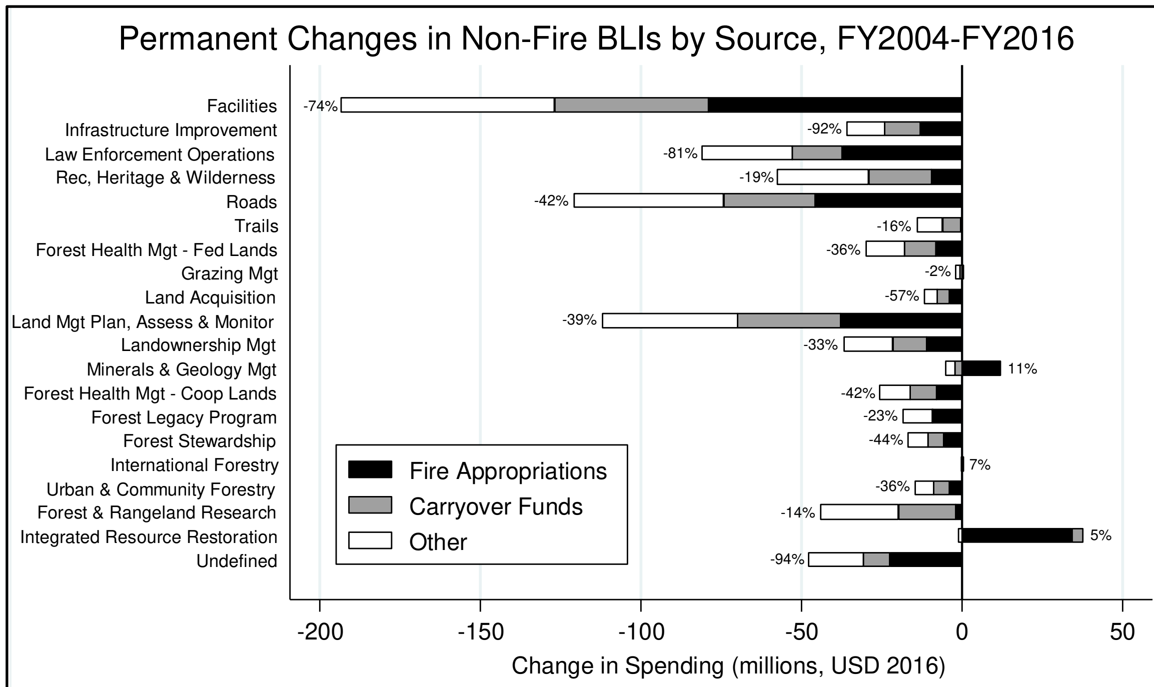
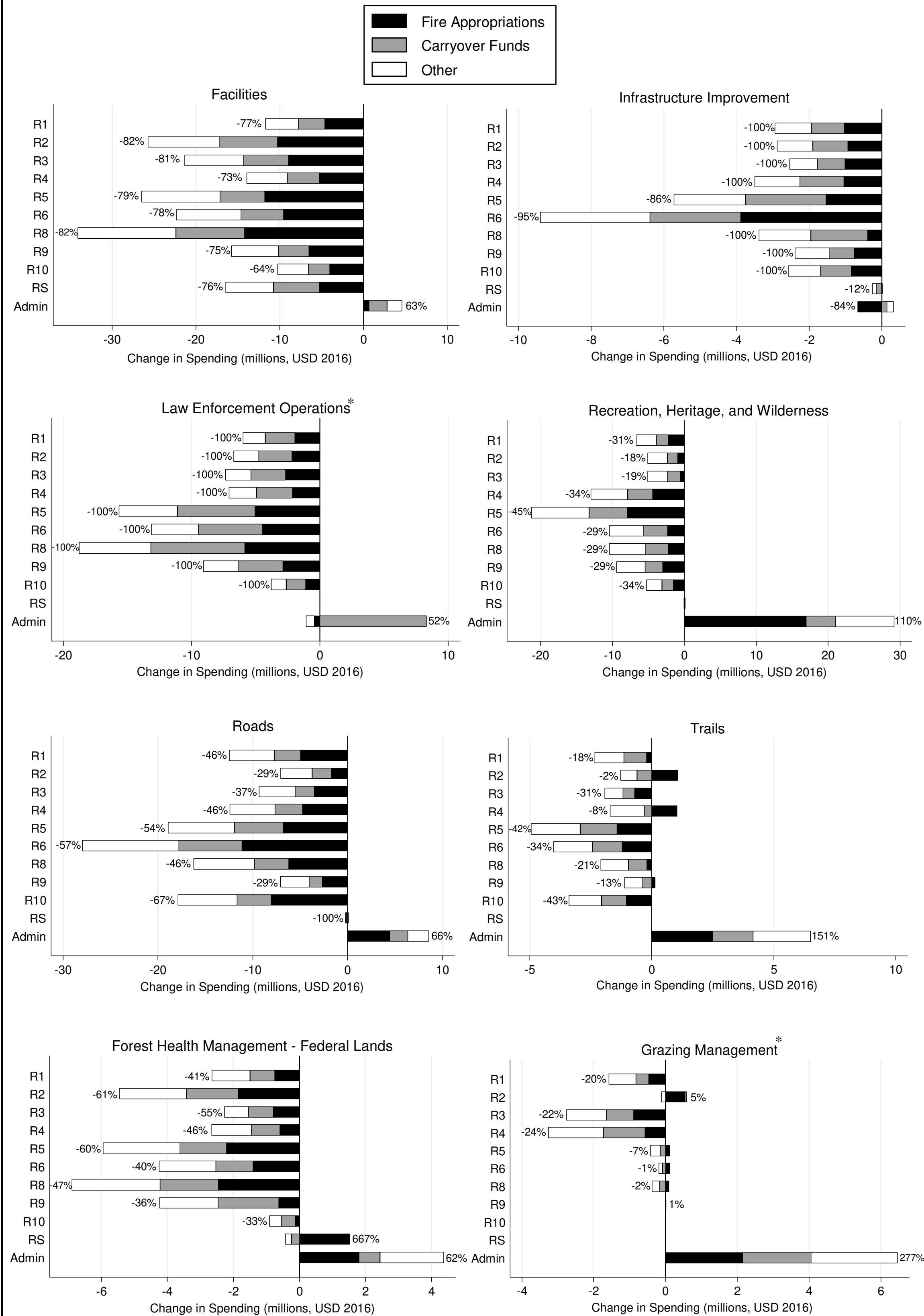
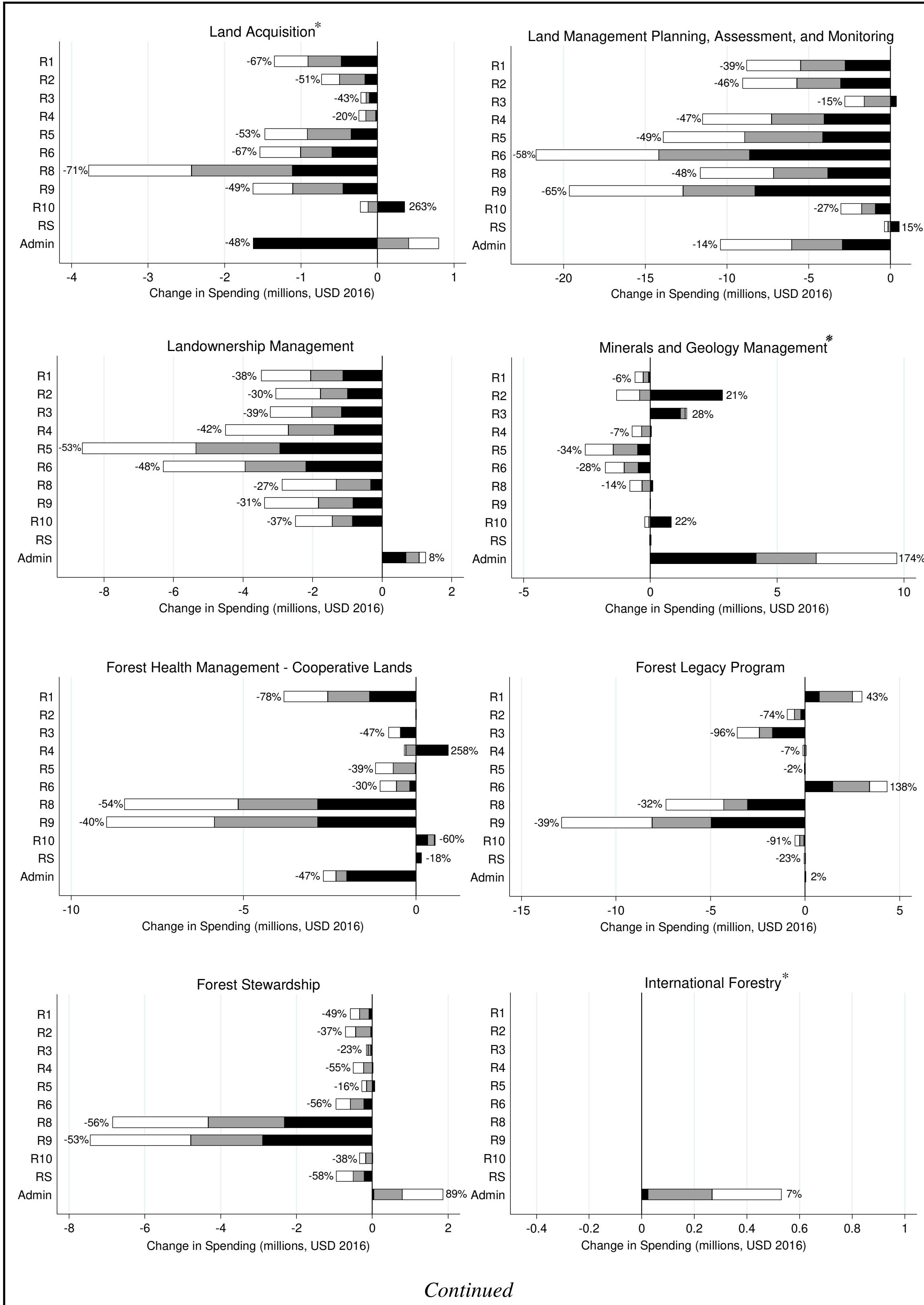


Figure 2.4

These reflect actual changes from FY2004-FY2016 and the sources of change are based on estimates from Model 7. The temporary effect from fire (through supplemental funds) is not included here so that only permanent effects are shown.


Permanent Changes in Non-Fire BLIs by Region and Source, FY2004-FY2016
Fire Appropriations
Carryover Funds
Other
Facilities
Infrastructure Improvement
Law Enforcement Operations*
Recreation, Heritage, and Wilderness
Roads
Trails
Forest Health Management - Federal Lands
Grazing Management*
Change in Spending (millions, USD 2016)
Continued



Continued

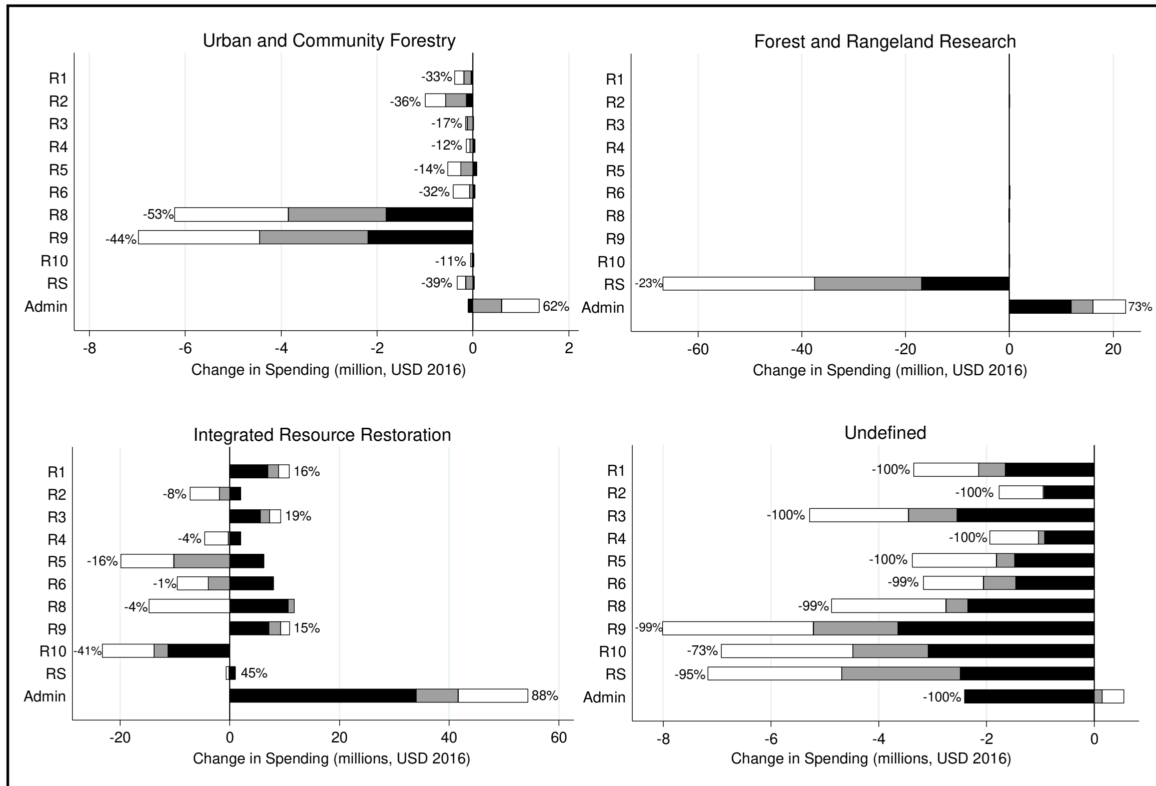


Figure 2.5

These reflect actual changes from FY2004-FY2016 and the sources of change are based on estimates from Model 8. The temporary effect from fire (through supplemental funds) is not included here so that only permanent effects are shown.

*Denotes that estimates for the BLI are only statistically significant in a few instances, or not at all.

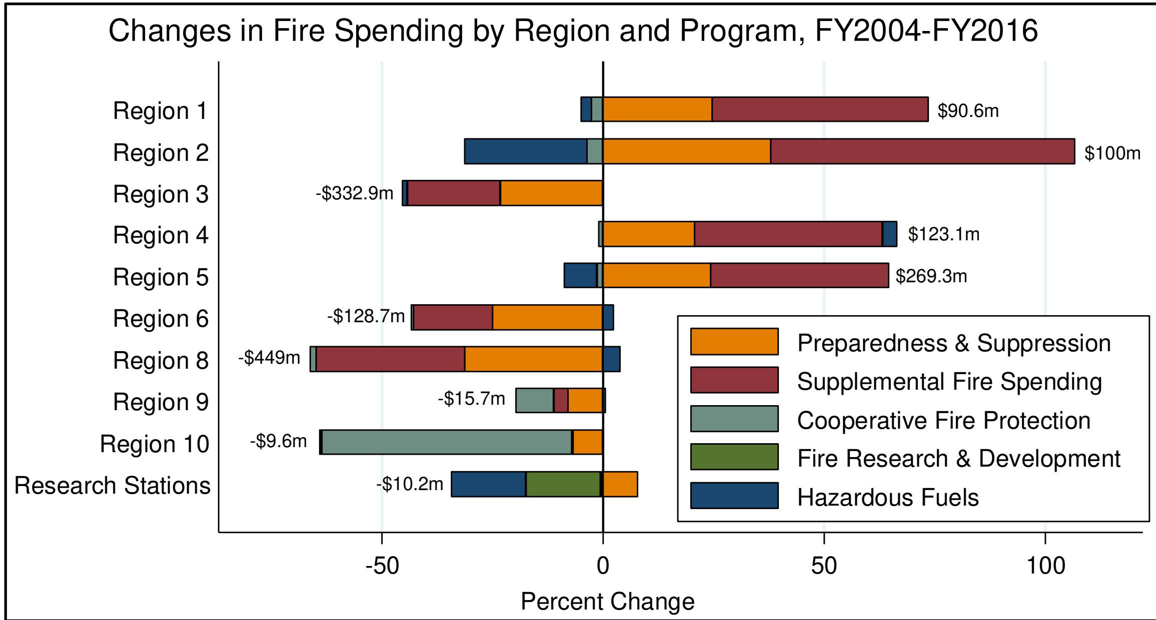


Figure 2.6

Fire spending on suppression and supplemental fire spending are separated by region based on acreage burned in each region and year. The entity Administrative Offices is excluded here for scaling reasons; they had an increase in Fire Appropriations of 555.7% ($552.5m) with 529% to Preparedness & Suppression and 25% Hazardous fuels.

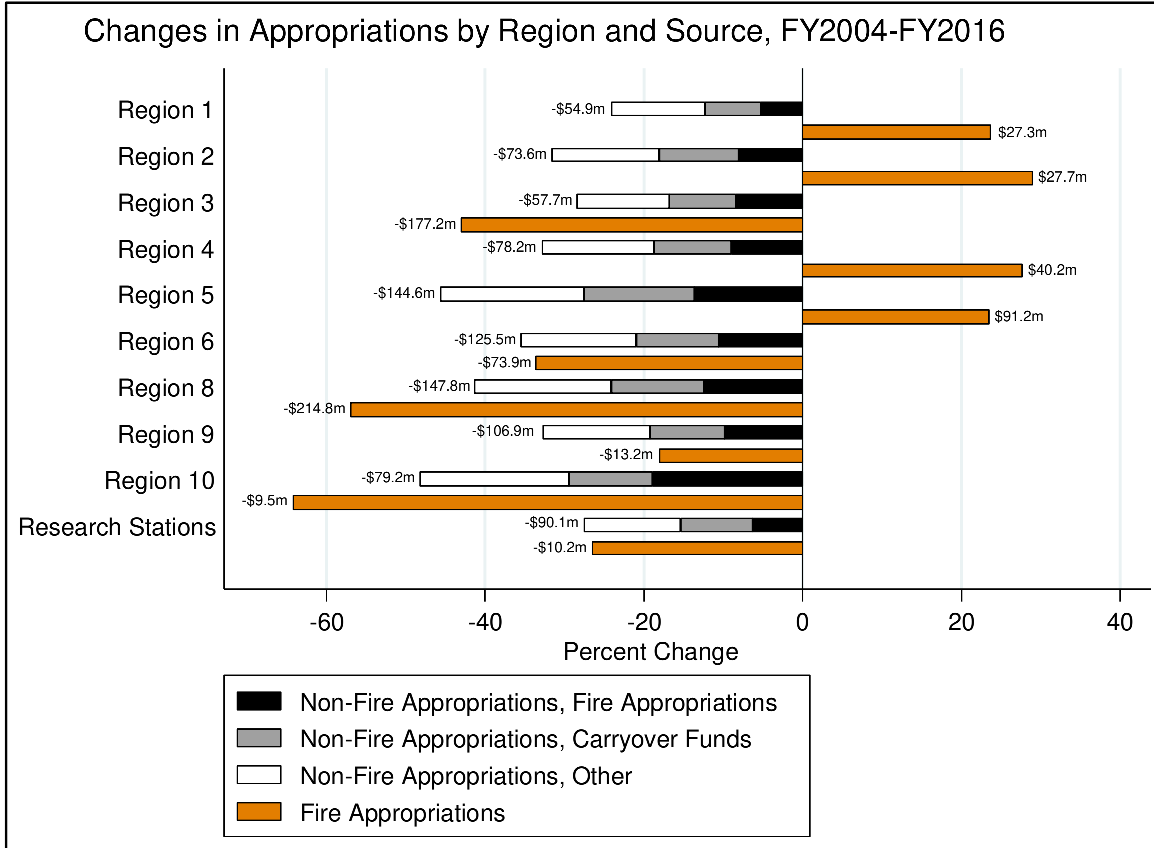


Figure 2.7

Fire spending on suppression and supplemental fire spending are separated by region based on acreage burned in each region and year. The estimates for the source of change in Non-Fire Appropriations are from Model 8. The entity Administrative Offices is excluded here for scaling reasons; they had an increase in Fire Appropriations of 555.7% ($552.5m) and an increase in Non-Fire Appropriations of 50% ($141.6m) and 20.8% corresponded with Fire Appropriations, 15.9% Carryover Funds, and 13.3% Other.

Chapter 3

Vulnerability to Climate-Induced Changes in Grazing Services on National Forest Land in the Intermountain West

3.1 Introduction

Climate change and associated stressors are likely to alter the flow of future grazing services provided by rangelands in the western United States. Changes in temperature, precipitation, and evapotranspiration are expected to influence vegetation and hydrologic trends across rangelands in the region, potentially altering the flow of future grazing services for livestock beneficiaries. Rangelands managed by the U.S. Forest Service are an important source of forage for livestock operators in the Intermountain West and grazing on National Forest land supports employment and income in many local economies. This study uses spatial data on environmental, economic, and social conditions to characterize rangeland grazing vulnerability across counties in the Intermountain West that depend on National Forest land for grazing services. The beneficial role of National Forest land in local economic conditions is also examined, along with potential environmental costs associated with grazing.

Recent research projects that there will be reduced vegetation production in southern and western regions of the United States, and in northern and interior regions the benefits of increased productivity are limited by increases in heat stress and forage variability (Reeves et al., 2017). Multiple indicators point toward increasing vulnerability of cattle production in southwestern regions and suggest significant change to the livestock industry (Reeves et al., 2017). Past research has also found that optimal livestock stocking rates and livestock profitability decrease under climate change scenarios with increased precipitation and vegetation variability (Ritten et al.,

2010). Grazing allotments that are expected to experience increased variability in precipitation and forage production are thus vulnerable to adverse changes in future grazing services. Stress from disturbances such as wildfire, drought, and invasive species also make the provision of future grazing services uncertain (Littell et al., 2013; Seidl et al., 2016).

There is a diversity of habitat, climatic conditions, and geology across grazing allotments in the Intermountain West. This assessment is intended to identify the most vulnerable counties in the region that depend on National Forest land for livestock grazing. Only grazing services derived from lands managed by the Forest Service in Region 4 are considered, and only those counties with grazing allotments on National Forest land are assessed. This encompasses 1,426 grazing allotments spanning across 67 of the 85 counties in the region. This assessment is intended to help inform future National Forest land management decisions and adaption efforts by identifying potential changes in future grazing services associated with climate-related changes across the region. The underlying drivers of vulnerability are also pinpointed, separated between environmental, economic, and social sources of exposure to change, sensitivity to change, and ability to adapt to change. Finally, the relationship between forage appropriation on National Forest land and local economic conditions is examined, along with adverse effects of forage appropriation on environmental conditions.

Vulnerability studies such as Reeves et al. (2017) have assessed environmental vulnerability across the region, concluding that the livestock industry is likely to experience numerous changes, but they do not account for economic or social conditions. Other work focuses solely on social factors of vulnerability (e.g. Cutter et al., 2003) or solely on economic factors (e.g. Williamson et al., 2012). This study seeks to build on that work, analyzing several environmental, economic, and social factors together to classify vulnerability across the region using a multidimensional index.

In doing so, this work provides a comprehensive view of vulnerability for the livestock industry and grazing beneficiaries across the Intermountain West. The framework used to measure vulnerability relies on a simple aggregation method of standardized variables. This makes the analysis straightforward and the results easy to understand. This approach also provides a tractable framework to motivate future work looking at climate-induced changes for other ecosystem services and settings.

The final vulnerability score is intended to reflect relative vulnerability as opposed to absolute vulnerability. This approach identifies the parts of the region that are most vulnerable to future changes and does not seek to describe absolute changes that might occur in the future. The actual changes any area will face depend on numerous site-specific characteristics such as weather, geography, land condition, and human actions. Since this information is largely unknown, this work does not provide insight into site-specific mitigation actions. Rather, this study highlights the areas across the region which are most likely to experience adverse changes in rangeland grazing services and require adaptation and mitigation efforts from land managers in the future. This work also describes economic impacts flowing from National Forest land across the Intermountain region, as well as potential environmental damages to vegetation, water, and soil conditions associated with grazing.

This paper proceeds as follows. First, the literature is reviewed to see how grazing services are projected to change across the West and determine how vulnerability has been defined and measured in the past. The next section covers the modeling framework used to measure vulnerability per indicators of exposure, sensitivity, and adaptive capacity in each county, as well as describe economic and environmental impacts associated with grazing on National Forest land. Following that is a discussion of the spatial data utilized to calculate vulnerability and assess

grazing on Forest Service allotments in the region. Vulnerability is then classified across the region based on environmental, economic, and social factors, and several maps and tables are provided to give detailed information on the drivers of vulnerability in each county. The impacts of grazing on National Forest land are also examined. The paper finishes with a discussion of the limitations of this study and insights for managing grazing services in the region.

3.2 Literature

Many livestock ranches in the western United States depend on public lands for a viable economic enterprise, and proper grazing of livestock on public lands is being recognized as an important ecosystem service derived from those lands (Rimbey et al, 2015). Recent research predicts that there will be reduced vegetation production in southern and western regions of the United States, and in northern and interior regions the benefits of increased aboveground net primary productivity (NPP) are limited by increases in heat stress and forage variability (Reeves et al., 2017). This has important implications for the livestock industry, as past research has also found that optimal livestock stocking rates and livestock profitability decrease under climate change scenarios with increased precipitation and vegetation variability (Ritten et al., 2010). Stress from disturbances such as wildfire, drought, and invasive species make the provision of future grazing services even more uncertain (Littell et al., 2013; Seidl et al., 2016). In the Northern Rocky Mountains, increased temperatures and growing season length are expected to increase NPP on rangelands, particularly at higher elevations (Reeves et al., 2014; Reeves et al., 2017). Increased atmospheric CO2 concentrations may also increase rangeland productivity by increasing water use efficiency (Izaurralde et al., 2011; Polley et al., 2013; Reeves et al., 2014).

Meanwhile, in low-elevation, moisture-limited areas of the Northern and Middle Rockies, without significant increases in precipitation, increased temperatures will increase evaporative demand, reducing soil moisture and productivity (Polley et al., 2013). As drought episodes and widespread drought conditions occur more frequently, they are posing increasingly larger economic, social, and environmental challenges (Estrela and Vargas, 2012; Hayes et al., 2000). In the end, the multitude of opposing and compounding effects connected with climate-induced changes make it unclear how grazing services might change in the future. By utilizing data on a wide range of key drivers across environmental, economic, and social sources, a vulnerability score can serve to identify areas that are most likely to experience adverse changes as well as struggle to adapt to those changes.

Numerous studies classify vulnerability for various ecosystem services across the United States. Looking at the Rocky Mountains, one study finds that although increased temperatures and atmospheric concentration of CO2 have the potential to increase timber and forage production, those gains may be offset by wildfires, droughts, insect outbreaks, non-native species, and altered species composition (Littell et al., 2013). A more recent study looking at the West predicts an increase in forage quantity in northern areas, a move from woody dominance toward grassier vegetation types overall, a substantial increase in the number of heat-stress days across the region, and greater interannual variability of forage quantity (Reeves et al., 2017). These trends together suggest declining forage production in southern and western regions and increasing vulnerability for cattle production in southwestern regions. Opposing indicators in northern regions point toward the need for cattle operations to increase flexibility to take advantage of periods of favorable production while preparing for uncertainty, variability, and increasing stress from individual factors (Reeves et al., 2017).

Fortunately, livestock production in the southwest is adapted to low rainfall and high ambient temperatures, but they will have to continue to adapt management strategies in an increasingly arid and variable climatic environment (Havstad et al., 2018). This includes reduced stocking rates, proper grazing management practices, diversified ranch income strategies, employing animal genetics suited to arid environments with less herbaceous production, erosion control conservation practices, alternative forage supplies, practices that reduce heat stress, and accessing additional rangelands (Joyce et al., 2013). Livestock producers and land managers will need to thoroughly understand the vulnerabilities and sensitivities that face them as well as the ecological characteristics of their specific landscapes in order to cope with the emerging climatic changes across the region (Havstad et al., 2018). According to Havstad et al. (2018), successful future policies should focus on vulnerabilities of rangeland-based animal agriculture to climatic change, rather than any specific consequences of particular anticipated changes. This suggests that a vulnerability index is a desirable way to measure future changes in grazing services associated with changing climate conditions.

Forage production is closely linked with water conditions, and in a nationwide assessment of nonpoint source threats to water quality, a broad division is found at about the 100th meridian, with eastern areas typically under greater stress from higher housing, road, and agriculture densities and higher levels of atmospheric deposition in the eastern division (Brown and Froemke, 2012). The approach used by these researchers, and commonly by others, assesses relative vulnerability, which captures relative possibilities rather than an estimate of actual probabilities. Aggregating across stress indicators, areas are ordered from the lowest to the highest level of vulnerability. Such an ordering is sometimes referred to as a disturbance index (Stein et al., 2002; Wang et al., 2008; Falcone et al. 2010) since it measures the extent of changes across a landscape.

Utilizing an ordering approach places no value judgments on the condition of any one area but does provide clear relative information that shows where environmental conditions and ecosystem services have the greatest likelihood of changing.

Relative vulnerability is sensitive to spatial boundaries. At the national level, there is often great variation between the East and the West. Depending on one's focus, this may limit the insights one can obtain. Instead, looking at relative vulnerability at a regional level allows one to compare across areas that are more homogeneous, providing greater insight and detail for the conditions in that region. As the scale becomes finer, however, there is less variation to explore. If the spatial boundaries are too small, then relative vulnerability between areas becomes meaningless. The desirable scale therefore depends on the research focus.

Vulnerability is a multidimensional idea associated with different conceptualizations, and there remains uncertainty in its measurement and classification (Panda, 2009). One of the better-known definitions of vulnerability comes from the International Strategy for Disaster Reduction, which defines vulnerability as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impacts of hazards." The concept of vulnerability has been used by various researchers in different settings and is centered on the research objective and methodologies employed. The political-economy perspectives on vulnerability emphasize the socio-political, cultural, and economic factors that together explain the differential exposure to hazards, differential impacts, and differential capacities to cope with hazards (Panda, 2009). Building from a focus on disasters and hazards, there has been an emergence of systems-oriented research attempting to understand vulnerability in a holistic manner situated within natural and social systems. An important advance

in this is from Turner et al. (2003) where their coupled vulnerability framework seeks to analyze the elements of vulnerability; exposure, sensitivity, and adaptive capacity.

Classifying vulnerability per indicators of exposure to change, sensitivity to change, and ability to adapt to change has become the common practice (e.g. Schroter et al., 2005; Parry et al., 2007; Crossman et al., 2012; Notre Dame Global Adaptation Initiative, 2018) and is adopted for this assessment. In general, exposure captures the character, magnitude, and rate of change and variation to which a system is exposed; sensitivity captures the structural factors that either heighten or lessen the impact of exposure; and adaptive capacity captures the ability of a system to adjust to change. Consideration of both biophysical and social vulnerability is increasing in the scientific community (Clark et al. 1998; Luers et al. 2003; O'Brien et al. 2004; Polsky et al. 2007). Social determinants contribute to the adaptive capacity and vulnerability of communities or systems today, and biophysical changes alongside social and other prevailing conditions affect exposure and vulnerability in the future (Tiani et al., 2015).

Economic studies of vulnerability often focus heavily on adaptive capacity. Factors contributing to adaptive capacity deficits include cases of irrational agent behavior and cases where there are political, social, and economic system failures (Williamson et al., 2012). Economic system properties such as scale, diversity, relative mix of the private and public sectors, innovation, organizational/managerial capital, substitutability of inputs, factor mobility, and liquidity of assets can affect the capacity of economic systems to adapt (Williamson et al., 2012). For this study, exposure is defined as a function of environmental factors, while sensitivity and adaptive capacity are based on several environmental, economic, and social variables that are readily available and spatially consistent across the region. For economic variables, attention is placed on livestock employment (total employment and industry concentration) and livestock income (worker, firm,

and industry concentration), with several other variables included to address local economic conditions. The livelihood of workers in the agricultural industry are especially vulnerable to the effects of climate change and drought, as this industry is highly dependent on water and vegetation conditions (Badjeck, 2010).

Pre-existing economic and social conditions play a significant role in the ability for particular communities to respond to adverse changes (Masozera et al., 2007). For social factors, many vulnerability studies utilize population and housing characteristics. The number and composition of populations that could be impacted by changing conditions is integral information for management and adaptation (Maantay and Maroko, 2009; Cutter et al., 2000). For example, aging demographics of western ranchers could be a deterrent to implementing various adaptations (Havstad et al., 2018). A fundamental part of risk management also consists of understanding the vulnerability of the elements at risk, which includes people as well as their properties (Erich, 2002). Housing and population information are therefore both important to include in vulnerability assessments. Travel and vehicle data are also important to consider for managing sensitive areas (Kolen et al., 2010). Information on health insurance is also an important measure for vulnerability, as insurance provides a safety net and allows populations to recover more quickly (Cutter, 2000; Masozera et al. 2006). Those who work outdoors, as many in the livestock industry do, are vulnerable to heat stress, which can decrease productivity and induce health risks such as dehydration, heat stroke, and long-term damage to major organs and physiological functions (Parsons, 2003; Bridger, 2003; Kjellstrom et al., 2010). Climate change is expected to increase both the intensity of heat exposure and the amount of areas vulnerable to it (Kjellstrom et al., 2010).

According to Havstad et al. (2018), there are four primary pathways in animal production in which climate change is expected to affect animal agriculture: 1) feed-grain production, availability, and price, 2) rangeland, pasture and forage crop production and quality, 3) animal health, growth, and reproduction, and 4) disease and pest distributions. Of these four pathways, the first two dealing with feed and forage production are likely the most immediately vulnerable to climate change (Elias et al., 2015). This study concentrates on the second pathway, forage production and quality, with a specific focus on National Forest land in the Intermountain region. Livestock production in the southwest U.S. is expected to be reduced by lower forage quality and quantity and a decrease in voluntary animal intake associated with lower forage quality, higher temperatures, and heat stress (Havstad et al., 2018). Forage quality is expected to decrease as a result of increased ambient temperatures, and these declines in forage quality can result in reduced animal intake and lower animal performance, such as reduced daily weight gains (Craine et al., 2010). Ultimately the livestock industry is expected to experience decreased forage quality and quantity as climate conditions change across the region, with important economic implications.

3.3 Model

The model developed for this assessment is intended to identify grazing beneficiaries that are vulnerable to climate-induced changes in grazing services on Forest Service land in Region 4. In this study, vulnerability is intended to simultaneously capture environmental, economic, and social conditions. Vulnerability (V) is measured per indicators of exposure to change (E), sensitivity to change (S), and ability to adapt to change (AC) as proposed by Turner et al. (2003). Vulnerability is calculated for each county (i) as:

$$V_i = f(E_i, S_i, AC_i) \tag{3.1}$$

Vulnerability is always an increasing function of exposure and sensitivity, and a decreasing function of adaptive capacity. This specification is desirable for its mathematical and intuitive simplicity. Each indicator is a standardized composite of several underlying variables (x) that are together intended to capture E, S, and AC, respectively. For this assessment, variables are standardized and combined to measure vulnerability using a simple summation of z-scores (z). The z-scores are calculated for each county (i) by converting variables to a mean of zero and a standard deviation of one by subtracting the mean (μ) from each observation (x) and dividing by the standard deviation (σ) as:

$$z_i(x_i) = \frac{x_i - \mu}{\sigma} \quad (3.2)$$

This method allows conditions to be interpreted relative to the average in the region and gives equal weight to each variable during the aggregation process.

Exposure is defined as a function of environmental variables, separated between expected climate-induced changes in vegetation conditions and expected changes in water conditions on Forest Service grazing allotments, calculated for each county as:

$$E_i = z_i(x_{vegetation}) + z_i(x_{water}) \quad (3.3)$$

Exposure is therefore measured by giving equal weight to projected changes in vegetation and water conditions. Note that here exposure is a function of only environmental variables, while sensitivity and adaptive capacity are defined as a function of environmental, economic, and social variables, with equal weight attributed to each source. Sensitivity and adaptive capacity are calculated for each county as:

$$S_i = z_i(x_{environmental}) + z_i(x_{ecnomomic}) + z_i(x_{social}) \quad (3.4)$$

$$AC_i = z_i(x_{environmental}) + z_i(x_{ecnomomic}) + z_i(x_{social}) \quad (3.5)$$

The final measure of vulnerability reflects a summation of standardized indicators for exposure, sensitivity, and adaptive capacity as:

$$V_i = z_i(E_i) + z_i(S_i) - z_i(AC_i) \tag{3.6}$$

This method of aggregating z-scores is intended to be simple and intuitive, and gives equal weight to exposure, sensitivity, and adaptive capacity during the calculation. Exposure, sensitivity, adaptive capacity, and the final measure of vulnerability are classified as either Low, Moderate Low, Moderate, Moderate High, or High. These five categories are generated by ranking z-scores and looking at each quintile (i.e. the distribution is separated into equal fifths). This is a common technique used to create disturbance indices and intended to compare relative conditions across the sample region.

To determine the economic importance of grazing on Forest Service allotments in the Intermountain region, the relationship between forage appropriation and select economic conditions is explored. The appropriation rate is a measure of authorized grazing consumption divided by the amount of available forage on each allotment. The numerator reflects Forest Service grazing authorization decisions and the denominator captures forage availability. The higher the appropriation, the closer the land is to carrying capacity. As covered in more detail in the next section, the sample used for this assessment is primarily cross-sectional data across 67 counties, with several variables that are averaged across years. This means that data limitations prevent the use of rigorous regression analysis to identify causal relationships between variables of interest. Nonetheless, simple regressions looking across counties are used to help understand the economic impacts of grazing on National Forest land, and regressions looking across grazing allotments are be used to assess adverse environmental effects. This serves to coarsely describe benefits for the

livestock industry from grazing on Forest Service land in Region 4, as well as potential environmental costs.

Several univariate ordinary least squares (OLS) regressions, or simple linear regressions, are run for select economic variables to describe the beneficial role of grazing on Forest Service allotments in each county. The forage appropriation rate, which reflects the demand of forage divided by the amount available, is used as the key independent variable to assess impacts of grazing on Forest Service allotments. Several economic variables are examined as dependent variables, focusing on livestock employment (total employment and industry concentration) and livestock income (worker, firm, and industry concentration). The following models are estimated across counties:

$$Livestock\ Employment_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.7)$$

$$Livestock\ Employment\ Concentration_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.8)$$

$$Livestock\ Income\ Per\ Worker_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.9)$$

$$Livestock\ Business\ Net\ Income_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.10)$$

$$Livestock\ Earnings\ Concentration_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.11)$$

While higher forage appropriation on Forest Service allotments may provide economic benefits, it often comes with environmental costs. To get an idea of adverse environmental effects from higher forage appropriation rates, several environmental conditions are examined again with simple linear regressions. Attention is placed on vegetation conditions (rangeland vegetation and riparian vegetation), water conditions (quality and quantity), and soil conditions. Unlike economic conditions, this environmental data is available for each Forest Service grazing allotment in the region. The following models are estimated across grazing allotments (*j*):

$$Rangeland\ Vegetation\ Condition_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.12)$$

$$Riparian\ Vegetation\ Condition_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.13)$$

$$Soil\ Condition_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.14)$$

$$Water\ Quality\ Condition_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.15)$$

$$Water\ Quantity\ Condition_i = \beta_0 + \beta_1(Forage\ Appropriation_i) + \varepsilon_i \quad (3.16)$$

Together, these simple regressions provide a coarse measure for the economic benefits associated with grazing on National Forest land in Region 4, as well as potential environmental costs. Note that there is likely to be a high degree endogeneity between the dependent and independent variables in each of these models. This means that these models only describe the relationship between the variables of interest, but do not identify causality. If values are placed on economic gains and environmental damages, then the optimal forage appropriation rate is simply that which equates marginal benefit with marginal cost. That said, the optimal appropriation rate is likely to differ for each grazing allotment due to environmental, economic, and political factors, making it inappropriate to try and assess a single optimal appropriation rate for an entire region. Nonetheless, the impacts highlighted in this study can motivate future research that aims to identify causal relationships and the magnitude of costs and benefits. Ideally, this could help inform rangeland management so that costs and benefits can be adequately weighed to determine the optimal appropriation rate for each grazing allotment.

3.4 Data

The desirable scale for a vulnerability analysis is determined by the research focus. The Forest Service divides the nation into 9 geographically unique regions, each of which include several states and National Forests. For this assessment, the study focuses on Region 4 which is known as the Intermountain West Region. This region is used heavily for livestock grazing (more than any

other region) and encompasses nearly 34 million acres of National Forest System lands (the most in the nation). There is a diversity of habitat, climatic conditions, and geology across grazing allotments. Only grazing services derived from lands managed by the Forest Service in Region 4 are considered for this study. This encompasses 1,426 grazing allotments spanning 67 of 85 counties across 4 states in Region 4 (Utah, Nevada, most of Idaho, and part of Wyoming). Allotments that are closed are excluded from the assessment, leaving only the active and vacant allotments. Vacant allotments are included since they are often vacant to allow vegetation and environmental conditions to recover, meaning they are likely to be used for grazing in the future.

Vulnerability is a function of exposure to change, sensitivity to change, and ability to adapt to change. For this paper, exposure is a function of environmental variables, while sensitivity and adaptive capacity are defined as a function of environmental, economic, and social factors. Exposure captures projected changes in vegetation and water conditions from downscaled climate scenarios. All environmental variables are measured at the allotment level, while economic and social variables are only available at the county level, and thus vulnerability is assessed across counties. Environmental data is aggregated for each county using a weighted average based on the size of each Forest Service grazing allotment (i.e. larger allotments are given greater weight when calculating the county average).

Exposure is separated between expected climate-induced changes in vegetation conditions and expected changes in water conditions on Forest Service grazing allotments. Table 3.1 provides a list of the variables used to characterize exposure to climate-induced changes. Projected changes in forage provision for livestock grazing is approximated using projections of aboveground net primary productivity (NPP) on capable land. This is the land that is cable of being grazed, for example land that is not too steep for livestock to stand on. For this assessment, capable land is

defined and measured as non-forested, non-barren land with a slope below 40 percent. NPP measures how much carbon dioxide vegetation takes in during photosynthesis minus how much carbon dioxide the plants release during respiration. This measure is an important indicator for studying the health for plant communities. According to NASA, NPP is the single most fundamental measure of "global change" of practical interest for humankind. However, it is important to realize that NPP does not encompass vegetation type. While increased NPP is likely to correlate with greater forage, it is not necessarily a one-to-one relationship in some areas, as only some vegetation types are edible for livestock. Although vegetation type is not explicitly captured by the climate projections, it is addressed by other indicators, such as those used to measure sensitivity and adaptive capacity.

Both the absolute change in NPP and changes in NPP annual variability (measured by the coefficient of variation, or CV) are assessed using the A1B 2080 downscaled climate projection. Changes in the CV are estimated for 10-year periods relative to the base period of 2000-2010. Increased variability of precipitation and vegetation increases uncertainty for future grazing provisioning (Ritten et al., 2010). Expected hydrologic changes also come from the A1B 2080 climate scenario that is downscaled for higher resolution. Water projections are measured by changes in mean annual flow volume (ft3/s), changes in mean summer flow (June-September), and changes in runoff timing (median flow date). Reductions in water availability leave livestock beneficiaries vulnerable, and earlier runoff timing along with reductions in summer flow correspond with drought and water shortages, and also increase the risk of disturbances such as wildfire. Changes in summer streamflow capture surface water availability during grazing season, while annual streamflow captures overall surface water availability.

The A1B scenario is considered a middle-road projection by some, and by others a conservative and idealistic scenario. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies (IPCC). Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income (IPCC). The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). Balanced is defined as not relying too heavily on one particular energy source, under the assumption that similar improvement rates apply to all energy supply and end-use technologies (IPCC). This assessment uses the 2080 A1B projection for NPP and water to measure exposure to climate-induced changes across grazing allotments.

See figure 3.1 for projected changes in vegetation under the 2080 A1B scenario, and figure 3.2 for projected changes in water availability. Figure 4.3 provides projected changes in stream runoff timing. Despite increased stress on water resources in parts of the region, under the A1B scenario vegetation productivity across National Forest rangelands may actually increase in many areas due to warming temperatures. However, this does not capture potential shifts in vegetation composition. On average across the region, NPP is predicted to increase 22.8%, but annual vegetation variability (measured by CV) is expected to increase about 16 percentage points, from a CV of 12.6% to 28.6% in 2080. Mean annual stream flow is predicted to slightly increase on average, by 0.9%, but there is wide variation across the region, with declines as much as -18.5% in the low-elevation southwest, to increases of 13.3% in the high-elevation northern part of the

region. More concerning, however, is that the timing of stream runoff is predicted to shift much earlier in the year, having significant effects on water availability during the grazing season and warm summer months.

The median flow date for runoff is expected to shift about 20.9 days earlier on average, with shifts as much as 52.2 days earlier in extreme instances. Because of this, mean summer flow is predicted to decreases by -11.5% on average, with declines as much as -61.8% in some areas, but possible increases in some, as great as 7.2%. Earlier runoff timing appears to be associated with reduced streamflow in the summer and less NPP on average, even though mean annual streamflow may increase slightly in some of the same areas. This is the case for many allotments in the northern part of Region 4. Meanwhile, the southern part of the region is expected to experience little change in runoff timing, which is associated with more streamflow in the summer and higher NPP on average. However, many of the same areas are also expected to have reduced mean annual streamflow and increased NPP variability. This highlights the importance of simultaneously accounting for several environmental factors and trends in order to measure exposure to climate-induced changes.

One desirable feature of using standardization and evaluating relative vulnerability is that it avoids the need for assessing various climate change scenarios. Under alternative climate change scenarios, the distribution of z-scores may widen or narrow, but most allotments will remain in the same order relative to other allotments along the distribution. This implies that the climate scenario adopted should have little bearing on the final classification of vulnerability due to the method of standardization and relative ranking. The remaining variables included in this assessment reflect current and past environmental conditions, as well as economic and social conditions, analyzed together to measure sensitivity and adaptive capacity. Table 3.2 provides a list of variables used to

measure sensitivity, and table 3.3 provides a list of variables used to capture adaptive capacity. Variables are chosen based on data availability as well as expert input from the Forest Service.

The first environmental variables for sensitivity and adaptive capacity come from the Forest Service Intermountain Adaptation Partnership (IAP) 2017 assessment of climate-induced changes for non-forested vegetation across Region 4. Each vegetation type is given a sensitivity and adaptive capacity score (1-5) using a standardization method similar to that used in this study. The scores capture the expected response of vegetation to climate-induced changes by vegetation type. The sensitivity score incorporates resistance to changes in temperature, precipitation, and habitat condition. The adaptive capacity score incorporates landscape condition, characteristic species, genetic diversity, and occurrence of invasive species. For this assessment, each grazing allotment is assigned an average IAP score based on the percentage of land covered by each type of vegetation. This is calculated using spatial data and GIS software.

Additional environmental indicators come from the 2010 Forest Service Watershed Condition Framework, which is the agency's first national assessment of watershed conditions across all 193 million acres of National Forest System lands. It is intended to provide a consistent process for measuring and assessing watershed health and the watershed condition classifications (WCC) are meant to be comparable across the nation. The study classifies several key land conditions into categories of either impaired, at risk, or good. This assessment utilizes the WCC data to identify the existing conditions for rangeland vegetation, riparian and wetland vegetation, water quantity, water quality, soils, fire regime, and invasive species.

Rangeland vegetation condition captures whether each allotment reflects native or desired nonnative plant composition and cover as defined by site potential. Riparian and wetland vegetation condition addresses the function of native riparian vegetation along streams, water

bodies, and wetlands. Water quantity condition measures deviations from the natural flow regime with respect to the magnitude, duration, and timing of natural streamflow hydrographs, also addressing the extent of groundwater withdrawals. Water quality condition captures the alteration of physical, biological, and chemical impacts to water quality. Soil condition addresses alteration to natural soil condition, including productivity, erosion, and chemical contamination. Fire regime condition measures existing departures from historical ranges of variability in vegetation, fuel composition, fire frequency, fire severity, and fire pattern. Lastly, terrestrial invasive species condition captures current impacts to soil and vegetation due to terrestrial invasive species (vertebrates, invertebrates, and plants).

While these condition classifications cover a wide range of environmental conditions across grazing allotments, they are unfortunately based on observations made at a single point in time. Additional variables are included to identify important trends across grazing allotments in the region. The trend of NPP from 2000-2015 is included to determine if an allotment has recently experienced a downward or upward trend in vegetation productivity. The variability of NPP (CV) from 2000-2015 is included to capture the recent annual variability of vegetation. Drought resistance is measured based on the correlation between NPP and the Palmer Drought Severity Index from 2000-2015. Together, these environmental variables capture recent trends and current conditions for each grazing allotment, ultimately shaping how grazing services might change from climate-induced changes. Table 3.4 provides the summary statistics for all environmental variables included in this assessment, measured at the allotment level. Figure 3.4 shows the proportion of NPP on Forest Service grazing allotments that is consumed by livestock, or the forage appropriation rate, with detailed maps of forage availability and consumption. Stocking limits and

annual use are managed and monitored largely using the appropriation rate, as the amount appropriated has important environmental and economic implications.

The forage appropriation rate is a measure of authorized grazing consumption divided by the amount of available forage on each allotment. The higher the appropriation rate, the closer the land is to carrying capacity. For this assessment, the Forest Service provided internal data for the authorized animal unit months (AUMs) on each of the 1,426 allotments in Region 4 from 2014-2016. Authorized grazing is converted to lbs. per acre based on the assumption that one AU is roughly equivalent to a 1,000-pound cow and that daily forage intake is 2.6 percent of body weight (University of Nebraska, 2013). This implies that one authorized AUM is equivalent to roughly 790.83 lbs. of vegetation consumption. To measure the availability of vegetation for grazing, it is important to focus only on capable land. For this assessment, NPP is measured in lbs. per acre on capable land, which is measured as non-forested, non-barren land with a slope below 40 percent. Combining authorized AUMs with vegetation availability on capable land, the forage appropriation rate is captured as a ratio for each allotment using a 3-year average from 2014-2016. The appropriation rate is used as an indicator of environmental sensitivity, but total AUMs on each allotment is also important to consider.

In this sample, the appropriation rate is about 4.2% across allotments, ranging from 0% (vacant allotments) to 100% in a handful of extreme cases. After aggregating to the county level, the average appropriation rate on Forest Service land is about 3%, ranging from 0.1% in Idaho County, Idaho to 11.9% in Oneida County, Idaho. The more National Forest land authorized for grazing, the more exposed a community is to changes in National Forest grazing services. Total AUMs on National Forest land is therefore the first economic variable used for sensitivity. The average AUMs is about 22,968 in each county, ranging from 207 AUMs in Idaho County, Idaho to 126,243

AUMs in Elko County, Nevada. Total AUMs as well as the appropriation serve to link grazing on Forest Service allotments to local livestock industry conditions in each county. Additional variables are also included to address overall grazing (public and private) in each county across the region. First, the overall concentration of land used for grazing (percent of total land in the county) is included, which comes from the 2012 National Agricultural Statistics Service (NASS). Next, the ratio of average NPP on National Forest rangelands relative to average NPP on private rangelands is added. A higher ratio implies greater vegetation production on National Forest land relative to private land. Counties with no private rangelands are given a ratio of one. The ratio of average NPP on National Forest rangelands relative to average NPP on non-National Forest public rangelands is also included. A higher ratio implies greater vegetation production on National Forest land relative to other public rangelands, such as those managed by the Bureau of Land Management (BLM). Counties without non-National Forest pubic rangelands are given a ratio of one. Together, these variables serve to capture grazing land use in each area, both on public allotments and private rangelands.

To account for economic conditions in the local livestock industry, county level data is utilized from NASS (2015). This data is used to measure conditions for livestock workers and producers. The first variable is total livestock employment, which is influenced by population size in each county. In 2015, the average number of workers in the livestock industry was 388 per county, ranging from 28 workers to 1,790. The location quotient (LQ) for livestock employment is also included, which measures the concentration of labor in the livestock industry relative to the entire United States and is thus not influenced by population size. A LQ equal to one implies the same employment concentration as the entire country, while greater than one implies a higher concentration, and less than one implies a lower concentration. The average location quotient is

6.9 in the region, ranging from 0.01 to 32.6 across counties with National Forest land. The concentration of earnings coming from the livestock industry is also important to consider, so the proportion of income is calculated for each county. The average proportion of income going to the livestock industry is 4% but ranges from 0.04% to 33.5% across counties. The next variable captures livestock income per worker, with an average of $28,801 per year across the region. Together, these variables help to identify labor conditions in the livestock industry. Areas that depend heavily on the livestock industry for employment and wages are more sensitive to changes in grazing services.

The next variables address conditions for livestock businesses. Livestock business net income is included to measure the average financial situation for livestock producers in each county. This is measured as total annual revenue minus total annual expenses, divided by total annual expenses. This permits the measure to be interpreted as a percentage of total expenses, avoiding influence from the size of each local industry. Assuming competitive markets, a negative number indicates that the local industry is operating at a loss, zero implies that they breakeven, and a positive number means that the local livestock industry is profitable. The average business net income is 15.8% across the region but ranges drastically from -60.3% to 116.6%. The proprietor fraction of income is also included, which captures the fraction of livestock income that is received by the sole proprietorships and partnerships that run livestock operations. This excludes income received by corporate farms. Table 3.5 provides the summary statistics for all economic variables, measured at the county level. Figure 3.5 shows employment conditions in the livestock industry and figure 3.6 shows income conditions.

In addition to economic data pertaining directly to the livestock industry, other economic factors are also considered. This data comes from the U.S. Census Bureau's American Community

Survey (ACS). The 2015 5-year estimate is used since the 1-year and 3-year ACS estimates are only available for larger counties (population greater than 65,000 and 20,000 respectively). This allows for smaller counties to remain in the sample. Furthermore, a 5-year estimate is desirable for the purpose of this study, as averages across time are commonly used in calculating disturbance indices, as they provide a more representative picture than a single point in time. Income per capita and the unemployment rate are included, providing a measure of alternative employment opportunities. In 2015, the average income per capita was $26,660 and the unemployment rate was 4.1% in Region 4. That said, income per capita ranged from $14,653 to $47,733 across counties, and the unemployment rate ranged from 0.9% to 8.8%. The population under the poverty level is also included, with an average of 10.2% across the region, ranging from 2.4% to an extreme of 28.6%. Lastly, the average travel time to work is included, with an average of 21 minutes, ranging from 12.8 minutes to 37.9 minutes across counties. Many of these economic variables are used to capture sensitivity to changes in grazing services, but a handful are instead used to capture adaptive capacity. In particular, income per worker, livestock income per worker, livestock business net income, and proprietor income are used to measure economic adaptive capacity, while the remaining are used to measure economic sensitivity.

The ACS data is also used to provide important social and demographic information. Table 3.6 provides the summary statistics for all social variables included in this analysis, measured across counties. First, the average household size is included, with an average of 2.8 persons per household and ranging from 2 to 3.75 persons. The proportion of households classified as family households is also included, with an average of 70.9%, ranging from 54.8% to 85.8% across the region. Households without a vehicle is also included, with an average of 3.65 and a range of 0% to 8.5% across counties. Several demographic factors are also included for each county. The

population with a disability averaged 13.6%, ranging from 5.1% to a high of 24.9%. The population that is non-U.S. born averaged 6.42% across the region, ranging from 0.7% to 30.6%. The average population age 18 and under was about 27%, ranging from 17.7% to 35.8%. The population age 65 and over averaged 22.3%, ranging from 6.1% to 26.6%. Lastly, the non-white population averaged 8.4%, ranging from 1.1% to an extreme of 50.4% across counties. Educational attainment and health insurance status is also included, which are included as important social measures of adaptive capacity, while many other social variables are used to describe sensitivity. The average population with a bachelor's degree or higher was 22.3%, ranging from 7.6% to 53.9%. The population with health insurance coverage averaged 84.2%, ranging from 62.2% to 96%.

In total, this study classifies vulnerability to climate-induced changes in National Forest grazing services in the Intermountain region using 43 environmental, economic, and social variables. These variables are categorized under exposure, sensitivity, and adaptive capacity in order to generate a comprehensive index of vulnerability. Exposure is a function of 4 key environmental variables that reflect projected changes in vegetation and water conditions across Forest Service grazing allotments. Sensitivity is a function of 24 variables that capture current and recent environmental (8), economic (8), and social (8) conditions. Adaptive capacity is function of 15 variables that also measure current and recent environmental (8), economic (4), and social conditions (3). Included are several variables that capture the importance of National Forest land in the local economy and community.

To determine the economic importance of grazing on Forest Service allotments in the Intermountain region, the relationship between forage appropriation and select economic conditions is explored. The sample used for this assessment is primarily cross-sectional data across

67 counties, with several variables that are averaged across years. This means that data limitations prevent the use of rigorous regression analysis to identify causal relationships between variables of interest. Nonetheless, simple regressions looking across counties are used to help understand the economic impacts of grazing on National Forest land, and regressions looking across grazing allotments are be used to assess adverse environmental effects. This serves to coarsely describe benefits for the livestock industry from grazing on National Forest land in Region 4, as well as potential environmental costs. Several economic variables are examined as dependent variables, focusing on livestock employment (total employment and industry concentration) and livestock income (worker, firm, and industry concentration).

While higher forage appropriation on Forest Service allotments may provide economic benefits, it often come with environmental costs. To get an idea of adverse environmental effects from higher forage appropriation rates, several environmental conditions are examined again with simple linear regressions. Attention is placed on vegetation conditions (rangeland vegetation and riparian vegetation), water conditions (quality and quantity), and soil conditions. Unlike economic conditions, this environmental data is available for each Forest Service grazing allotment in the region. These regressions are therefore run at the grazing allotment level, providing increased variation and more precise empirical estimation. Together, these simple regressions provide insight into the economic impacts associated with grazing on National Forest land in Region 4, as well as adverse environmental effects associated with grazing.

3.5 Results

The A1B climate projections suggest that despite increased stress on water resources in parts of the region, vegetation productivity across National Forest rangelands may actually increase in

many areas due to warming temperatures and CO_2 fertilization effects. These trends are likely associated with the high elevation of some Forest Service grazing allotments. This suggests that some areas of National Forest land, particularly those at higher elevations, may help support adaptation needs on lower-elevation National Forest lands, as well as on private and other public lands that are adversely affected by changing conditions. Expected changes in vegetation productivity trend closely with changes in water conditions across the region. The northern part of the region is projected to get wetter on average, but earlier runoff timing is expected to reduce streamflow during the warmer months of the year, and vegetation productivity is expected to remain unchanged or only increase slightly on average. Meanwhile, in the warm and dry southern part of the region, runoff timing is not expected to change much, and the summer months are expected to get wetter and increase NPP.

Mean annual streamflow is expected to increase slightly in the northern part of the region (by about 0-5%) but decline by 10% or more in the south. Runoff timing is expected to be much earlier in the northern part of the region, with the median flow date coming as much as 30 days earlier. This is associated with reduced summer streamflow of around 20% or more. Together, these opposing trends in water in the north imply that average annual NPP is not expected to change much. However, in the southern part of the region runoff timing is not expected to change much and summer streamflow is therefore expected to remain roughly the same, or actually increase slightly. This appears to be associated with increases in NPP as much as 30% on some allotments. That said, it is important to keep in mind that NPP is not a one-for-one proxy for forage availability, as it fails to capture vegetation type. The variables used to capture current conditions, such as the IAP sensitivity and adaptive capacity scores for non-forested vegetation, are intended to address differences in vegetation types and the response to climate-induced change.

Although at first glance it appears that many parts of the region will experience increases in NPP, it is important to note that the variability of NPP (CV) is expected to unambiguously increase across the region. The coefficient of variation (CV) can be interpreted as a percentage. The projections show that NPP variability is expected to increase by 40 percentage points or more on some allotments. This is the case for grazing allotments with little to no expected changes in average NPP as well as allotments expecting large changes in NPP. Variability is crucial for livestock operators given that livestock profitability decrease under increased precipitation and vegetation variability (Ritten et al., 2010).

Figure 3.7 provides the sensitivity score for each county and figure 3.8 shows the adaptive capacity score. This is broken out between environmental, economic, and social sources of sensitivity and adaptive capacity. Figure 3.9 gives the final vulnerability classification for each county in Region 4, along with maps of exposure, sensitivity, and adaptive capacity scores that include environmental, economic, and social factors. Table 3.7 gives a breakdown of exposure by county, separating expected changes in vegetation and water. Counties with high exposure are most likely to experience future declines in AUMs on National Forest grazing allotments, so the total authorized AUMs and the average forage appropriation rate are included in the table to highlight the magnitude of grazing on National Forest allotments. Table 3.8 provides the environmental, economic, and social sensitivity rankings for each county, along with the total sensitivity score. Table 3.9 shows the adaptive capacity rankings by county, again separated between environmental, economic, and social adaptive capacity. Table 3.10 gives the final vulnerability ranking for each county, combining all sources of exposure, sensitivity, and adaptive capacity.

The results indicate that vegetation exposure is highest in Idaho and Nevada, with relatively less exposure across Utah and the southwest part of Wyoming. However, Idaho and Wyoming are most exposed to changes in water conditions, particularly due to much earlier runoff timing and reduction in mean summer stream flows. Overall, counties in Idaho and Wyoming have the highest total exposure, while Utah only has two counties ranked as high exposure (Cache County and Summit County) and Nevada only has one county highly exposed (Washoe County). Looking at the sources of sensitivity, environmental sensitivity is the greatest in Nevada, with all counties receiving a high sensitivity rank, except for one county with a moderate-high score. Economic sensitivity is overall greatest in Utah and Idaho, but there is substantial variation across counties within each state, with every state including counties ranked at either extreme of low or high economic sensitivity. Social sensitivity was lowest in Wyoming, and highest in Nevada, but again there is significant variation within each state. Overall, total sensitivity is highest in Nevada and lowest in Wyoming, while Utah and Idaho have counties spread across the distribution.

For adaptive capacity, Nevada received the lowest environmental adaptive capacity scores, while Idaho and Wyoming had high rankings and Utah is varied across counties. That said, economic adaptive capacity is relatively high in Nevada as well as Utah and parts of Idaho, with lower rankings in Wyoming. However, social adaptive capacity is relatively high in Wyoming, and lowest in Nevada. Overall, total adaptive capacity is lowest in Nevada and varied across the other states. The final climate-induced vulnerability score, across all sources of exposure, sensitivity, and adaptive capacity are significantly varied across the Intermountain region. This highlights the heterogeneity in environmental, economic, and social factors across counties. In general, counties in Nevada ranked moderate-high and high for vulnerability, and Utah had the most counties ranking moderate-low and low with no counties receiving a high vulnerability score.

Wyoming also did not have any counties with high vulnerability scores and tends to fall in middle of the distribution. Meanwhile, Idaho has the most variation across counties, with several counties receiving a high vulnerability score and several a low vulnerability score, with everything in between.

These findings are consistent with other work on climate change in the West. In the Northern Rocky Mountains, increased temperatures and growing season length are expected to increase net primary productivity on rangelands, particularly at higher elevations (Reeves et al., 2014; Reeves et al., 2017). Increased atmospheric CO2 concentrations may also increase rangeland productivity by increasing water use efficiency (Izaurralde et al., 2011; Polley et al., 2013; Reeves et al., 2014). However, in low-elevation, moisture-limited areas of the Northern and Middle Rockies, without significant increases in precipitation, increased temperatures will increase evaporative demand, reducing soil moisture and productivity (Polley et al 2013). Increased wildfire and establishment of nonnative species may also decrease rangeland productivity (Littell et al., 2013).

Increased temperatures and drought are expected to elevate the risk and severity of wildfire in many parts of the region. This can impact both forage and water resources and therefore future grazing provisioning. Although much of the northern part of the region is expected to get wetter on average, the area is also likely to experience earlier runoff and large declines in water during the warm summer months. Earlier snowmelt and runoff correspond with drier conditions and an earlier start to the fire season, ultimately leading to a longer fire season and potentially more extreme wildfires. Dry conditions and infestations from insects, disease, and invasive species also increase both the probability and duration of wildfire. Increased storm severity can also increase the risk of lighting igniting fires. Climate-induced changes that impact fire seasons therefore have the potential to also influence future grazing services.

This study identifies the most vulnerable counties in Region 4 to climate-induced changes in grazing services on National Forest land, including a breakdown of exposure, sensitivity, and adaptive capacity across environmental, economic, and social sources. This pinpoints the drivers of vulnerability across counties and helps inform grazing management and climate change adaptation efforts. To understand the role of grazing services on National Forest land in each county, several simple linear regressions are run. These estimates describe the average relationship between National Forest grazing services and local economic impacts in each county. Additional regressions are run to examine the relationship between grazing and environmental conditions on each National Forest grazing allotment. These estimates describe the potential environmental costs associated with grazing.

For the regression models, the forage appropriation rate is used to measure grazing services on National Forest land, which reflects the demand of forage divided by the amount available. This is used as the key independent variable to assess economic impacts of grazing on National Forest allotments and the environmental impacts. Several economic variables are examined as dependent variables, focusing on livestock employment (total employment and industry concentration) and livestock income (worker, firm, and industry concentration). For environmental effects, attention is placed on vegetation conditions (rangeland vegetation and riparian vegetation), water conditions (quality and quantity), and soil conditions. Together, these univariate regressions provide a coarse measure for the economic benefits associated with grazing on Forest Service land in Region 4, as well as the environmental costs. Table 3.11 provides the estimates for select economic variables, and table 3.12 provides estimates for select environmental variables.

The results show that the forage appropriation rate on Forest Service grazing allotments is important in counties with high total livestock employment, and with a high employment and

earnings concentration in the livestock industry. In other words, grazing on National Forest land significantly helps support local livestock employment and earnings. There is also a positive relationship for earnings per livestock worker and livestock business net income, but the estimates are not statistically significant with this sample. A 1 percentage point increase in the forage appropriation rate across all Forest Service allotments in a county (the average appropriation rate is 3% across both active and vacant allotments) is associated with a 14.6% increase in livestock employment, a 8.7% increase in livestock employment concentration, a 4.1% increase in livestock income per worker, a 2.7% increase in livestock business net income, and a 15.8% increases in livestock earnings concentration. The estimates for livestock employment and employment concentration are statistically significant at the 5 percent level, and the estimate for livestock earnings concentration is statistically significant at the 10% level. These relationships are plotted in figure 3.10, depicting the fitted line and confidence intervals for each univariate regression.

It is important to emphasize that these estimates should not be interpreted as causal, and instead describe whether grazing on National Forest land may play an important role in local economies in the Intermountain region. If there were no relationships identified by these estimates, then one could conclude that grazing on National Forest land plays a minimal role in local economic conditions. However, that is not the case, and these results suggest that future research should further explore these relationships to determine the magnitude of economic benefits stemming from grazing on National Forest land in the region. Future work could also assess other public land in the Intermountain region, such as land managed by the BLM and state agencies. In many settings, ranchers rotate livestock across several grazing allotments in a given season, some private and some public. For example, many ranchers graze on BLM land early in the grazing season (Spring), but then shift to higher-elevation Forest Service land later in the season (Summer), while

sometimes also intermittently grazing on private lands. This assessment only examines the role of Forest Service land in providing grazing services, but future work could include other forms of public land and control for conditions on private land.

While higher forage appropriation on Forest Service allotments may provide economic benefits, it can often come with environmental costs. The results suggest that rangeland and riparian vegetation are both adversely affected by higher forage appropriation rates, and both estimates are statistically significant at the 1% level. Water quality and water quantity are also adversely affected, and the estimates are statistically significant at the 5% level. The relationship with soil conditions is not statistically significant, but the estimates suggest that higher appropriations also adversely affects soil conditions. These relationships are plotted in figure 3.11, depicting the fitted line and confidence intervals for each univariate regression. These results indicate that grazing on National Forest land plays an important role in local economies and communities in Region 4, and that it is important to weigh the economic benefits with the environmental costs of grazing. The forage appropriation rate reflects changes in both forage demand and supply, and it is an important indicator used by public land managers to determine stocking limits and annual authorized use on grazing allotments. If values are placed on economic gains and environmental damages, then the optimal forage appropriation rate is that which equates marginal benefit with marginal cost. That said, the optimal appropriation rate is likely to differ for each grazing allotment due to environmental, economic, and political factors, making it inappropriate to try and assess a single optimal appropriation rate for an entire region. Nonetheless, the impacts highlighted in this study motivate future research and help inform rangeland management on National Forest lands in Region 4, particularly as it pertains to climate change vulnerability and the need for adaptation efforts.

3.6 Conclusion

Past vulnerability studies often focus solely on environmental factors (e.g. Reeves et al., 2017), solely on social factors (e.g. Cutter et al., 2003), or solely on economic factors (e.g. Williamson et al. 2012). This study builds on that work, analyzing several environmental, economic, and social factors together to classify vulnerability across the region using a multidimensional index. In doing so, this work provides a comprehensive view of vulnerability for the livestock industry and grazing beneficiaries across the Intermountain West. Particular emphasis is placed on Forest Service grazing allotments, which are found to contribute to local economic conditions. However, a high forage appropriation rate is also associated with adverse effects on rangeland vegetation and water conditions across Forest Service grazing allotments. Overall, the drivers of vulnerability are heterogeneous across the region, suggesting that management decisions and adaptive efforts may be best served at the local level. This work helps inform grazing management and climate change adaptation efforts in the Intermountain region by identifying the drivers of vulnerability among environmental, economic, and social factors.

Despite increased stress on water resources in parts of the region, vegetation productivity may actually increase in many areas due to warming temperatures and CO2 fertilization effects at high elevations. This suggests that some areas of National Forest land, particularly those at higher elevations, may support adaptation needs on lower-elevation lands, public and private. The results show that stream runoff will likely come earlier in most parts of the Intermountain region, with significant declines in water availability during the summer in the northern part of the region, affecting vegetation availability. The final climate-induced vulnerability score, across all sources of exposure, sensitivity, and adaptive capacity are significantly varied across the Intermountain region. This highlights the heterogeneity in environmental, economic, and social factors across

counties. In general, counties in Nevada ranked moderate-high and high for vulnerability, and Utah had the most counties ranking moderate-low and low with no counties receiving a high vulnerability score. Wyoming also did not have any counties with high vulnerability scores and tends to fall in middle of the distribution. Meanwhile, Idaho has the most variation across counties, with several counties receiving a high vulnerability score and several a low vulnerability score, with everything in between.

One limitation of this work is that changes in NPP do not reflect changes in vegetation composition. This can have important implications since past work predicts a shift in vegetation types over time (Reeves et al., 2017). To address this, additional environmental variables were included to account for shifts in vegetation composition, such as the IAP sensitivity and Adaptive Capacity scores which consider vegetation type. Nonetheless, future work could provide additional value by assessing different types of vegetation, focusing on those that are most utilized for grazing purposes. Additional detail could also be provided by analyzing cattle grazing separately from other livestock, such as sheep and goats. This study also only provides information on projected changes in surface water conditions. Groundwater is not included in this study and represents an important substitute to surface water, especially during times of drought when surface water is limited. Including variables that reflect groundwater conditions could enhance the vulnerability analysis. Lastly, this study only captures exposure to environmental changes since the focus is placed on climate-induced changes. Projected changes in population and development are not included, nor other economic and social factors of exposure to future changes. Including economic and social projects of future changes could enhance the vulnerability score generated by this work.

Consistent with other work (Reeves et al., 2017), expected changes in northern regions point toward the need for cattle operations to increase flexibility to take advantage of periods of

favorable production while preparing for uncertainty and variability. Fortunately, livestock production in the southwest is adapted to low rainfall and high ambient temperatures, but they will have to continue to adapt management strategies in an increasingly arid and variable climatic environment (Havstad et al., 2018). For centuries the rangeland livestock industry has developed management strategies and conservation practices that impart resilience to common and often prolonged climatic extremes, especially droughts, which can seriously impact production from these animal agriculture systems (Havstad et al., 2006). However, producers and land managers will need to thoroughly understand the vulnerabilities and sensitivities that face them as well as the ecological characteristics of their specific landscapes in order to cope with the emerging climatic changes across the region (Havstad et al., 2018). Increasingly flexible management practices will be a key for economically and ecologically adapting to increasingly arid conditions (Torell et al., 2010). Maintaining grazing flexibility has been shown to be important for managing variable forage conditions, and its importance increases with the level of variability (Torell et al., 2010).

Adaptive strategies range from reduced stocking rates, proper grazing management practices, diversified ranch income strategies, employing animal genetics suited to arid environments with less herbaceous production, erosion control conservation practices, alternative forage supplies, practices that reduce heat stress, and accessing additional rangelands (Joyce et al., 2013). According to Badjeck (2010), responses to climate change can be anticipatory or reactive and should include: (1) management approaches and policies that build the livelihood asset base, reducing vulnerability to multiple stressors, including climate change; (2) an understanding of current response mechanisms to climate variability and other shocks in order to inform planned

adaptation; (3) a recognition of the opportunities that climate change could bring; and (4) adaptive strategies designed with a multi-sector perspective.

Due to changes in forage quantity and quality, the livestock industry will likely need to exploit animal genetics that are suited to more arid environments (Estell et al. 2012). That said, Chen et al. (2018) argue that both equity and efficiency should be considered when allocating resources for climate change adaptation. To evaluate equity, one must determine if resources were distributed to areas of greatest need, and to evaluate efficiency, one must compare the cost and benefit of adaptation efforts. Vulnerability assessments provide information on the distribution of the need for adaptation and ultimately help land managers use resources more efficiently. Vulnerability indices such as these can also be used to analyze various economic implications, such as the cost of debt (Kling et al., 2018). This study provides a tractable framework to motivate future work looking at climate-induced changes in grazing services, one that can also be adapted to assess vulnerability for other ecosystem services and settings.

3.7 Chapter 3 Tables

Table 3.1	Exposure Variables	
Type	Variable	Source
Environmental	Projected change (%) in net primary productivity, A1B 2080	Forest Service, 2017
	Projected change (%) in variability of net primary productivity, A1B 2080	Forest Service, 2017
	Projected change (%) in mean summer streamflow, A1B 2080	USDA Stream flow metrics, 2016
	Projected change (days) in runoff timing, A1B 2080	USDA Stream flow metrics, 2016

Exposure variables are captured at the allotment level (n=1,462).

Table 3.2	Sensitivity Variables	
Type	Variable	Source
Environmental	IAP non-forested vegetation climate change sensitivity score, 2017	Forest Service IAP Assessment, 2017
	Trend of net primary productivity, 2000-2015	Forest Service, 2017
	Coefficient of variation of net primary productivity, 2000-2015	Forest Service, 2017
	Correlation of annual net primary productivity and drought, 2000-2015	Forest Service, 2017 Palmer Drought Index
	Forage appropriation rate, 2014-2016 average	Forest Service, 2017
	Rangeland vegetation condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Water quantity condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Water quality condition (1-3), 2010	USDA Watershed Condition Classification, 2010
Economic	Authorized AUMs on Forest Service rangelands in the county, 2014-2016 average	Forest Service, 2017
	Total employment in the livestock industry, 2015	USDA National Agricultural Statistics Service, 2015
	Land in grazing (%), 2015	USDA National Agricultural Statistics Service, 2015
	Livestock industry employment location quotient, 2015	USDA National Agricultural Statistics Service, 2015
	Livestock industry earnings concentration (%), 2015	USDA National Agricultural Statistics Service, 2015
	Unemployment Rate (%), 2015	ACS 5-year estimate
	Poverty rate (%), 2015	ACS 5-year estimate
	Average travel time to work (minutes), 2015	ACS 5-year estimate
Social	Average household size, 2015	ACS 5-year estimate
	Homes built in 1939 or earlier (%), 2015	ACS 5-year estimate
	Households with no vehicle (%), 2015	ACS 5-year estimate
	Population 18 and under (%), 2015	ACS 5-year estimate
	Population 65 and older (%), 2015	ACS 5-year estimate
	Population non-white (%), 2015	ACS 5-year estimate
	Population with disabilities (%), 2015	ACS 5-year estimate
	Population non-U.S. born (%), 2015	ACS 5-year estimate

Sensitivity variables are captured at the county level (n=67).

Table 3.3	Adaptive Capacity Variables	
Type	Variable	Source
Environmental	IAP non-forested vegetation climate change adaptive capacity score (1-5), 2017	Forest Service IAP Assessment, 2017
	Fire regime condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Terrestrial invasive species condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Riparian and wetland vegetation condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Soil condition (1-3), 2010	USDA Watershed Condition Classification, 2010
	Projected change in mean annual streamflow (%), A1B 2080	USDA Stream flow metrics, 2016
	Ratio of net primary productivity on National Forest rangelands relative to private rangelands, 2000-2015	Forest Service, 2017
	Ratio of net primary productivity on National Forest rangelands relative to other public rangelands, 2000-2015	Forest Service, 2017
Economic	Livestock industry proprietor income (%), 2015	USDA National Agricultural Statistics Service, 2015
	Livestock industry income per worker, 2015	USDA National Agricultural Statistics Service, 2015
	Livestock industry business net income, 2015	USDA National Agricultural Statistics Service, 2015
	Income per capita, 2015	ACS 5-year estimate
Social	Family households (%), 2015	ACS 5-year estimate
	Population with bachelor's degree or better (%), 2015	ACS 5-year estimate
	Population with health insurance (%), 2015	ACS 5-year estimate

Adaptive capacity variables are captured at the county level (n=67).

Table 3.4	Summary Statistics for Environmental Variables				
Variable	Average	Median	Min	Max	Std. Dev.
Projected change in NPP, (percent change, 2080)	22.79	12.61	1.26	311.77	33.32
Projected change in NPP annual variability (CV as a percentage, future minus current, 2080)	16.05	12.02	-39.97	162.69	19.58
Projected change in mean annual stream flow (percent) (2080)	0.93	2.42	-18.49	13.29	6.18
Projected change in mean summer stream flow (percent) (June-September) (2080)	-11.54	-7.81	-61.79	7.16	13.13
Projected change in surface water runoff timing (days) (median flow date, 2080)	-20.92	-19.94	-52.2	0.035	8.51
IAP climate change sensitivity score (1=low, 5=high)	2.3	1.98	0.15	5	1.36
IAP climate change adaptive capacity score (1=high, 5=low)	2.04	1.83	0.14	5	1.15
Rangeland vegetation condition (2010) (1=good, 3=impaired)	1.48	1.2	0	3	0.57
Riparian and wetland vegetation condition (2010) (1=good, 3=impaired)	1.79	2	1	3	0.58
Water quantity condition (2010) (1=good, 3=impaired)	1.61	1.5	1	3	0.61
Water quality condition (2010) (1=good, 3=impaired)	1.63	1.44	1	3	0.7
Soil condition (2010) (1=good, 3=impaired)	1.58	1.5	1	3	0.58
Fire regime condition (2010) (1=good, 3=impaired)	1.91	2	1	3	0.55
Terrestrial invasive species condition (2010) (1=good, 3=impaired)	1.38	1	1	3	0.54
NPP trend (correlation of NPP and time, 2000-2015)	0.36	0.39	-0.58	0.96	0.26
NPP annual variability (CV, 2000-2015)	0.13	0.11	0.05	0.52	0.05
Drought resistance (correlation of NPP and Palmer Drought Index, 2000-2015) (more positive=less resistant)	0.39	0.44	0.49	0.91	0.27
Appropriation rate for livestock (percent, 2014-2016 avg.)	4.2	2.47	0	100	7.41
NPP on capable Forest Service land (non-forested, non-barren, aboveground,	2,418	2,347	323	6,200	1,167

slope below 40%, lbs. per acre, 2014-2016 avg.)					
Authorized grazing consumption on Forest Service land (lbs. per acre, 2014-2016 avg.)	93.77	56.61	0	2,285	171.3
Ratio of NPP on National Forest rangelands relative to other public rangelands (average, 2014-2016)	1.06	1	0.099	4.6	0.74
Ratio of NPP on National Forest rangelands relative to private rangelands (average, 2014-2016)	0.92	0.99	0.10	5.35	0.69

These statistics are at the grazing allotment level (n=1,426) across Forest Service Region 4 allotments that are active or vacant. For vulnerability classification this data is weighted by the size of each allotment to aggregate to the county level.
NPP=aboveground net primary productivity, CV=coefficient of variation.

Table 3.5 Summary Statistics for Economic Variables

Variable	Average	Median	Min	Max	Std. Dev.
AUMs on Forest Service land (average, 2014-2016)	22,968	15,512	207	126,243	23,548
Land in grazing (percent of total land, 2012)	13.35	9.95	0.17	52.43	11.72
Livestock industry employment location quotient (2015) (1=concentration of US)	6.9	4.87	0.12	32.61	6.41
Livestock industry employment (total, 2015)	388	261	28	1,790	379
Proprietor fraction of livestock industry income (percent, 2015)	50.96	57.21	0	93.04	27.77
Livestock industry fraction of total earnings (percent, 2015)	4.0	1.98	0.04	33.52	6.04
Livestock industry business net income (percent of costs, 2015)	15.84	12.61	-60.25	116.58	25.8
Livestock industry income per worker (USD 2015)	28,801	24,353	4,028	89,381	19,454
Income per capita (USD 2015)	23,660	22,635	14,653	47,733	5,835
Unemployment rate (percent, 2015)	4.12	3.8	0.9	8.8	1.61
Poverty rate (percent, 2015)	10.23	10.1	2.4	28.6	4.21
Travel time to work (minutes, 2015)	20.96	20	12.8	37.9	5.12

These statistics are at the county level (n= 67) across counties in Forest Service Region 4 that have at least one Forest Service grazing allotment in the county.
NPP=aboveground net primary productivity.

Table 3.6 Summary Statistics for Social Variables

Variable	Average	Median	Min	Max	Std. Dev.
Average household size (persons, 2015)	2.8	2.75	2.03	3.75	0.37
Family households (percent, 2015)	70.88	71.7	54.8	85.8	6.75
Homes built in 1939 or earlier (percent, 2015)	11.47	9.7	1	28.6	8.02
Households without a vehicle (percent, 2015)	3.65	3.5	0	8.5	1.84
Population with a disability (percent, 2015)	13.56	12.9	5.1	24.9	4.49
Population non-U.S. born (percent, 2015)	6.42	5.3	0.7	30.6	4.82
Population age 18 and under (percent, 2015)	26.95	27.7	17.7	35.8	5.09
Population age 65 and over (percent, 2015)	15.1	13.9	6.1	26.6	5.05
Population non-white (percent, 2015)	8.38	6.8	1.1	50.4	7.32
Population with a bachelor's degree or higher (percent, 2015)	22.34	20	7.6	53.9	8.85
Population with health insurance (percent, 2015)	84.19	84.3	62.2	96	4.72

These statistics are at the county level (n= 67) across counties in Forest Service Region 4 that have at least one Forest Service grazing allotment in the county.

Table 3.7			Climate Change Exposure by County		
County	Vegetation Exposure	Water Exposure	Total Exposure	AUMs	Forage Appropriated
			Idaho		
Adams	H	MH	H	38,786	1.6%
Bannock	H	ML	H	31,861	6.0%
Bear Lake	ML	H	MH	29,752	2.9%
Blaine	ML	MH	MH	6,632	0.7%
Boise	H	M	MH	2,738	0.3%
Bonneville	MH	M	M	38,486	2.0%
Butte	M	ML	ML	6,630	1.5%
Camas	ML	H	MH	7,796	0.9%
Caribou	M	M	M	46,131	2.9%
Cassia	H	ML	MH	59,933	6.4%
Clark	MH	M	MH	38,629	4.3%
Custer	ML	MH	ML	62,919	2.5%
Elmore	M	MH	MH	38,394	2.6%
Franklin	MH	H	H	11,503	3.4%
Fremont	H	MH	H	26,054	2.3%
Gem	H	MH	H	9,301	2.2%
Idaho	H	H	H	207	0.1%
Lemhi	M	M	M	35,113	1.1%
Madison	ML	M	ML	5,528	4.7%
Oneida	H	ML	MH	46,914	11.9%
Power	MH	ML	M	6,953	2.5%
Teton	ML	MH	M	7,640	1.5%
Twin Falls	MH	MH	MH	7,472	5.6%
Valley	ML	H	H	14,215	1.0%
Washington	H	M	MH	15,512	2.5%
			Nevada		
Carson City	MH	ML	M	1,730	2.2%
Douglas	H	L	M	2,710	3.0%
Elko	M	M	M	126,243	5.4%
Eureka	MH	L	L	2,924	2.0%
Humboldt	M	M	M	32,409	6.4%
Lander	M	L	ML	11,129	3.8%
Lyon	H	L	M	4,097	4.0%
Mineral	H	L	M	3,235	2.8%
Nye	M	L	ML	22,725	1.8%
Washoe	H	H	H	1,628	1.8%
White Pine	MH	L	ML	23,681	2.5%
			Utah		
Beaver	M	ML	ML	8,165	1.8%
Box Elder	L	M	L	9,122	7.9%
Cache	MH	H	H	33,055	4.2%
Daggett	L	M	ML	9,262	1.8%

Duchesne	L	H	ML	23,433	2.5%
Emery	ML	M	ML	15,698	5.1%
Garfield	L	L	L	52,417	3.7%
Grand	L	M	L	3,858	2.4%
Iron	L	L	L	12,608	2.4%
Juab	L	ML	L	13,779	3.2%
Kane	L	ML	L	3,437	1.4%
Millard	H	L	MH	19,388	2.6%
Morgan	ML	MH	M	597	0.9%
Piute	M	ML	ML	21,588	3.3%
Rich	M	MH	MH	8,693	4.7%
San Juan	L	L	L	23,428	2.1%
Sanpete	L	MH	L	48,485	4.6%
Sevier	L	ML	L	90,238	5.4%
Summit	ML	H	H	17,215	1.7%
Tooele	MH	ML	ML	16,305	7.3%
Uintah	L	MH	ML	6,677	4.1%
Utah	ML	ML	L	26,629	2.1%
Wasatch	L	H	M	57,055	3.9%
Washington	ML	L	L	19,219	4.4%
Wayne	L	L	L	14,135	4.4%
Weber	ML	L	L	2,254	0.2%
Wyoming					
Lincoln	MH	H	H	43,517	1.6%
Sublette	M	H	H	79,428	2.4%
Sweetwater	MH	H	H	1,154	0.2%
Teton	M	MH	MH	11,175	0.5%
Uinta	MH	H	H	19,252	1.5%

H=High, MH=Moderate High, M=Moderate, ML=Moderate Low, L=Low. Exposure is separated between vegetation and water conditions. Counties with high exposure are most likely to experience future declines in AUMs on Forest Service grazing allotments. Total authorized AUMs and the average forage appropriation rate are included to highlight the magnitude of grazing on Forest Service allotments.

Table 3.8 Climate Change Sensitivity by County

County	Environmental Sensitivity	Economic Sensitivity	Social Sensitivity	Total Sensitivity
		Idaho		
Adams	ML	H	ML	M
Bannock	MH	ML	M	M
Bear Lake	M	MH	ML	M
Blaine	ML	L	L	L
Boise	MH	MH	L	M
Bonneville	L	ML	MH	ML
Butte	M	L	ML	ML
Camas	L	ML	ML	L
Caribou	ML	L	M	L
Cassia	MH	H	H	H
Clark	M	M	H	H
Custer	M	MH	L	M
Elmore	MH	MH	M	MH
Franklin	M	H	MH	H
Fremont	L	ML	ML	L
Gem	L	H	MH	MH
Idaho	L	L	M	ML
Lemhi	L	M	M	ML
Madison	ML	M	L	ML
Oneida	H	H	H	H
Power	ML	ML	H	MH
Teton	L	M	L	L
Twin Falls	MH	H	MH	MH
Valley	M	L	L	L
Washington	ML	H	H	H
		Nevada		
Carson City	MH	L	ML	ML
Douglas	H	ML	ML	MH
Elko	H	MH	L	M
Eureka	H	ML	M	MH
Humboldt	H	MH	MH	H
Lander	H	MH	MH	H
Lyon	H	MH	H	H
Mineral	H	M	H	H
Nye	H	M	H	MH
Washoe	H	L	H	M
White Pine	H	ML	H	H
		Utah		
Beaver	M	M	MH	M
Box Elder	MH	MH	MH	MH
Cache	M	M	M	M
Daggett	M	L	L	L

Duchesne	ML	H	ML	M
Emery	MH	L	M	ML
Garfield	MH	M	H	MH
Grand	M	L	L	L
Iron	H	MH	M	H
Juab	L	ML	MH	M
Kane	M	L	ML	L
Millard	ML	MH	H	MH
Morgan	ML	MH	ML	ML
Piute	MH	H	H	H
Rich	M	H	MH	H
San Juan	ML	H	H	H
Sanpete	ML	H	MH	MH
Sevier	MH	MH	MH	MH
Summit	L	ML	L	L
Tooele	H	M	M	MH
Uintah	ML	L	M	ML
Utah	M	H	M	M
Wasatch	ML	M	ML	ML
Washington	H	L	M	M
Wayne	MH	ML	ML	ML
Weber	L	ML	MH	ML
		Wyoming		
Lincoln	L	M	L	L
Sublette	L	H	L	L
Sweetwater	MH	ML	L	ML
Teton	L	L	L	L
Uinta	L	M	ML	L

H=High, MH=Moderate High, M=Moderate, ML=Moderate Low, L=Low.

Table 3.9	Climate Change Adaptive Capacity by County			
County	Environmental Adaptive Capacity	Economic Adaptive Capacity	Social Adaptive Capacity	Total Adaptive Capacity
		Idaho		
Adams	ML	MH	ML	ML
Bannock	M	ML	M	M
Bear Lake	MH	M	MH	MH
Blaine	H	MH	MH	H
Boise	M	M	ML	M
Bonneville	ML	MH	H	MH
Butte	MH	MH	ML	M
Camas	H	M	L	M
Caribou	M	MH	H	MH
Cassia	MH	H	ML	MH
Clark	M	L	L	L
Custer	MH	MH	M	H
Elmore	ML	H	ML	M
Franklin	M	MH	MH	MH
Fremont	H	H	MH	H
Gem	M	L	L	L
Idaho	H	L	ML	M
Lemhi	MH	MH	L	M
Madison	MH	ML	H	H
Oneida	M	ML	M	ML
Power	MH	MH	M	MH
Teton	H	L	MH	M
Twin Falls	H	H	ML	MH
Valley	H	MH	M	MH
Washington	L	H	L	ML
		Nevada		
Carson City	L	H	MH	MH
Douglas	L	M	M	L
Elko	L	H	ML	ML
Eureka	L	ML	L	L
Humboldt	L	ML	L	L
Lander	L	L	ML	L
Lyon	L	L	L	L
Mineral	L	L	L	L
Nye	L	H	ML	H
Washoe	ML	H	L	ML
White Pine	L	M	L	L
		Utah		
Beaver	ML	L	MH	ML
Box Elder	M	M	H	MH
Cache	ML	M	H	MH

Daggett	M	H	H	H
Duchesne	H	MH	M	MH
Emery	MH	M	MH	M
Garfield	M	M	ML	ML
Grand	M	L	L	L
Iron	ML	ML	M	ML
Juab	L	ML	MH	L
Kane	MH	MH	L	ML
Millard	ML	MH	M	M
Morgan	M	M	H	H
Piute	ML	ML	ML	ML
Rich	ML	H	H	H
San Juan	ML	L	L	L
Sanpete	H	H	MH	H
Sevier	ML	ML	ML	ML
Summit	MH	H	H	H
Tooele	ML	H	H	H
Uintah	MH	L	M	ML
Utah	H	M	H	H
Wasatch	MH	L	H	MH
Washington	L	L	MH	L
Wayne	L	ML	M	L
Weber	H	ML	MH	M
		Wyoming		
Lincoln	MH	ML	H	M
Sublette	H	M	MH	H
Sweetwater	M	ML	M	ML
Teton	H	M	H	H
Uinta	H	L	M	M

H=High, MH=Moderate High, M=Moderate, ML=Moderate Low, L=Low.

Table 3.10	Climate Change Vulnerability by County			
County	Total Exposure	Total Sensitivity	Total Adaptive Capacity	Vulnerability
		Idaho		
Adams	H	M	ML	MH
Bannock	H	M	M	MH
Bear Lake	MH	M	MH	M
Blaine	MH	L	H	L
Boise	MH	M	M	MH
Bonneville	M	ML	MH	ML
Butte	ML	ML	M	ML
Camas	MH	L	M	M
Caribou	M	L	MH	L
Cassia	MH	H	MH	H
Clark	MH	H	L	H
Custer	ML	M	H	ML
Elmore	MH	MH	M	MH
Franklin	H	H	MH	H
Fremont	H	L	H	L
Gem	H	MH	L	H
Idaho	H	ML	M	H
Lemhi	M	ML	M	ML
Madison	ML	ML	H	L
Oneida	MH	H	ML	H
Power	M	MH	MH	M
Teton	M	L	M	ML
Twin Falls	MH	MH	MH	M
Valley	H	L	MH	M
Washington	MH	H	ML	H
		Nevada		
Carson City	M	ML	MH	ML
Douglas	M	MH	L	MH
Elko	M	M	ML	MH
Eureka	L	MH	L	MH
Humboldt	M	H	L	H
Lander	ML	H	L	H
Lyon	M	H	L	H
Mineral	M	H	L	H
Nye	ML	MH	H	M
Washoe	H	M	ML	H
White Pine	ML	H	L	H
		Utah		
Beaver	ML	M	ML	MH
Box Elder	L	MH	MH	L
Cache	H	M	MH	MH
Daggett	ML	L	H	L

Duchesne	ML	M	MH	ML
Emery	ML	ML	M	ML
Garfield	L	MH	ML	M
Grand	L	L	L	M
Iron	L	H	ML	M
Juab	L	M	L	M
Kane	L	L	ML	L
Millard	MH	MH	M	MH
Morgan	M	ML	H	ML
Piute	ML	H	ML	H
Rich	MH	H	H	MH
San Juan	L	H	L	MH
Sanpete	L	MH	H	L
Sevier	L	MH	ML	L
Summit	H	L	H	L
Tooele	ML	MH	H	ML
Uintah	ML	ML	ML	ML
Utah	L	M	H	L
Wasatch	M	ML	MH	ML
Washington	L	M	L	M
Wayne	L	ML	L	L
Weber	L	ML	M	L
		Wyoming		
Lincoln	H	L	M	M
Sublette	H	L	H	ML
Sweetwater	H	ML	ML	MH
Teton	MH	L	H	L
Uinta	H	L	M	M

H=High, MH=Moderate High, M=Moderate, ML=Moderate Low, L=Low.

Table 3.11 Univariate Estimates for Select Economic Variables
Independent Variable: Average Forage Appropriation Rate (0-100) on Forest Service Grazing Allotments

Dependent Variable	Coefficient	R^2	n
Total Livestock Employment (natural log)	0.146** (0.061)	0.09	67
Livestock Employment Location Quotient	0.631** (0.278)	0.042	67
Livestock Income Per Worker (natural log)	0.041 (0.047)	0.015	67
Livestock Business Net Income	0.0036 (0.011)	0.001	67
Livestock Earnings Concentration	0.006* (0.004)	0.046	67

Each of these univariate models are estimated separately and describe the basic relationship between forage appropriation for livestock on Forest Service grazing allotments and select economic conditions across counties in Region 4. ***1% significance, **5% significance, *10% significance.

Table 3.12 Univariate Estimates for Select Environmental Variables
Independent Variable: Average Forage Appropriation Rate (0-100) on Forest Service Grazing Allotments

Dependent Variable	Coefficient	R^2	n
Rangeland Vegetation Condition (1=Poor, 3=Good)	-0.008*** (0.02)	0.011	1,426
Riparian Vegetation Condition (1=Poor, 3=Good)	-0.007*** (0.002)	0.009	1,426
Soil Condition (1=Poor, 3=Good)	-0.003 (0.002)	0.002	1,426
Water Quality Condition (1=Poor, 3=Good)	-0.005** (0.002)	0.002	1,426
Water Quantity Condition (1=Poor, 3=Good)	-0.007** (0.003)	0.008	1,426

Each of these univariate models are estimated separately and describe the basic relationship between forage appropriation for livestock on Forest Service grazing allotments and select environmental conditions across allotments in Region 4. ***1% significance, **5% significance, *10% significance.

3.8 Chapter 3 Figures

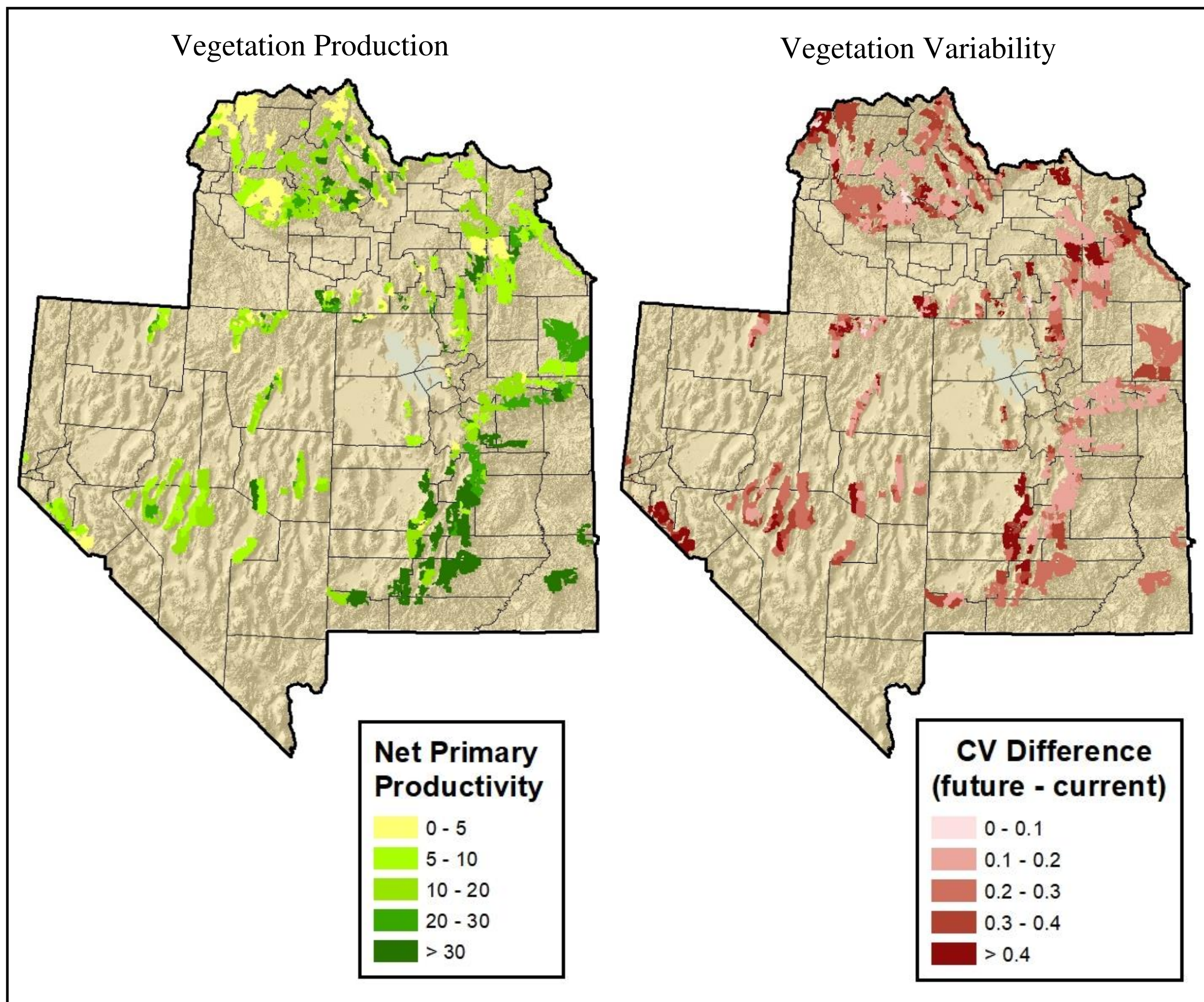


Figure 3.1: Projected Change in Vegetation by Allotment, A1B 2080 Scenario

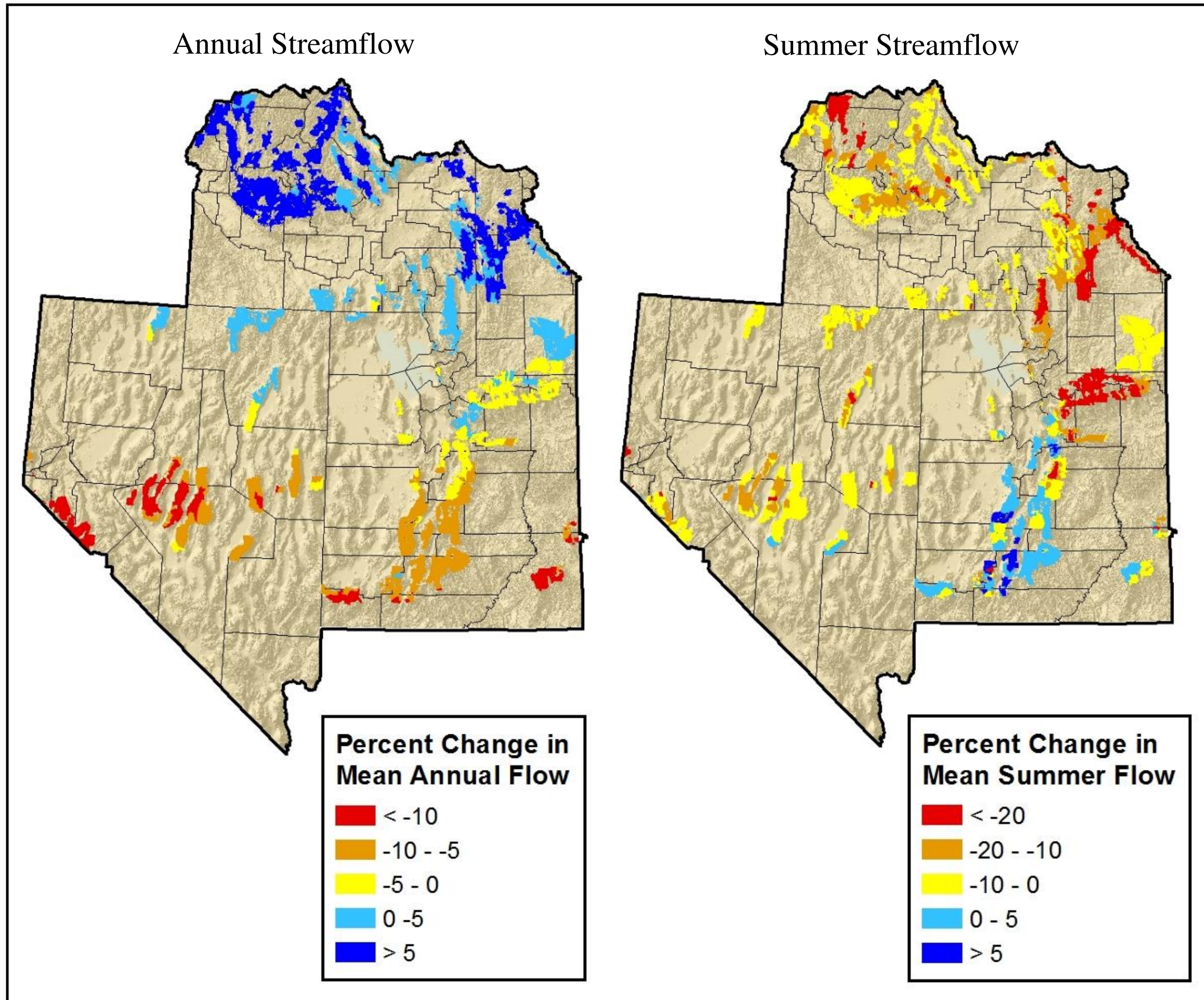


Figure 3.2: Projected Change in Water Availability by Allotment, A1B 2080 Scenario

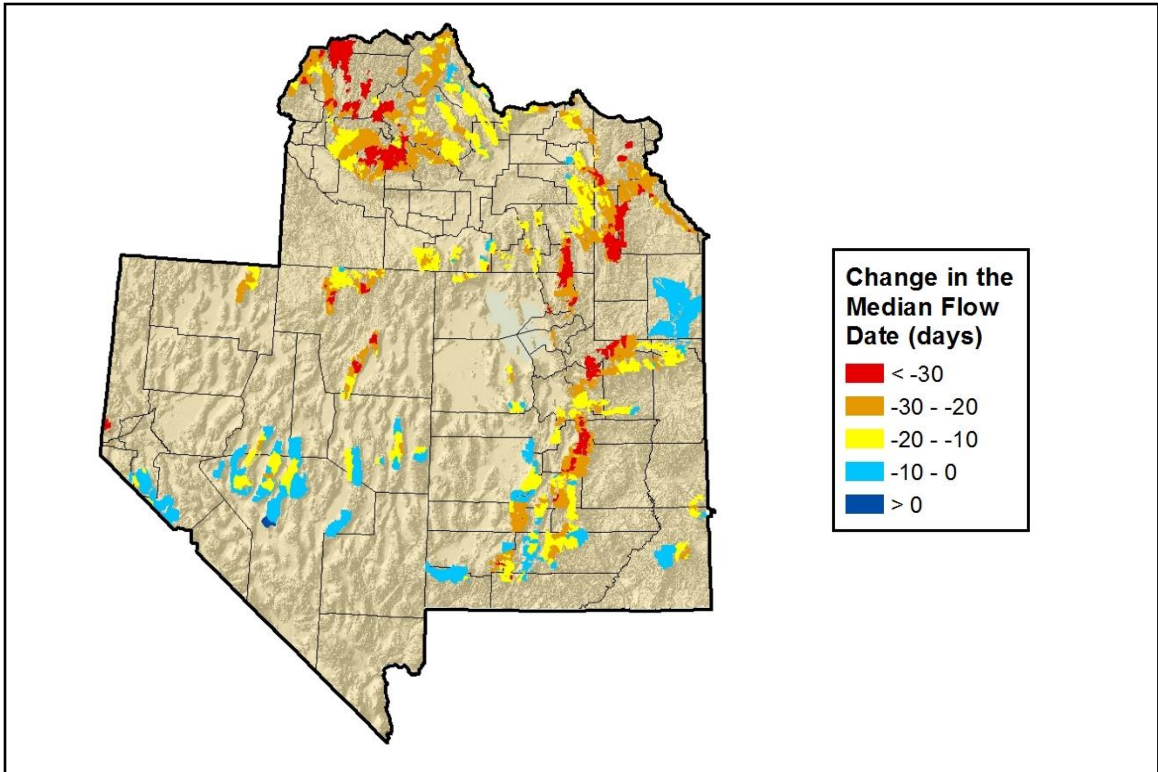


Figure 3.3: Projected Stream Runoff Timing by Allotment, A1B 2080 Scenario

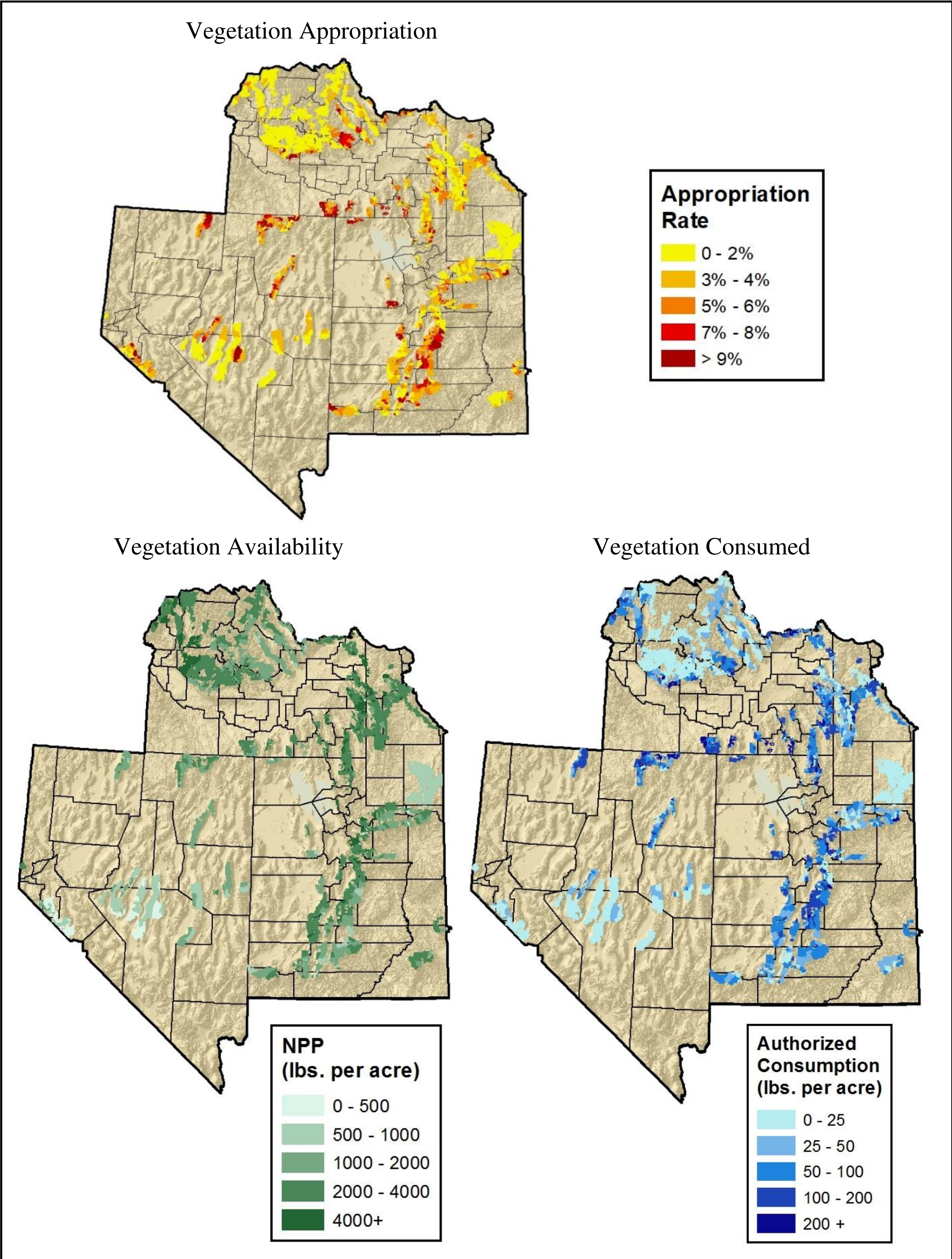


Figure 3.4: Appropriation Rate on Forest Service Grazing Allotments, 2014-2016

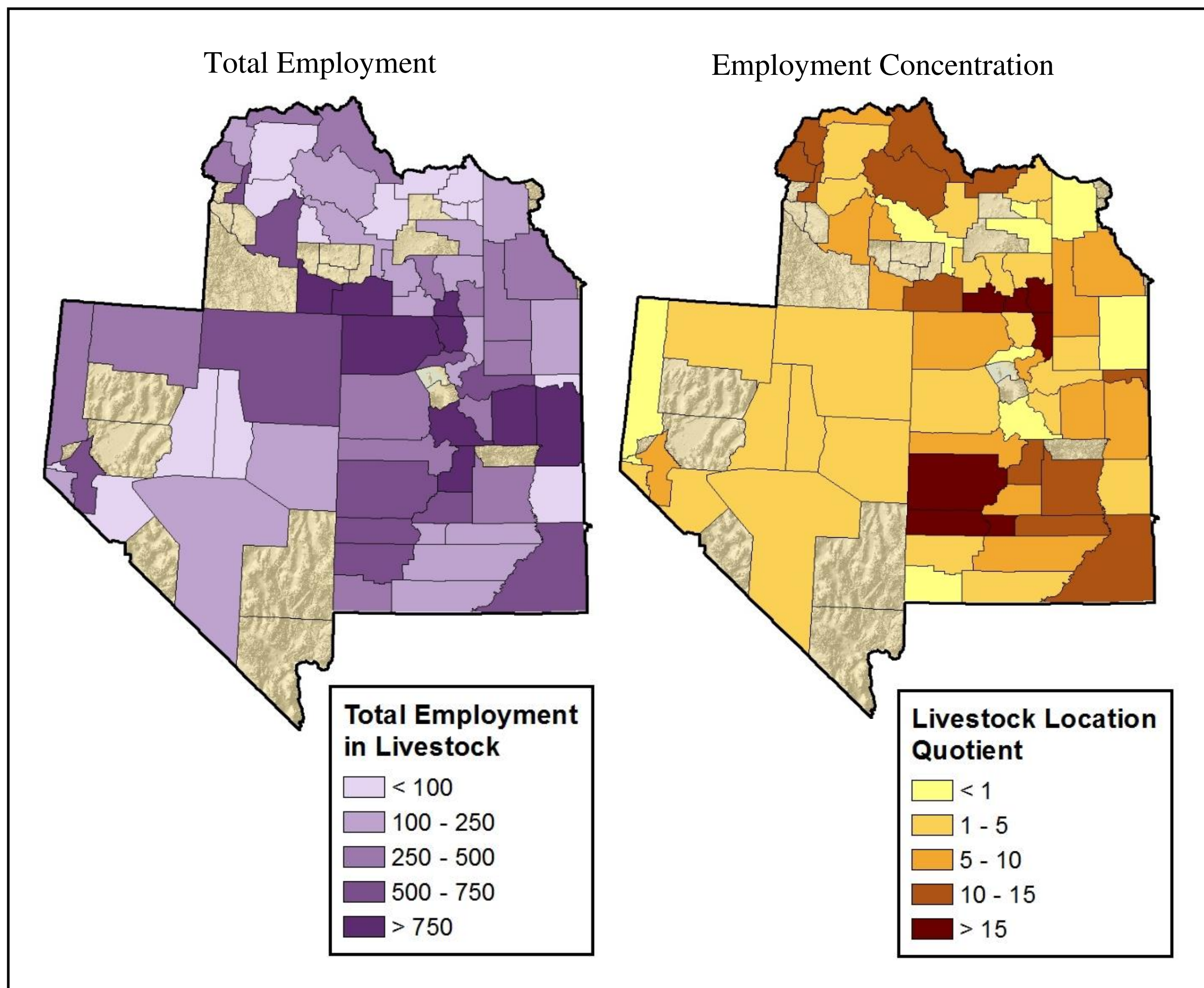


Figure 3.5: Employment in the Livestock Industry, 2015

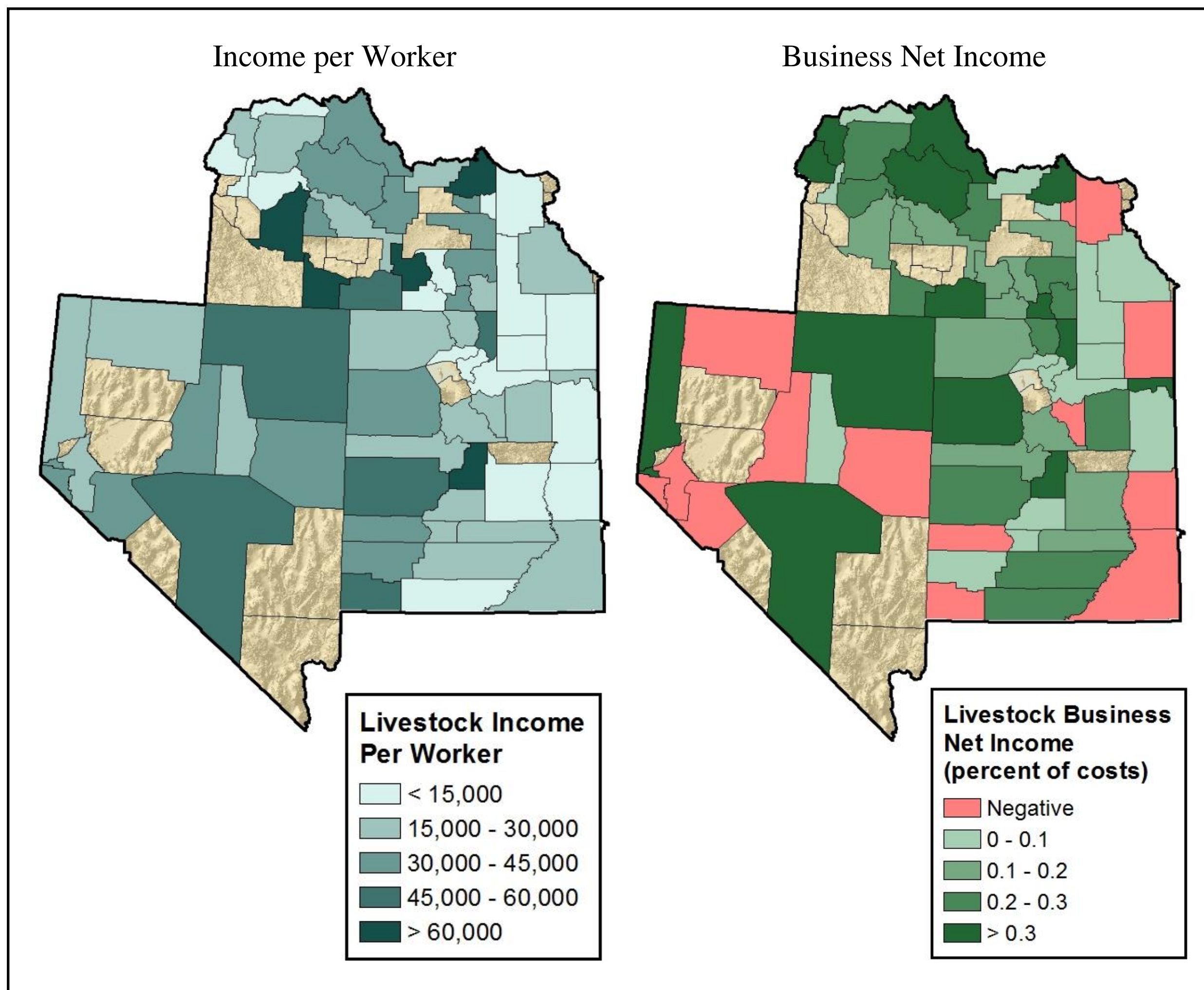


Figure 3.6: Income in the Livestock Industry, 2015

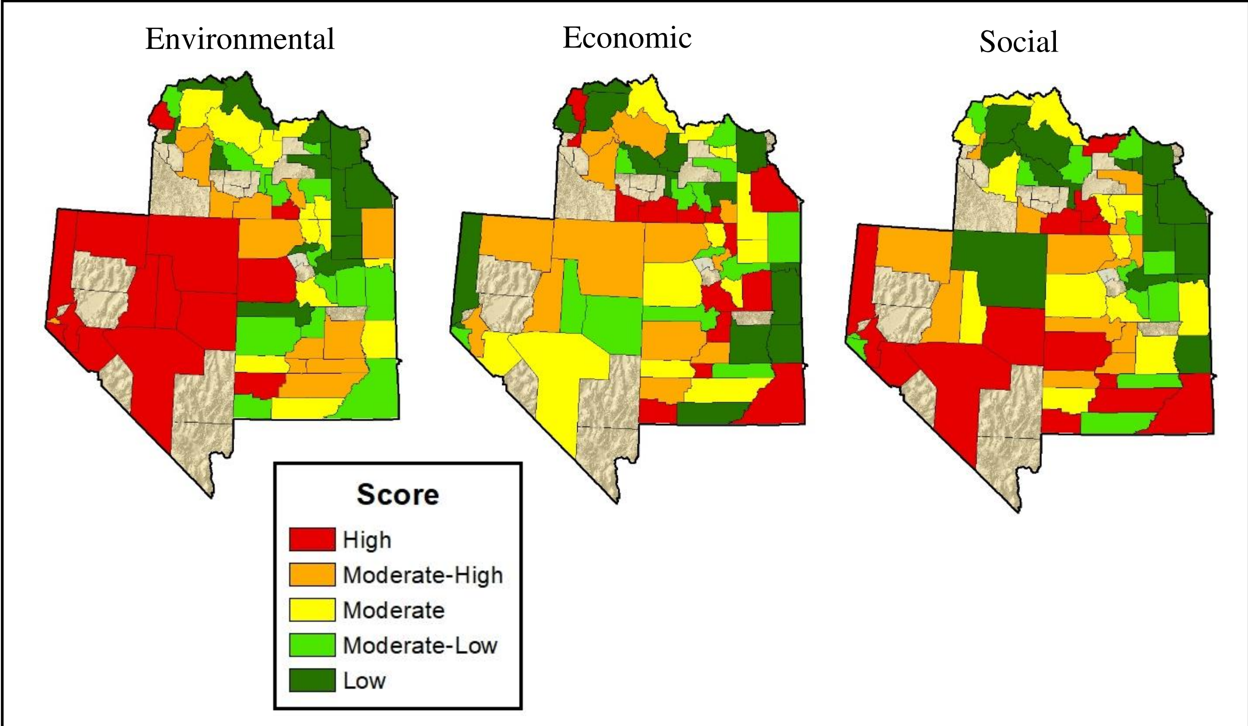


Figure 3.7: Sensitivity Score by Source

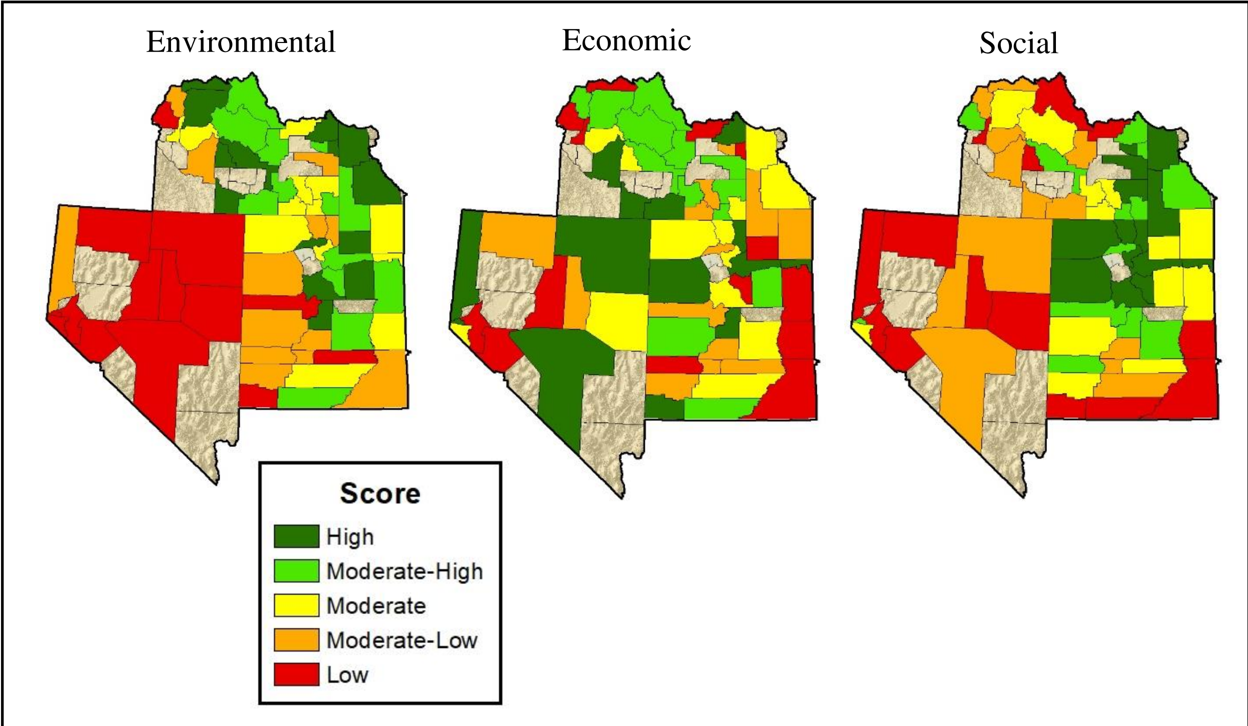


Figure 3.8: Adaptive Capacity Score by Source

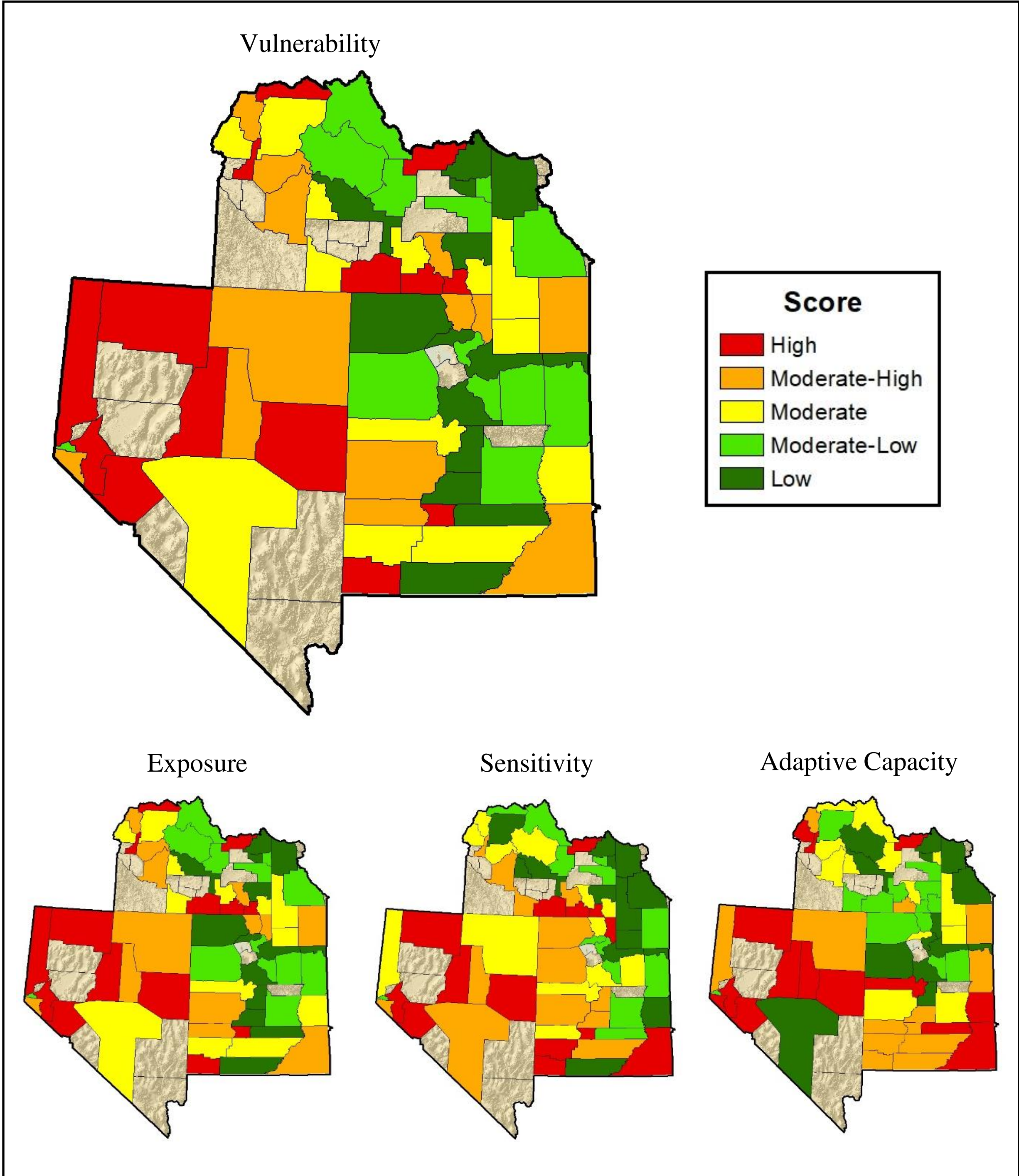


Figure 3.9: Final Vulnerability Score by Source

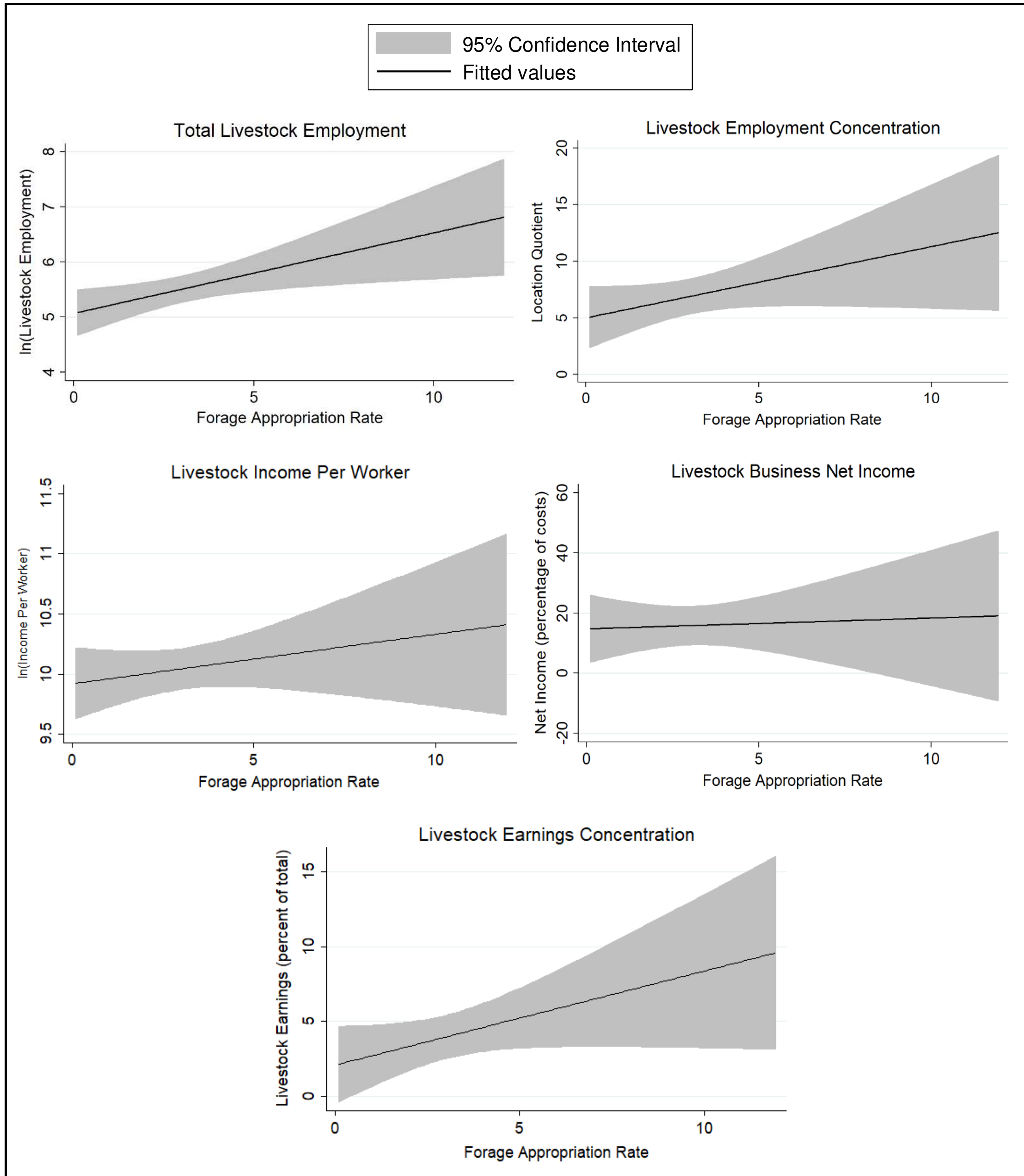


Figure 3.10: Forage Appropriation on Forest Service Land and Select Economic Variables

Each of these univariate models are estimated separately and describe the basic relationship between forage appropriation on Forest Service grazing allotments and select economic conditions across counties in Region 4.

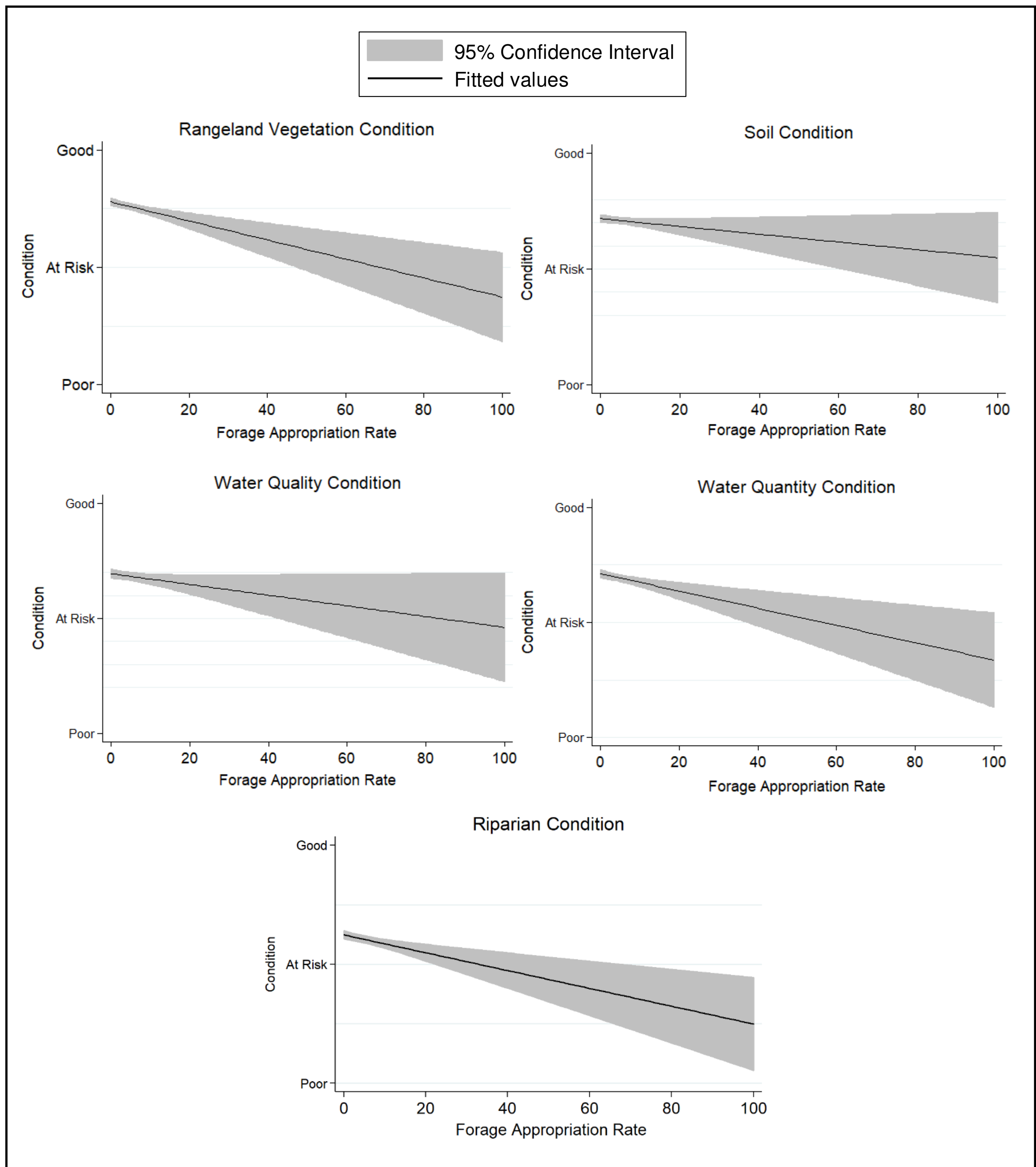


Figure 3.11: Forage Appropriation on Forest Service Land and Select Environmental Variables
Each of these univariate models are estimated separately and describe the basic relationship between forage appropriation on Forest Service grazing allotments and select economic conditions across counties in Region 4.

Conclusion

This dissertation evaluated the effect of natural disturbances on the provision of ecosystem services. Each chapter assessed ecosystem services from a different but complementary dimension, utilizing an interdisciplinary approach that built on previous economic and ecological work. The first chapter examined whether small and frequent wildfires affect drinking water prices, finding both short-run and long-run effects on downstream surface water resources and subsequent prices. The results indicate that water system variable cost rises immediately following a wildfire, encouraging capital investment to reduce variable cost and resulting in a significant effect of wildfire on fixed cost in the long run. The second chapter examined how increased Forest Service spending on fire management has affected non-fire management. The results indicate that spending on fire has increased in western regions, with spending cuts across non-fire and fire programs, and large impacts on eastern regions. In many cases it is a combination of direct and indirect effects that contribute to spending cuts in non-fire programs, and many programs experience additional cuts not associated with fire.

The third chapter explored climate-induced changes in rangeland grazing services on National Forest land in the Intermountain West, measuring vulnerability based on environmental, economic, and social factors. Grazing on National Forest land was found to contribute to local economic conditions but is also associated with adverse effects on rangeland vegetation and water when the forage appropriation rate is high. Overall, the drivers of vulnerability are heterogeneous across the region, suggesting that management decisions and adaptive efforts may be best served at the local level. This dissertation helps inform land and resource management in the face of growing natural disturbances and motivates future research looking at the provision of ecosystem services. The methods employed are innovative and can be extended to other ecosystem services and settings.

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