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A Statewide Evaluation of Fuel Treatment Effectiveness in Altering Wildfire Outcomes on Public Lands in Utah

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A STATEWIDE EVALUATION OF FUEL TREATMENT EFFECTIVENESS IN ALTERING WILDFIRE OUTCOMES ON PUBLIC LANDS IN UTAH

by

Jamela Charmaine Thompson

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

Larissa L. Yocom, Ph.D. Major Professor	Eric Thacker, Ph.D. Committee Member
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UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

A Statewide Evaluation of Fuel Treatment Effectiveness in Altering Wildfire Outcomes on Public Lands in Utah

by

Jamela C. Thompson, Master of Science

Utah State University, 2023

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Department: Wildland Resources

Wildland fuel treatments are widely implemented on public lands in the western United States to modify wildfire behavior and mitigate negative fire effects. Treatments alter the combustible biomass on the landscape by reducing, restructuring, and disrupting heavy fuel loads and continuity. Federally managed land comprises a majority of the land area of Utah, where the U.S. Department of the Interior Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS) have implemented thousands of fuel treatments. Identifying current landscape-scale patterns and factors driving treatment effectiveness is fundamental for improving the spatial arrangement and rate of implementation for future treatments. The objective of my study was to conduct a statewide evaluation of fuel treatment effectiveness on BLM and USFS managed lands in Utah using multiple scales and metrics of effectiveness: 1.) Encounter rates, 2.) Burn severity, 3.) Manager reports, and 4.) Ecological health. This thesis examines the current status of fuel treatment effectiveness on public lands in Utah and provides methods suitable for scaling to the geographic administrative levels that treatments are implemented, such as BLM districts and USFS forests. In Chapter 2, I calculated encounter rates statewide, analyzed burn severity in 48 treatments in forested vegetation that burned in wildfires, and summarized manager accounts of treatment effects when encountered by fire. In Chapter 3, I measured ecological health metrics associated with Wyoming big sagebrush ecosystem resilience to fire and resistance to cheatgrass in juniper mastication treatment sites that were burned by wildfire. Fuel treatments were found to be effective in their primary goals of altering fire behavior, based on the metrics of burn severity and manager reports. Juniper mastication treatments were ineffective at improving the measured ecological health metrics. Fuel treatments were seldom encountered by wildfire, a pervasive issue in fuels and wildfire management. Expanding the treated area network and increasing the use of unplanned fire to treat additional landscape would result in higher encounter rates between treatments and wildfires and thus, the circumstances in which treatments are effective.

(118 pages)

PUBLIC ABSTRACT

A Statewide Evaluation of Fuel Treatment Effectiveness in Altering Wildfire Outcomes on Public Lands in Utah

Jamela C. Thompson

Fuel treatments are land management activities that reduce living and dead flammable materials on the landscape to mitigate undesirable wildfire behavior and effects. Common treatments in the western United States include mechanical methods such as thinning and mastication, prescribed burns, and chemical methods, such as herbicide application. Treatments usually have multiple objectives, including reducing fire intensity, protecting natural and cultural resources, slowing or disrupting a potential future fire's path, supporting ecosystem health, and reestablishing low to mid severity fire cycles in ecosystems. Although treatments can potentially modify fire behavior and ecological health, they generally cannot prevent fires from igniting, eliminate fires from occurring, or consistently stop active fires from spreading. The majority of fuel treatments are never encountered by wildfire, which limits our understanding of effectiveness. In Utah, treatments are primarily implemented by the U.S. Department of the Interior Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS). In order to increase understanding of fuel treatment effectiveness, I conducted a statewide study, including 3,208 fuel treatments and 1,558 wildfires on BLM and USFS managed lands across Utah from 1997 to 2019. The objective of my study was to evaluate treatment effectiveness using four metrics: 1.) Encounter rates, 2.) Burn severity, 3.) Manager reports and 4.) Ecological health. In Chapter 2, I summarized treatment and wildfire distributions and calculated a treatment encounter rate of 8.7%. I also analyzed burn severity in 48 treatments in forested vegetation, finding that treatments significantly reduced burn severity, especially in areas that had been treated repeatedly. Finally, manager observations from treatments encountered by fire were summarized, with findings that managers reported fuel treatments to be effective in the majority of encounters. Chapter 3 evaluated ecological health in juniper mastication treatments, using field measurements, and found no treatment effect on cheatgrass, bare ground, or sagebrush density post-fire. In conclusion, fuel treatments were effective in their primary goals of altering fire behavior and effects, based on the metrics of burn severity and manager reports. However, fuel treatments were seldom encountered by wildfire, and juniper mastication treatments were ineffective at improving the measured ecological health metrics. These findings suggest that expanding treated areas to improve encounter rates will increase the circumstances in which treatments are effective.

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PREFACE

Chapters 2 and 3 were written as independent manuscripts for future submission to peer-reviewed journals, resulting in some repetitive language between chapters. The pronoun “we” has been used in each chapter in preparation for publishing with co-authors.

CHAPTER 1

INTRODUCTION

Wildland fuel treatments are widely applied on public lands in the western United States (U.S.) in an effort to alter wildfire risk and behavior (Hoffman et al. 2018; Cochrane 2012; Finney 2004). The U.S. Department of Agriculture's (USDA) U.S. Forest Service (USFS) and four bureaus within the U.S. Department of the Interior (DOI) (Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), National Park Service (NPS), and U.S. Fish and Wildlife Service (USFWS)) are responsible for wildland fire management and implementing fuel treatment projects on federal and tribal lands (U.S. Department of the Interior 2023). In Utah, where 63% of the land is federally owned and managed (Gorte et al. 2012), the BLM and USFS have implemented thousands of fuel treatments through their Hazardous Fuels Reduction (HFR) programs. Fuel treatments are designed to reduce the availability and continuity of combustible biomass on the landscape (Graham et al. 2004). Treatments are designed with multiple objectives, which can include reducing burn severity, protecting natural and cultural resources, slowing or disrupting a potential future fire's path, increasing use of managed wildfires, supporting ecosystem health, and facilitating fire-resilient landscapes (Pilliod et al. 2017).

Federal wildfire suppression costs are continuing to increase (National Interagency Fire Center 2022). From 2017 to 2021, the Forest Service and DOI agencies spent a total average of $2.8 billion annually on wildfire suppression, with 2021 suppression costs exceeding $4 billion (National Interagency Fire Center 2022). In the meantime, budgets allocated for fuels management have historically been insufficient for reducing hazardous fuels at an effective rate (Kreitler et al. 2020). The U.S. Department of the Interior's Wildland Fire Management program reported spending $220 million on fuels management in 2021, a fraction of what was spent on suppression (U.S. Department of the Interior 2023). However, support for fuels treatments is increasing; the Infrastructure Investment and Jobs Act of 2021 authorized nearly $3 billion to the USDA Forest Service and $878.0 million to multiple DOI agencies for fuels-related projects through 2026 (U.S. Department of the Interior 2023). The Forest Service announced plans to apply this funding to treat 20 million acres on USFS lands and 30 million acres on other federal, state, tribal, and private lands in the West (U.S. Department of Agriculture 2022).

Wildland fuels are often described in terms of fuel load, type, time-lag class, continuity, and arrangement. Fuel load is a measure of living and dead biomass in an area that is reported as mass (tons or kg) of available fuel per unit area (acre or hectare). Wildland fuel types are classified by the dominant vegetation, within six coarse categories of grass, shrub, grass-shrub, timber litter, timber-understory, and slash-blowdown. Dead fuels are classified in terms of their time lag, which is the drying time required to remove approximately 63% of the difference between the moisture in a woody fuel particle and the equilibrium of the surrounding environment (Keane 2015). Size classes are associated with time lag classes, such as twigs in the 1-hr fuels, small branches in the 10-hr fuels, dead tree limbs in the 100-hr fuels, and logs in the 1000-hr fuels (NWCG 2020). The continuity of horizontal fuels is generally described as uniform, where fuels are within proximity to sufficiently carry fire, or described as patchy, where fuels are more widely dispersed. The vertical arrangement of fuels is described in strata, which include ground fuels (litter and duff), surface fuels, ladder fuels, and aerial fuels (crown or canopy) (NWCG 2020). Fuel properties and classifications are important for informing fuel treatment plans, fire behavior models, and wildland fire operations.

The four broad categories of federal fuel treatment applications are prescribed fire, mechanical, chemical, and biological. Fuel reduction is achieved through consumptive methods such as prescribed fire, which is often applied in combination with mechanical thinning (Reinhardt 2008). Restructuring or reducing larger fuel classes into 1-hr or 10-hr fuels is accomplished with mastication treatments by mulching, shredding, chipping, and mowing materials (Kreye et al. 2014). Fuel breaks and herbicide treatments reduce horizontal fuel continuity to slow fire spread. Treatments that reduce ladder fuels, i.e. fuels that connect fire spread from the ground to the canopy, act to disrupt vertical continuity in order to decrease the risk of active canopy fires. Commercial harvesting is an authorized use across federal agencies (Gorte et al. 2012) and may be incorporated into fuels reduction plans as stand-alone fuel treatments or within a series of noncommercial harvesting and prescribed fire applications (Jain et al. 2021).

The BLM and USFS tend to manage distinct but overlapping ecosystems. In western states, the BLM primarily manages rangeland, sagebrush steppe, and desert habitats, with an emphasis on grazing, livestock, energy, and minerals. The USFS mainly manages forests and woodlands, some of which are designated wilderness (Gorte et al. 2012). Fuels management plans are designed to modify fire behavior while addressing the unique vegetative communities, fuel conditions, fire regimes, management history, and objectives of the unit being managed. For example, considerations for fuel treatments in cold-desert sagebrush habitat, which is largely managed by the BLM, include the risk of ecosystem-altering annual grass invasion (Chambers et al. 2014), sage-grouse habitat protection (U.S. Department of the Interior 2020), and the variability of sagebrush recovery from fire (Chambers et al. 2014; Chambers et al. 2019). A unique factor in USFS fuels and wildfire management strategies is the ability to designate portions or entire wildfires on federal lands as managed fires for objectives “other than full suppression” (Fillmore et al. 2021).

Fuel treatment effectiveness has been evaluated in both modeled and empirical approaches (Fig. 1.1). A nationwide study in the U.S. found that only 6.8% of fuel treatments that are at least 2.5 km outside of the WUI have been encountered by wildfire (Barnett et al. 2016b). Regional and landscape scale studies found treated acres to make up a nominal 1% of total area burned by fire (Barnett et al. 2016a; Kolden 2019; Prichard et al. 2021). These findings highlight one of the main criticisms of fuel treatments, which is that they are ineffective because most treatments are never encountered by wildfire (Yocom 2013; Barnett et al. 2016b; Prichard et al. 2021). Although ecological benefits can still be realized, the absence of subsequent wildfire limits our understanding of treatment effectiveness for the main objective of altering fire behavior and effects. However, decades of fuel treatments and historic wildfires are now publicly available as spatial datasets, making more empirical evaluations possible (Barnett et al. 2016b).

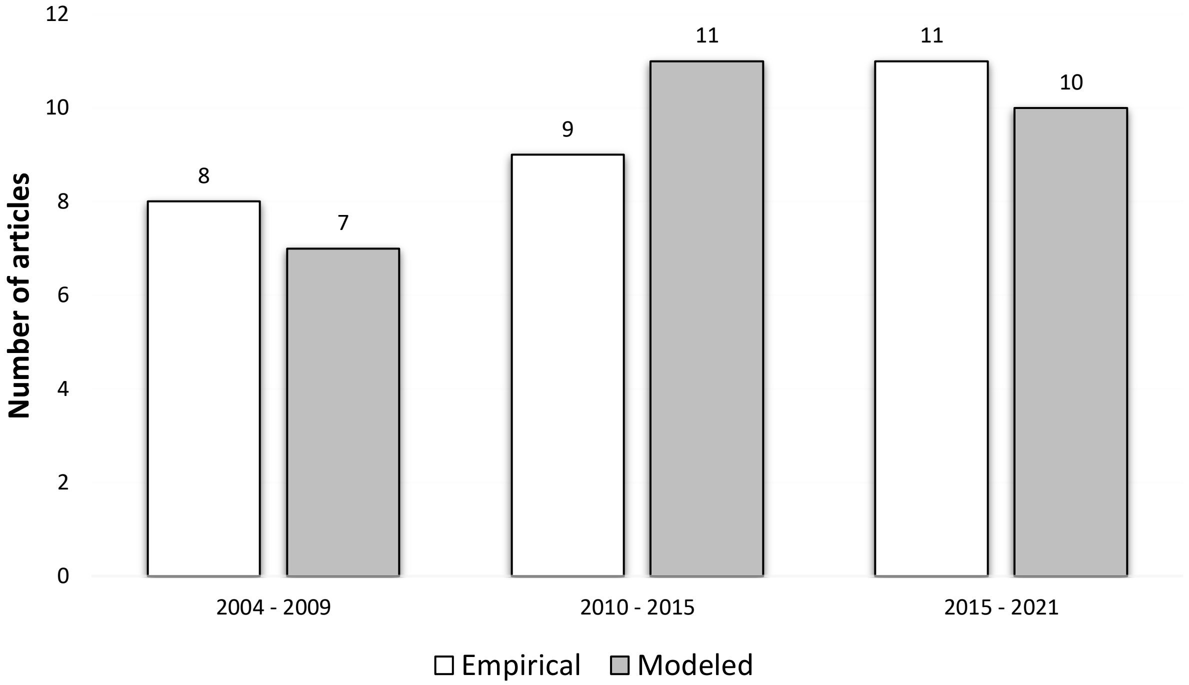

Figure 1.1. Number of empirical and modeled studies about fuel treatment effectiveness from 2004 – 2021. Articles from the SCOPUS search were reviewed and 58 articles related to fuel treatment effectiveness and fuel treatment effects are included here. There was a nearly even amount of modeled and empirical studies on fuel treatments.

The number and area of treatments that are feasible to accomplish are limited by operational, economic, social, and political factors (Finney 2001). Although fuel treatments usually occur at the local stand scale, their spatial arrangement and rate of implementation can affect outcomes at the landscape scale (Finney 2004; Finney 2007; Ager 2010). Treatments that are strategically placed as part of a landscape-level network can reduce fire spread and intensity at the landscape scale if the dominant fire weather patterns and fire behavior for the local area are considered in the design (Finney 2001; Hoffman et al. 2018). Modeled studies have shown that the spatial arrangement of fuel treatments can have an effect on fire behavior, even if treatments occupy only a small part of the landscape. Since previous research has shown that both larger and newer treatments are more likely to be encountered by wildfires (Barnett et al. 2016b), there is a tradeoff between maintaining existing treatments to extend longevity and implementing new fuel treatments to expand the extent of the existing network. The ability to efficiently manage fuels in an increasingly complex wildfire context is essential for the effective allocation of resources and preserving healthy ecosystems.

Our current understanding of fuel treatment effectiveness comes predominantly from low-elevation, pine-dominated systems, thin-and-burn treatment regimes, and single-fire case studies (Kalies and Yocom 2016). In an effort to expand our understanding to additional vegetation types and study fuel treatment effectiveness at a statewide scale, my thesis is focused on fuel treatments and wildfires across federal lands in Utah, spanning a wide range of ecological conditions, and addresses ecosystem issues specific to the Intermountain West. This thesis assesses fuel treatment effectiveness on public lands in Utah using multiple scales and metrics of effectiveness to address the complex outcomes of treatments. My objective was to measure treatment effectiveness using four metrics: 1) Encounter rates, 2) Burn severity, 3) Manager reports, and 4) Ecological health. I utilized existing federal spatially explicit datasets, national remotely-sensed burn severity indices, land manager assessment reports, and field data.

In Chapter 2, I summarized the current spatial and temporal distribution of thousands of fuel treatments and historic wildfires on public lands statewide in Utah. This empirical dataset was then used to evaluate fuel treatment effectiveness by quantifying fuel treatment and wildfire encounter rates. I also compared burn severity metrics in treated and untreated areas of fires and contextualized my findings with manager evaluations of fuel treatment and wildfire interactions. Chapter 2 addresses the following questions: 1) What is the probability that a treatment is encountered by fire in Utah? 2) What treatment factors affect the likelihood of being encountered? 3) Are fuel treatments effective in reducing burn severity and does severity vary with the number of treatment entries? 4) Do land managers find fuel treatments to be effective when encountered by wildfire?

Chapter 3 examines understory plant recovery in juniper mastication treatments that were encountered by wildfire. Ecological health metrics that are associated with Wyoming sagebrush (*Artemesia tridentata* Nutt. ssp. *wyomingensis*, Beetle & Young) community resilience and resistance were measured in treated and untreated areas of three fires in a split-plot sampling design. In Chapter 3 I asked: Do pre-fire juniper mastication treatments 1) improve Wyoming sagebrush abundance post-fire? 2) decrease cheatgrass cover post-fire? 3) decrease bare ground cover post-fire?

Chapter 4 synthesizes my findings from the statewide assessment in Chapter 2 and the field study in Chapter 3. I discuss nuanced considerations for measuring and interpreting fuel treatment effectiveness and offer corresponding management implications.

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CHAPTER 2

FUEL TREATMENT EFFECTIVENESS AND LIMITATIONS IN ALTERING WILDFIRE OUTCOMES ON PUBLIC LANDS IN UTAH

Abstract

Wildland fuel treatments are widely implemented in the western United States to reduce and restructure combustible biomass, and thus modify wildfire behavior, risk, and burn severity. Previous research has suggested that because the scale and extent of treated areas represent a small percentage of the landscape, treatments are rarely encountered by fire and the primary objective to alter wildfire outcomes is never realized. As the number of treated acres as well as acres burned in wildfire continue to grow, increasing our understanding of fuel treatment and wildfire interactions and resulting treatment effectiveness is essential for optimizing the spatial arrangement and implementation rate of future treatments. Where fires and treatments do interact, much of our understanding of fuel treatment effectiveness in reducing fire severity comes from dry pine ecosystems. The objective of our study was to evaluate fuel treatment effectiveness on a statewide scale, on federal lands in Utah, using multiple metrics of effectiveness: encounter rates, burn severity, and manager reports. As the principal federal land management agencies in Utah, the U.S. Department of the Interior Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS) implement thousands of fuel treatments throughout the state. We utilized publicly available, spatially explicit databases to include 3,208 completed fuel treatments and 1,558 historic wildfires on BLM and USFS managed lands in Utah from 1997 to 2019. We used spatial analysis to derive fuel treatment and wildfire encounter rates and used generalized linear models

(GLMs) to test how treatment year, size, and type influenced the likelihood of encounters. We then used predictive modeling to simulate results from the GLMs to derive the predicted probability of encounters. We then subset the fuel treatment and wildfire encounters to conduct a burn severity analysis on 48 forested encounters from 2001 to 2018 to evaluate whether fuel treatments reduced burn severity of subsequent fire compared to adjacent, untreated controls. We used the Monitoring Trends in Burn Severity raster datasets to extract Differenced Normalized Burn Ratio (dNBR) values for our analysis. Finally, we summarized Fuel Treatment Effectiveness Monitoring (FTEM) assessments from managers reporting effectiveness while treatments were burned in a wildfire. Our study found that from 1997 to 2019, 8.7% of fuel treatment entries on BLM and USFS managed lands in Utah were encountered by wildfire and 4% of treatment hectares burned. Treatment factors including year, size, and type were all predictors of the likelihood that a treatment was encountered by subsequent fire. The predicted probability of being encountered by fire increased for treatments completed in older years compared to those finished in more recent years, given an average treatment size (351 ha) and across treatment types. For example, a broadcast burn in 1997 had a predicted probability of 0.64 of being encountered, whereas a broadcast burn of the same size, but completed twenty years later in 2017 only had a 0.37 predicted probability of being encountered. Larger treatment size increased the likelihood of a treatment being encountered by wildfire, with greater increases in size yielding greater effects. For example, the predicted probability of a broadcast burn being encountered by wildfire for a 20.2-hectare (50 acre) treatment was 0.086, for a 202.3-hectare (500-acre) treatment it was 0.089, and for a 2023.4-hectare (5,000-acre) treatment it was 0.12. Our burn severity analysis found that fuel treatments reduced burn severity by an average of 50 dNBR points compared to adjacent, untreated controls ($p < .001$). In the 18-year range of fuel treatment and wildfire encounters included in our burn severity analysis, units that received multiple treatment entries had a greater reduction in burn severity than single treatment units, but the difference of 16 dNBR points was non-significant ($p = 0.33$). Reports by 13 managers found treatments to be effective for contributing to fire management and changing fire behavior. Our findings suggest that fuel treatments are effective when encountered, but the effectiveness potential is restricted by an insufficient amount of treated area on the landscape limiting encounters with wildfires.

Introduction

Strategic management of wildfire potential is critical to the preservation of healthy ecosystems and watersheds, recreation, timber production, and cultural resources on public lands. Patterns of fire activity can be described using variables such as area burned and fire rotation (Parks *et al.* 2015), which is the amount of time required to completely burn an area equal to a defined area of interest on the landscape (Baker and Ehle 2001). A fire surplus or deficit describes the difference between observed fire activity and modeled predictions of expected fire activity for an ecosystem's fire regime (Parks *et al.* 2015). In the western United States (U.S.), some fire-suppressed forested regions are experiencing a fire deficit, while semi-arid shrub-dominated systems such as the Great Basin are facing a fire surplus (Parks *et al.* 2015). Quaking aspen (*Populus tremuloides* Michx.) is an example of a fire-deficit forest type that constitutes 1.6 million acres in Utah (Werstak *et al.* 2016). Aspen communities require regular disturbance, such as wildfire, because they are a clonal species and in the Interior West, their primary reproductive strategy is through root production (Werstak *et al.* 2016). In the absence of disturbance, conifers can become the dominant canopy in aspen stands through succession, replacing shade-intolerant aspens over time (Ramsey and West 2009; Werstak *et al.* 2016). For an example of a fire surplus, low- to mid-elevation cold desert shrublands in Utah's Great Basin ecosystem are imperiled by the grass-fire cycle, which is associated with increasing fire return intervals (Chambers *et al.* 2014). Invasive annual grasses, namely cheatgrass (*Bromus tectorum* L.), are causing ecosystem level transformations (D'Antonio and Vitousek 1992; Chambers *et al.* 2014), by altering vegetation composition, structure, and the amount and availability of fuel, and thus, the fire regime (Chambers *et al.* 2019).

Within the fire behavior triangle of fuels, weather, and topography, fuels are the only component that can be directly manipulated through land management (McHugh 2006; Hoffman *et al.* 2018). Wildland fuels are the combustible live and dead biomass on the landscape (Keane 2015). Fuel treatments are intentional modifications to the structure and availability of vegetation in order to alter wildfire risk, behavior, and effects across the landscape (Finney 2004; Cochrane 2012; Hoffman *et al.* 2018). Federal agencies such as the U.S. Department of the Interior (DOI) Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS) established fuel reduction programs to reduce hazardous fuels, minimize wildfire risk to human communities, and improve ecosystem health by creating fire-resilient landscapes. Mechanical treatments act as fire surrogates to rearrange fuels through thinning, clearcutting, masticating, slashing, and compacting (Kreye *et al.* 2014). Consumptive treatments such as prescribed fire often follow mechanical treatments to reduce the remaining fine and coarse woody debris (Reinhardt 2008), as mechanical treatments alone may increase the surface fuel load (Hoffman *et al.* 2018).

Our current understanding of fuel treatment effectiveness is primarily evidenced from simulation modeling and forested ecosystems in the western U.S. (Jain *et al.* 2021), with a higher representation of dry-pine forests (Kalies and Yocom 2016). Common response variables used to evaluate fuel treatment effectiveness in altering wildfire characteristics include rate of fire spread, fire behavior, fire extent, and burn severity (Kalies and Yocom 2016; Jain *et al.* 2021). Burn severity is a measure of ecological change (Key and Benson 2006) caused by fire, and treatments can potentially mitigate fire severity (Safford 2009; Prichard 2014). A synthesis (Jain *et al.* 2021) of fuel treatment effectiveness literature on the landscape scale that included simulated model studies (85) and empirical studies (26) concluded that fuel treatments were effective in reducing fire severity in and out of the treated area. Case studies (16) included in the review reported that treatments reduced severity inside the treatment, but there were insufficient reports of severity outside the treatment to summarize effectiveness (Jain *et al.* 2021). Treatment effects vary by treatment type and vegetation (Kalies and Yocom 2016), with thin and burn treatments having the greatest positive effect reported (Ritchie *et al.* 2007; Hudak *et al.* 2011; Prichard and Kennedy 2012; Cram *et al.* 2015; Kalies and Yocom 2016). In dry pine forests, thin and burn treatments are the most consistently effective fuel treatment type for reducing burn severity, crown and bole scorch, and tree mortality because they effectively remove surface, ladder, and canopy fuels (Kalies and Yocom 2016). Fuel treatments have been shown to both reduce subsequent fire severity or increase it (Povak *et al.* 2020). For example, one study found that harvest and planting treatments that were burned by wildfire less than ten years after completion increased burn severity (Cansler *et al.* 2022*a*). Treatment effectiveness is influenced by how completely fuel reduction objectives were met, intensity of treatment, weather conditions during the wildfire event, fuel accumulation post-treatment, and the spatial arrangement of treatments (Finney 2004).

Evaluating the change in fire behavior is a metric of effectiveness that can usually only be reported by people who witness an active wildfire and is difficult to reconstruct post hoc. For example, managers have reported strategic benefits from fuel treatments during active fires, such as providing anchor points for direct attack (Barnett *et al.* 2016), improved visibility for crews and spot fire suppression, increased penetration of retardant to surface fuels, and safer access to the fire (Kalies and Yocom 2016).

Wildland fuel treatments are rarely tested by wildfire within their effective lifespan (Rhodes 2004; Baker and Rhodes 2008; Campbell 2012; Barnett *et al.* 2016), resulting in sparse documentation of encounters and little known about the ecological outcomes of encounters. A nationwide study in the U.S. on federal lands outside of the wildland urban interface (WUI) found an overall fuel treatment encounter rate of 6.8% (Barnett *et al.* 2016). Treatment factors such as size, age, and number of times treated influenced their likelihood of being encountered by fire and their effectiveness. Larger treatments are more likely to be encountered by fire (Barnett *et. al.* 2016) and fuel treatment effects are greater farther into treatments, suggesting the benefits of larger treatment sizes (Symons *et al.* 2008; Safford *et al.* 2009; Kennedy and Johnson 2014). Encounter rates have been found to be higher in treated areas that were treated multiple times (Barnett *et al.* 2016). Previous studies have found that fuel treatment effectiveness and encounters decrease as time-since-treatment increases (Omi *et al.* 2006; Barnett *et al.* 2016) but with some treatments still exhibiting changes in fuel loading or structure for up to three decades (Povak *et al.* 2020; Cansler *et al.* 2022*a*, 2022*b*).

Determining fuel treatment encounter rates and treatment effectiveness in reducing burn severity and changing fire behavior is important for assessing landscape-scale effects and informing effective spatial arrangement and rate of implementation of future fuel treatments. The objective of our study was to evaluate fuel treatment effectiveness on public lands in Utah using multiple metrics of effectiveness: encounter rates, burn severity, and manager reports. We utilized existing spatial datasets of completed fuel treatments and historic wildfires on BLM and USFS managed lands in Utah from 1997 to 2019, Landsat-derived remotely sensed burn severity data, and interagency Fuel Treatment Effectiveness Monitoring (FTEM) reports. This study is designed to assist land managers with difficult decisions about where to focus fuel treatment efforts. Land managers are ultimately tasked with weighing the tradeoffs between elongating the effective window of current treatments on the landscape and expanding the footprint with new treatments.

Methods

Study area

We examined fuel treatments and wildfires statewide in Utah that occurred within the administrative boundaries of Bureau of Land Management (BLM) and U.S. Department of Agriculture Forest Service (USFS) public lands. Of Utah's 52.7 million acres, about 33.3 million acres, or 63% of the total land, were federally owned as of 2018, ranking it the second highest state for federal land ownership. The BLM is the majority public landowner in Utah, holding 22.8 million acres, or 42% of total land, and the USFS is the second largest public landowner, owning 8.2 million acres, or 15% of total land (Vincent and Hanson 2020). Most land managed by the BLM is located in the west and southeast and the entire state is divided into five regional districts: West Desert, Green River, Color Country, Paria River, and Canyon Country, which are subdivided by field offices. The USFS-owned land broadly bisects the state from the north-northeast corner to the southwest corner and consists of five national forests entirely within the state: Ashley, Dixie, Fishlake, Manti-La Sal, and Uinta-Wasatch-Cache, and two extending from Idaho: Caribou-Targhee and Sawtooth (Ramsey and West 2009).

Utah is characterized by a wide range of terrain, elevation, and climatic life zones. Much of the state is classified as a steppe or semiarid climate region, which experience hot and dry summers, cold winters, and low total annual precipitation of about 13 to 38 cm. Areas of higher elevation valleys and mountains are considered humid continental climate areas and have cool summers, cold winters, and about 25 to >140 cm total annual precipitation. Elevations in the state range from the lowest elevation of 664 m at Beaver Dam Wash to the highest elevation at 4,123 m at King’s Peak (Ramsey and West 2009). Precipitation and temperature occur on a gradient that strongly correlates with elevation, creating conditions that impact vegetation growth and distribution. Generally, increasing elevation is correlated with increasing precipitation, decreasing temperature, and decreasing reference evapotranspiration (RET). Reference evapotranspiration is the total amount of water evaporated from the surface or plant transpiration within a given amount of time. Drier conditions occur when the amount of precipitation is lower than the RET, which is seen in 91% of the state (Ramsey and West 2009).

Climatic life zones are ecological classifications based on the relationship between RET and precipitation, which determines water availability. The seven life zones found in Utah, in order of ascending elevation, include desert, semidesert, upland, mountain, high mountain, subalpine, and alpine zones. Water is a limiting environmental factor in the desert and semidesert zones because the RET is higher than precipitation for 10 or more months out of the year. In upland, mountain, and high mountain zones the RET is higher than precipitation for approximately 5 to 6.5 months out of the year. Water availability increases in the subalpine and alpine zones, as they have a relatively low annual RET (Ramsey and West 2009).

The desert zone has a mean annual temperature of 2.2 °C in winter months (December to March) and 23.7 °C in summer months (July to September), a yearly average precipitation of 19.1 cm, occurs at elevations from 625 m to 1543 m, and covers 11% of the state in over 6 million acres. The dominant generalized vegetation cover in the desert zone includes blackbrush-Mormon tea communities (23%) (*Coleogyne ramosissima* Torr. and *Ephedra viridis* Coville) and salt desert shrub (17%) (*Atriplex* spp. L). The semidesert zone has a mean annual temperature of 0 °C in winter months and 20.6 °C in summer months, a mean annual precipitation of 20.32 cm to 30.48 cm, occurs at 1372 m to 1951 m, and occupies about 60% of the state. This shrub-dominated zone is relatively flat and supports the majority of the state's rangeland. Pinyon-juniper is the most abundant vegetation cover type in the semidesert zone, occupying 24% or 7,864,329 acres and 75% of pinyon-juniper communities are found within this zone (Ramsey and West 2009). Pinyon-juniper woodlands are characterized by the presence of at least one pinyon species, such as singleleaf pinyon (*Pinus monophyla* Torr. & Frém.) and two-needle pinyon (*Pinus edulis* Engelm.) and at least one juniper species, such as Utah juniper (*Juniperus osteosperma* Torr.), common juniper (*Juniperus communis* L.), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) (Shaw *et al.* 2005; Werstak *et al.* 2016). Salt desert shrub (*Atriplex* spp. L) covers 5,770,808 acres or 18%, and big sagebrush (*Artemisia tridentata* Nutt.) covers 4,559,135 acres or 14%.

The upland zone has a mean annual temperature of -2.94 °C in winter and 16.6 °C in summer, 49.8 cm total mean annual precipitation, occurs from 1768 m to 2530 m, and covers 17% of the state across 9,271,582 acres. This zone is found in the foothills surrounding mountains and the dominant vegetation types are big sagebrush (*Artemisia tridentata*) covering 2,638,458 acres or 28%, pinyon-juniper (*Pinus* spp. And *Juniperus* spp.) covering 2,492,596 acres or 27%, and oak brush, including curl-leaf mountain mahogany (*Cercocarpus ledifolius* Nutt. Ex Torr. & A. Gray), alder-leaf mountain mahogany (*Cercocarpus montanus* Raf.), Gambel oak (*Quercus gambelii* Nutt.), scrub oak (*Quercus turbinella* Greene), and big tooth maple (*Acer grandidentatum* Nutt.) covering 1,070,979 or 11% of the upland zone.

The mountain zone has a mean annual temperature of – 4.78 °C in winter and 14.1 °C in summer, 66.8 total mean annual precipitation, occurs from 2103 m to 2804 m, and covers 6.6% of the state across 3,561,884 acres. The terrain of the mountain zone ranges from meadows and plateaus to steep mountain slopes. The dominant vegetation types are big sagebrush (*Artemisia tridentata*), covering 933,994 acres or 26%, aspen (*Populus tremuloides* Michx.) covering 881,192 acres or 25%, and a smaller component of oak brush (*Cercocarpus* spp., *Quercus* spp., and *Acer* spp.) covering 13% of this zone.

The high mountain zone has a mean annual temperature of – 6.1 °C in winter and 12.2 °C in summer, 82 cm total mean annual precipitation, occurs from 2377 m to 3048 m, and covers 3.3% of the state across 1,792,646 acres. This zone is an ecotone between mountain and subalpine zones and the terrain ranges from meadows and plateaus to steep peaks, slopes, and ridges. The cover types are forested (63%), low shrublands (16%), and meadows (4%), consisting mainly of aspen (*Populus tremuloides*), big sagebrush (*Artemisia tridentata*), lodgepole pine (*Pinus contorta* Douglas ex Loudon) and spruce-fir. Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies* *lasiocarpa* var. *lasiocarpa* Hook. ex Nutt.) are the dominant species in the canopy either singularly or in a mixed composition, cover 1.1 million acres in the state, and are mostly found in the mountain, high mountain, and subalpine zones.

The subalpine zone has a mean annual precipitation of 78.74 cm to 101.6 cm and occurs from 2713 m to 3353 m. This zone borders the upper tree line and spruce-fir is the majority vegetation cover at 32%. Finally, the alpine zone has a mean annual temperature of 0 °C, 104.14 cm mean annual precipitation, occurs above the upper tree line from 3292 m to 4123 m, covers 50,650 acres, and the sparse vegetation mainly consists of small cushion plants (Ramsey and West 2009).

Data acquisition

To investigate the current spatial and temporal distribution of fuel treatments and historic wildfires on public lands in Utah, and to map where they have interacted, spatially explicit polygon shapefiles of completed BLM and USFS fuel treatment perimeters and historical wildfire perimeters were acquired from the BLM Navigator (https://navigator.blm.gov/) and FSGeodata Clearinghouse (http://data.fs.usda.gov/geodata/edw/datasets.php) public data portals. Additional wildfire polygon perimeters were accessed from the Monitoring Trends in Burn Severity (MTBS) (https://www.mtbs.gov/) portal and the Utah Forest Institute (unpubl. data) (Utah Fire Atlas 2022).

To assess whether fuel treatments are effective in reducing burn severity, we utilized several remotely sensed Landsat Thematic Mapper ™, Enhanced Thematic Mapper (ETM+), and Operational Land Imager (OLI) products through the Monitoring Trends in Burn Severity (MTBS) (https://www.mtbs.gov/), LANDFIRE (https://www.landfire.gov), and Utah Department of Natural Resources Wildfire Risk Assessment (UWRAP) (https://wildfirerisk.utah.gov/) data portals. The MTBS program maps the burn severity and extent of wildfires that are greater than 404.6 hectares (1000 acres) in the West from 1984 to present in the United States by using Landsat data (Landsat TM and ETM+) and the differenced Normalized Burn Ratio (dNBR) to generate burn severity raster data and fire perimeters (https://www.mtbs.gov/). The Differenced Normalized Burn Ratio (dNBR) is one common index used to estimate burn severity (Key and Benson 2006). LANDFIRE is an interagency, geospatial database that provides landscape scale geospatially referenced data for vegetation, wildland fuels, and fire regimes in the United States. We used the LANDFIRE 1.1.0 product with 2008 Landsat imagery to select encounters that occurred in forested areas based on canopy height. ArcGIS Pro 2.8.1 and the packages *rgdal* (Bivand *et al.* 2021), *sf* (Pebesma 2018), *raster* (Hijmans 2021), *rgeos* (Bivand and Rundel, 2021), *readxl* (Wickham and Bryan, 2019), *nngeo* (Dorman 2022), and *dplyr* (Wickham *et al.* 2021) were used in the R Statistical Environment (R Core Team 2021) for data preparation and statistical analysis.

To learn about public land manager perceptions of fuel treatment effectiveness when encountered by wildfire, we used Fuel Treatment Effectiveness Monitoring (FTEM) reports (unpubl. data) accessed from the Interagency Fuel Treatment Decision Support System (IFTDSS) application. The FTEM database is a tool used by federal agency managers (Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, Forest Service, and National Park Service) to report a fuel treatment effectiveness assessment when wildfires start in or burn into a fuel treatment.

Data processing

Datasets were cleaned and standardized in R and ArcMap 10.7.1 (Redlands 2011). Managed wildfires were excluded as treatments, as they were unplanned and were included in the wildfire data. Prescribed fires were considered treatments and excluded from the wildfire dataset. Wildfires represented by multiple polygons, such as spot fires, were merged into a single polygon per fire. Treatments were binned into twelve categories: broadcast burn, pile/jackpot burn, compact/pile, masticate/chip/mow, chain/clearcut, slash/lop & scatter, thin, herbicide, seed, fuel break, noxious weeds, and other. The number of entries was identified by combining overlapping treatment polygons together and defining areas that were treated multiple times as unique treatment units. Areas that experienced multiple wildfires were also identified. Treatments smaller than 0.4 hectares (1 acre) were excluded. Our final dataset included 1,558 wildfires and 3,208 fuel treatments on BLM and USFS land in Utah from 1997 to 2019.

Encounters were defined as interactions where wildfires intersected a prior fuel treatment and burned a minimum of 0.4 hectares (1 acre) of the treated area. The *rgeos* package (Bivand and Rundel 2021) was used to intersect fuel treatments and wildfire polygons. We derived treatment encounter rates based on the number of treatment units encountered by fire as a percentage of total treatment units on the landscape.

To investigate treatment effectiveness in reducing fire severity, we selected forested areas where only one fire encountered a treatment, choosing not to sample second wildfires (reburns). Treatments were organized by number of fuel treatment entries: either single treatments or multiple treatments (Fig. 2.1, Panel A). To contrast severity in treated and untreated areas of fires, we first defined sampling areas. To avoid sampling on the transitional edge of encounters, we excluded a 120 m buffer applied to treatment perimeters. This created a sampling area for treated areas that was at least 60 m inside the edge of the treatment and a sampling area for untreated areas that was at least 60 m outside the edge of the treatment. The sampling distance into untreated areas of the fire was a maximum of 500 m away from the treatment (Fig. 2.1, Panel B). We used ArcMap to generate random points in the treated and untreated sampling areas of the fires, at a minimum distance of 60 m apart (Fig. 2.1, Panel C). Points were associated with treatment attributes if they were within treatments or with the nearest treatment if they were in untreated areas. We extracted continuous dNBR values from the MTBS raster data for each point (Fig. 2.1, Panel D). Point values used in the final burn severity analysis met the following criteria: 1.) Treated and untreated dNBR values were represented for each unique treatment, 2.) There was a minimum of six points each in the treated and untreated sample areas, 3.) Sample points were forested (canopy height > 0) (LANDFIRE 2020).

To extract information from the FTEM dataset, we selected FTEM entries with a treatment area in Utah and retained questions and variables within the FTEM report with a minimum 50% response rate. Fuel treatment types were binned by the categories used in the first three stages of our study. Nine treatment categories were represented in the FTEM reports: broadcast burn, pile/jackpot burn, compact/pile, masticate/chip/mow, slash/lop & scatter, thin, herbicide, seeding, and other. We performed a descriptive analysis of survey questions about fuel treatment and wildfire interactions, descriptive fire behavior, and also summarized responses about effectiveness across treatment types, treatment age when encountered, and age of treatment.

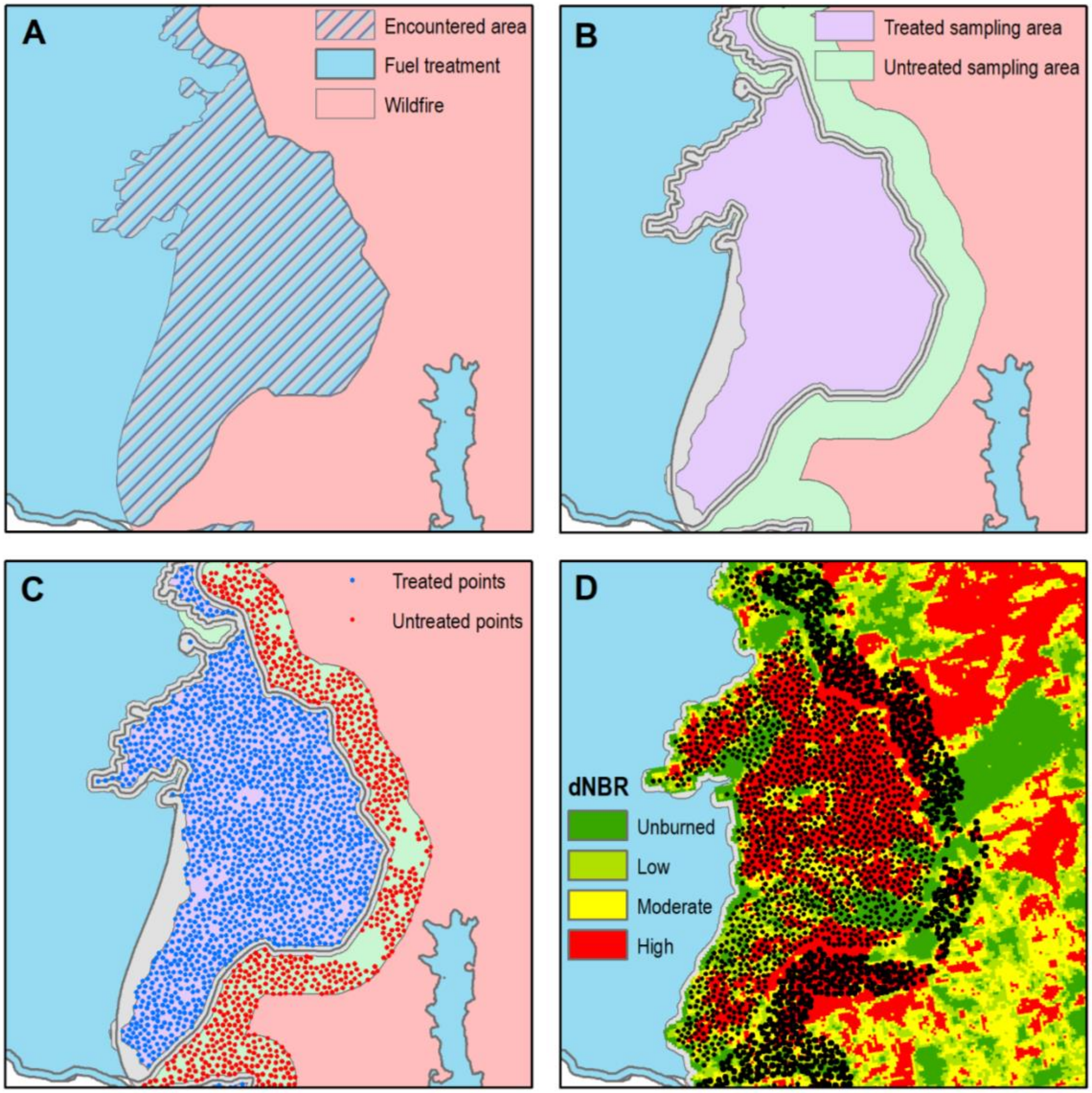

Figure 2.1 Burn severity sampling diagram illustrating the spatial methods used to generate dNBR values from paired sampling areas interior of and adjacent to burned fuel treatments. Steps included A.) Identify fuel treatment and wildfire encounters, B.) Define sampling areas that exclude the transitional edge and also constrain distance, C.) Generate random points in treated and untreated areas with a minimum distance apart, and D.) Extract dNBR values from the MTBS raster data for each point.

Statistical analysis

The likelihood of a fuel treatment being encountered by wildfire was considered a binomial trial, where encounters were a successful trial outcome. We fit a generalized linear model (GLM) with a binomial distribution and logit link function to model per-trial success probability as a function of the predictor variables. Treatment year, size, and treatment type were included in the model. Treatment year was used instead of treatment age in testing the likelihood of encounters because year is independent of the outcome, whereas the treatment age when it was encountered is a treatment attribute specific only to treatments that were encountered. Treatment year and size were continuous variables and treatment type was a categorical variable. We used “predict” and “plogis” functions in the GLM package to calculate predicted probabilities of simulated datasets using our GLM model, then back-transformed the predicted values and confidence interval estimates from the link scale into probabilities.

To analyze burn severity differences between treated and untreated areas of wildfires, we used the lme4 package (Bates *et al.* 2015) to fit linear mixed effects models (LMMs). We tested the response of dNBR values given the fixed covariates of treatment status (categorical with two levels: treated or untreated) and the random effects factor of unique treatment unit (grouping factor: 48).

To investigate whether the number of treatment entries impacts burn severity, we fit a linear mixed effects model with the response variable being the difference in dNBR values between treated and untreated sampling areas. First, we calculated the average dNBR value for areas within a fire that were untreated but adjacent to a treatment. Then, we calculated the difference in severity between treated and untreated areas by subtracting the average untreated value from each treated severity value in the associated treatment unit. We tested the difference in severity values as our response to the fixed covariate of number of entries (categorical with two levels: single or multi) and the random effects factor of unique treatment unit (grouping factor: 48). We used the difference in severity as our response to test treatment effects because although untreated sample areas were adjacent and associated with a treatment, the untreated areas do not have treatment attributes, such as number of entries, to include in the model. We tested 23 single treatments and 25 treatment units that had multiple entries.

Results

Statewide overview

In Utah between 1997 and 2019 the BLM completed 1,426 fuel treatments and the USFS completed 1,782 fuel treatments for a combined total of 3,208 treatments that met our criteria (Fig. 2.2). Cumulative treatment hectares are the sum area of treatment entries, even if the same geographic area is repeatedly treated. This is an important distinction from actual area treated, which is the net total of treated landscape. We identified each footprint as a unique treatment unit, whether it had been treated once or multiple times. There were 1,124,957 cumulative treatment hectares, of which there were 484,666 net hectares across 3,083 unique treatment units.

Fuel treatments included in the analysis were a minimum of 0.4 hectares (1 acre) in size, ranging to the largest project which treated 16,629 hectares in a series of broadcast burning, thinning, pile/jackpot burns, and compact/pile applications. The median fuel treatment size was 81 hectares (Fig. 2.3), and the average treatment size was 351 hectares. Thinning accounted for the most cumulative area treated and highest number of treatment events, followed by broadcast burns with the second most area treated and the masticate/chip/mow category with the second highest number of treatments (Table 2.1). In the same period, 1,558 wildfires burned 1,504,693 cumulative hectares of BLM and USFS land total, with 1,322,299 footprint hectares (Fig. 2.2). Fires ranged from 0.002 hectares (0.005 acres) to the 2007 Milford Flat fire covering 148,358 hectares, which was the largest area burned in a single fire. The median fire size was 57 hectares (Fig. 2.3) and the average fire was 966 hectares. Areas that were burned repeatedly were identified, with some areas experiencing a maximum of six fires.

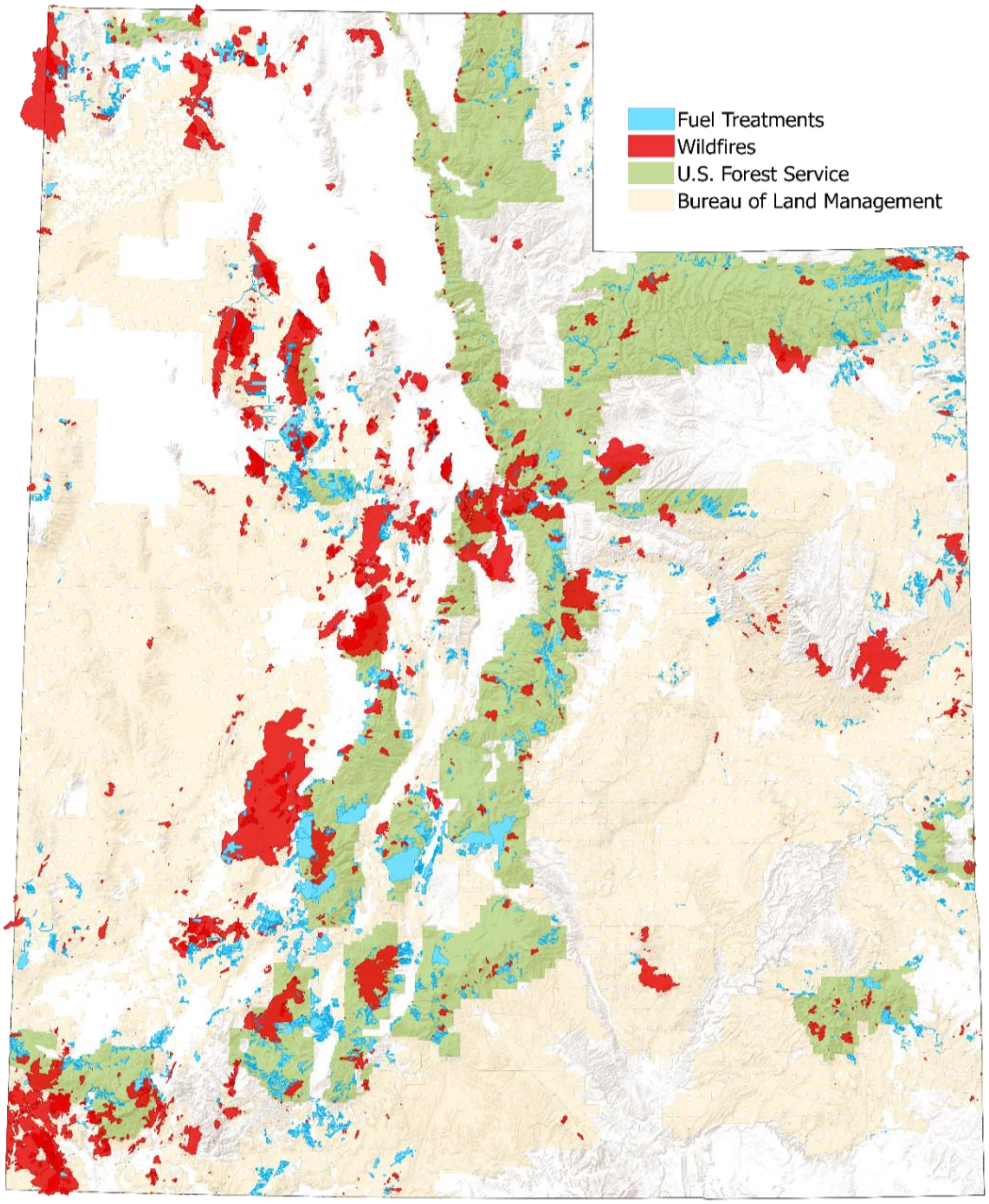

Figure 2.2 Spatial distribution of fuel treatment and wildfire perimeter boundaries on Bureau of Land Management and Forest Service managed lands in Utah from 1997 – 2019.

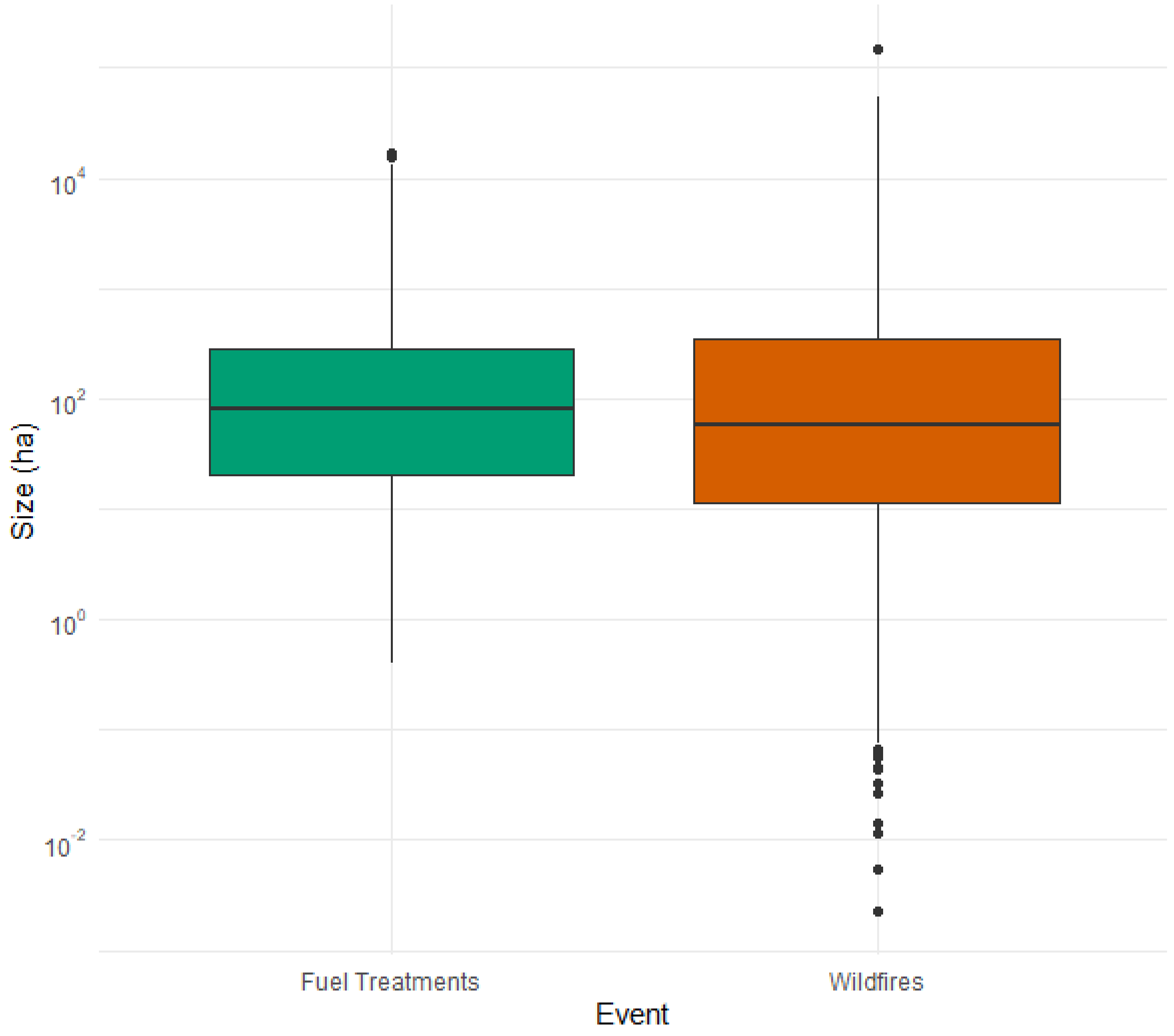

Figure 2.3 Distribution of fuel treatment and wildfire sizes on public lands in Utah, 1997 – 2019, including fires < 1 ha.

Table 2.1 Number of treatment events, cumulative treatment area (ha) and predicted probability of being encountered by wildfire for BLM and USFS fuel treatments in Utah from 1997-2019 arranged by treatment type. The number of treatment events included each individual treatment entry and cumulative treatment area was calculated as a cumulative sum, including areas that were repeatedly treated (multiple entries). Predicted probability of being encountered by wildfire was modeled from GLM outcomes.

Treatment Type	Number of Treatment Events	Cumulative Treatment Area (ha)	Predicted Probability of being Encountered by Wildfire
Thin	688	251,974	0.06
Broadcast burn	288	235,624	0.09
Seeding	323	141,289	0.11
Compact/pile	348	107,523	0.08
Pile/jackpot burn	370	106,376	0.06
Masticate/chip/mow	480	97,371	0.08
Slash/lop	291	87,946	0.04
Chain/clearcut	104	33,849	0.05
Other	198	27,094	0.06
Noxious weed	30	15,655	0.41
Herbicide	49	12,757	0.12
Fuel break	39	7,523	0.06
Totals	3,208	1,124,981	-

Table 2.2 Summary of unique treatment units by number of treatment entries, number of treatment events, area treated (ha), number of times burned, and treated area burned (ha). Locations that received two or more overlapping fuel treatments were considered multiple treatment entries and associated treatment polygons were combined into unique treatment units.

Number of Treatment Entries	Number of Treatment Events	Area Treated (ha)	Number Times Burned	Treated Area Burned (ha)
1	1,280	265,700	149	10,114
2	852	111,249	52	3,403
3	461	49,997	51	5,400
4	258	18,413	11	405
5	79	1,659	1	17
6	60	1,772	3	26
7	36	705	0	0
8	26	4,271	0	0
9	9	10,663	1	644
10	6	8	0	0
11	6	1,327	0	0
12	3	1,826	0	0
13	4	16,991	0	0
14	2	73	0	0
18	1	24	0	0
Totals	3,083	484,678	268	20,009

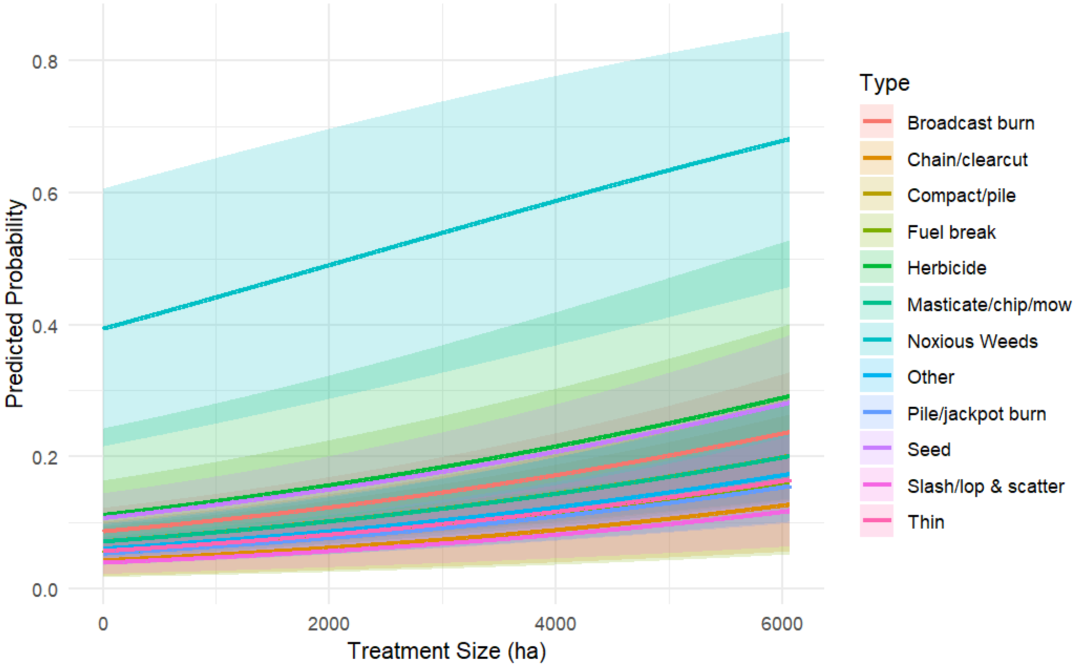

Figure 2.4 Predicted probability of a fuel treatment being encountered by wildfire in an average year across treatment size. Each line represents one of twelve treatment types.

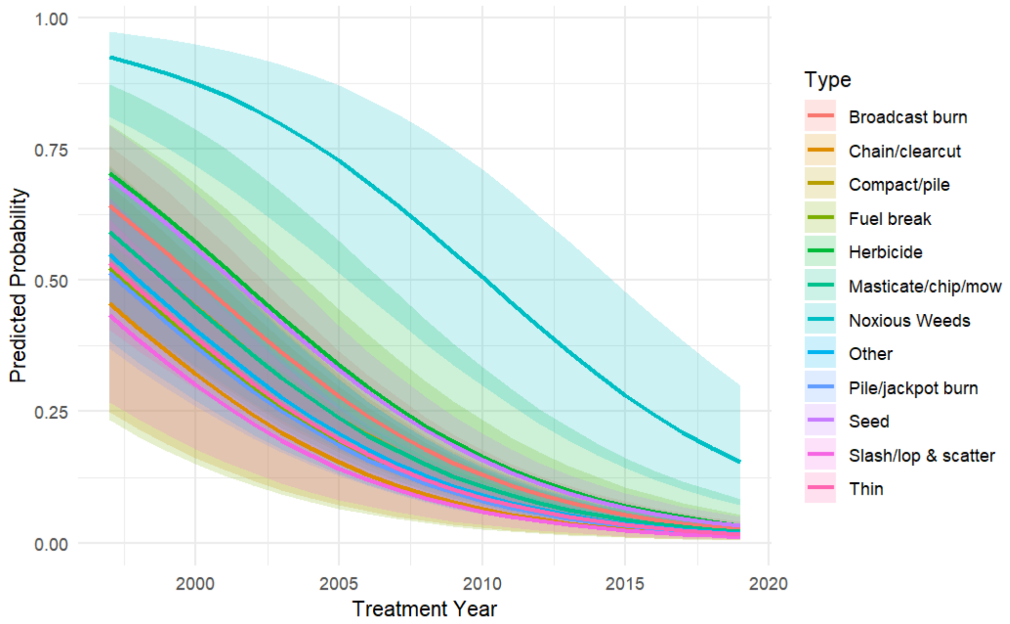

Figure 2.5 Predicted probability of an average-sized fuel treatment size being encountered by wildfire across treatment years. Each line represents one of twelve treatment types.

Encounters

A total of 268 of the 3,083 treatment units were encountered by subsequent fire, resulting in a treatment encounter rate of 8.7%. Of the treatment footprint hectares, 4% burned in subsequent fire. A total of 112 of the 1,558 wildfires encountered fuel treatments, resulting in a wildfire encounter rate of 7.2%. The covariates of fuel treatment year, size, and type were all predictors of fuel treatment and wildfire encounters, and model fitness was significant ($p < .001$). Treatment year was used in the model instead of treatment age because year is attributable to every treatment, regardless of its encounter status. From 1997 to 2019, treatments completed in earlier years were more likely to be encountered than treatments of the same average size (351 ha) and type that were completed in more recent years. For example, a broadcast burn in 1997 had a predicted probability of 0.64 of being encountered, whereas a broadcast burn of the same size completed twenty years later in 2017 only had a 0.37 predicted probability of being encountered (Fig. 2.4). Increasing treatment size improved the predicted probability of a fuel treatment being encountered for every treatment type, given the average treatment year of 2012. For example, increasing a 20.2-hectare (50 acre) broadcast burn tenfold to 202.3 hectares (500 acres) increased the predicted probability of being encountered by fire from 0.086 to 0.089. Further increasing the treatment size to 2023.4 hectares (5,000 acres) resulted in a 0.12 predicted probability of being encountered (Fig. 2.5). Noxious weed treatment types were the most likely to be encountered ($p < .001$) with a 0.41 predicted probability and were 10 times more likely to be encountered than the least likely treatment type, which was slash and lop and scatter ($p = .02$) with a 0.041 predicted probability, given an average treatment size in an average treatment year. Average predicted probability of being encountered for the remaining treatment types ranged from 0.045 to 0.118.

Burn severity

We sampled burn severity inside and outside of 48 fuel treatment units that were encountered by wildfire in our burn severity analysis. Eight treatment types were represented in the 48 units: broadcast burn, pile/jackpot burn, compact/pile, masticate/chip/mow, slash/lop & scatter, thin, seeding, and other. There were 26,716 points placed in the sampling areas. On average, burn severity in treated areas was less than in untreated areas (dNBR difference of 50; $p < .001$). Fuel treatment units where there had been multiple entries reduced severity more than single fuel treatments, but the difference was non-significant (p = 0.33).

FTEM

Our data included 323 FTEM reports from 13 BLM land managers in Utah from 2002 to 2021. Fuel treatments in the masticate/chip/mow category were the treatment type most frequently encountered and reported in FTEM. The first set of questions about fuel treatment effects on fire management and behavior gave respondents the option to select “Yes” or “No”. Managers reported that the majority of fuel treatments encountered by wildfires contributed to the control and/or management of the fire, changed fire behavior, and were strategically located to facilitate control of the fire (Table 2.3).

The question, “How did the treatment contribute to the control of the fire?” allowed respondents to select one to four answers, leave no response, or leave a comment. In nearly two thirds of events where fuel treatments were encountered by wildfire, fuel treatments were reported to have contributed to their ability to use direct attack. The fire spread was arrested in the treatment unit in about a third of the reports. There were also a few instances where treatments slowed fire spread or were used for burnout operations (Table 2.4). The response options for this question were not mutually exclusive, so respondents could report multiple treatment contributions per encounter.

Respondents were asked to report the dominant type of fire spread inside and outside of fuel treatments (Fig. 2.4). They could choose from one to three answers, leave no response, or leave a comment. Responses were more frequently selected for the dominant type of fire spread inside the treatment (n = 283) than outside the treatment (n = 207). Surface fires were the majority type of dominant fire spread reported inside fuel treatments. Active fires and surface fires were nearly equally reported as the dominant type of fire spread outside of treatments. Response options were also not mutually exclusive for this category, so different types of fire spread could be co-occurring at each encounter.

Table 2.3 Manager responses to three questions about fuel treatment effects on fire management and behavior for fuel treatment encounters from 2002 to 2021.

FTEM Survey Questions	Total Responses	Total Managers	Affirmative Responses	Percentage
Did the treatment contribute to control and/or management of the fire?	n = 323	n = 13	264	82%
Did the fire behavior change as a result of the treatment?	n = 323	n = 13	274	85%
Was the treatment strategically located in order to facilitate control of the fire?	n = 313	n = 13	296	95%

Table 2.4 Total number of selections for four possible treatment contributions to the control of fire.

How did the treatment contribute to the control of the fire? (Select 1 to 4 or leave blank)	Total Selections (n = 323)
Able to do direct attack	199
Used treatment for burnout operations	18
Arrested fire spread or fire spread was arrested in the treatment unit	105
Slowed fire spread	43

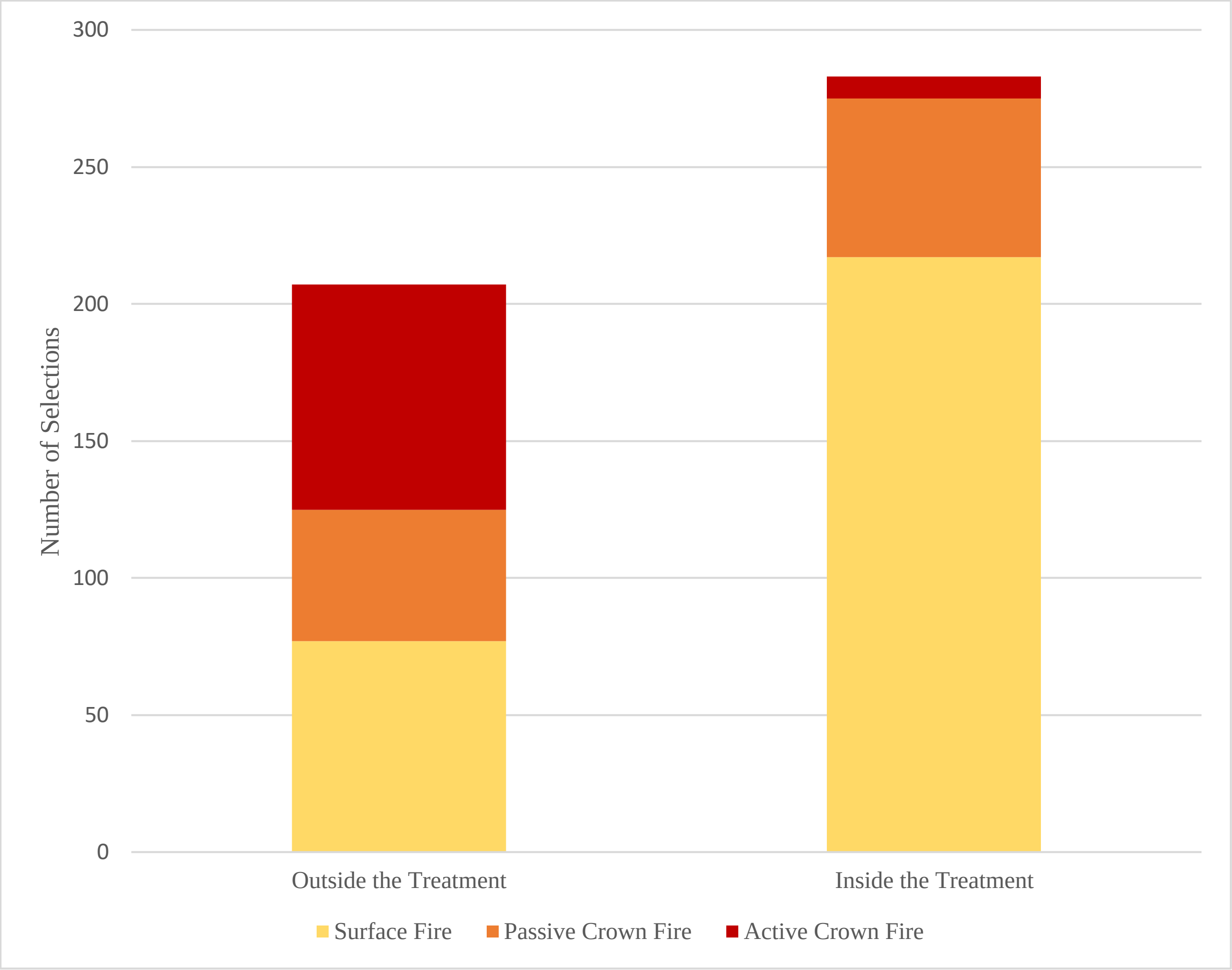

Figure 2.6 Reported dominant type of fire spread outside the treatment and inside the treatment in FTEM reports from 2002 to 2021.

Discussion

We extracted 23 years of BLM and USFS fuel treatments and wildfires across Utah to compile large, complex datasets and identified 268 fuel treatment and wildfire encounters. We approached fuel treatment effectiveness using three metrics of effectiveness: 1.) Encounter rates, 2.) Burn severity, and 3.) Manager reports.

Wildland fuel treatments are rarely tested by wildfire, which is reflected in the national treatment encounter rate of 6.8% and 7.7% of total treated area burned (Barnett *et al.* 2016). We calculated encounter rates on public lands in Utah as one of our metrics of effectiveness because encounters reflect effective spatial arrangement of treatments on the landscape. The finer scale of our statewide analysis and wider range of wildfire sizes, which captured fire perimeters smaller than the 405-ha (1000-acre) MTBS minimum, likely contributed to our treatment encounter rate of 8.7% being slightly higher than the national average of 6.8% (Barnett *et al.* 2016). However, it is still relatively low in terms of treated area experiencing wildfire, which was only 4%. Logistically, only a small portion of the burnable landscape can be treated at a given time. There is currently no standard of success for encounter rates, but generally increasing encounters is desirable for maximizing fuel treatment benefits, such as reducing burn severity and creating conditions to manage beneficial fires.

To investigate whether treatment characteristics affected a treatment's likelihood of being encountered by fire, we analyzed the year, size, and type of treatments that were encountered. We found that treatments completed in older years were more likely to be encountered by wildfire, likely due to a greater window of time in which fires can occur. We used treatment year to derive the likelihood of a treatment being encountered by fire because the year of completion is attributable to every treatment, regardless of its encounter status. Similar to Barnett *et al.* 2016, we found that larger treatments were more likely to be encountered by fire. We found noxious weed treatments to be the most likely type to be encountered and the slash/lop and scatter category the least likely type encountered. Although noxious weed treatments were the least frequently applied type and the third smallest total amount of treated area (Table 2.1), they had the second highest average treatment size, after broadcast burns. Slash and lop & scatter treatments ranked in the middle of treatment types for frequency, area treated, and average treatment sizes. We conclude that the results for how treatment types affect the likelihood of encounters are a function of treatment size, rather than meaningful attributes influencing encounter occurrences. Therefore, managers wanting to increase the likelihood of a treatment being burned in a future wildfire should plan for larger treatment sizes.

While our focus was on treatment characteristics (i.e., year, size, and type) that influence rates of wildfire encounters, treatment year of completion does not indicate the treatment’s age when burned in wildfire, so additional analysis of treatment ages is necessary to evaluate how age affects the likelihood of being encountered and treatment longevity. Assigning treatment age as the difference between the year of completion and the end of the study’s range in 2019 would provide an additional predictor variable to fit a GLM with encounter status as a binomial trial. Evaluating the distribution of treatment ages of the subset that were encountered (8.7%) could be informative for prioritizing treatment unit maintenance and incorporating the existing treatment network into plans for managed wildfires. There is wide variation in previous findings about treatment ages, including treatments most frequently burning within their first year of completion

(Barnett *et al.* 2016), Australian prescribed fire treatments being encountered at a 22.5% rate within five years (Price 2010), and most fuel treatments not being intersected within a 15-year window of effectiveness (Yocom 2013). Inconsistent patterns for treatment ages when encountered can likely be attributed to a difference in methods. We tested each fuel treatment year individually for encounters, regardless of their presence within units that received multiple treatment entries, whereas other studies limited treatment attributes to the most recent treatment layer involved in a wildfire interaction (Barnett *et al.* 2016).

Most wildfire perimeters included in this study were relatively small; 75% of fires were ≤ 359 hectares and the median fire size was 57 hectares. However, the average wildfire size of 966 hectares was influenced by less frequent, but more extensive, wildfire incidents. For example, the largest wildfire included in our analysis was nearly 100,000 hectares greater in size than the second largest fire. Our study retained the most comprehensive range of wildfire sizes available within the period (1997 – 2019) to represent wildfire range of variability. Our analysis of encounters focused on treatment characteristics as they are a result of deliberately planned projects, whereas wildfire characteristics are a result of stochastically occurring events. We found that 7.2% of wildfires encountered treatments, but the likelihood of encounters could be further elucidated by evaluating wildfire characteristics similar to the modeled treatment attributes, such as year and size. Additional predictor variables for wildfires could include ignition type (lightning or human-caused), reburns, and suppression status (full-suppression or managed for objectives other than full suppression). Including suppression status as a predictor variable would be novel as suppression activities are rarely accounted for with encounters and influence treatment efficacy.

Our study provides a baseline of knowledge about the status of fuel treatment and wildfire encounters on public lands in Utah and would be strengthened by further analyses of the relationship between the sizes of fuel treatment and wildfire perimeters and the outcomes of encounters. Evaluating the proportion of treated area that burned when encountered and the sizes of the associated treatment and wildfire would help us better understand how relative sizes influence fire spread. This analysis would require new geospatial parameters and processing, as fuel treatment and wildfire perimeters cause uniquely challenging spatial and temporal layer combinations. For example, some multiple treatment entries partially overlap with one another and one or many wildfires partially burn treated areas. That would mean that in a given area, the fire(s) has burned different proportions of different treatment layers. The most recent layers of fuel treatments and wildfires could be extracted to calculate proportions of treated areas burned, but the number of treatment entries and historic wildfires should still be retained as an attribute, as past management activities and wildfire incidents impact consequent fuel loading (Cansler *et al.* 2022a). Our study defined encounters as interactions where a minimum of 0.4 hectares (1 acre) of a fuel treatment was burned by subsequent fire, but further geospatial analysis to evaluate wildfires that closely bordered treatments would provide more distinction for these interactions and nuance for treatment effectiveness. Categories of interactions could include wildfire perimeters that burned within 30 m of a treatment perimeter, encounters where fires burned ≤ 50% of a treated area, encounters where fires burned ≥ 50% of a treated area, and encounters where fires burned > 100% of a fuel treatment perimeter. Suppression activities should be included when modeling these interactions to avoid overinflating the effectiveness of treatments. Identifying bordering interactions could capture the utility of existing fuel treatments in facilitating wildland fire operations, which in turn increase the effectiveness of the treatment. For example, one study found that fuel breaks alone arrested less than 1% of wildfires and fire suppression activities were essential to fuel break efficacy (Syphard *et al.* 2011). The spatial complexity of treatment and fire layers persists here, so analyzing a range of fire and treatment proximities would require a separate analysis, likely using a subset of the top layers of treatment and fire perimeters. Modeling the relationship between wildfire and treatment sizes and the resulting proportions of area burned at the geographic scale in which fuel treatments are applied, i.e., BLM districts, USFS national forests and/or for local vegetation types, would be informative for establishing optimal treatment size targets.

We tested if fuel treatments were effective for burn severity reduction. Burn severity is a focal metric in many fuel treatment effectiveness studies because it is a measure of ecological change (Key and Benson 2006) caused by fire, and remote sensing technologies have made severity data readily available. The large spatial extent and stochastic nature of fires makes remote sensing the most cost-effective method for gathering data across the U.S. for fires over multiple decades (Eidenshink *et al.* 2007). Fuel treatment plans often cite burn severity reduction as a primary treatment objective for longer-term outcomes such as preventing active crown fires and stand-replacing fires, retaining desirable plant species, and supporting fire-resilient landscapes. We found that overall, fuel treatments significantly reduced burn severity compared to untreated areas (dNBR difference of 50; *p* < .001), with multiple entries reducing severity by 16 dNBR points more than single treatment units (*p* = 0.33). Modest changes in dNBR values still incorporate considerable uncertainty, especially at intermediate levels (Furniss *et al.* 2020). A meta-analysis of 19 publications found that fire severity can be reduced by thin and burn treatments that focus on canopy fuels and retaining large-diameter trees (Martinson and Omi 2013). Another study found that thinning treatments reduced fire severity compared to adjacent, untreated plots (Strom and Fule 2007). Additional studies have concluded that treatments can potentially mitigate fire severity (Safford 2009; Prichard 2014), with varying results. While most of the treatment types included in our burn severity analysis could be regrouped into a broader thin and burn category, over a third of the remaining treatment types were masticate/chip/mow, seeding, and other. Our study examined the aggregate effects of treatments reducing burn severity on the landscape and detected a positive treatment effect that is representative of multiple treatment entries and types. Our finding that fuel treatments reduce burn severity supports the implementation of new fuel treatments to expand treated area networks. Our finding that multiple treatment entries reduce severity more, though not significantly, supports the maintenance of treatment units that currently exist. Given that larger treatments are more likely to be encountered by fire and burn severity is significantly reduced in treated areas, implementing new treatments or expanding the extent of existing treatments may be a greater priority for reducing burn severity than conducting repeat treatments, with the exception of thin-and-burn treatment regimens.

The Fuel Treatment Effectiveness Monitoring (FTEM) application is an interagency database to report the effects of fuel treatment and wildfire encounters that occur on public lands. This system offers land managers the opportunity to highlight and document aspects of treatment effectiveness that are otherwise undetectable in post-hoc approaches. Public land managers and wildland fire personnel work closely with fuel treatments, from designing treatment prescriptions and objectives, project implementation, maintenance, and use of treated areas as anchor points, helispots, and fireline construction during wildfire operations. However, their firsthand accounts of fuel treatment and wildfire interactions are sparse in the fuel treatment effectiveness literature, an imbalance that hinders an effective integration of scientific findings and adaptive management. Our study summarized responses in 323 FTEM reports from 13 BLM land managers in Utah from 2002 to 2021 as our third metric of fuel treatment effectiveness and was restricted to questions or categories that received a minimum 50% response. We found that managers were overwhelmingly positive in their responses to the “Yes” or “No” questions about treatments contributing to control and/or management of the fire (82% affirmative), changing fire behavior (85% affirmative), and being strategically located to facilitate control of the fire (95% affirmative) (Table 2.3). These results suggest that fuel treatments effectively aid in wildfire suppression activities and change fire behavior when encountered, but the questions could be expanded upon and modeled to further identify and improve the factors that contribute to treatment effectiveness. For example, what factors contribute to treatments being strategically located, how are they used to facilitate control of the fire, and how do those relate to the proportion of treatment burned? For each encounter in the 323 reports, one to four responses were selected to describe how the treatment contributed to the control of the fire: able to do direct attack (199), used treatment for burnout operations (18), arrested fire spread or fire spread was arrested in the treatment unit (105), and slowed fire spread (43). This finding further supports that fuel treatments are beneficial to fire suppression activities and that overall, managers find fuel treatments to be effective even if they don’t slow or arrest fire spread. The dominant fire type inside and outside of fuel treatments could be reported in up to four selections as surface fire, passive crown fire, active crown fire, or no response. Surface fire was more frequently reported inside treatments (n = 217) than outside treatments (n = 77), but the dominant fire spread was more frequently reported for inside treatments (n = 283) than outside treatments (n = 207) overall, so a comparison between the dominant fire types at individual encounters is recommended to attribute treatment effect. Similarly, more active crown fires were reported outside the treatment (n = 82) than inside treatments (n = 8), but further analysis is needed to draw conclusions about fuel treatment effects on the dominant type of fire spread. Jain *et al.* 2021 also found that fuel treatment effects were more frequently reported inside treatments than outside treatments. Without equal data collected for both inside and outside the treatment at encounters, there is also a possibility that selective reporting can result in a bias towards observing and reporting desired treatment effects, such as a majority of dominant surface fire within treatments and a majority of active crown fires outside of the treatment.

The low response rate to fuel treatment effectiveness questions and insufficient fire weather data limited the scope of our qualitative analysis of manager reports. Emphasizing consistent and complete data collection in FTEM reports, including weather, fire attributes, and fire behavior outside of treatments would increase the viability of this interagency database for use in scientific studies. Lowering barriers to collecting and entering data may help improve this, such as populating the weather measurements from Fire Effects Monitors on the incident and using app-based platforms for immediate field data entry when possible. Future analyses of FTEM reports would benefit from including data from multiple agencies at a regional extent to utilize more of the available data for statistical analyses. Incorporating FTEM reports in scientific studies is an opportunity to increase the representation of public land manager experiences in the literature and improve our understanding of conditions contributing to treatment effectiveness.

Our study demonstrates several strengths and opportunities for research and management applications. We drew from publicly available federal datasets and national remotely sensed data to analyze encounters and burn severity. The federal spatial datasets for fuel treatments and wildfires and the FTEM reports are rarely utilized in fire effects literature. Our research was conceptualized by fuels and wildfire managers in the BLM and USFS, with the goal to inform management implications. Of our study's three metrics of effectiveness, fuel treatments encountered by wildfires were found to be the most effective by land managers, followed by burn severity, and were the least effective based on encounter rates. The divergence in effectiveness between our metrics demonstrates the complexity and nuances of fuel treatment and wildfire interactions on the landscape. We posit that our metrics of effectiveness can be scaled up to regional and national applications and scaled down for evaluations within the administrative boundaries where fuel treatments are completed, such as BLM districts and USFS national forests. Combining our methods for measuring effectiveness with public land manager institutional knowledge could mitigate constraints that we encountered in our statewide scale, such as the magnitude of spatial complexity with thousands of treatments and fires. Some treatment effectiveness benefits such as treatments arresting fire spread, reducing burn severity, and reducing fire behavior are contingent upon fires encountering treatments. Encounter rates in Utah are comparable to the national average but highlight the prevailing issue that the current extent and pace of treatments are ineffective in landscape-scale wildfires (Prichard *et al.* 2021). Treatments were effective in reducing burn severity in forested areas, with multiple treatment entries having a slightly higher reduction in severity. Treatments were found to be effective in manager reports in contributing to fire management and affecting fire behavior. While we conclude that fuel treatments are effective when encountered, the infrequent rate of wildfires burning fuel treatments demonstrates the need to expand treated areas to a greater proportion of the landscape.

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CHAPTER 3

EFFECTS OF JUNIPER MASTICATION TREATMENTS ON POST-FIRE ECOLOGICAL OUTCOMES IN SAGEBRUSH SHRUBLAND

Abstract

Woody plant expansion, altered fire regimes, and invasive annual grasses are highly interconnected, ecosystem-level issues currently threatening sagebrush shrubland communities in the Great Basin ecoregion. Increasing tree dominance in sagebrush habitat is associated with a decline in understory shrub, grass, and forb components and can lead to vegetation type conversion from shrubland to closed-canopy woodland or cheatgrass monocultures. Heavy fuel loads in dense stands create favorable conditions for invasive annual grass establishment by increasing the risk of homogenous, high severity fire and thus, altering post-fire successional dynamics. Pinyon-juniper reduction is commonly achieved with mastication, which is the mechanized shredding, chipping, mowing, or mulching of woody plants. Managing cold desert ecosystems is increasingly viewed through a resilience and resistance framework, to evaluate and support a habitat's resilience to disturbances such as wildfire and resistance to invasive plants. The objective of this study was to assess fuel treatment effectiveness of juniper mastication treatments on public lands in Utah when encountered by wildfire. We used a split-plot design at six replicate sites to sample juniper mastication treatment units and adjacent, untreated control areas burned by a single wildfire. We used a split-plot design to sample treated and untreated areas of the fires using line point intercept and belt transect surveys. We tested three metrics of ecological health that are related to resilience and resistance in

Wyoming big sagebrush (*Artemesia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) habitat: cheatgrass cover, bare ground cover, and sagebrush density. We predicted that fuel treatments encountered by wildfire would decrease cheatgrass cover, decrease bare ground cover, and increase sagebrush density compared to the untreated control. Our results found no evidence that juniper mastication treatments improved post-fire responses of the three ecological health metrics we tested. Pre-treatment tree density and understory cover, which is unknown in our plots, has been found to be the most important predictor of post-treatment succession.

Introduction

Big sagebrush (*Artemesia tridentata* L.) shrubland communities in the Great Basin floristic region of the Intermountain West are experiencing ecosystem decline driven by woody plant establishment and infilling, altered fire regimes, invasive annual grass establishment, anthropogenic disturbances, and climate change (Miller et al. 2000; Chambers and Wisdom 2009; Davies et al. 2011). These highly interconnected changes are contributing to the loss of native big sagebrush community ecosystem functioning and land-type cover through vegetative type conversions (Chambers and Wisdom 2009) from shrublands to pinyon-juniper woodlands (Miller et al. 2008) and homogenous invasive grasslands (Brooks and Pyke 2001).

Cold desert sagebrush ecosystems have declined from an estimated 25 million ha in the late 1800's to an estimated 13 million ha (Miller et al. 2011), occupying only 56% of its historic range (Schroeder et al. 2004). One study assessed land-use/land-cover (LULC) change using satellite imagery from 1973 to 2000 in the four ecoregions of the basin and range province in the U.S. (Northern Basin and Range, Central Basin and Range, Mojave Basin and Range, and Sonoran Basin and Range). They found the grassland/shrubland classification (minimum 10% of the area had vegetative cover predominantly covered with grasses, forbs, or shrubs), which included native sagebrush and invasive grasses, was the majority land-cover type (82.6% in 2000), but also experienced the greatest net loss of 8,782 km^2 (–1.3%), from 587,024 km^2 in 1973 to 578,242 km^2 in 2000 (Soulard and Sleeter 2012). The Central Basin and Range ecoregion experienced the greatest change in land-cover type of the four ecoregions from 1992 to 2000 due to an increase in wildfire activity (Soulard and Sleeter 2012).

Big sagebrush (*Artemisia tridentata* spp.) shrubs reproduce by seed and do not regenerate vegetatively or by sprouting (Shultz et al. 2006). Seed sources can be limited by disturbance events such as wildfires that result in high mortality of mature sagebrush (Longland and Bateman 2002; Welch and Criddle 2003). Most seeds have short dispersal distances (Welch and Criddle 2003) of < 1-2 m (Welch 2005), with the farthest observed distance being 33 m (Daubenmire 1975). Sagebrush shrubs experience the highest mortality in the seed or seedling growth stages and in semiarid environments successful recruitment occurs in pulses, with mean recruitment intervals of 1.6 to 2.3 years for three big sagebrush subspecies (*Artemisia tridentata* ssp. *wyomingensis, tridentata, and vaseyana*) (Perryman et al. 2001). Surviving plants can reach maturity in 2-3 years under favorable conditions (Daubenmire 1975; Young et al. 1989; Welch et al. 1990) but have been reported to take as long as 20 years (Weldon et al. 1958). Big sagebrush are long-lived species, with one study documenting a 55-yr old basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*), a 75-yr old Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and an 81-yr old mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) in Wyoming (Perryman et al. 2001).

Wildfires were historically infrequent in Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) ecosystems that were fuel limited, with some fire rotation estimates ranging from 100 to 240 years (Baker 2006; Miller et al. 2013; Chambers et al. 2019). Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) sites historically experienced fire return intervals as frequently as 10-12 years due to higher fuel availability (Miller et al. 2013). The highly variable fire return intervals in sagebrush communities (Brooks and Chambers 2011) likely contributed to plant species with low resiliency to fire (Chambers et al. 2014a, 2019). Post-fire big sagebrush shrub recovery to pre-fire densities is a multidecadal process (Shinneman and McIlroy 2016). One study that measured mountain big sagebrush recovery following a 360-acre fire found that sagebrush had only reestablished an approximate distance of 42 feet per year in the 14 years postfire and had a sparse canopy cover of 3%, compared to the 30% cover in the adjacent unburned control (Welch and Criddle 2003). Another study compared Wyoming and basin big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and *tridentata*) regeneration in 16 fires (5 to 28 years old) in the Columbia Basin to unburned controls. They found that seedling establishment occurred within the first few years following most fires and on average, it took post-fire shrubs 14 years to reach the large-mature class (> 5 cm stem diameter). This study's model predictions also found the cover of big sagebrush shrubs and the density of large-mature sagebrush did not recover to pre-fire levels after 28 years (Shinneman and McIlroy 2016). They also found that large-mature shrub density and sagebrush cover increased with time since fire and in plots that had greater precipitation in the winter immediately following the fire (Shinneman and McIlroy 2016).

Pinyon and juniper (PJ) woodlands are defined by the presence of at least one pinyon (*Pinus* spp. L.) species and at least one juniper (*Juniperus* spp. L.) species (Shaw et al. 2005), the most common of which for the Great Basin and Colorado Plateau include: singleleaf pinyon (*Pinus monophylla var. monophylla* Torr. & Frém), two needle pinyon (*Pinus edulis* Engelm.), Utah juniper (*Juniperus osteosperma* (Torr.) Little), western juniper (*J. occidentalis* Hook.), Rocky Mountain juniper (J*uniperus scopulorum* Sargent, Gard. & Forest) and Sierra juniper (*Juniperus grandis* R.P. Adams) (Miller and

Tausch 2001; Miller et al 2019). Semiarid conifer woodlands can also have a dominant overstory of a single species of pinyon (*Pinus* spp. L.) or juniper (*Juniperus* spp. L.) (Miller et al. 2019). Pinyon and juniper woodlands occupy an estimated 19 million hectares in the Intermountain West (Davies et al. 2011), primarily in the Great Basin and Colorado Plateau (Miller et al. 2019). They are the predominant forest type in Utah, accounting for 59% of the state's total forested area (minimum 10% tree cover) across 4.3 million hectares (Ramsey and West 2009; Werstak et al. 2016). Pinyon and juniper woodlands have expanded and contracted as much as about 914 m (3,000 ft) in elevation over the past 20,000 years as climate conditions have fluctuated, but the most significant movements have occurred in the last two centuries (Miller and Tausch 2001). Miller et al. (2019) synthesized 1,000 publications related to pinyon and juniper woodlands and consolidated terminology to describe PJ woodland dynamics, including classifying stands as persistent or newly expanded. Persistent woodlands occur on sites where the soil, climate, and disturbance regimes favor a pinyon and/or juniper dominant canopy and trees have been a major stand component for the past several hundred years. The canopy varies from sparse to relatively dense and the understory has low total plant cover that may be dominated by shrubs, forbs, and rarely grasses, with frequent bare soil or rock cover. Newly expanded woodlands refer to pinyon and juniper establishment in areas that were previously non-woodland (Romme et al. 2009; Miller et al. 2019). Stands are also often referred to as pre-settlement or post-settlement, with the introduction of livestock by Eurasian settlers in the 1850's as the benchmark. Infilling refers to persistent or post-settlement woodlands experiencing an increase in tree density. Newly expanded pinyon and juniper communities that are expected to replace the preexisting vegetative community through succession are described in three phases. Here, dominance refers to the primary vegetation layer influencing ecological site processes and phases are quantified using the total tree cover as a proportion of total perennial cover (total tree / total tree + shrub + perennial grass = tree cover) to generate a total tree dominance index (TDI). In Phase I, tree cover is less than one-third and shrubs and herbs are the dominant vegetation. In Phase II, tree cover is one-third to two-thirds and trees co-dominate with shrubs and herbs. In Phase III, tree cover is greater than two-thirds and trees are the dominant plant component (Table 3.1) (Williams et al. 2017; Miller et al. 2019).

Table 3.1 Phases of pinyon and juniper tree cover quantified as a tree dominance index using total tree cover as a proportion of total perennial cover (total tree / total tree + shrub + perennial grass = tree cover). Trees increase as the dominant vegetation (the primary vegetation layer that influences ecological site processes) and the shrub and herb components become less dominant as tree cover increases. Adapted from Miller et al. 2005 and Williams et al. 2017.

Phase	**Tree Cover**	**Dominant Vegetation**
Phase I	> 0.34	Shrubs and herbs dominant, trees present
Phase II	0.34 - 0.67	Trees codominant with shrubs and herbs
Phase III	< 0.66	Trees dominant

Pinyon-juniper establishment and densification can convert big sagebrush (*Artemisia tridentata* spp.) ecosystems to homogenous woodlands with sparse understories, lacking both sagebrush and native perennial herbaceous plants (Miller et al. 2005, 2008; Chambers and Wisdom 2009). Loss of shrub cover and perennial understory vegetation caused by woody succession is associated with habitat loss for diverse and obligate wildlife, decreased resiliency to fire, increased bare ground between plants, decreased water infiltration, and reduced productivity (Schlesinger et al. 1990; Roundy et al. 2014; Bestelmeyer et al. 2018; Fick et al. 2022). Pinyon-juniper expansion into mid to upper elevation sagebrush can potentially alter the fire regime as an increase in heavy woody fuel loads can lead to decreased fire frequency, but increase the risk of homogenous, high severity fires (Miller et al. 2005; Chambers and Wisdom 2009), and less severe fire weather is required for large fire occurrence (Minnich 2001).

Loss of shrub and perennial herbaceous plant diversity, increased risk of large, high severity fire, and an increase in abiotic resource availability to invasive plant species are consequences of woody plant expansion, and these changes can precipitate an alternate state of dominant annual grass cover (Syphard et al. 2017; Chambers et al. 2019). A resilience and resistance framework can be utilized to evaluate sagebrush ecosystem health by identifying environmental and disturbance factors that influence ecosystem resilience to fire, resistance to annual grass invasion, and spatial resilience (Chambers et al. 2014b; Rodhouse et al. 2021). Resistance and resilience are interrelated concepts, where a habitat's resilience to wildfire influences its resistance to invasive plants (Chambers et al. 2019). Mid-elevation Wyoming sagebrush systems are particularly vulnerable to irreversible ecosystem transitions due to their low to moderate resilience to wildfire and low resistance to annual grass invasion (Chambers et al. 2014b).

Pinyon-juniper removal projects in sagebrush habitats address issues of resilience and resistance by decreasing the tree component, reducing fuels and wildfire risk, supporting habitat connectivity (Chambers et al. 2019) and biodiversity, and improving soil stabilization and hydrology (Archer et al. 2011, Fick et al. 2022). Mastication is a commonly applied, non-consumptive, mechanical fuel treatment that generally uses tractors with rotor attachments (Monsen et al. 2004; Havrilla et al. 2017; Munson et al. 2020) to reduce woody fuels by mulching, chipping, shredding, or mowing (Kreye et al. 2014). This fire surrogate is often applied in PJ stands that have newly expanded into sagebrush communities where fire exclusion is prioritized due the slow recovery of sagebrush to pre-burn levels (Beck et al. 2009; Miller et al. 2019) and a high risk of fire-facilitated annual grass invasion. Although mastication is an effective method for decreasing woody plant cover (Fick et al. 2022), the redistribution of vertical fuels into irregularly shaped fuel particles and densely compacted fuel beds results in inconsistent fire behavior effects (Kreye et al. 2014). Field studies report conflicting outcomes on fire effects, in some cases decreasing fire intensity (Kreye 2012) and in other examples exacerbating fire behavior (Bradley et al. 2006; Kreye et al. 2014). Tree reduction treatments are recommended for retaining the site's sagebrush component when tree dominance is at a low to mid tree dominance index in Phase I (0 – 0.34) to early Phase II (0.34 – 0.67) (Table 3.1) (Williams et al. 2017). Another study that modelled the mean effects of PJ reduction treatments relative to synthetic control found that treatments resulted in a 1.5% increase in shrub cover, a 5% increase in perennial grass and forb cover, and a 1% increase in annual grass and herbaceous cover on average, after five years (Fick et al. 2022). PJ reduction treatments also reduced bare ground cover by an average of ~0.5% (Fick et al. 2022). Tree reduction projects in Phase 3 stands are considered higher risk for erosion and annual plant invasion, as dense stands are associated with greater annual grass and bare ground cover, and tree removal increases bare ground exposure (Fick et al. 2022). However, leaving dense stands untreated increases crown fire potential, an occurrence that would further facilitate invasive plant spread and soil erosion (Miller and Tausch 2001). If a primary management objective includes retaining native shrubs, grasses, and herbaceous vegetation, using mechanical treatments in Phase 1 and 2 (Table 3.1) to prevent tree infilling is crucial because the composition of the pretreatment plant community influences post-disturbance recovery (Williams et al. 2017).

The effectiveness of mastication treatments in reducing the potential undesirable consequences of wildfire and newly expanded juniper stands on sagebrush ecosystem health should be evaluated as land managers consider ecological thresholds and prevention of transitions to homogenous alternative states. Our main question was: do mastication treatments improve the resiliency and resistance of the understory plant community, allowing greater post-fire recovery? We assessed fuel treatment effectiveness at six study sites on public lands in Utah where wildfire burned juniper mastication treatments. These treatments were designed to reduce woody expansion, which is associated with a decline in shrub cover (Williams et al. 2017), a diminished understory with less shrubs, perennial forbs, and perennial grasses to outcompete cheatgrass from establishing, and an increase in bare ground (Fick et al. 2022). We used ocular vegetation surveys to measure these three metrics of ecological health: sagebrush (*Artemisia spp.* L.), cheatgrass (*Bromus tectorum* L.), and bare ground cover in treated and untreated areas of each fire. We expected to see that pre-fire treatments resulted in more desirable post-fire outcomes. Specifically, we expected greater sagebrush cover, less cheatgrass cover, and lower bare ground in treated areas of the fire compared to untreated areas.

Methods

Study Sites

The Great Basin floristic region is an endangered, semi-arid to arid, cold desert bordered by the Sierra Nevada Mountain range on the west and by the Uinta and Wasatch Mountains on the east (Chambers and Wisdom 2009; Leydsman McGinty and McGinty 2009). The Central Basin and Range is an ecoregion of the Great Basin covering 343,169 km^2, the majority of which extends across Nevada (65.4%), the western half of Utah (25.1%), and smaller portions in Idaho (5.6%), California (3.7%), and Oregon (0.2%) (Soulard 2012). Regional climate trends are arid to semi-arid, as the bordering mountain ranges limit moisture from the Pacific Ocean and Gulf of Mexico (Rogers 1982), resulting in the annual relative evapotranspiration (RET) to exceed the annual precipitation (Ramsey and West 2009). The basin and range topography of this ecoregion consists of generally parallel, north-south oriented mountain ranges with some peaks over 3,000 m (10,000 ft) and expansive desert valleys (Soulard and Sleeter 2012). The Great Basin floristic region is primarily federally managed by the United States (U.S.) Department of the Interior (DOI) Bureau of Land Management (BLM) (54%) and Department of Agriculture (USDA) Forest Service (USFS) (14%) (Chambers and Wisdom 2009).

The dominant vegetation cover that characterizes the Great Basin are salt desert shrub, sagebrush (*Artemesia* spp.) shrubland and steppe, and pinyon (*Pinus* spp. L.) and juniper (*Juniperus* spp. L.) woodlands (Chambers and Wisdom 2009). The semidesert zone occupies 60% of Utah and contains a majority of the state’s salt desert shrub (90%), shrub steppe (92%), big sagebrush (54%) and pinyon-juniper (75%) (Ramsey and West

2009). This zone has a mean annual temperature range of 0 °C to 20.6 °C, an elevation range of 1372 m to 1951 m, and a mean annual precipitation range of 20.3 cm to 30.5 cm (Ramsey and West 2009). Sagebrush shrubland and steppe are similar vegetative communities but are distinguished by the relative proportions of sagebrush shrub, grass, and forb components. Sagebrush shrublands have a dominant sagebrush overstory with a varying composition of grasses and forbs. In steppe communities, sagebrush shrubs are equal or co-dominant with herbaceous plants such as bunchgrasses (Ramsey and West 2009, Miller et al. 2011). In Utah, big sagebrush communities may have co-dominant shrubs such as yellow rabbitbrush (*Chrysothamnus viscidiflorus* (Hook.) Nutt.) and antelope bitterbrush (*Purshia tridentata* (Pursh) de Canolle), perennial grass components, and about 25% or less cover of perennial herbaceous plants (Ramsey and West 2009). Within the state, big sagebrush (*Artemesia tridentata* Nutt.) dominant vegetation cover occupies 3.4 million hectares and shrub steppe occupies 832,123 hectares, which are mostly concentrated in the northern part of the state and primarily used for livestock grazing (Ramsey and West 2009). Cold desert shrubland communities occur on a strong environmental gradient; as elevation increases, temperature decreases and moisture availability increases, yielding higher plant productivity and thus increasing fuel abundance and fuel continuity of shrublands occurring at higher elevations (Chambers et al. 2014b). For example, the three most common big sagebrush subspecies, basin big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata* (Beetle & Young) Welsh), Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young), and mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle) demonstrate distinct yet overlapping ranges of ecological site conditions and productivity. Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) occupies the lowest range of elevation (150 to 2,150 m) and annual precipitation (180 to 300 mm), resulting in the lowest aboveground annual herbaceous productivity (490 to 990 kg/ha) of the three subspecies. Basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) occupy sites at elevations from 610 to 2,140 m, have an annual precipitation of 200 to 400 mm, and have an aboveground annual herbaceous production of 868 to 2,350 kg/ha. Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) occupies the highest elevation of the subspecies from 1200 to 3200 m, with an annual precipitation of 350 to 450 mm, which generates the highest annual productivity of 1120 to 3080 kg/ha (Miller et al. 2011). Shrubland communities dominated by sagebrush cover in the Great Basin supports over 350 sagebrush-associated plant and animal species of concern (Suring et al. 2005a, 2005b; Wisdom et al. 2005). Sagebrush cover is an indicator of post-fire shrub recovery and habitat suitability for sagebrush obligates, such as the near-threatened greater sage grouse (*Centrocercus urophasianus*) that require a mean shrub cover of 15-25% for part of their lifespan (Stiver et al. 2015).

Site selection

Our study area was northwestern Utah in the Great Basin floristic ecoregion. The criteria for selecting sites were 1) the fuel treatment and wildfire encounter occurred on Bureau of Land Management (BLM), State of Utah School and Institutional Trust Lands Administration (SITLA), or United States Forest Service (USFS) managed lands, 2) dominant vegetation was grass/shrubland using the 40 Scott and Burgan Fire Behavior Fuel Models (LANDFIRE 2016), 3) a single wildfire encountered the treatment and burned at least 40 ha (100 acres), 4) paired plots could be placed within treated and untreated areas of the fire, and 5) plots could be placed at least 50 meters from roads. We identified six study sites that met the criteria, where mastication treatments were completed by the Bureau of Land Management (BLM) and subsequently were encountered by wildfire (Figure 3.1, Table 3.2). Fuel treatments were targeted in sagebrush habitat to reduce juniper fuel loading, disrupt fuel continuity to reduce the risk of high-severity crown fire, and reverse closed-canopy succession that can facilitate postfire cheatgrass invasion (UWRI; https://wri.utah.gov/wri/). Treatments occurred between 2008 and 2016, and treatments ranged in size from 197 ha to 433 ha. Treatments were carried out using tractors and excavators with Fecon mulching heads to shred, grind, and mulch juniper trees (UWRI; https://wri.utah.gov/wri/).

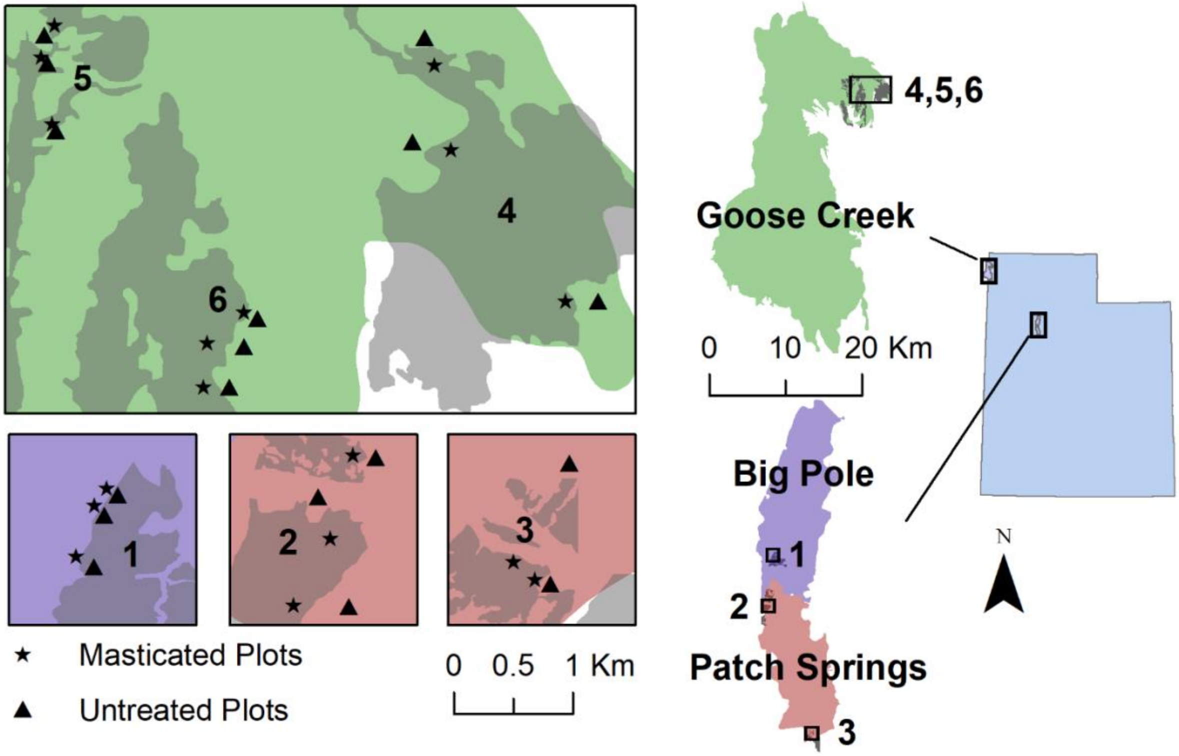

Figure 3.1 Reference locations for six study sites and plots where juniper mastication treatments were encountered by wildfire. The 2018 Goose Creek Fire encountered three treatments (top panel) in Box Elder County in northwestern Utah. The 2009 Big Pole Fire encountered one treatment (bottom left panel) and the 2013 Patch Springs fire encountered two treatments (bottom center and right panels) in Tooele County.

Table 3.2 Site summary of fuel treatment and wildfire years, final size (ha), and proportion of treatment burned. Study sites where mastication treatments were encountered by subsequent wildfire. Treatment numbers are identified on the map in Figure 3.1.

Tx No.	Treatment Name	Tx Year	Tx Size (ha)	Wildfire Name	Wildfire Year	Wildfire Size (ha)	% of Treatment Burned
1	Iosepa Bullhog 2	2008	242	Big Pole	2009	17775	100
2	Iosepa Bullhog 4	2011	275	Patch Springs	2013	12550	82
3	Terra East Bullhog 1	2008	197	Patch Springs	2013	12550	38
4	West Grouse Creek Bullhog 1	2016	416	Goose Creek	2018	53512	74
5	West Grouse Creek Bullhog 2	2014	434	Goose Creek	2018	53512	100
6	West Grouse Creek Bullhog 3	2015	384	Goose Creek	2018	53512	92

Sampling Methods

After sites were selected using spatial data, we used a GIS to place temporary paired plots in treated and untreated areas of each fire. In the field, we navigated to plots using Gaia GPS and a handheld Garmin GPSMAP® 64st unit. Once in the vicinity of each set of paired plots, we verified that 1) there was physical evidence of fire, such as charring, and 2) there was physical evidence of treatment in the treated plot, such as shredded juniper materials.

At five of the sites, three pairs of plots were established (Figure 2, Figure 3 left and center panels), while the sixth site (Terra East Bullhog 1) had two pairs of plots (Figure 3, Panel C). Plots were placed at least 50 m from roads and a minimum of 100 m into their respective masticated or untreated area of the fire. Surveying was completed in

July and August of 2020. Plots were 30 m × 30 m in size, demarcated by a baseline meter tape running parallel to the contours along the base of the slope. Three transect tapes were evenly spaced 8 meters apart perpendicular to the baseline tape at the 7 m, 15 m, and 23 m marks for line point intercept and belt transect surveys (Figure 3.2).

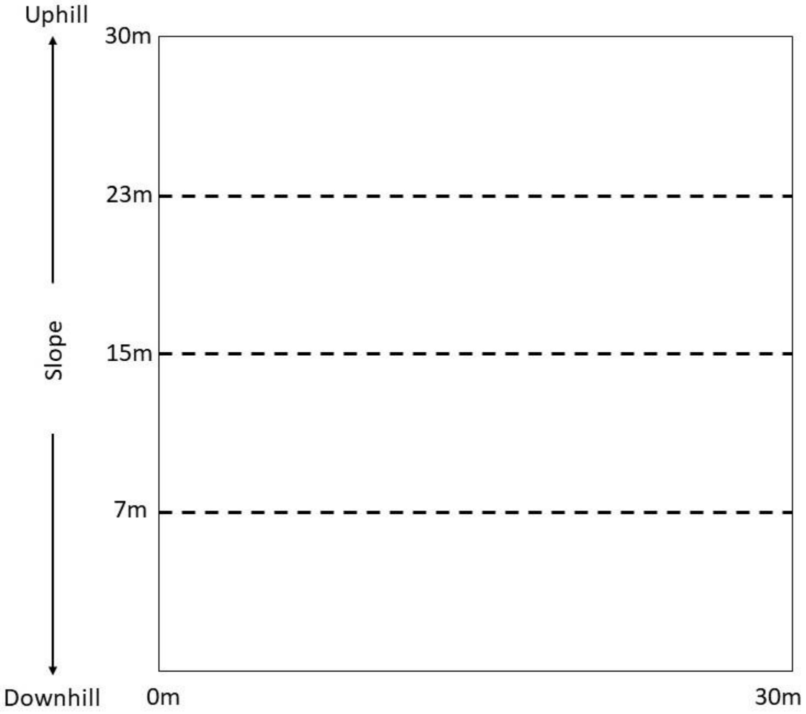

Figure 3.2 Diagram of plot design. Plot boundaries are represented by the solid lines and dotted lines represent the three transects used for surveying. Figure adapted from Bourne and Bunting (2011).

Line point intercept

The line point intercept (LPI) method (Bonham 1989; Bourne and Bunting 2011) was used to measure tree and shrub canopy, foliar vegetation, and soil surface classes, as defined by SageSTEP protocol. We dropped a pin flag about 5 cm above the vegetation on the uphill side of each transect at every half meter. Trees and shrubs that were taller than the height of the outstretched arm were recorded as living or dead canopy hits. All materials that made contact along the pin were recorded as foliar vegetation by plant functional group (grass or forb) or in the soil surface class, with the exception of cheatgrass and shrubs being identified to species. There were 60 points per transect for a total of 180 points per plot. Cover was estimated by the number of hits out of 180 points for each vegetation category.

Belt transects

Counts of live shrubs that were 5 cm or greater in height were recorded using a one-meter belt on each side of the three transects (2 m wide × 30 m long) (Krebs 1989; Salzer 1994; Bourne and Bunting 2011). *Artemesia* species were pooled together to include Wyoming big sagebrush (*Artemesia tridentata* Nutt ssp. *Wyomingensis* Beetle & Young) and black sagebrush (*Artemesia nova* A. Nova). For each plot, the sagebrush counts were scaled to estimate sagebrush density per hectare.

Statistical Analysis

We used a split-plot design with paired plots as the blocks. Each block was associated with one of three wildfire occurrences. The treatment factor for plots was the treatment assignment of masticated or untreated, resulting in 34 plots. The packages *glmmTMB* (Brooks et al. 2017), *DHARMa* (Hartig 2021), *emmeans* (Lenth 2021), and *car* (Fox and Weisberg 2019) were used in the R Statistical Environment (R Core Team 2021) to fit statistical models.

To model cheatgrass and bare ground cover, a beta-binomial GLMM with a logit link function was used because a binomial GLMM was over-dispersed for both response variables (Harrison 2015). The beta binomial distribution was used for line point intercept hits, where each pin flag drop was a binary probability trial (success or failure) of touching a cover type (180 trials per plot). Fixed effects factors were treatment assignment (categorical with two levels: masticated or untreated) and number of years elapsed between treatment and fire (categorical with five levels). The plot pairs were the random effects factor (categorical with 17 levels). To model sagebrush density, a negative binomial GLMM with a log link function was used because sagebrush count data was over-dispersed with a Poisson distribution. The negative binomial was used for the count data and covariates in the experimental structure included treatment assignment as a fixed effect and plot pair as a random effect.

Results

Treatment means were back-transformed to the response scale using the *emmeans* package (Lenth 2021). Mean cheatgrass cover was 24% in masticated plots and 19% in untreated plots. There was slightly more variation of cheatgrass cover in the masticated plots, with 95% confidence intervals ranging from 15% to 32%, versus the confidence intervals of the untreated plots that ranged from 12% to 26%. The model from the beta binomial distribution resulted in no significant difference in cheatgrass cover between treated and untreated plots (-0.2719, p = 0.30). Overall patterns of cheatgrass cover within pairs and sites were not distinguishable (Figure 3.3) and time between treatment and fire was not an important predictor of cheatgrass cover.

The mean response for bare ground cover was 37% for both masticated plots and untreated plots, resulting in no significant difference in the model (-0.02722, p = 0.86). The variation within masticated plots was similar to the variation within untreated plots, with 95% confidence intervals for masticated plots being 31% to 43% and in untreated plots 30% to 43%. Overall patterns of bare ground cover within pairs and sites were not distinguishable (Figure 3.4) and time between treatment and fire was not an important predictor of bare ground cover.

Both plots in eight pairs in the Big Pole (2009) and Patch Springs (2013) fires had zero shrubs from the belt transect surveys, except for one shrub in one plot. Consequently, we analyzed shrub count data from only nine plot pairs in the Goose Creek (2018) fire, representing three mastication treatments. Sagebrush density was found to have a mean response of 10,000 shrubs per hectare in masticated plots and 6,179 shrubs per hectare in untreated plots, resulting in no significant difference (-0.4814, $p = 0.46$). Our results detected no evidence of a treatment effect on sagebrush density (Figure 3.5). Overall, there was no evidence of treatment effect on the three ecological health metrics we tested: cheatgrass cover, bare ground cover, and sagebrush density.

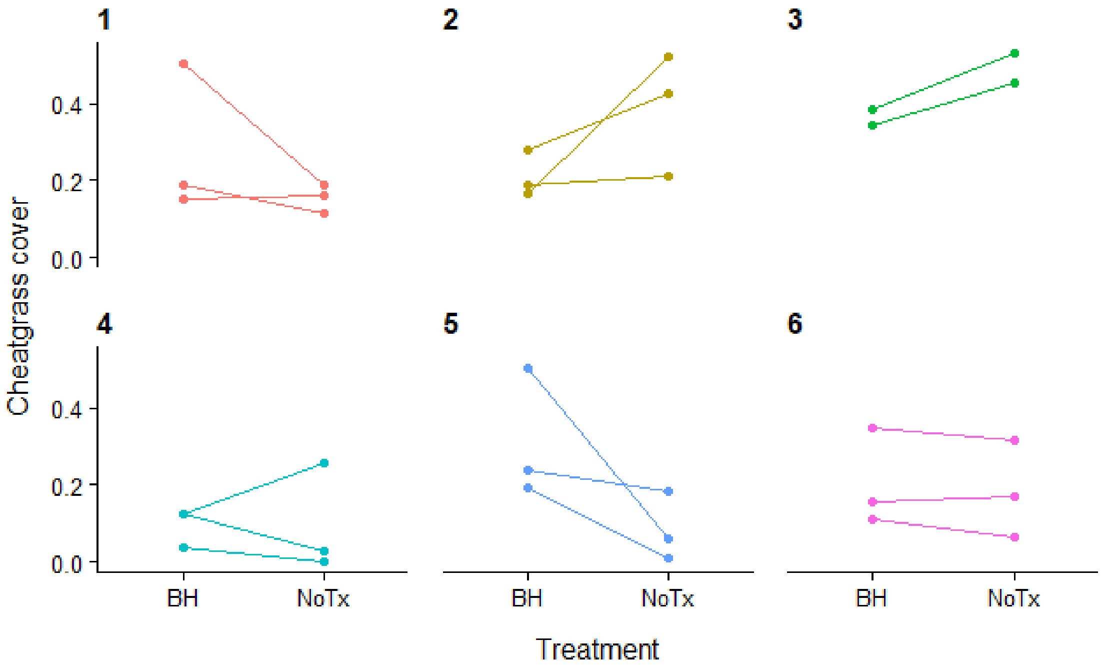

Figure 3.3 Mean cheatgrass cover in paired plots at six sites where juniper mastication treatments were encountered by wildfire. "BH" represents Bullhog® mastication treatments and "NoTx" represents untreated areas.

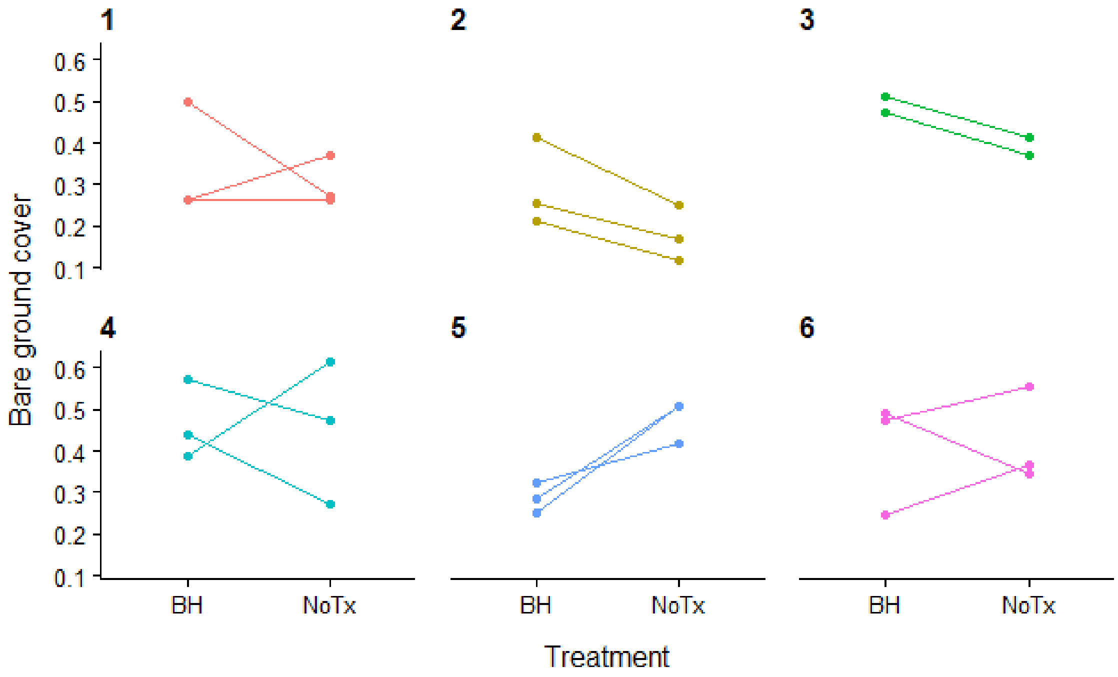

Figure 3.4 Mean bare ground cover in paired plots at six sites where juniper mastication treatments were encountered by wildfire. “BH” represents Bullhog® mastication treatments and “NoTx” represents untreated areas.

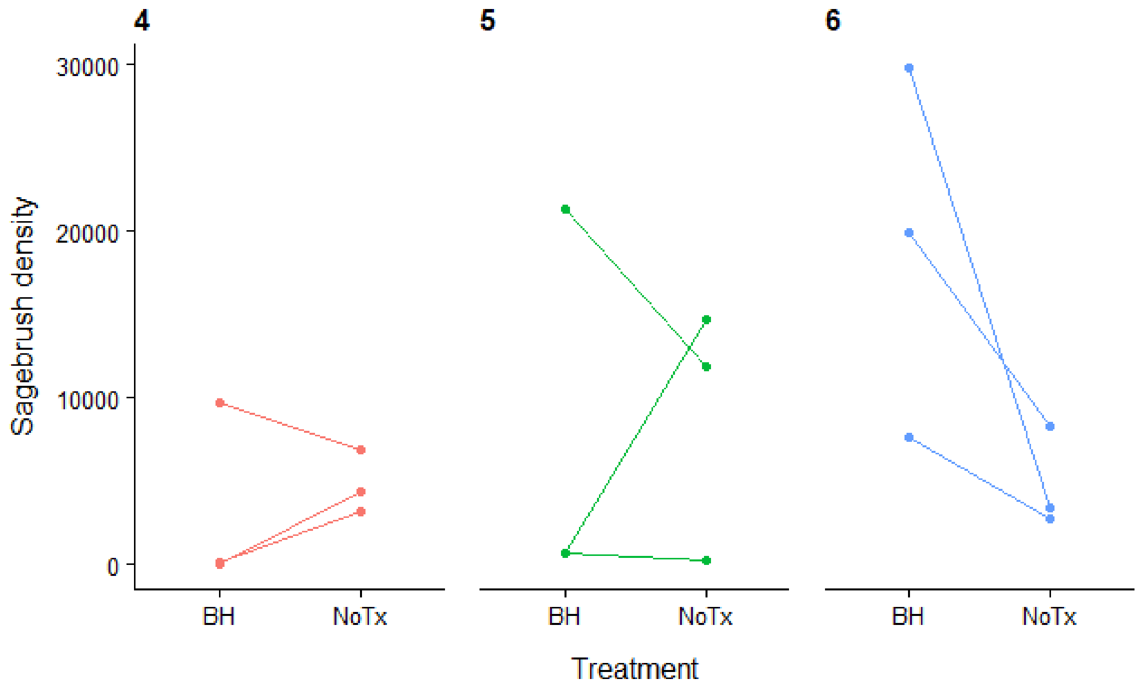

Figure 3.5 Sagebrush density in paired plots at three sites where juniper mastication treatments were encountered by wildfire. Shrub density was calculated for the three sites in the Goose Creek Fire. The belt transect counts in the three treatments in the Big Pole and Patch Springs fires resulted in only one shrub counted. “BH” represents Bullhog® mastication treatments and “NoTx” represents untreated areas.

Discussion

Juniper mastication treatments did not improve post-fire ecological health as measured by cheatgrass cover, bare ground cover, or sagebrush density. Belt transect surveys resulted in a count of zero sagebrush shrubs (with the exception of one shrub) in eight pairs of plots in three treatment sites. In the other three treatment sites, sagebrush shrubs were present, but we found no difference in sagebrush density between treated and untreated plots. Cheatgrass cover was similar across treated and untreated plots. Our findings are consistent with experimental studies that found fuel treatments may not reduce the risk of cheatgrass invasion; in a study in the Colorado River Basin, mastication was associated with a greater increase in annual herbaceous cover than hand-cutting when measured at five- and ten-years post-treatment. Burning treatments resulted in a 1% annual herbaceous cover increase after 15 years (Fick et al. 2022). Mastication may increase water and space availability for cheatgrass establishment, weakening sagebrush community's resistance to annual grass invasion. There was no difference in bare ground cover between masticated and untreated plots. This result supports the findings of another study, where pinyon juniper treatments resulted in a negligible decrease in bare ground cover compared to the control (Fick et al. 2022). Bare ground exposure is a concern with PJ removal treatments due to their reduction of protective vegetative cover and soil disturbance (Fick et al. 2022). This can lead to erosion and a decline in resistance to cheatgrass (Leffler and Ryel 2012), as invasive annual grasses can efficiently inhabit the newly available spaces (Miller and Tausch 2001).

The post-treatment succession of sagebrush communities experiencing woody infilling is largely determined by the pre-treatment plant community composition. In sagebrush habitats, as tree cover increases, shrub and grass cover decreases (Williams et al. 2017). As woody succession continues, the understory plant community is outcompeted, degraded, and becomes less resistant to annual grass invasion and less resilient to wildfire. Tree cover prior to treatment is associated with higher average cover of annual grasses and bare ground posttreatment (Fick et al. 2022). Mastication treatments with the objective of native perennial understory recovery have been recommended in early phases 1 and 2, before tree cover dominance has peaked and the understory has been lost (Williams et al. 2017). In a simulation study of fuels management outcomes in Wyoming sagebrush systems, ecological health classifications influenced the probability of treatment success. A cost-benefit analysis found treatments to be economically and ecologically effective only in healthy systems, where ecological thresholds have not been crossed into a degraded state (Taylor et al. 2013). Depending on the stage of juniper infilling at the time of treatments in this study, the shrub component may have already become too degraded to have adequate cover of seeding adults to reestablish post-treatment. The phase of pretreatment tree cover, which is unknown in our plots, could be driving the trajectory of sagebrush, cheatgrass, and bare ground density and cover responses (Fick et al. 2022). A lack of treatment effect in the density and cover of our responses could occur if the understory was already degraded.

Although including number of years elapsed between treatment and fire did not improve the fit of our models, it could help contextualize our findings. The treatments included in our study were only on the landscape for one to five years before being encountered by wildfire. On the timescale of sagebrush habitat recovery, five years is likely not enough time for posttreatment understory benefits to be fully realized. In addition, three mastication treatments in one of the wildfires were surveyed only two years postfire. It is possible that understory cover differences between mastication treatments and untreated areas of wildfires could emerge in a longer period of recovery between treatment to fire and postfire to survey. The variability of site conditions pre-treatment and during the wildfire limits the extrapolation of our results to other treatments. Factors such as pre-treatment juniper density, pre-fire understory plant cover, species composition of postfire seed mixes, precipitation, and grazing intensity were not measured or included in our models.

Our study considered how the interaction between mastication treatments and wildfires impact post-fire ecological health using real-world treatments and wildfires. Prior field studies have been experimental, where mechanical treatments and controlled burns were implemented as separate disturbances on the landscape (Miller et al. 2014; Williams et al. 2017). Our empirical study highlights the limitations of understory cover improvements when mastication treatments experience wildfire shortly after project completion. Mastication treatments are increasingly placed in areas of high wildfire risk and even experimental treatment plots have inadvertently burned (Miller et al. 2014; Wozniak et al. 2020). Although mastication treatments may have benefits that we did not measure such as reductions in fire intensity or ease of suppression, our results indicate that mastication treatments are limited in their ability to reduce negative fire effects on cheatgrass cover, bare ground cover, and sagebrush density.

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CHAPTER 4

CONCLUSION

I reviewed the spatial and temporal distribution of fuel treatments, wildfires, and their interactions on public lands in Utah and is the first empirical fuel treatment effectiveness study representing the Intermountain West. This multi-scale approach used four metrics to evaluate fuel treatment effectiveness: 1.) Encounter rates, 2.) Burn severity, 3.) Manager reports, and 4.) Ecological health.

Between 1997 and 2019, the footprint of treated area was about 485,622 hectares and the footprint of area burned by wildfire was about 1.3 million hectares public lands in Utah. The largest treatment unit was 16,187 hectares in size, while the largest fire was 148,358 hectares. The median treatment size was larger than the median for fires, but fire sizes had a much greater range of variability, caused by an abundance of small fires and the few rare fires that were over 40,000 hectares. These statewide summary statistics reiterate the scale discrepancy between treatments and fires, and thus, the relative proportion of the landscape that each can effectively alter. After establishing this baseline overview, I calculated an encounter rate of 8.7% for unique fuel treatment units and 4% for unique hectares treated that were encountered by wildfire. Generalized linear models were used to test if treatment attributes affected the likelihood of being encountered by fire. Larger and older treatments were the most likely to be encountered, as were treatments in the noxious weed category. Slash/lop and scatter treatments were the least likely type to be encountered. Noxious weed treatments had the second largest treatment sizes on average, but were infrequently applied and accounted for only a small number of treated hectares. However, their high encounter likelihood is a function of treatment size, rather than meaningful attributes influencing encounter occurrences.

Burn severity metrics quantify ecological change caused by fire and are focal in the design and implementation of fuel treatments and fire-related research. Treatment effectiveness in reducing burn severity was analyzed by fitting a linear mixed effects model to test the response of Differenced Normalized Burn Ratio (dNBR) values extracted from Monitoring Trends in Burn Severity raster layers in treated and untreated areas of 48 fires. Overall, fuel treatments reduced burn severity compared to untreated areas, and multi-treatment units were more effective in reducing severity.

When a wildfire starts or burns into a fuel treatment on public land, managers report a fuel treatment effectiveness assessment to the interagency Fuel Treatment Effectiveness Monitoring (FTEM) database. FTEM assessments capture valuable information about the benefits and limitations of fuel treatments, interactions, and fire behavior from managers experiencing the outcomes on-site. There were 323 FTEM reports from 13 BLM managers in Utah between 2001 and 2021 included in my summary. In a high majority, managers found fuel treatments to be effective in contributing to control and/or management of the fire, changing fire behavior, and being strategically located to facilitate control of the fire. The dominant type of fire spread inside treatments was most frequently surface fire, while surface fire and active crown fire were reported near equally outside the treatment.

Improving ecological health conditions is often a secondary objective of fuel treatments, with the primary objective being to alter fire behavior. Effects on ecological health were evaluated in a field study of six juniper mastication sites that were burned by subsequent wildfire. Cheatgrass cover, bare ground cover, and sagebrush density were measured as metrics of ecological health in Wyoming big sagebrush habitat and are related to resilience and resistance concepts in cold desert shrubland ecosystems. Resilience is an ecosystem's ability to recover after a disturbance such as fire, and resistance is an ecosystem's ability to resist invasive plants, such as cheatgrass. Treated and untreated areas of the fires were sampled in a split-plot design using line point intercept and belt transect surveys. A beta-binomial GLMM was fit to model cheatgrass and bare ground cover, resulting in no significant difference for cheatgrass or bare ground between treated and untreated plots. A negative binomial GLMM was used to model sagebrush density, also resulting in no significant difference between treated and untreated plots. Fuel treatments were found to be ineffective as measured by cheatgrass cover, bare ground cover, and sagebrush density.

Publicly available, pre-existing, federal data portals and databases were central to our work. There are currently several decades of spatially explicit fuel treatment and wildfire datasets that will continue to accumulate valuable data. Spatial data is inherently complex, but requiring higher degrees of data cleaning and standardization for data entries and spatial attributes by agencies prior to data publication would increase the viability of federal datasets for fire related research. The numerous unique spatial and temporal combinations of treatments and fires created project barriers, namely partially overlapping and multi-polygon instances, where one-size solutions were not appropriate. This study would have benefitted from a spatial tool that combines overlapping polygons and preserves each feature's attributes in their unique combinations.

Extracting the most recent, top layer of treatments for all analyses could have been a more feasible approach that would be sufficient for broadscale spatial analysis. Separating thin-and-burn regimens as a treatment type could have been informative as they are commonly applied and studied, but those regimens were also present in multi-treatment units, so their effects were dually tested in the burn severity reduction analysis. BLM and USFS datasets were combined for our statewide evaluation, but additional analysis of treatment effectiveness for each agency might offer clearer insight and management implications. The statewide datasets that I've compiled of fuel treatments and wildfires could be useful in future studies. Analyzing fuel treatment distribution in relation to wildfire risk on the landscape could inform effective spatial arrangement of treatments. Wildfire ignition datasets could also be incorporated to analyze how treatments affect fire spread and burn severity. Future treatment effectiveness studies in sagebrush habitat would benefit from including perennial grass cover as a metric of effectiveness because of its association with sagebrush ecosystem resilience.

My results suggest that fuel treatments are effective in their primary objective of altering fire behavior and effects when encountered by fire and that mastication treatments were ineffective at improving ecological health in sagebrush habitat. A standard does not currently exist for a "successful" fuel treatment and wildfire encounter rate. However, low encounter rates do suggest the disproportionately small treatment footprint on the landscape is not sufficient for mitigating undesirable fire behavior and outcomes, since most treatments will never be intersected by fire. My evaluations of encounter rates, treatment attributes, and burn severity metrics support management strategies that include expanding treated area on the landscape and increasing treatment sizes. Extending new treatments from current multi-treatment unit perimeters should be considered in prioritization planning, as multi-treatment units are particularly effective at reducing burn severity. Increasing fuel treatment and wildfire interactions would increase the circumstances in which fuel treatments are effective.