Wildfire: It’s Complicated

History, Effects, and Solutions

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Introduction:

As summer ends, the air over Bozeman settles into a melancholy haze. Each night, the sun's pink orb descends over the blurred lines of mountaintops. The prevalent smell of campfire smoke instills nostalgia in some, fear in others. People seek solace indoors from the harsh environment outside their windows. Is this the new normal?

The increasing prevalence and intensity of wildfires is not an issue unique to Bozeman. In the western United States as well as globally, prime wildfire conditions are affecting more people and ecosystems. Although fire has long been used as a cultural tool, modern forest management, fire suppression, human development, and climate change have allowed it to reach unprecedented levels. Consequently, wildfire threat to human health and communities has increased, imposing dangerous conditions upon susceptible individuals and minority communities. Furthermore, wildfire impacts ecological systems including soil, vegetation, invasive species, and wildlife.

Luckily, there are solutions to the wildfire problem. These include education, community planning, and effective forest management, such as prescribed burning and grazing operations. Here in Bozeman, the Forest Service recognized a need for action and implemented the Bozeman Municipal Watershed Project to mitigate the effects of a potentially catastrophic wildfire. To examine this solution, we analyzed potential fire ignition and proliferation scenarios in a model of a theoretical fire in Hyalite Canyon near Bozeman. Wildfire is complicated; there is no one historic factor or solution to nullify its detrimental effects.

Chapter 1: *History and Effects*

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History and Effects

Humans have greatly influenced natural ecosystems and natural processes; therefore, it is no surprise that we have influenced fire and its ability to act as a natural process. Wildfire in the western U.S. is common and a cyclic part of nature. Humans have created management practices and altered the landscape, in turn affecting the natural, beneficial fire regime that takes place in the west. To understand this issue, we examined the history of cultural burning and federal forest management, along with the effects of climate change and human influences on the landscape. As humans continue to alter the way fire acts as an ecological disturbance, we will see varying social and ecological responses.

Cultural burning

Cultural burning is considered the first fire management strategy used by humans. The term “Cultural burning” refers to the Indigenous practice of “the intentional lighting of smaller, controlled fires to provide a desired cultural service, such as promoting the health of vegetation and animals that provide food, clothing, ceremonial items and more” (Roos, 2021). Fire was an essential aspect of indigenous people’s way of life all around the world. The Aboriginals of Australia, Native Alaskans, Native Americans, and Native Hawaiians all used fire as a tool to improve their lives. The Australian Museum conservatively estimated—through artifacts and thermoluminescence dating—that the first nation’s people have lived in Australia for 65,000 years (Australian Museum, n.d.). There is no current evidence to prove that cultural burning has been practiced for 65,000 years, but the importance of fire in indigenous people’s communities makes it highly likely that they practiced cultural burning for at least several thousand years. Native Americans are also thought to have used cultural burning as a tool for several thousand years (U.S Department of the Interior, 2022).

Great Plains Native Americans were nomadic in the sense that they migrated cyclically because of seasonal changes. Because of this, the indigenous people had great knowledge of the land. After leaving their camp, the Sxʷpaam , translated to, “the one who makes fire,” has the duty of setting the fires before they leave (Figure 1.1). Since the indigenous people had a great understanding of the land, they believed that natural disturbances—such as fire—were beneficial to the ecosystem. They understood that plants and animals that they relied on needed various habitat types and patchiness in the landscape. The tribes would light fires frequently to promote this landscape variability (CSKT Division of Fish, Wildlife, Recreation, and Conservation, n.d.).

Figure 1.1. Maidu/Wintun/Hoopa/Yurok tribes sets fire to a redbud pile. (2020). UCDavis. Retrieved from https://climatechange.ucdavis.edu/climate/news/rethinking-wildfire

The Sxʷpaam is an extremely knowledgeable and trained person and they would not burn in random areas. They focused on areas where fire would be beneficial for the next few years. For example, the Sxʷpaam would burn in areas where Plains Indians would collect berries. This way, the understory vegetation was not overgrown and allowed for easier berry collection. Additionally, the Sxʷpaam was in charge of taking care of the fire. Salish tribal elder, Eneas, recalled that “my grandfather used to say they carried their ashes [and hot coals] in a kind of a container...they’d take good care of the fire... So they kept that on a separate...horse” (Traditional Culture 2022). Restarting fire was a common practice by using drills or flint. Similar accounts are taken from the Kootenai people of British Columbia. For short journeys, coals placed within ashes were carried on sticks to their destination. The fire-keeper held two separate bags. One that had tinder and the other contained tree fungus that easily ignited a spark. Fire was a tool and they used it wisely, and while accidents happened, they were rare.

Overall, fire was a tool that advanced ecological diversity and minimized the risk of catastrophic wildfires. Indigenous people from all over the world have used this tool to manage land for plants, animals, crops, travel, and hunting (U.S Department of the Interior 2022). Fire was beneficial to the landscape and was the most common disturbance in the Western U.S. It allowed for a patchy landscape that benefited a diverse range of species. Additionally, particular fire regimes “tend(ed) to favor tree species that were more fire resistant and less vulnerable to insect attack and disease infection” (CSKT Division of Fish, Wildlife, Recreation, and Conservation, n.d.). Furthermore, fire impacts forest nutrient cycling. With frequent fires, nutrients become more available to plants and organisms. However, without frequent fire, fuel loads from dead brush build up. Once a fire occurs, there can be a catastrophic burn because there is a lot of fuel for the fire to consume. This can result in long-term damage to soil health by burning organic matter, roots, and organisms in the soil. In this modern age, people are starting to understand the importance of cultural or prescribed burns. A recent study in the Pacific West U.S. examined prescribed fire and found that the treatments promoted desirable plant qualities, reduced the chances of pest presence, and enhanced structural qualities that relate to weaving and significant cultural uses (Long et al., 2021).

Modern forest management

Fire management is a tricky story, and it spans a huge timeline with many interesting characters. It includes those involved in fighting fires, politicians, those who live in fire threatened areas, those who have businesses in fire threatened areas, and as the list goes on, fire effects in the modern setting will likely impact almost everyone living in the United States, even those living in areas that are less prone to wildfires historically. A 2008 a study in California was conducted to examine the economic impacts on a community where fire occurs regularly. With the complexity of fire, the economic impact of fire was interconnected in many ways, demonstrating that private-sector businesses were forced to decrease wages and employment, leading to a community shift (Davis et al., 2014). The need for a shift in fire management is evident as impacts and frequency of fire increases.

The history of fire management in the United States supports fear of fire, rather than the importance that fire plays ecologically. Fire management begs the question of how fire and humans can live harmoniously, and how humans can play a part in the health of forests.

Finding this harmonious living with fire as an ally, one must also look at the history of fire management, the impact of past decisions, and the current situation. Fire management has a history that coincides with the rough history of the United States. European colonization of

North America not only shifted the power of decision making, but it also disconnected the land from most people who now call the United States home. After European settlement, fire practices quickly shifted to suppression, and in response, shifted the landscape's cycling. After the period of European colonization, the live and dead vegetation that contribute to canopy and surface fuels began to accumulate, shifting the fire regime towards higher severity (Hagmann et al., 2021; Ryan et al., 2013).

Fire Exclusion and Suppression

Throughout the 1900s, the United States Forest Service implemented many policies and marketing tactics to broadcast their negative viewpoints on fire. For example, in 1944 Smokey the Bear was created, making it possible to engage with the public on a personal level, ensuring they knew that “Only YOU can prevent fires!” This is a good reminder that human actions can cause destructive fires; however, it was largely centered on the idea that all forest fires are bad. Additionally, the 10:00 am rule was implemented in 1935, which stated that all fires should be out by 10:00 am the morning after they were reported. It was not until the 1960’s that people began to think differently, understanding that fires are an important part of the ecosystem. Extensive scientific research continued to convey the importance of natural fire regimes, which began to change the Forest Service and public sentiment on fire. New policies started to evolve, the “let-burn” policy stated that the Forest Service would let natural fires burn with no intervention if they were not a threat to human life or infrastructure. Today, most people understand the importance of fire, however, there is still some disconnect between perception and reality, especially because fires are growing in intensity and severity.

In the 21st century, fire management is not an easy topic to dissect. Instead of facing the impact of fire with science alone, we are left with diving into politics, economics, social implications, growing urbanization, and the actual impact of fire and its relationship with the land. The study of how prescribed burns (commonly referred to as Rx burns), along with many other techniques to cut down fuel loads, can be implemented back into the landscape will be a helpful point to study and involve in the discussion of fire and its complexities.

Expansion of the Wildland Urban Interface

With the changing climate, growing populations in the wildland urban interface (WUI), and historical fire suppression, wildfires are increasingly becoming a major environmental and social issue (Zald and Dunn, 2018). There are many aspects of fire ecology that we did not understand a century ago. This historical lack of knowledge created 100 years of mismanagement when it came to fire suppression and prevention. Even though today research has progressed immensely, many communities across the western United States are not taking sufficient precautionary steps to protect themselves from large, destructive wildfires.

Although there is sufficient research and agreement in fire ecology where professionals generally understand how we can mimic (to some extent) natural fire regimes, management practices to do this are increasingly difficult to implement. One of the reasons is due to the different ownerships of land throughout much of the west. Often these landowners and institutions that oversee certain fire prone areas and forests have very conflicting objectives when it comes to land use and management, which makes it nearly impossible to implement a universal operation of eco-beneficial practices (Zald and Dunn, 2018).

A study conducted on how different factors affect fire severity supports the idea that historical fire suppression has had a large impact on fire regimes (Zald and Dunn, 2018). The study also found that fires that burned on private land, despite the weather condition, burned much more severely than fires on lands managed by the Bureau of Land Management (Zald and Dunn, 2018). Publicly owned land had more variable age classes in the forests with older trees dominating the landscape and a more heterogeneous spatial structure. This was in contrast to private land or forest plantations in which the trees were all very similar in age class and much more homogenous throughout (Zald and Dunn, 2018). This reinforces the idea that land management differs greatly based on ownership and has a very large impact on fire severity.

One of the reasons wildfire has become such a complex issue is because of the rapid development of the WUI. This refers to the area where human development meets with grassland, forest, shrubland and other natural, uninhabited areas. This increases the difficulty of managing fires from an ecological perspective but also a social perspective because what is best ecologically generally contradicts what is best socially (Stein, 2013).

Approximately 32% of the housing in the United States is located in the WUI (Radeloff et al., 2005) (Figure 1.2), and this number is only expected to increase. As of the year 2000, nearly 37 million homes were located in the WUI (Stein, 2013). Additionally, in the Southwest and the Rocky Mountains almost every urban area has an outer ring located in the WUI (Hammer et al., 2009) which can become problematic not only for infrastructure in the WUI but also for homes located nearby. Even homes that are not directly situated near wildlands can be prone to wildfires, as infrastructure can be well connected and with the right weather conditions (wind, dry conditions) embers can travel for miles (Stein, 2013). Since fire plays an important ecological role in 94% of wildlands across the continental United States (Stein, 2013) it is inevitable that much of the infrastructure located in the wildland urban interface is in danger of fire at some point in the next few decades.

Figure 1.2. Distribution of the wildland urban interface in 2010 across the continental United States. Source: compiled by S.I. Stewart and V.C. Radeloff based on the 2010 census, the 2006 National Land Cover Dataset (NLCD), and the Protected Area Database v.1.1 (Stein, 2013).

Human Ignition

The rapid expansion of the WUI has also increased the possibility of more human caused fires. From 2001 to 2011, nearly 85% of fires in the United States were caused by humans, as documented by the National Fire Agency (Stein, 2013). The areas with the most acreage burned by wildfires that were human caused were in the south and southwestern U.S. (Figure 1.3) which is consistent with the highest amount of population growth (Stein, 2013).

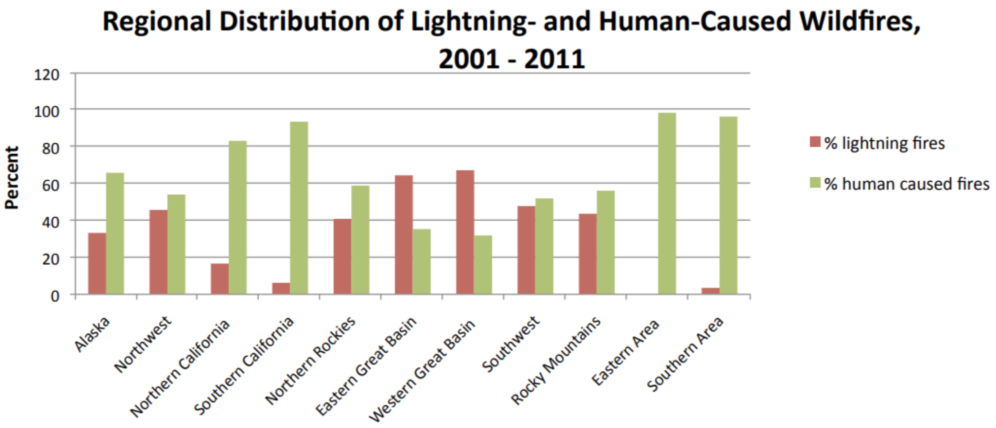

Figure 1.3. Percentage of fires caused by humans in certain areas of the United States (Stein, 2013).

Ultimately, the WUI is expanding across the western United States and globally. This is making it increasingly difficult to mitigate wildfire risk while also maintaining the process and ecological importance of natural fire regimes. It is imperative that these communities are well informed and prepared for the inevitable occurrence of fire.

In recent years, humans have been the igniters on several large, devastating wildfires. Research has shown human-caused wildfires have killed more trees and spread much faster than burns started by natural causes such as lightning. Recent studies have shown that human ignition is to blame for 84% of all wildfires in the U.S. and these fires typically spread 1.83 km a day compared to 0.83 km a day for lightning-induced burns (Joosse, 2020). Human ignition is becoming increasingly common and adding to the complicated relationship humans have with fire.

Historical Fire Regimes, Climate Change and Ecological Evidence of Human Disturbance

Topography and vegetation influence fire severity more than top-down drivers such as weather and climatic conditions, however, these larger aspects can exacerbate fires when they burn during extreme weather events (Dillon, 2011; Birch, 2015).

Historical mismanagement paired with climate change has created the perfect storm for the high severity and high intensity fires that we have seen ravaging the western U.S. An abundance of fuels and shifting fire regimes due to woody encroachment, increased fuels, invasive species, drought, insects, disease, and complications with human disturbance make this issue challenging and intertwined with social, economic, and environmental factors. Forest fires in the western U.S. have been increasing in size and severity, and have led to climatic shifts, community structure alterations, and fire regime and ecosystem shifts (Marlon et al., 2012).

Due to changes in the amount of biomass burned, there has been a growing fire deficit through the 20th century, as well as predicted rises in biomass burning which is consistent with rising temperatures and increased drought (Marlon et al., 2012). Based on historical records, biomass burning has had a dynamic equilibrium with the climate. As temperature and drought increased, so did the amount of burning biomass. Based on research by Marlon et al. (2012), as we see increases in temperature and drought, which are some of the effects of anthropogenic climate change, we will see responses in fire regimes that are beyond what we have seen in the past 3,000 years (Marlon et al., 2012). Furthermore, anthropogenic climate change will shift fire disturbance, and alter vegetative communities, which will also influence fire regimes (Halofsky et al., 2020). Below is a figure from Halofsky et al. (2020) that displays how the indirect effects of climate change (such as high severity fires) can cause shifts in vegetation and community structure (Figure 1.4). The figure shows that disturbances drive ecosystem changes, which can alter fire regimes, which then alter the vegetative community and overall landscape patterns.

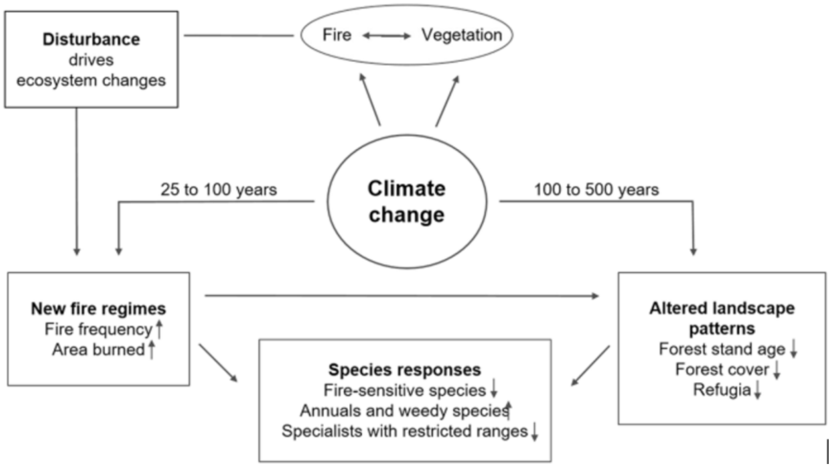

Figure 1.4. Climate change and fire can alter vegetative and fire regimes. This has effects on plant species and overall forest composition and ecosystem function.

The historical repeated fire in dry pine and mixed-conifer forests in the western U.S. helped to burn and remove ladder fuels and create a patchwork forest mosaic that allowed the forest to resist crown fires (Prichard, 2021). Now we have seen what fire exclusion has done to our forests as it has led to denser forests with layered canopies, homogenous structures, and a greater number of fire intolerant species (Prichard, 2021). Findings from recent research have shown summer temperatures in the west are rising due to climate change and becoming drier, creating dry and easily ignitable fuels (Singh, 2021). Fire seasons have expanded compared to their historical seasons, no longer are they a few months of the year; instead, we are seeing the potential for fires year-round in many regions. This long-lasting fire season is not part of the natural fire process that the west evolved with and can be directly correlated to the warming temperatures of anthropogenic climate change (Thompson, 2022).

Climate change exacerbates the severity and dangers of wildfires. Greenhouse gas emissions and forest losses from wildfires amplify global warming, which is creating hotter, drier summers conducive to burning. More evaporation from soil moisture increases flammable vegetative fuel, and differences in land and ocean temperatures boost winds that enhance oxygen availability and accelerate fire spread. Globally, there have been wildfires of unprecedented scale and duration, such as in Australia and the Amazon rainforest in 2019 and 2020 (Xu et al. 2022). In the U.S., the warming climate is responsible for half of the recent increase in burned area (Burke et al. 2021). Without action, this positive feedback loop between human-caused climate change and wildfire will continue to make human and environmental risks more severe.

Conclusion

It is clear how human history is linked to wildfire. Through the indigenous practice of cultural burning, the ecosystem remains balanced with wildfire benefitting the landscape. Through colonialism and federal fire management, this natural process has been altered which has led to where we are now. Anthropogenic climate change paired with an abundance of fuels, shifting fire regimes and human disturbance are all factors that play into how we have altered natural fire ecology. The literature has an abundance of data that makes it clear that climate change and humans on the landscape are very strongly linked to our current challenges with wildfires. Humans are the key players in the creation of the current challenges we are facing with fire. It will be vital that accurate fire ecology is taught going forward to ensure we make effective policy and that we can limit creating challenges for ourselves in the future, especially as the impacts of climate change worsen.

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Chapter 2: *Impacts on Human Health and Communities*

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Introduction

Wildfire is a prominent environmental issue that can also be destructive socially. Anthropogenic climate change and poor human decision-making have amplified the hot, dry seasons conducive to burning, allowing wildfires to become disproportionately frequent and severe. These wildfires adversely affect human health in various ways, including long-term respiratory issues and injury from proximal exposure. However, some individuals are more susceptible than others are, and socioeconomic status dictates wildfire response. Social inequality and lack of insurance accessibility force some people to become climate refugees. The increasing intensity of wildfire worldwide is becoming detrimental to people's health and the communities they live in.

Human Health

Large, high intensity fires disproportionately impact human health and socioeconomic well-being alongside environmental changes and are especially prevalent in the western United States, Canada, Russia, and Australia (Palaiologos et al. 2019). Large fires can adversely affect humans through smoke inhalation, death, and displacement, opening the discussion about human vulnerability and resilience to fire (Rongbin et al. 2020). Current fire predictions project a higher likelihood of forest fires occurring near large cities and a global fire frequency increase of 27% by 2050; these predictions account for the human-driven factors of population growth, land cover changes, and increasing global temperatures (Yaoxian et al. 2015). In addition, smoke exposure from large fires can be detrimental to the health of people thousands of miles away from the burn site, creating a dynamic between the natural and human realms that is both dangerous and unjust. Increased fire and decreased air quality have been changing communities across the US, especially in the West; people are unable and unwilling to stay in high-risk areas. Wildfire impacts human health and well-being in diverse ways, and the exact consequences should be further investigated to inform best treatment and mitigation strategies alongside the fight against climate change.

Wildfire smoke releases thousands of chemical compounds that vary with fuel type, temperature, and wind conditions (Youssouf et al. 2014). Primary emissions include fine and coarse particulate matter (PM), over 80% of which is less than 2.5 µm long ($PM_{2.5}$); carbon monoxide (CO); methane (CH_4); nitrous oxide (N_2O); nitrogen oxides (NO_x); volatile organic carbons (VOCs); and polycyclic aromatic hydrocarbons (PAHs) (Reid et al. 2016; Youssouf et al. 2014). These primary emissions are of prominent concern for public health; the Clean Air Act regulates PM, NO_2, CO, and O_3 emitted from other sources (Cascio 2018). Ground level ozone (O_3) can also form from the interaction of NO_x and VOCs with direct sunlight. O_3 and aerosols are secondary pollutants that can spread over vast distances along with PM (Xu et al. 2020). PM_{10} exposure is harmful as well; a study of Australian bushfire smoke saw an association of raised PM_{10} levels and incident levels of COPD and asthma (Finlay et al. 2012). One case study in Sub-Saharan Africa focused on Benzo(a)pyrene (BaP), the most toxic PAH, which is released by vegetation burning in African wildfires (Wu et al. 2022). This compound is highly carcinogenic with several exposure routes, and long-term exposure is associated with cardiovascular disease and pregnancy outcomes. It also undergoes long-range atmospheric transport and has been found all the way in the Arctic from Sub-Saharan burn events (Wu et al. 2022). The harmful emissions from wildfire smoke have a significant atmospheric effect that can impair human health over broad geographic areas.

There are strong associations between wildfire smoke and all-cause mortality. An estimated 339,000 premature deaths globally occur annually due to smoke exposure, and the World Health Organization estimates that fine PM in outdoor and indoor environments together produce 7 million premature deaths per year globally (Reid et al. 2016; Wang 2020). Respiratory morbidity, which includes asthma, chronic obstructive pulmonary disease, bronchitis, and pneumonia, increases the most with $PM_{2.5}$ exposure (Cascio 2018). Smoke exposure also exacerbates asthma, and medication use for obstructive lung diseases has increased (Reid et al. 2016). Upon exposure, inhaled particulates react with neural receptors in the lungs and activate reflex with the nervous system, increasing blood pressure and altering heart rhythms. In the alveolar-capillary cells in the lungs, oxidative stress and inflammatory response increase the likelihood of blood clots. In addition, fine particulate matter (<1 μm) can cross cell membranes and act systemically away from the lungs. Affected airway function weakens resistance to viruses and bacteria, amplifying the risk of infection (Cascio 2018). The oxidative stress from smoke inhalation in the respiratory tract can further result in antioxidant depletion and DNA damage (Reid et al. 2016).

Although positive associations between $PM_{2.5}$ exposure and out-of-hospital cardiac arrests and ischemic heart disease have been observed, there are inconsistent results regarding the effects of smoke exposure on cardiovascular morbidity across the literature. Cardiovascular effects stem from exposure to fine PM, whereas coarse PM inhalation is responsible for pulmonary effects (Cascio 2018). For example, $PM_{2.5}$ levels in Spain were 75% higher than the World Health Organization standard after a fire, and the fine particles have been seen to reach the alveoli and instill chronic lung disease and emphysema (Youssouf et al. 2014). Another study conducted over a particularly bad fire season in Colorado in 2012 found a positive association between $PM_{2.5}$ and asthma and wheeze as well as respiratory disease and emergency room visits (Alman et al. 2012). Similarly, there were 1,483 and 1,080 premature deaths from vegetation fire $PM_{2.5}$ across 27 European countries in 2005 and 2008, respectively (Kollanus et al. 2017). Smoke exposure strongly impacts all-cause mortality and respiratory health.

Smoke exposure in pregnant women can also dictate birth outcomes. Although there is limited data, it has been found that wildfire smoke is associated with low birthweight (Reid et al. 2016). Babies exposed to smoke in utero had a birthweight 6.1 grams lower than those without, and effects were most pronounced from exposure during the second trimester (Youssouf et al. 2014).

Some people are more at risk to all-cause and respiratory repercussions than others are. Not everyone exposed to wildfire will experience health implications, but with increasing population size, more people are at risk (Cascio 2018). Those at greatest risk include adults over the age of 65, pregnant women, children, and individuals with preexisting cardiac or respiratory conditions (Xu et al. 2020). There is also greater risk for individuals with chronic inflammatory diseases, such as obesity or diabetes, and for those with specific genetic polymorphisms (Cascio et al. 2018). A large proportion of the total population is affected by wildfire smoke exposure, and as smoke concentration and/or individual susceptibility increases, so too does the severity of the effects (Figure 2.1).

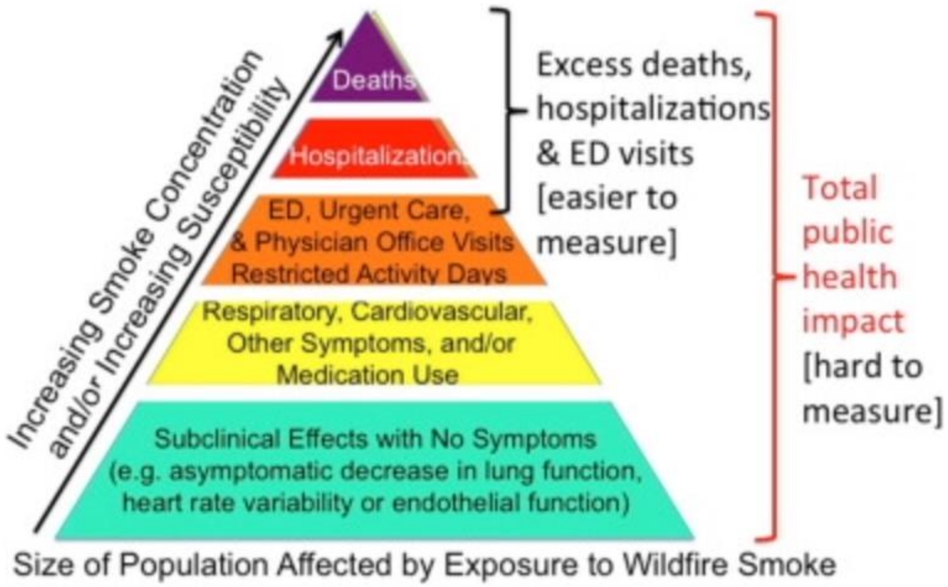

Figure 2.1. Health impacts of wildfire smoke with more severe effects associated with greater smoke concentrations and vulnerable populations (Cascio 2018).

Wildland firefighters on the frontlines of smoke exposure experience exaggerated health impacts as compared to civilians. While there is inadequate research on the long-term effects on firefighters, such as chronic illnesses, many short-term issues have been studied (Olorunfemi et al. 2016). Wildland fire fighting already comes with intense risk due to dangers from falling or blowing debris. There have been many cases of firefighters being caught and killed by a fire when the wind direction suddenly changes. Another prominent danger is prolonged exposure to intense smoke. Effects like lung inflammation and immediate immune suppression make respiratory infection more likely. Research has found different forms of smoke inhalation associated with chronic diseases such as COPD, tuberculosis, lung cancer, and bronchitis (Olorunfemi et al. 2016). For firefighters, cardiovascular disease is the leading cause of death, and they often experience decreased lung function, pulmonary inflammation, and other respiratory symptoms (Youssouf et al. 2014).

Wildfire also imposes more immediate health risks. It is common for wildland firefighters to sustain injuries from falling trees, debris, or burns, but some fires take unpredictable turns and injure or kill civilians. Being unpredictable in nature due to wind, there can be serious consequences to improper evacuation efforts. A group of 2009 wildfires in Australia killed 173 people and hospitalized 210 others (Rongbin et al. 2020). In California, there were 30 wildfire-related deaths in the first nine months of 2020 (Farkhondehmaal & Ghaffarzadegan 2022). Proximity to fires can generate burns, injuries, deaths, and mental health effects. Driving during a fire can also be dangerous because thick smoke can cause low visibility. In addition, smoke can increase ambient air pollution up to 1000 km away, causing eye irritation and corneal abrasions (Xu et al. 2020). Other health effects include drowsiness, coughing, and irritation from VOC exposure. Wildfire proximity manifests immediate health risks that are just as critical as long-term effects.

Indirect health effects of wildfire include drinking water contamination. Water quality for agricultural, industrial, domestic, and ecological needs are linked to forest health, and as forests burn, they release sediments, nutrients, heavy metals, and other contaminants that degrade water quality. Wildfires also affect hydrologic properties such as infiltration, interception, and evapotranspiration. Furthermore, fire induces water repellency in soils, resulting in greater overland flow and increased peak flows. Wildfires increase soil susceptibility along with sediment loading and downstream contaminants (Bladon et al. 2014). Drinking water contamination and downstream transport can adversely influence the health of communities that may not seem directly impacted by wildfire. The Bozeman Municipal Watershed Project, which will be discussed in detail later, aims to mitigate these risks within the local community.

At the local scale, Montana is familiar with the human and environmental implications of wildfire. Montana is projected to experience a 4-6 °F increase by mid-century and has endured a warming trend over the last 120 years, inviting more wildfires to burn. PM reduces visibility, traps heat, and creates dangerous air quality, which can incur cardiovascular, respiratory, immunological, and neurological problems, such as increased risk of dementia. Hazardous air quality from smoke in the western U.S. is responsible for a 7.2% increase in respiratory hospital admissions in adults over age 65. In Montana, days with extreme fire danger are projected to increase by 10 mid-century. Wildfire proximity here is particularly dangerous because although 64.1% of Montana houses are in the wildland-urban interface and at higher risk of burning, Montana is a rural state, making it difficult for some people to obtain healthcare (Adams et al. 2021). Climate change has amplified the dangers of wildfire in the western U.S. and will continue to do so unless action is taken.

Wildfire threat could be eased by the implementation of early wildfire warning systems as proposed by the International Conference on Forest Fire Research. Early prototypes of such systems have been successfully tested in Spain using real-time satellite surveillance (Finlay et al. 2012). These systems, along with efficient evacuation strategies, will help protect civilians in the face of a wildfire.

Communities

Another significant impact of wildfires on humans is damage to property and infrastructure. Conversation about how communities can respond and adapt to wildfires is on the rise. The burden of property destruction differs by economic circumstances. Many fires are started and destroy property in the WUI, where forested land borders and intertwines with infrastructure and makes it the most fire-prone area due to various man-made ignitions and destructible properties. Communities in the WUI vary economically based on location. Low-income communities have a much more difficult time reacting to and recovering from a disaster such as fire. On the other hand, affluent neighborhoods in the WUI are known to spend millions of dollars on personal wildfire prevention, whereas public agencies for fire prevention are typically underfunded (Garrsion & Huxman 2020). It is important to consider what specific factors make some communities more vulnerable than others. Accessing transportation to evacuate can be more difficult for low-income communities, and these places may have smaller highways and may experience traffic constrictions during a wildfire. There are also fewer resilience resources like property insurance in disadvantaged areas. It has been found that a general lack of ability to participate in fire mitigation is correlated with less education in lower income communities (Palaiologos et al. 2019). It is critical to provide more inclusivity in mitigation and education efforts regarding fire alongside a focused effort by government agencies to minimize risk in fire-prone, disadvantaged areas.

Besides the possibility of losing one's home, numerous other factors influence human resilience following a fire. Race, age, and income, for example, can play a role. Wealthy people, people without kids, and people with family and friends will be able to recover more easily after a wildfire. On the other hand, language barriers can inhibit access to aid, in some instances isolating some communities. Lack of transportation and other resources also leave lower income people at a disadvantage. Inability to afford or find insurance can play a large role in people's decisions to move away from natural disasters, but lower income people have a harder time doing so (Headwater Economics 2021). A lack of efforts to minimize these disadvantages creates unjust dangers in the event of a wildfire.

There are systems in place to mitigate the number of refugees after a fire and help them rebuild where their home once stood. Fire insurance, for example, usually covers property loss and damage, including the house and surrounding land. However, with an increase in fires, there has also been an increase in canceled insurance policies. Many insurance companies will not cover “high risk” areas, which are growing at a concerning rate (Quinton 2019). This leaves many people without insurance or paying much higher rates than normal for additional fire coverage. This is not feasible for many groups of people; about 350,000 Californians were not able to get coverage as of 2019 (Shrimali 2019). Homeowners in lower risk areas, but risk areas nonetheless, have opportunities to get insurance through ways like clearing dangerous trees and maintaining understory growth, but this is again not an affordable option for everyone.

Climate change refugees are defined as anyone forced to leave their home, state, or country due to severe climate events (Berchin et al. 2017). Unlike other refugees (from religion, race, or war, for example), climate refugees are not recognized legally under the 1951 Refugee Convention. Although similar circumstances cause all of the above to become refugees, the concept of climate refugees is a novel idea and thus has less protection and assistance readily available. The number of climate refugees has increased with increasing natural disasters such as wildfire. Wildfires drastically affect the populations around them in diverse ways. They destroy homes, cause air quality to become dangerous, and can be overall traumatic experiences. People either have to leave or want to leave to avoid losing their homes or worse. Personal actions that can be taken to protect oneself are depicted in Figure 2.2.

In 2018, fires displaced 16.1 million people around the globe, 1.2 million of those being in the United States (Martin 2019). There were 97,196 structures destroyed by 2,475 fires from 2005-2022 (Headwaters Economics 2022). There is not enough housing available for the number of people being displaced. Additionally, Jesse Keenan, an associate professor at Tulane University, estimates that upwards of 50 million Americans could be relocating to the Upper Midwest and New England regions in response to increasing climate impacts in the coming years (Hurdle 2022). Headwaters Economics reported on the number of structures that were affected and by how many fires. In 2022 alone, there have been 54,200 wildfires and approximately 6.9 million acres burned. In 2021, there were 59,000 fires and 7.1 million acres burned. 5,972 structures were burned in 2021, and 60% of those were residences (CRS 2022).

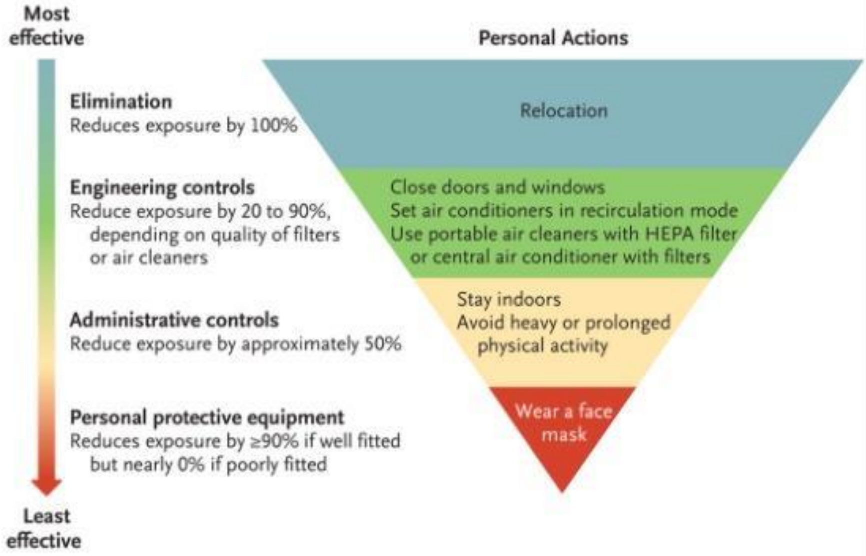

Figure 2.2. Potential solutions people can take to mitigate health effects from wildfire. Effectiveness lessens as you move down the pyramid (Xu et al. 2020).

Fire risk is highly prevalent in the western United States, especially in states like California. As mentioned above, hundreds of thousands of Californians cannot find fire coverage, and many more are affected by fire even with insurance (Shrimali 2019). In Mariposa County, CA, the Oak Fire burned nearly 20,000 acres and destroyed around 127 homes. The county population from the last census has decreased by about 1,000 people; wildfire undoubtedly impacted this number. Some residents were placed in trailers provided by the state but many left to stay with family or relocated altogether (Delgado 2022). While temporary housing can eliminate some stress post-fire, it does not eliminate it entirely. It gives victims time to look for affordable housing, but it does not make it easier to find. Many residents of the western U.S. are migrating east to escape fires completely. People do not want to be burdened by the emotional, psychological, and physical damage that fires present.

Although the western U.S. may experience the most direct impacts from fire, the entire U.S. experiences indirect impacts like housing availability, job availability, and growing population densities. Redfin, a nation-wide real estate brokerage, conducted a U.S. general-population survey for homeowners or renters. They asked how much climate change and impending climate disasters impacted their decision to relocate and found that almost 50% of all surveyed said they were large factors. It also found that 79% of people surveyed would be wary about purchasing a new home in areas of high risk of natural disasters (Katz 2021). This survey shows how scared people really are of fires and other natural disasters like flooding and sea level rise. However, on the flip side of people abandoning their high-risk homes is lower costs for buyers moving in. While the cost of a house itself might be cheaper than in other states, the costs of fire insurance or the house burning down will likely match or exceed the initial cost of housing in most places. In a time of housing shortage and high housing costs, it is not practical to think that the Midwest and eastern U.S. can accommodate as many refugees from the West as there are estimated to be in the coming years.

This problem exists here in Bozeman, Montana. The 2020 fire in the Bridger foothills destroyed 30 homes (Dore 2021). One resident who lost her home in that fire could not justify spending money to rebuild on the plot of land where her home once stood and instead decided to buy property in Manhattan, MT, an area with lower fire risk. This resident would be considered a climate refugee, despite the small distance she traveled to avoid the future risk. This is not the case for everyone. Many climate refugees have to go farther. They may willingly choose this or they may be forced to do so because of costs, housing availability, job opportunities, or other factors that influence finding a place to live.

Conclusion

To preserve human health and communities, it is important to focus efforts on combating climate change and promoting sustainable development to minimize the effects of wildfire. This will instill environmental, social, and economic benefits. It is estimated that wildfire smoke in the western U.S. incurs $165 million annually in healthcare costs (Cascio 2018). In addition, more people are developing land in vulnerable areas where housing is inexpensive, but this development must include fire-defensive strategies, such as in-home filtering to decrease inflammation and oxidative stress (Popovich & Plumer 2022; Cascio 2018). Larger fires that do not threaten structures present more health risks than smaller ones that do, so it is important to strategically focus policy and firefighting efforts as well (Burke et al. 2021). Wildfire is integrated into a cyclic pattern between human and natural systems; there is no single action solution for this non-linear relationship (Farkondehmaal & Ghaffarzadegan 2022). Although humans have instigated the wildfire issue, we must also abate it in the interest of protecting our own health and well-being. Wildfire is a prominent threat to human health and communities and we will see increased risks as fires occur more frequently and severely. Wildfire can have different effects on different people and thus different solutions are needed case by case. It is important to find and utilize solutions to limit impacts from wildfire on the health and resilience of humans and their communities.

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Chapter 3: *Ecological Impacts of Wildfire*

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Introduction

Wildfires are a natural disturbance regime that are necessary to the successional pattern of forest ecosystems, which further aids in ecological heterogeneity for a resilient and robust range of ecosystem services. Most often thought of as an ecological reset for the given area, fire has numerous ecological benefits and drawbacks. Yet, in a progressively wildfire-dominated landscape—driven by decades of fuel load accumulation and the intensifying effects of climate change—the immediate and prolonged effects to ecological systems are rather uncertain and not well understood. A few ecological components of concern that we focus on here are the underlying soil, vegetation, invasive species regimes, and wildlife.

Impact to Soil Systems

Soils play a large role in watersheds and depending on how fire has affected them may lead to differing postfire outcomes for a watershed. Low intensity fires can actually benefit soils by increasing nutrient availability such as more available nitrate and calcium (Scharenbroch, 2012) which are essential nutrients for plants. Soil structure is weakened, but maintains a solid structure afterwards (Chief et al., 2012), meaning it is more resistant to erosion. Also, soil organic matter (SOM), which is an important carbon sink as well as an important factor for soil health, remains for the most part after low severity burns (Gonzalez-Perez et al., 2004). High severity burns however have drastically different results. Soil nutrients are lost through volatilization caused by excessive heat. Soil structure becomes structureless and prone to erosion and degradation (Pereira, 2018). SOM also volatizes, and little if any is left after the high severity burn (Gonzalez-Perez et al., 2004). Understanding the severity of the fire on different parts of the watershed will lend insight into how healthy and intact soils will be post fire.

Other aspects of soil such as the CEC, or cation exchange capacity which refers to a soils capacity to hold on to cations, and nitrogen leaching are important to understanding how a watershed will be impacted post fire. In a study on how fire affected the CEC of soil, the study found that the CEC was different between high severity burn areas and low severity burn areas. In the high severity burned areas, the CEC was 57-82% lower than an unburned area as opposed to low severity burned areas, which contained a CEC 31-53% lower than an unburned area (Ulery, 2017). The reddened zones refer to high severity burn while the blackened zones refer to low severity burn. With the loss of CEC, especially in the high severity burn, the nutrients would likely leave the system leaving a less nutrient rich soil.

As for the nitrogen leaching, the more severe the fire, the more nitrogen leaves the system through erosion and leaching into streams. One study followed stream water chemistry for 14 years after a high severity burn, and found that nitrogen levels remained elevated in the streams. In addition, the watershed systems failed to retain 50% of the nitrogen inputs into the system. The excess nitrogen in the streams caused problems for the aquatic ecosystems, damaging the overall health of the watershed (Rhoades, 2018) usually in the form of excess algae forming, which uses up dissolved oxygen in the aquatic system inhibiting or killing other organisms. As for watershed implications, the nitrogen level and storage could take up to decades to recover back to post fire conditions, depending on burn severity.

Microbes such as bacteria and fungi in soil are also important to look at when evaluating how a watershed will be impacted. Microbes and fungi are important for providing nutrients that plants need. Research however is relatively new on microbes due to the complexity of microbial communities. The study below (figure 3.1) assessed microbe community composition post fire. They found that during the short term after a severe fire, microbial communities populations drastically dropped. Heat resistance microbes would be the least affected, but after time the microbial community would reestablish itself, though the community changes (Barreiro, 2021). Understanding how the microbial community changes after a fire will give insight to productivity of a watershed as well as possible remediation efforts that may be able to help reduce the effects from high severity burns.

As for fungi, heat resistant fungi often prosper after a fire. A recent study has shown that the heat resistant fungi are locally abundant after a fire and are distributed throughout the burned areas as opposed to only specific areas. The heat resistant fungi also seem to have an ecological effect on the plant community structure after a fire as they seem to reduce coniferous tree seedling biomass (Day, 2021), allowing for other plants to establish. However, the heat resistant fungi often decline after a fire, allowing for natural succession of the microbial community as well as the plant community to occur (Day, 2021). With higher frequencies of fire, heat resistant fungi may become more dominant in soils, changing the historic overall composition of the microbial communities in soil, which could lead to different plant community establishment due to the fungi inhibiting coniferous tree seedling growth.

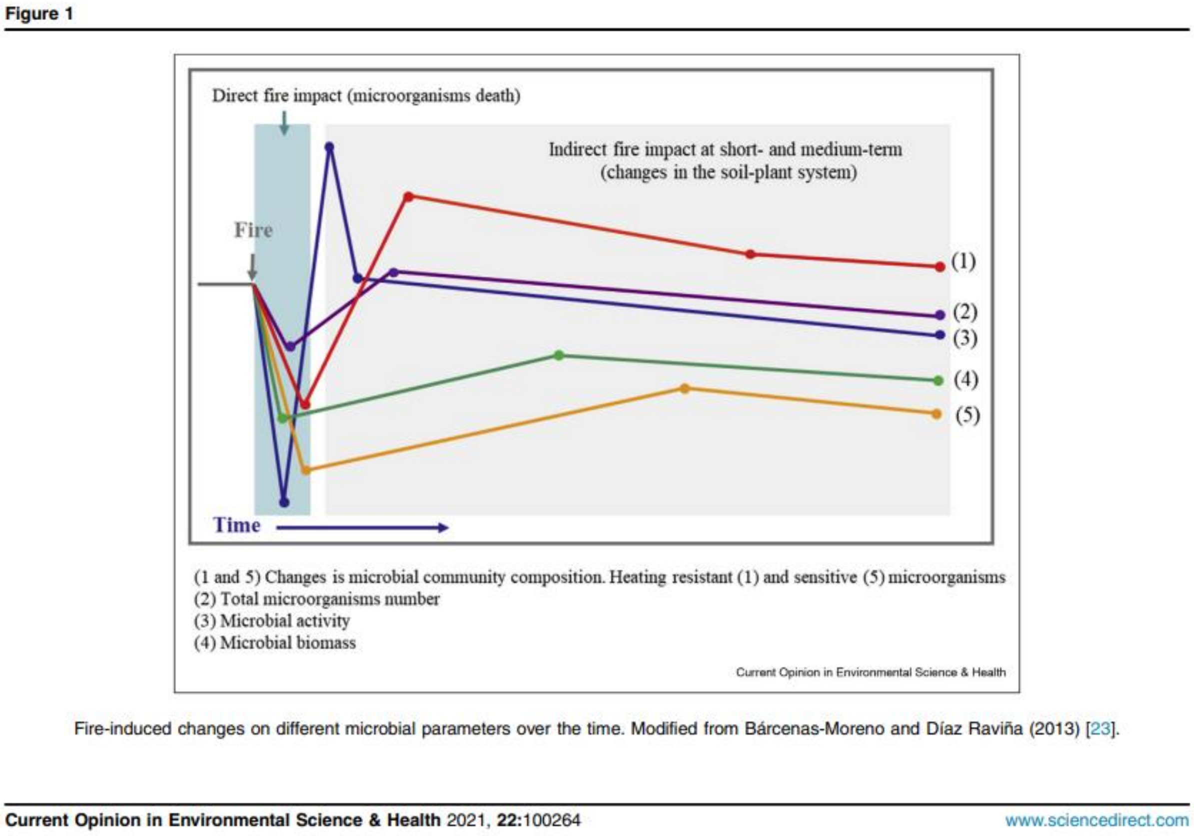

Figure 1

(1 and 5) Changes is microbial community composition. Heating resistant (1) and sensitive (5) microorganisms
(2) Total microorganisms number
(3) Microbial activity
(4) Microbial biomass

Current Opinion in Environmental Science & Health

Fire-induced changes on different microbial parameters over the time. Modified from Bárcenas-Moreno and Díaz Raviña (2013) [23].

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Figure 3.1. Fire induced changes on different microbial parameters over time.

Impact to Vegetation

A plant's ability to survive a fire, no matter the severity, is based on the species' adaptations or mechanisms (Belcher, 2013). The way that a species has adapted is dependent on its functional traits; these are the morphological, physiological, and phenological characteristics that influence survival, growth, and reproduction (Violle, 2007). It is these adaptive traits that "provide a fitness advantage in a given environment" (Keeley, 2011). The four main strategies that plants use to survive in a post-fire environment are resisters, persisters, invaders, and avoiders (Belcher, 2013).

Resisters are species that can survive and persist in low-intensity fires due to their physiological adaptations. An example of these adaptations includes thick bark, which serves as a protective layer from heat damage during a surface fire. Bark thickness is the dominant factor determining the extent to which living tissue is heated (Keeley, 2011; van Mantgem & Schwartz, 2003). Ponderosa pines (*Pinus ponderosa*) are a common tree species found across montane ecosystems of western North America; this species is “self-pruning”, meaning their lower branches will naturally fall off to reduce the likelihood of flames spreading to the treetops in the event of a fire (NPS, 2020).

As a persister, the plant can regenerate quickly post-fire despite the original plant being damaged or killed by the fire. This is seen in Lodgepole Pines (*Pinus contorta*) which produce serotinous cones that require temperatures of 45-50°C to break open and release the seeds (Lotan, 1976). Serotinous cones are an important adaptation that is seen across many species that grow in fire-prone areas by having canopy-stored seeds that are released by fire. Allowing for germination in the first growing season post-fire which maximizes plant age and seed availability by the time of the next fire (Enright, 2002).

Invaders are the species that are most likely to grow after a burn, they most likely were not abundant prior to the fire but can take advantage of the conditions following. These are the fast-growing weedy annual species that occur early in the successional timeline (Belcher, 2013). The avoiders are species of plants that are not well suited for fire conditions, so they grow best in areas that are not prone to burning, they are often referred to as fire sensitive. Many native species in these fire-prone areas have developed one or multiple of these traits to help them survive and resist the impacts of fire.

Ecological succession is important in understanding the strength and resilience of an ecosystem following a major disturbance such as a wildfire. Post-fire succession described by Nobel and Slatyer uses the idea of vital attributes (Zwolinski, 1988). These vital attributes are the "attributes of a species which are vital to its role in a vegetation replacement sequence". This is important when understanding the successional stages in an environment that has recurrent disturbances such as fire (Noble and Slatyer, 1980). It is from the idea of vital attributes that the four survival strategies of plants came from. The proposed successional stages of vegetation following a wildfire are as follows:

1. Species immediately present following a fire are species that persisted or resisted through the fire. This was dependent on the species that were present before the disturbance.
2. With only persister species present competition is low, allowing for recruitment to occur. This is the process in which new individuals are added to a population, this is commonly done through seedling germination, survivorship and growth (Eriksson & Ehrlen, 2008).
3. With the establishment of the persister species and new recruited species they will continue to grow increasing competition which causes limited recruitment.
4. In the event that a fire does not occur again these species that have established themselves will begin to re-generate and become the dominant species.
5. If a fire does occur again the cycle would restart and there would be a shift in new species in that area (Noble and Slatyer,1980, Zwolinski, 1988).

Using this successional model it looks at the entire community of an area, but an individual species' life history could be examined to better understand how species have evolved with the continual shifts in dominant species in a fire-prone area.

These adaptive traits have been considered in relation to a single fire, but an individual plant can be exposed to multiple fires that each have different characteristics, this is why the whole life cycle of the species must be considered (Chandler, 1983). Natural fire regimes are shifting due to anthropogenic and climate pressures and plants are also adapting to these pressures; it is the long-term post-fire changes that can show how an ecosystem is evolving (Belcher, 2013). Vegetation responses to fire are linked to individual life cycle stages, depending on what stage a plant is in in the event of a fire can influence its survival and recovery (Miller, 2019). Fires in the spring versus the fall have different effects because of the timing in the individual life cycle of different species. A spring fire is more likely to damage annual grasses that haven’t produced seed yet whereas perennial species are still dormant and can resprout later in the season (Wright, 1969).

Alongside changing fire regimes, fires in recent years have become more severe. The severity of a fire is summarized by the ecological impacts of a fire which is typically measured by visual indicators after the fire (Pourreza, 2013). The relationship between fire severity and species response is an important one to understand changes in community diversity after a fire. A high-severity burn in the Sierra Nevada mountains in California resulted in lower local plant diversity, but this area was historically known to have low to moderate-severity fires (Richter, 2019). Management and human implications are altering the natural fire regime that these landscapes have historically experienced, leaving a negative impact on the natural plant communities. Another study in the Intermountain West (Idaho, Montana, Washington) looked at burn sites ten years following fire (Strand, 2019) and found that in low to moderate burn severity areas there was an increase in biodiversity (Strand, 2019). It is the low to moderate burn severity that acts as maintenance to the ecosystem by removing low-growing underbrush that acts as a competition for established species (Cal Fire, 2022). With the removal of competition for established species, it also leaves open space for non-native species to establish

Impact to Invasive Species Regimes

Invasive plants play a role in changing fire dynamics across the globe. Non-native plants can be both a cause and an effect of increased fire and its consequences. Invasive grasses are problematic when it comes to these issues. These species can establish and take over after a disturbance (post fire) and they dry out early in the growing season increasing the frequency of fire. In this section, three invasive grasses and their connections with wildfire will be discussed. Cheatgrass (*Bromus tectorum*) is an invasive grass that has been established in the western US for a century. Its relationship with wildfire has been well studied and documented. Ventenata (*Ventenata dubia*) is a new invader in the western US and presents new challenges and research opportunities to understand how it will change fire dynamics as it spreads. Gamba grass (*Andropogon gayanus*) is an invasive grass in Australia and has become increasingly troublesome as it alters fire patterns in the areas where it has established.

Cheatgrass (*Bromus tectorum*) is a winter annual grass not native to western North America. It is found in Europe and Asia, and has a propensity to fill niches created by human disturbance (Young & Fay, 1997). Cheatgrass was first identified in the US around the turn of the 20th century, during which time westward expansion and over grazing was common. The dry cool climate of the intermountain west, like the steppes of Eurasia, provided ideal conditions for cheatgrass to grow. This combined with the competitive advantage cheatgrass has over native perennial bunch grasses and forbs, as well as the high amounts of overgrazing related disturbance, the perfect conditions existed for a complete takeover of the west's rangelands

(Yensen, 1981). Cheatgrass primarily existed along roadsides until 1915 where it then started to move into rangelands. At this point many rangelands were drastically over-grazed by virtue of the unlimited nature of open range grazing that occurred prior. At the time many viewed the invasion of cheatgrass as a positive event, as there was now a fast-growing grass establishing on degraded rangelands (Yensen, 1981). Cheatgrass's early spring emergence provided livestock with forage sooner than native bunch grasses. Some deliberately aided the introduction of cheatgrass, by burning sagebrush rangelands so this new grass could more easily spread (Young & Fay, 1997).

Although cheatgrass was hailed as a positive change on the landscape and was helped in its conquest, by the 1930's negative impacts were beginning to emerge. The free for all days of the wild west were over and a new age of range management had begun. Federal laws like the Taylor Grazing Act of 1934 and the research of G.D. Pickford and R.F. Daubenmire during the 1930's and 1940's ushered in this new era. Pickford's research, conducted in Utah, outlined the following pattern of cheatgrass on rangelands "a) cheatgrass invasion, b) excessive grazing, c) increase in cheatgrass, d) frequent wildfires, and e) continued dominance by cheatgrass" (Young & Fay, 1997). Daubenmire's research and others showed that Cheatgrass could establish in a new area from a small number of seeds in the seed bank. A degraded landscape was not needed for cheatgrass invasion, however, the level of degradation affected the speed of the spread. Cheatgrass's large seed production, ability to grow from the seed bank, and rapid growth in the spring gave it a significant advantage over native plants they were competing with (Young & Fay, 1997). At this point, there was too little understood about cheatgrass too late and management was largely ineffective. By the 1940's many range managers were becoming increasingly concerned with the risk of cheatgrass and its link to wildfire (Young & Fay, 1997).

High abundance of cheatgrass in the western US is both a cause and an effect of increased fire. Prior to cheatgrass invasion the shrublands of western North America had a fire return interval of 60 to 110 years. Post-cheatgrass invasion, these areas had a return interval of 3 to 5 years (D’Antonio et al., 1992). One of the reasons for this shortened fire return interval is cheatgrass's early season growth and then senescence. This results in a large quantity of dried litter at the peak of summer, primed for ignition. Cheatgrass can establish quickly after fire and can take over sites where fire has disturbed the native vegetation. A positive feedback loop is created where more fire leads to more cheatgrass and more cheatgrass leads to more fire (D’Antonio et al., 1992). However, some research indicates this feedback loop is dependent on climate and disturbance is the key driver of cheatgrass invasion post fire (Taylor et al., 2014). Cheatgrass tents to invade post-fire when the climate is warm and precipitation is low. In places where native vegetation communities are intact and climate is moderate with higher precipitation, cheatgrass establishment post-fire is not significant compared with unburned areas (Taylor et al., 2014). Taylor also found that a fire break made by a bulldozer resulted in significantly more cheat grass establishment. This indicates that cheatgrass invasion is linked to disturbance, which could include high severity fire. In a drying and warming west, this does not bode well for limiting the fire-cheatgrass positive feedback loop.

Ventenata (*Ventenata dubia*) is a winter annual grass native to northern Africa. It was first discovered in North America in Washington state during 1952 (Harvey et al., 2020). The expansion of ventenata is attributed to the movement of contaminated hay and spread along roadways (Wallace et al., 2015). Ventenata is currently invading Montana and is of concern due to its potential for negative economic and ecological effects (Harvey et al., 2020). Anecdotal observations indicate that ventenata is not palatable for livestock consumption, causing problems for farmers and ranchers. Ecologically, ventenata can outcompete native perennial grasses, leading to less biodiversity and soil erosion due to ventenata's shallow root structure. Ventenata can produce 40,000 seeds per square meter, and some research indicates that climate change will provide favorable conditions for ventenata spread (Harvey et al. 2020).

One climate change related issue that may increase the spread of ventenata is wildfire. Like cheatgrass, ventenata invasion has been linked to the disturbance window created post-wildfire (Tortorelli et al., 2020). Ventenata has shown high establishment in burn areas with low shrub density. If high severity fire removes sagebrush from the landscape, then ventenata can take over and limit reestablishment of sagebrush. This can shift areas historically dominated by sagebrush to areas dominated by annual grasses (Tortorelli et al., 2020). This will in turn alter the fire regimes and increase the occurrence of wildfire. Ventenata differs from other non-native annual grasses in that it invades forest scablands. These areas are not invaded by cheatgrass and medusahead (*Taeniatherum caput-medusae*) as the soil in these areas does not suit their needs (Tortorelli et al., 2020). This creates a new issue where areas not previously at risk of annual grass invasion now are, particularly considering the increased frequency of fire. Unlike cheatgrass, ventenata is still a relatively new invader in western North America so the long-term impacts are not yet known (Tortorelli et al., 2020). However, research suggests that a positive feedback loop between ventenata spread and increased wildfire is likely.

Gamba grass (*Andropogon gayanus*) is a perennial grass that is native to Africa and was introduced to northern Australia during the 1930's. The grass was intentionally introduced by the Australian government for pasture improvement (Head et al., 2015). Gamba grass can grow to great heights, up to 4 meters tall, much larger than the native grasses that reach heights of 1 to 3 meters. It produces large quantities of seed, up to 70,000 seeds per square meter (Head et al., 2015). These two factors combined with gamba grass's ability to grow in many environments means it can out compete native grasses and take over native vegetation. Today gamba grass covers hundreds of thousands of hectares in northern Australia and its range is still growing (Head et al., 2015). The increased amounts of gamba grass and the changing environmental conditions have the potential to significantly alter fire regimes in northern Australia and create an annual fire cycle (Rossiter et al., 2003). One of the issues with gamba grass is that it produces four times more biomass than native vegetation produces and thus fuel loads are much higher. Fire intensity is much higher in gamba grass systems, with fire intensity being eight times higher, compared with native systems (Rossiter et al., 2003). The increased height of gamba grass increases the height that flames will extend to in the tree canopy. Leaf char height can be 10 meters higher in gamba grass systems compared to native systems (Rossiter et al., 2003). Gamba grass can burn twice a year given its fast early season growth rate and fast return interval post-fire. This is a concern for land managers going forward, as they will have to dedicate more resources to wildfire (Rossiter et al., 2003). Trees are at risk in northern Australia as gamba grass will increase the likelihood that grass fires will jump to the canopy. If trees are burned, then their reestablishment will be limited as their seeds will be unable to grow due to the frequency and intensity of gamba grass fires. Gamba grass has significantly altered the fire dynamics of northern Australia and as the effects of climate change continue to unfold the negative impacts will only increase.

As land-use changes and variation in climate and wildfire become more prevalent across the globe, these invasive grasses will grow in the area, and they will continue to affect fire dynamics. It is therefore important that we study invasive plant species and their relationship with fire to limit the negative consequences that can arise.

Impact to Wildlife

Disturbance regimes—such as flood events, disease outbreaks, sudden shifts in climate, wildfire and more—foster a mosaic of successional habitat which is fundamental towards maintaining a healthy and resilient ecosystem (Kuuluvainen et al., 2021). The fire severity mosaic creates a diverse array of habitat suitable for a greater number of species occupancy and use. Some species will be adversely affected while others may benefit from a fire. For instance, a high-severity fire that burns both the understory and canopy, commensurate with dead standing trees, shrubs, tree seedlings, and herbaceous plants may see increased use by certain species (Swanson et al., 2011). Spotted owls (*Strix occidentalis*), previously thought of being old-growth obligates with negative responses to fire, have appeared to be fairly resilient to mixed–high severity fires (Lee, 2018). Similarly, ungulates like bison (*Bison bison*) and domestic cattle have been observed to prefer recently burned patches (Allred et al., 2011), which illustrates a relationship between time since a fire event and forage abundance and quality.

Members of the browsing and grazing community routinely make site-specific foraging decisions regarding quality and quantity. In response to wildfire, some studies have shown high-quality forage is readily available following a fire event, albeit not in any considerable quantity (Snobl et al., 2022; Proffitt et al., 2019). As time increases following a fire event, forage biomass increases and nutritional value and palatability declines. Therefore, tradeoffs exist and many species have been observed to select for vegetative patches of intermediate quality to account for availability (Tyers, 2003; Allred et al., 2011). However, many nuances are present and are not well understood. Post-fire forage dynamics will ultimately vary depending on the severity of fire, terrain, forest-type, the herbivore of interest, weather patterns before and after the disturbance, establishment of native and/or non-native species, etc. Studies suggest that larger herbivores may select for burned and unburned patches, while smaller mammals have been found to be most abundant after high severity fire (Allred et al., 2011). This is perhaps indicative of the tradeoff between high quality forage available immediately after a fire and the abundance associated with unburned patches.

Species-specific movement in response to wildfire is highly variable, and the knowledge of immediate to short-term behavioral responses is limited (Kreling et al., 2021). For instance, black-tailed deer have been known to return to their home range within hours after a fire, despite significant losses in nutritional and cover vegetation. Spotted owls—who exhibit strong site fidelity—have actually been known to return to previously occupied spaces, even in the case of mixed–high severity fires (Lee, 2018). However, species may also exhibit strong site fidelity because of their limited mobility or sparse resource availability, thus wildfire may pose a significant risk to these members. In the case of summer fires in Montana, Jennifer Ramsey, a wildlife veterinarian from the Department of Fish, Wildlife, and Parks (FWP) states that the agency has observed increased black bear activity in areas surrounding a fire in the fall (Jennifer Ramsey, personal communication, October 18, 2022). This activity may be caused by the bears' primary food source being eliminated, thus they need to venture further from their home range to prepare for hibernation.

Fires in forested landscapes alter the composition of nutritional and cover vegetation, which may influence the distribution and demography of a species (Snobl et al., 2022). A prime example of this disturbance regime and subsequent wildlife response was well researched during the 1988 wildfires in Yellowstone National Park (Singer et al., 1989). This large-scale disturbance provided a unique opportunity to study numerous large mammals, mainly elk populations, in response to large stochastic fire events.

Preceding the fire in the park, extensive droughts significantly reduced grassland productivity—by as much as 50% for elk summer range grazing—further causing synergistic effects for post-fire ungulate forage abundance. Of the nearly 800,000 acres (36%) of the park that was affected by these fires (*1988 Fires - Yellowstone National Park [U.S National Park Service]*, n.d.), relatively few animals died as a direct result of the fire: 246 elk, 2 moose, 4 mule deer, and 9 bison were found dead due to a combination of smoke inhalation and the flames (Singer et al., 1989). Of the extensive number of fires in the park, it was documented that anywhere between 2–50% of elk winter ranges burned, further causing an unprecedented rise in mortality rates during the winter of 1988–1989. It was estimated that 24–27% of the northern Yellowstone elk herd died from natural causes—stemming from a combination of summer drought, extensive fire, and a lack of forage abundance (Singer et al., 1989).

Migration corridors are crucial traveling routes that access seasonally available resources, breeding grounds, and summer and winter ranges—most notably practiced by large mammals, fish, birds and insects (e.g. mule deer, elk, grizzly, salmon, monarch butterflies, etc.) (Middleton et al., 2020). Previous documentation of migration corridors affected by wildfire are limited, and long-term research appears to be constrained to the Intermountain West and focused on ungulate populations. Winter range sites, characterized by mountain foothills and low elevation grasslands have been primarily susceptible to wildfire. In a recent report of ungulate migrations in the Western United States, wildfire has been noted to be a challenge to mule deer migration corridors because of diminishing habitat and nutritional resources (Kauffman at al., 2022).

The responses of wildlife to wildfire are numerous, nuanced, and rather complex. Depending on a number of characteristics—forest type, severity of fire, duration of fire, successional timeframe of select plants, proximity to adequate resources, proximity to urban areas, and considerably more factors—wildlife may respond differently with their own novel mechanisms for post-disturbance behavior. While wildfire continues to exacerbate alongside climate change and rising temperatures, it seems more crucial than ever to gather a better understanding of wildlife responses to wildfire, prescribed burning, and the broader scope of forest management practices. Additionally, as an ever-increasing number of people and investment is integrated on wildland urban interfaces, the potential for wildlife-human conflict is on the rise. Not to mention, living and recreating in this interface may promote the involuntary spread of invasive species through human activity, and may increase competition for shared resources at the finer scale, i.e. seasonal berry picking, mushroom hunting, etc. It is clear more research is needed to understand the effects of fire disturbance on wildlife, especially in a progressively wildfire dominated landscape, as to develop management policies in the best interest of forest occupants.

Conclusion

Fire represents a process of renewal for a given ecosystem. The underlying soil, as well as flora and fauna are impacted by a number of direct and indirect influences. Making sense of these affected processes to better inform forest management practices, i.e., timber sales, watershed analysis, invasive species threats, etc., is crucial to building an integrated forest management plan. Acknowledging each component of the forest ecosystem, from the health of the underlying soil and nutrient availability, to native and or non-native species establishment, and the expected behavior of wildlife are only a few metrics to assess when it relates to the ecosystem as a whole.

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Chapter 4: *Proposed Solutions*

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At this point, it is apparent that wildfire is a complex issue. Fortunately, there are solutions to minimize fire impact and spread. It is important to know that there will not be one solution that fixes all issues. An integrated management approach is needed to effectively manage wildfires. Within the integrated management approach, it is essential to use a combination of some or all proposed solutions based on situational needs of a wildfire risk to a community. Solutions that will be addressed will be what individual citizens can do, such as education, grazing management for fuels reduction, community planning and involvement, and what can government agencies can do, such as prescribed fires and cultural burns.

To combat the increased wildfire threat associated with the expansion of the WUI, "fire-adapted" communities have designed numerous methods to increase wildfire resilience. Wildfire resilience refers to a lower risk of damage caused by a potential wildfire, and a higher ability to rebuild after such an event. A common starting point to optimize these factors in preparation for a fire is a Community Wildfire Protection Plan (CWPP). A CWPP is a comprehensive document that outlines fire preparation measures a community plans to implement, and is part of a national program by the Wildland Fire Leadership Council to establish more fire-adapted communities. Eligible communities that establish CWPPs may be awarded federal funding to help with implementation (https://www.fs.usda.gov/managing-land/fire/grants). As outlined by FEMA, there are three necessary components of a CWPP: collaboration between local agencies/interested parties (including but not limited to local government, fire department, and forest management), prioritization of areas for fuels reduction, and recommendations to community members about individual measures to help reduce vulnerability of personal property. By establishing these three key elements, a community will be more prepared to respond to a wildfire event. Today, CWPPs are very standard, with most WUI communities having a recently updated plan (Figure 4.1).

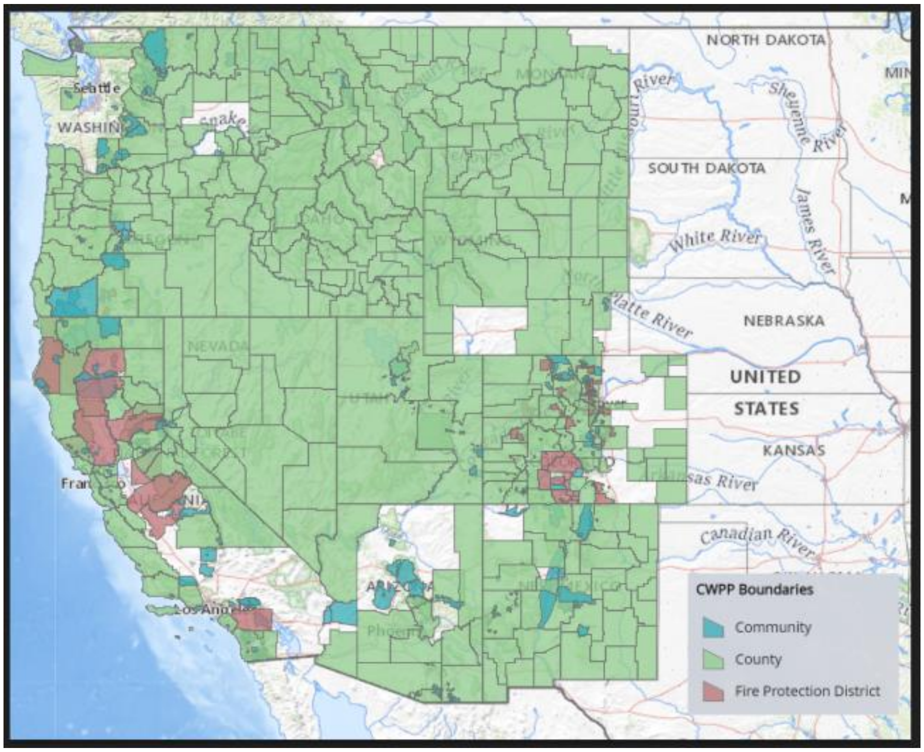
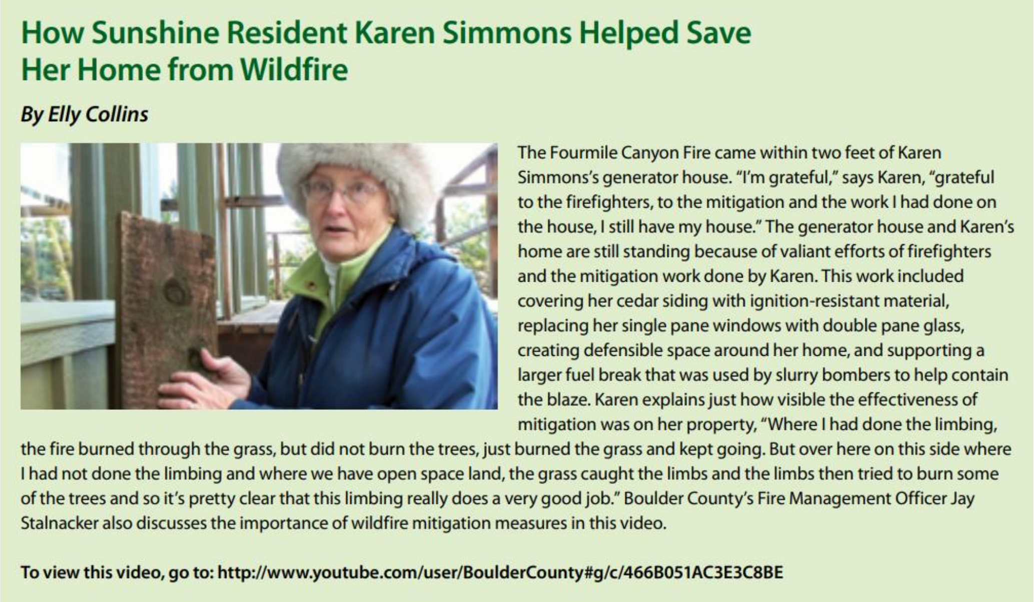


Figure 4.1. Map of Western US communities with a current CWPP. Source: fireadapted.org

Many of these plans go beyond the three required CWPP elements, giving a more advanced outline of the considerations being made to further prepare the community for a wildfire. One common element that a CWPP may include is wildfire risk models, which will help highlight areas of highest concern for fire mitigation efforts, and what areas are threatened most. Many CWPPs also define boundaries of different fire districts, helping to plan for what the immediate fire response for any location in the area would look like. Another aspect of wildfire that more advanced CWPPs may address is the ecological importance of wildfire to the forest. By taking this into consideration, communities can plan to safely use wildfire as a tool to preserve healthy forests. As one of the required CWPP elements, community recommendations are a central point in most plans. Methods of incorporating these recommendations vary, with some communities including step-by-step wildfire mitigation lists, and some giving recommendations throughout the plan where they are relevant. The CWPP for Boulder County, Colorado approaches this aspect of the plan in several ways, including planning public education/awareness events or giving example success stories of community members who prepared their spaces for fire (Figure 4.2).



How Sunshine Resident Karen Simmons Helped Save Her Home from Wildfire

By Elly Collins

The Fourmile Canyon Fire came within two feet of Karen Simmons's generator house. "I'm grateful," says Karen, "grateful to the firefighters, to the mitigation and the work I had done on the house, I still have my house." The generator house and Karen's home are still standing because of valiant efforts of firefighters and the mitigation work done by Karen. This work included covering her cedar siding with ignition-resistant material, replacing her single pane windows with double pane glass, creating defensible space around her home, and supporting a larger fuel break that was used by slurry bombers to help contain the blaze. Karen explains just how visible the effectiveness of mitigation was on her property, "Where I had done the limbing, the fire burned through the grass, but did not burn the trees, just burned the grass and kept going. But over here on this side where I had not done the limbing and where we have open space land, the grass caught the limbs and the limbs then tried to burn some of the trees and so it's pretty clear that this limbing really does a very good job." Boulder County's Fire Management Officer Jay Stalnacker also discusses the importance of wildfire mitigation measures in this video.

To view this video, go to: http://www.youtube.com/user/BoulderCounty#g/c/466B051AC3E3C8BE

Figure 4.2. Example of Boulder County CWPP community recommendation. Source: bouldercounty.gov

After outlining all of the measures that are determined to be useful for community resilience, many CWPPs will include a section overviewing how the plan will be put into action and continue into the future. This is very important to the plan, as it assigns specific roles to involved parties, and provides a timeline of how methods outlined in the plan will be implemented. By including this section, it helps to ensure that the document will lead to furthering community wildfire resilience. CWPPs are valuable starting points in protecting WUI areas from wildfire damage, as they require extensive thought and community cooperation to be developed. Citizens in these areas should be aware of how their CWPP addresses threats posed by wildfire, and what it recommends to defend individual properties.

When it comes to protecting structures from wildfire, there are several prevailing strategies recommended by experts. One such strategy is wildfire resistant construction materials, which make structures less susceptible to ignition during a fire. As it can be costly to replace housing materials, homeowners in high risk areas should be aware of the most critical points on their homes when it comes to wildfire-proofing. It has been found that the most vulnerable point of a home to ignition is the roof, and the number one predictor of structure survivability is whether it has an untreated wooden roof, with structures with untreated wooden roofs being between 2 and 21 times more likely to be destroyed in a fire, depending on distance from combustible vegetation (Smith et. al., 2008).

To further exemplify Boulder, Colorado, a policy was made in light of this fact to prevent new homes in high wildfire risk areas from being constructed with wooden roofs, beginning in 1989 (Boulder County Community Wildfire Protection Plan, 2011). Other areas also have implemented regulations regarding this, but all WUI homeowners should consider this when taking wildfire precautions.

Another prevalent strategy when protecting property from fire is the “defensible space” concept, which highlights the importance of removing combustible vegetation from the vicinity of a structure (Figure 4.3). This includes keeping roofs and gutters clear of debris buildup, reducing woody cover near structures, and avoiding the use of wood chip mulch (Quarles and Sindlar, 2011). The creation of defensible space in the 20-30 meters immediately adjacent to a structure was found to be most crucial, with little additional benefit in areas beyond 30 meters from the structure (Syphard, et. al., 2014). The two mentioned strategies are currently the top priorities for homeowners to protect their residences from wildfire damage, and are widely recommended by CWPPs to community members. By educating the at-risk public on wildfire in their community, wildfire resilience can be increased on individual to community-wide levels.

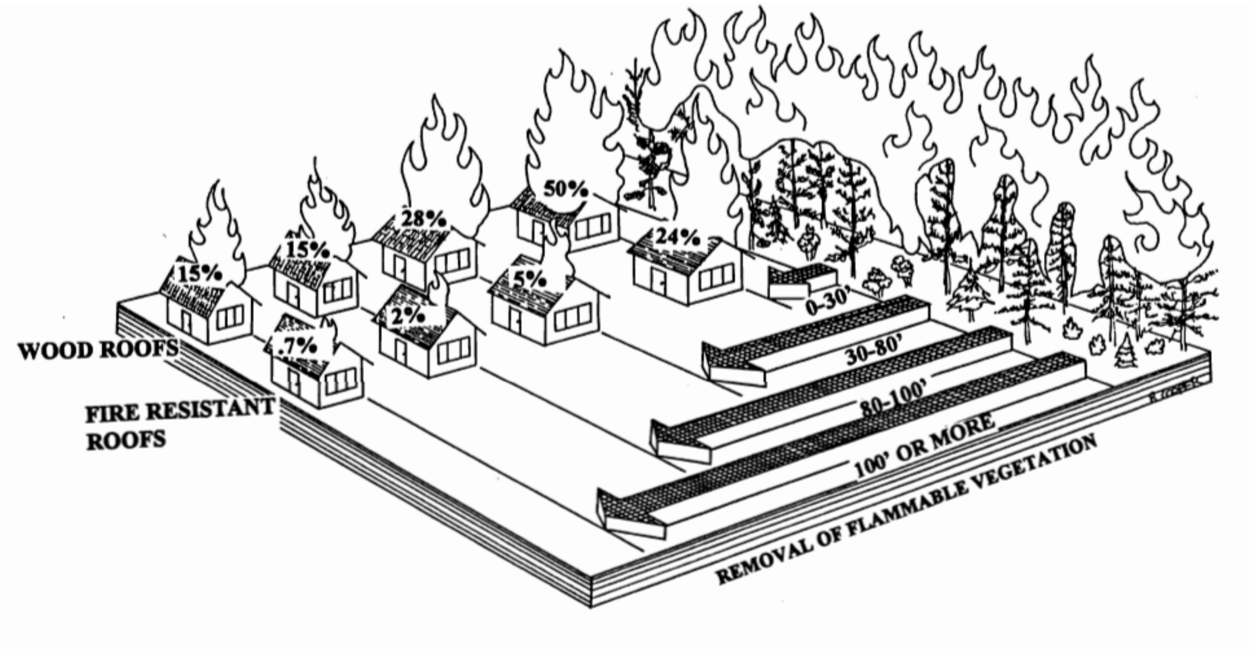


Figure 4.3. Percent of homes destroyed by wildfire. Source: Smith et. al., 2008.

To address the wildfire issue on the landscape level, forest management techniques are used to reduce duration and intensity of wildfires that could affect an area. Prescribed fire has been a solution that has been adapted and used over the years, but possibly not used to its full extent of capability. Prescribed fire is a controlled and low intensity fire, lit by humans to help reduce fuel and help promote a healthy fire cycle that can be used to help manage unexpected fires.

A study in the South Fork Salmon River drainage in the Payette National Forest, ID, provides some insight on the effects of prescribed burning and how it may provide the ability to reduce severity of wildfires to occur in the future (Arkle *et. al*, 2012) The study examined areas where prescribed burning was performed, with slightly differing treatments within each plot. Afterwards, GIS analysis of Landsat imagery was utilized to show the difference in normalized burn ratios of prescribed burn areas and areas that prescribed burns were not performed (Figure 4.4).

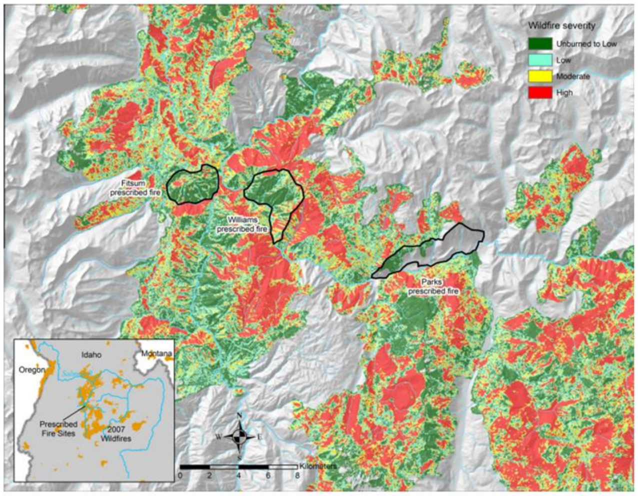


Figure 4.4: Study in the Salmon River Drainage showing impact of prescribed burning on wildfire severity (Arckle et. al, 2012).

The results of the study demonstrate the impact of prescribed fire on areas that have noticeable fuel build up, and provide evidence that the further inside the interior plot of prescribed burn, the less intense the wildfire will be, whereas the exterior areas experience less severe fire than the surrounding untreated areas, but more severe than the interior areas.

Even though it may seem like the same concept, prescribed fire and cultural burning are two different things. Prescribed fire is typically used by agencies that focus on reducing fuel loads and burning a specific amount of acreage. Cultural burning serves a different purpose. Cultural burns are strategically placed with the intent of returning to the area to make use of it again (Kerlin 2022). This differentiation is important because in today's society, mainly fire suppression or prescribed fires are the set techniques in place. This means that cultural burning hardly ever gets used for fire management.

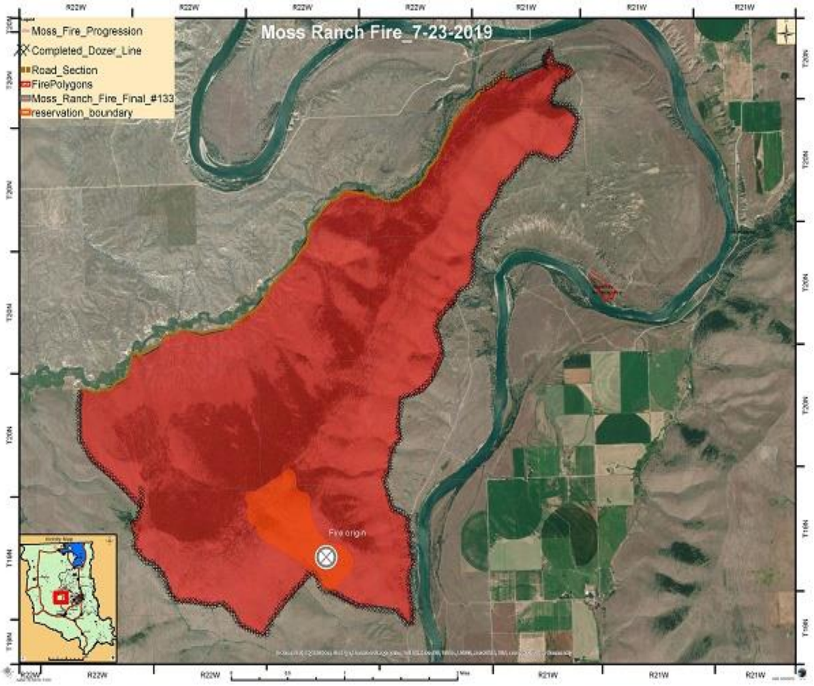


Figure 4.5. Moss Ranch fire perimeter; 8.2 square miles (5,300 acres). Darker red area shows original fire perimeter and area spread to the northwest. Photo by CSKT

A few hours away from Bozeman, the Confederated Salish and Kootenai Tribes reside on the Flathead Reservation. On the reservation, there is a robust tribal forestry service that still practices cultural burning and prescribed fires. In 2019, the tribe burned over 8.2 square miles (5,300 acres) at Moss Ranch, which suffered from fire exclusion (Figure 4.5). This instance of cultural burning was successful because they controlled the burn and no fire broke out. The tribal forestry service predicts that the burn will stop conifer encroachment and help improve wildlife habitat (Confederated Salish 2022).

Another practice that we can put into large-scale use today is grazing livestock in wildfire prone areas (rangelands and mountainous locations) for fuels reduction. This technique would also work to create fuel breaks around urban and developed areas. For example, the state of California has used high density and high intensity grazing with goats to promote a fire break through dense scrub to protect the Simi Valley library (Nelson, 2019). In this instance, grazing has single handedly avoided the loss of many historic records found inside this library. An additional benefit to using goats in this instance is the cost of manual labor vs. grazing. Goat crews typically cost an average of $500 while human crews can cost upwards of $28,000 (Nelson, 2019).

In order to make livestock grazing worthwhile to effectively cover a lot of acreage and have enough of an impact on the vegetation to create fire breaks, livestock must be grazed in high density and high intensity for short periods of time to make a difference. By doing so, not only is it the most efficient for ranchers and land managers, but it also has soil health benefits. Studies show that high density grazing for short periods of time promotes the best soil health by increasing the root growth and depth of vegetation (Volk et. al. 2021).

Along with soil health benefits, Travis Decker of Utah State University conducted a study to evaluate the vegetation dynamics and fire severity of grazed vs. ungrazed areas (Decker, 2018). In this study, it is important to note that some areas were grazed to ≥80% (greater than or equal to) cover, while other areas were grazed to ≤50% (less than or equal to) cover by sheep and goats. There were no significant results of lower fire severity by grazing ≥80% cover, therefore there is no need to overgraze areas in hopes of eliminating all fuels. Grazing as a tool for fuel management when implemented with proper intensity and timing leave rangelands less susceptible to high-intensity wildfires and can reduce the flame length and rate of spread of a wildfire in a previously grazed area (Decker, 2018). Another benefit of having previously grazed areas within an active wildfire is they can serve as safe areas for fire crews to enter and attack a larger wildfire.

An additional threat to Western landscapes are invasive plant species. Cheatgrass (*Bromus tectorum*) is one of the most abundant and hard to control grass species. “Cheatgrass is an invasive annual that dominates more than 100 million acres of the Great Basin in the western U.S. germinating each winter, cheatgrass grows furiously in spring and dies in early summer, leaving the range carpeted in golden dry tinder” (Kaplan, 2021). A technique that we can implement to combat the Cheatgrass issue is to graze the Cheatgrass early in the spring, before the plant matures and before native grass species take off. Not only will this limit reseeding and spread of Cheatgrass, but it will also eliminate the Cheatgrass fuel load come mid to late summer. By grazing the Cheatgrass early it will also give native plant species an upper hand in competition and will help select for native species to fight back against the Cheatgrass. Jim Baker of Montana Cattlemen's Association has put these practices in motion on his cattle ranch in Missoula County, Montana. “We have not seen any severe wildfire on our property in decades, and we see many more native species and species diversity by grazing cattle in the early spring to fight cheatgrass” (Jim Baker, personal communication, October 13, 2022). Another journal, states that annual invasive grass invasion of the sagebrush ecosystem is a major driver of the increase in fire frequency and large fires that threaten life and property (Davies et. al. 2021). With Sagebrush communities making up a large part of Western landscapes, it is important to note that these areas are becoming increasingly optimal for invasive species and risk of fire. By introducing grazing, it can be used to induce compositional changes in the plant community that can alter fuel characteristics (Davies et. al. 2021). By using the techniques of early spring grazing, we can help push these Sagebrush communities to be less susceptible to fire, decrease fuels, increase soil health, and promote the growth of native plant species.

As a result of the expansion of the wildland urban interface throughout the United States the amount of infrastructure that can be burned is increasing, as well as the potential harm to humans and society. Partially because of the lack of money for more extensive land management this idea of “fire-adapted” communities is becoming more appealing (NASF, 2009). These communities are well informed and engaged in the matter of fire in relation to infrastructure, landscaping, and surrounding ecosystems (Stein, 2013).

These “fire-adapted” communities are more likely to develop proactive approaches in responding to wildfire, instead of a responsive action after fire has occurred. This centers greatly around education with the idea that the more the public is informed about wildfire and the ecological importance of it, the better off these communities will be that are located in the wildland urban interface (Stein, 2013).

Oftentimes communities start to implement management strategies after a destructive fire has occurred, but this approach aims to limit that after-the-fact response and enable communities to make informed decisions about what is best for their community in protection from fire prior to harmful event. The public is much more likely to be open to solutions such as prescribed burning, grazing, and community planning if they understand why there is a need for this. Untimely, fire management needs to incorporate a multifaceted approach which requires strong connections between stakeholder, scientists, land managers, and the public, while making sure adaptive practices are economically, socially, and ecologically feasible (Penman, 2011).

With the combination of all proposed solutions, there are many instances where we can proactively prepare for wildfire in order to ensure the best outcome for communities that we all reside in as well as the ecological health of the natural ecosystems around us. Viable solutions will differ based on location and scenario, so it is important that agencies and individuals are educated on all of the methods used in the field in order to make the best management decisions based on situational needs of each wildfire application. As discussed, integrated management aims to optimize the balance of these different solutions. The following chapter including the Bozeman Municipal Watershed and Fire Models has room where some of these solutions could apply.

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Chapter 5: *Case Study of the BMWP and Modeling Wildfire & Nitrate Runoff in the BMWP*

Authors: Mackenzie Carlisle, Sam Lashley

BMWP Case Study - Purpose & Need for Action

In the early 2000's, the Bozeman and Hyalite Creek watersheds were analyzed by three different assessments, a US Forest Service risk assessment (2003), a Bozeman Creek watershed assessment done by the Bozeman Creek Watershed Council (2004), and one by the City of Bozeman Source Watershed Assessment (2004). These assessments separately found "that fuel conditions within the Municipal watershed posed risks to the municipal water supply in the event of a wildfire" (USDA Forest Service, 2010). In 2005, the Forest Service began the decision making process to bring this project into being with the overall goal to protect the Bozeman Municipal Watershed as well as nearby WUI areas and increase safety for wildland firefighters in the event of wildfire in that area. The supplemental FEIS for this project was signed in 2010 and the Record of Decision was signed in 2011. It is fairly well known that around 80% of Bozeman's water is supplied by Bozeman and Hyalite Creeks, with the other 20% sourced from Lyman Creek; with the entirety of Bozeman's water supply coming from National Forest land (Bozeman Watershed, 2012). Since these watersheds also overlap with WUI areas and fire in this watershed is inevitable, there is much to be concerned about. Without any action, the watershed treatment facility could become inundated with sediment and debris in the event of wildfire in the watershed, cutting off the flow of drinkable water to the city. This would leave Bozeman with an approximate two-day supply of water from the city's reserves. Given these circumstances, action must be taken to prevent this catastrophe, and the BMWP aims to be the appropriate action taken in this case.

Project Goals & Actions

The final set of treatments and actions decided upon for this project was listed as ‘Alternative 6’ in the proposal, which included adjustments to appropriately respond to public comment received prior. This alternative includes the following treatments to be performed on a combination of City of Bozeman and Forest Service lands: 497 total acres of skyline thinning, 805 total acres of helicopter thinning, 744 total acres of tractor thinning, 1,117 total acres of small diameter thinning, and 1,512 total acres of prescribed burning (USDA Forest Service, 2010) (Figure 5.1).

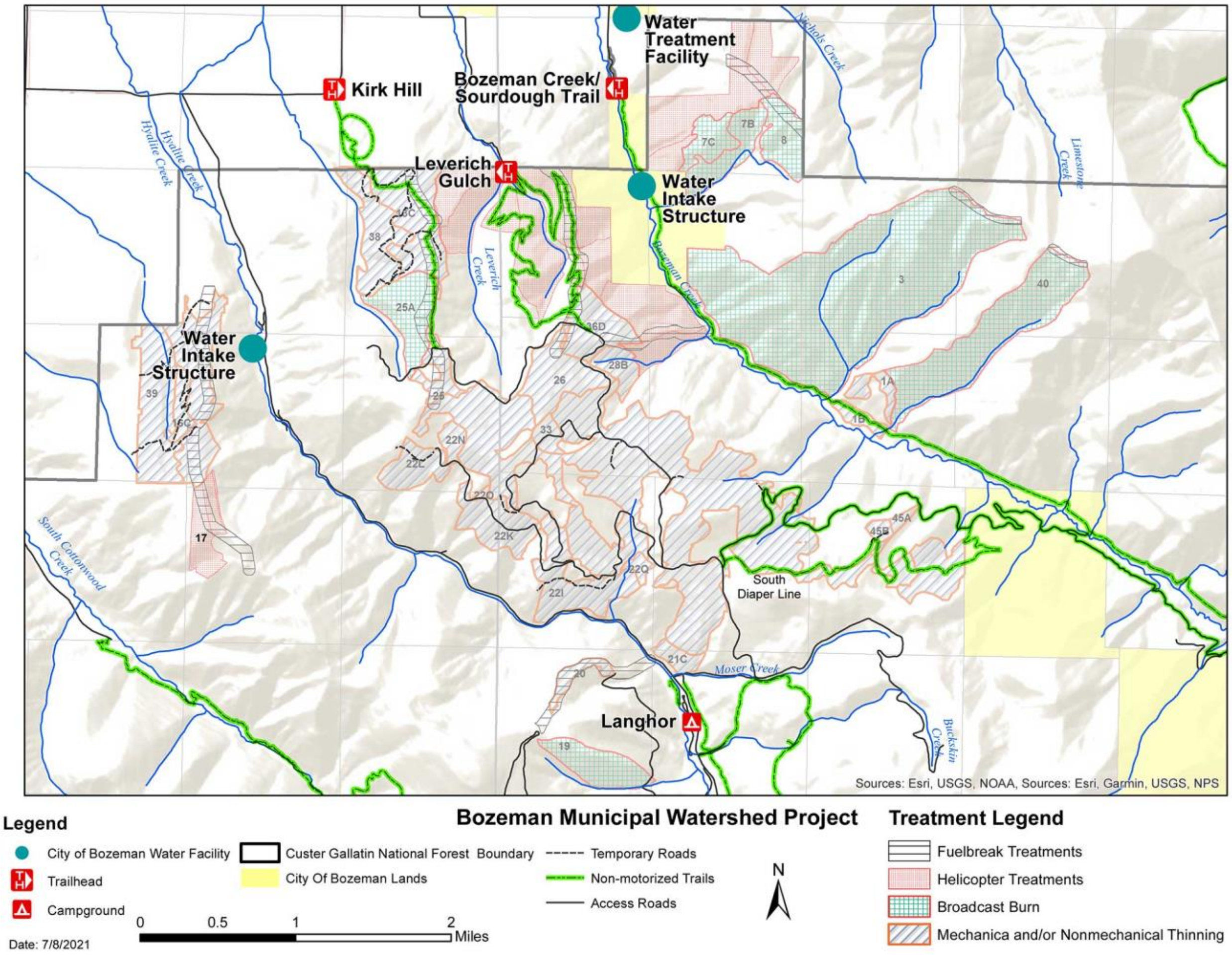

Figure 5.1. Forest fuels reduction treatments included in the BMWP; Source: bznwatershed.com

In comparison to other options put forth, alternative 6 includes reduced acreage for helicopter thinning as well as a reduced level of mechanical treatments done in the Gallatin Fringe Inventoried Roadless Area. In response to various comments from the public, Alternative 6 also includes measures to protect wildlife habitat, limit the spread of weeds and invasives, limit the effects of this project on recreation in the area, and to expand monitoring of soil and water quality, specifically on sedimentation. Various fuel breaks on ridgelines were also included to accommodate for acres lost from other treatments and to increase safety for firefighters as well as the likelihood of containing a fire in those areas.

From the start, this project has made efforts to maintain transparency about what it is and what it is proposing, and has made numerous efforts to keep the public informed and involved with the project. Most of the initial public comment made suggestions already listed in the alternatives, some were proposing different amounts of thinning versus logging. As mentioned earlier, some of the changes to Alternative 6 were brought upon in response to public comment. More recently, there has been a general sentiment that the view from town of the clustered logging is not aesthetically pleasing, however the project document notes that the clusters look worse than they imagined since the forests were already unhealthy and overrun with fuels. However, there are already plans in place to mitigate the health and aesthetics of these areas in addition to the treatments that have already taken place there. It is also noted by some that the Bozeman area has not seen a project that treats such a large amount of vegetation and area in decades, so some of this public reaction is likely stronger because in general, the public is not used to seeing treatments like these so close to home (USDA Forest Service, 2010). It is also likely that despite all of the effort to keep the public well informed, some still have outdated views on how best to maintain the health of our forests and surrounding areas. The project, through their website, has kept updates of project goals and the timeline of various treatments (Bozeman Watershed, 2012).

Implementation, Future Action & Projected Success

As of late 2022, the USFS has completed 615 acres of small diameter thinning, commercial harvest of 650 acres of a 898 acre timber sale, initial slash and hand pile burning of mechanical debris harvest, preparation of 208 acres for future timber sale and helicopter thinning, noxious weed pre-treatment spray on haul roads, and some roads have been decommissioned or temporarily recontoured (Bozeman Watershed, 2012). Future USFS project activities include the continuation of burning slash piles, broadcast burning, the continuation of larger diameter thinning by skyline logging, and another potential timber sale which would use helicopter logging in late 2023. The City of Bozeman has completed treatments on its own land under this plan, including 100 acres of the watershed that received helicopter treatments, mechanical treatments that are focused around the watershed intake structure, and a final road rehabilitation and grading of the Sourdough trail. In the future, the City of Bozeman will continue the burning of slash and hand piles as well 200 hundred acres of small diameter thinning (Bozeman Watershed, 2012). As mentioned above, this project also includes monitoring of species diversity, plant community structure, wildlife habitat, soil disturbance, water quality, invasive species, and fuel levels. The monitoring of these factors will help determine how the overall forest health is affected, if further action and treatments need to be taken, and over time - how successful the project was in reducing fuels and therefore wildfire severity.

Measuring the success of a project like this is multifaceted and takes time, so the work beforehand to determine what might work best is imperative and demands a fair amount of time as well. While this is true, it is still valuable to try to measure success throughout the project and maintain long-term monitoring well after the treatments are completed. This also helps inform decision makers on whether or not additional treatments are needed. There has been some uncertainty about fuel reduction treatments in general, and while we can attribute much of this to lingering sentiment over complete fire suppression, much of this uncertainty comes from a lack of quantitative data about fuel treatment success and fuel treatment theory failing to match up with fuel treatment practices (Omi, 2015). Ironically, fuel treatments were taking place before accompanying theory could back up the practice, and now with substantial advances in modeling and simulation, theory has quickly outpaced practice. This suggests that while we know more about how to better accomplish goals using various fuel treatments, that knowledge is not being fully implemented because the technology cannot account for logistical issues like budgets, land ownership, agency cooperation, and potential litigation setbacks. Fuel treatments can be hard to garner monetary support for, as they could be seen as superfluous at the time, and it is generally easier to find funding after fire has already started and become a (potentially) national emergency (Omi 2015).

While laws have been put into place to protect the environment, sometimes litigation over certain proposals and projects can actually hinder more than help. Part of the reason that the BMWP took over 15 years to begin was because of litigation, which is often a lengthy and expensive process. The Alliance for Wild Rockies & Native Ecosystem Council filed a lawsuit against the project in April 2012 over concern that the project treatments would endanger too many animals and their habitat, but specifically the grizzly bear and the Canada lynx (USDA Forest Service, 2012). That lawsuit was not resolved for nearly eight years. In another attempt to prevent the logging of larger diameter trees included in the project's treatments, the Cottonwood

Environmental Law Center sued in the summer of 2020, a judge then dismissed the case before the year's end, then the law center filed an appeal, which was voted against by the Bozeman Commission in the summer of 2021 (MTPR, 2021). On average, it takes 5.3 years for mechanical treatment to begin and 7.2 years for prescribed burning to begin once the environmental review process has been initiated by the Forest Service (Edwards, 2022). These averages are even longer for litigated projects. Ironically, these kinds of projects can be tied up in litigation for so long that wildfires ignite and burn in the very areas that the projects were trying to treat to prevent wildfires in the first place. This is a frustratingly repeated event and appropriate policies and routes of action can be put into place to keep these projects from being put off for so long.

Modeling Wildfire & Nitrate Runoff in the BMWP

Recapitulation

An increase in wildfire intensity and severity creates challenges for communities and people. One area of society that is increasingly at risk is the wildland urban interface or WUI. Fire management is becoming increasingly more complicated as more people live and work in the WUI (Stein, 2013). The rate of housing growth in moderate and high wildfire hazard areas in Gallatin County is 367% (Kimiko, 2022). The same alarming statistics can be found for Flathead, Ravalli, and Missoula counties. Clearly, housing developments in the WUI are not slowing down. Therefore, it is important to understand how fires spread and what measures can be taken to reduce the intensity and severity of wildfires in and near the WUI.

A critical ecosystem resource that often connects the WUI to population centers are municipal watersheds. Watersheds collect precipitation and provide municipalities with vital drinking water. As with the WUI, watersheds are also at an increased risk of wildfire. “Large and severe wildfires present a major threat to watershed health, because they can impair watershed condition, alter hydrologic and geomorphic processes, and ultimately degrade water quality” (Thompson et al., 2013). Many municipalities across the west have recognized the risks and consequences that wildfire poses to drinking water infrastructure. For example, 80% of Bozeman’s drinking water comes from Hyalite creek and Bozeman creek watersheds (Bozeman Watershed, 2012). Moving forward, it will be crucial to summarize and address the risks wildfire poses to communities.

As discussed earlier in the chapter, the current Bozeman Municipal Watershed Project (BMWP) aims to address the concerns associated with wildfire occurring south of Bozeman. The project encompasses city, state, and federal lands totaling close to 5000 acres of land located south of Bozeman, MT. The project will utilize small diameter thinning, commercial thinning, slashing, pile burning, broadcast burning, and logging to reach fuels treatment goals (Bozeman Watershed, 2012). Many critics of the project believe the fuel treatments will not adequately protect the watershed from wildfire and believe the damage done to wildlife and landscape aesthetics is too high a cost. Nearby residents such as those in the Limestone creek community have raised $453,000 to purchase a 25-year conservation easement that effectively bars any fuels treatments in the Limestone creek area. (Wright, et al., 2019). There are many stakeholders and agencies with differing opinions on how to manage the landscape. Therefore, through comprehensive wildfire modeling, risks can be accurately assessed and the need for land management be more clearly understood.

Wildfire Spread

Wildfire spread is primarily dictated by fuels, topography, and weather. Fuels are an important factor as this is an influence that can be manipulated much more easily than topography or weather. Fuels reduction and treatment projects aim to reduce the fuel loading, continuity, and combustibility in an area. The BMWP is implementing a variety of landscape treatments to accomplish this. It is important to understand how a wildfire will proliferate in the BMWP under certain weather conditions. Severe fire weather conditions are of particular interest as these “red flag” conditions are often the catalyst for disastrous wildfire events. The results of wildfire models can help determine the effects that weather, topography, and fuels have on wildfire spread and intensity. Decisions can then be made to determine appropriate fuels treatment measures for likely severe fire weather scenarios. This research will utilize a GIS modeling and simulation approach to quantify and portray the risks associated with wildfire in the Hyalite watershed. The research area will include the BMWP as well as surrounding forested and WUI lands. “Applying wildfire risk assessment models can inform investments in loss mitigation and landscape restoration and can be used to monitor spatiotemporal trends in risk” (Thompson, et al., 2015). Geospatial risk analysis can help visualize and quantify the spread of wildfire in a watershed. Results will be compared with proposed fuels reduction projects to determine the efficacy of the work being completed by BWMP. This will be accomplished by conducting wildfire spread simulations with and without fuels treatments proposed by the BMWP. Differences in arrival time and fire severity will provide evidence for the efficacy of fuels treatments in reducing fire intensity during severe fire weather conditions. Models will also show areas that could benefit from fuels reduction. Fire spread and intensity will be quantified and classified to show risk associated with the different ignition and weather scenarios. Outputs such as heat per unit area and fire line intensity can show areas where soils may become hydrophobic and are more susceptible to erosion/runoff. This information is crucial when determining secondary effects and quantifying contaminates entering waterways post-fire.

Threats to Water Quality

Wildfire presents a significant hazard to drinking water resources and a risk analysis is necessary to understanding the consequences of fire in the Bozeman municipal watershed. Research has shown that rainstorms after a wildfire can flood streams with "extremely high" levels of turbidity, phosphorus, nitrogen, and organic carbon (Hohner, et al., 2016). Damage as a direct result of wildfire is often less than secondary effects post-burn. The biggest threats to water quality after a wildfire are significant precipitation events. "The combined effects of climate change and a possible continuation of increasing fire frequency and severity will compound excess sediment issues that already exist" (Gould, et al., 2016). A severely burned watershed is primed for erosion and other forms of disturbance. Large amounts of precipitation in a short time will inundate watersheds with the above-mentioned contaminants. Turbidity and organic matter are especially hazardous to drinking water as they are difficult to remove and can necessitate plant shutdown for smaller or less advanced treatment facilities (Becker, et al., 2018). The consequences for citizens are determined by the robustness of water treatment facilities. Fortunately, Bozeman's drinking water treatment facility boasts state of the art filtration and sediment capture with contingencies and fail safes in place in the event of a wildfire (City of Bozeman, 2014). Operators at the drinking water treatment plant appear unconcerned with high levels of organic matter and nutrient contaminants in runoff after a wildfire (Patrick Yekal, 10/5/2020). They claim several contingency measures are in place at the plant to mitigate water contamination. These include an overflow lagoon, additional water treating capacity and the use of state-of-the-art carbon nanotube filters. In the event of a wildfire producing runoff with high sediment and nitrate concentrations they have the option to “sacrifice” a filter cell. This decision will ensure clean drinking water is still flowing to citizens at the cost of 1 of 8 filter cells. The main issue the treatment plant is concerned with is the physical blockage of intake pipes located in Bozeman Creek and Hyalite Creek. Therefore, the BMWP is focusing fuel reduction efforts within the vicinity of intakes to reduce fire severity and subsequent erosion.

One part of the watershed that is not receiving attention in the BMWP are the high-elevation headwaters above Hyalite reservoir. Covino et al 2019 found that “severely burned convergent hillslopes in headwater positions were associated with the highest stream NO3− concentrations due to the high proportional influence of hillslope water in these locations. Results in Rhoades (2019) suggest that targeted reforestation in severely burned convergent hillslopes in headwater positions may enhance the recovery of stream NO3− concentrations to pre-fire levels.” If severe wildfire, which is common in subalpine ecosystems, were to occur in the headwaters of the watershed it could be detrimental to water quality.

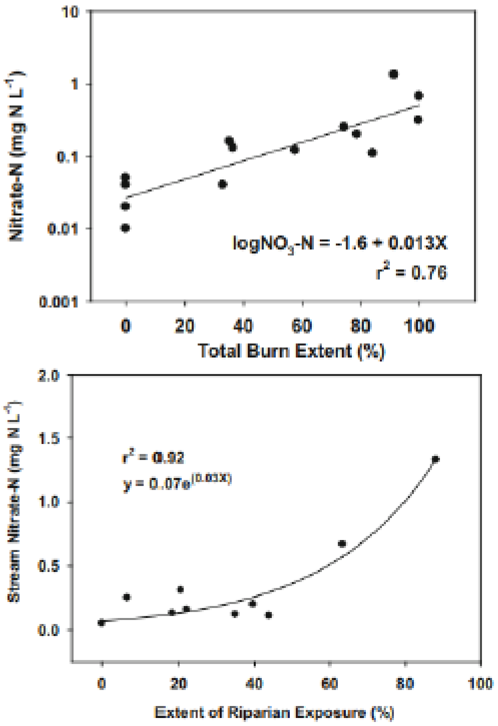

Figure 5.2: Two graphs showing relationships between dissolved nitrate concentrations and burn extent and riparian exposure.

Fire spread models can reveal burn severity and burn extent of catchments in the watershed. Rhoades (2019) found stream nitrate concentrations 10x higher in catchments with >60% total burn extent or >40% high severity burn extent (Figure 5.2). The study area in Rhea (2022) and Rhoades (2019) is similar in elevation, slope, and soil type to the Bozeman municipal watershed. In the tributaries of the Upper South Platte River average elevation is 2462m, average slope grade is 26-28%, and soils are coarse, sandy loam (Rhea, 2019). In Hyalite Canyon the average elevation is 2078 meters, average slope grade is 15-20%, and soils are coarse, sandy loam (Sugden, et al., 2015). Rhoades (2019) found that nitrate concentrations in the streams are similar throughout the water year following a fire. Therefore, seasonal variations will be negligible and ignored in this analysis. “Total burn extent explained 76% of the variation in Nitrate concentrations…” (Rhoades, et al., 2019). Burn extent will be used to predict Nitrate NO_{3-} stream concentrations by utilizing the equation $log\, log\, (NO_{3-})\ = 0.013x - 1.6, r^2 = 0.76$ formulated by Rhoades (2019), where burn extent is x (Figure 1). They found that burn extent correlated highest with NO_{3-} out of all predictor variables at a correlation coefficient of 0.43. Furthermore, riparian exposure (<30% woody cover within 20m buffer of stream) will be used to help classify nutrient runoff potential. Nitrate has an exponential relationship with riparian exposure as shown in the equation $NO_{3-} = 0.07e^{(0.03x)}$ where burn extent is x (Figure 5.2). Ideally, a vegetative index such as mean normalized difference moisture index (NDMI) would be used as this index is more sensitive to forest loss and recovery (Rhea, et al., 2022). NDMI cannot be calculated from modeled burn extents as spectral signatures cannot be reliably extrapolated from model output parameters such as heat per unit area and fire line intensity. Therefore, only total burn area extent and riparian exposure will be used to classify nitrate runoff potential of catchments in the BMWP.

Methods

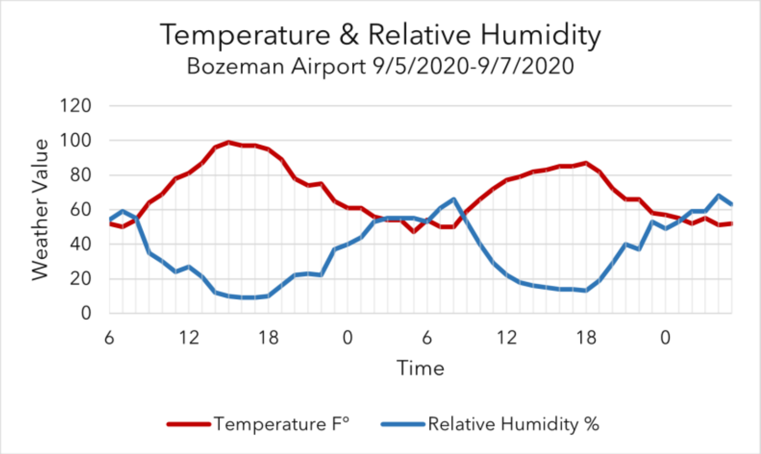

Figure 5.3: Temperature and relative humidity spanning a 48-hour period. Data was acquired from Weather Underground and was measured by a NOAA station located at the BZN Int'l airport.

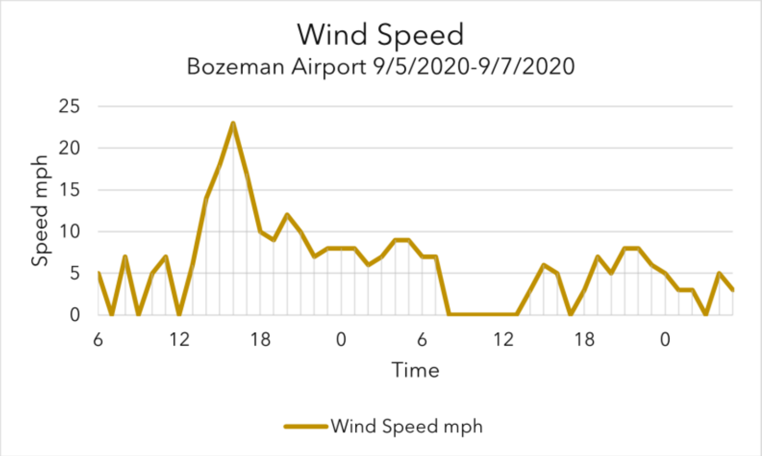

Figure 5.4: Wind speed spanning a 48-hour period. Data was acquired from Weather Underground and was measured by a NOAA station located at the BZN Int'l airport.

The simulation spanned a 48-hour period starting at 0600 and ending at 0600. Three ignition scenarios were accompanied by a severe fire weather meteorological parameter set

(Figures 5.3 and 5.4). Ignition scenarios included low-elevation immediately east of Hyalite canyon road, mid-elevation immediately south of Langhor campground, and high-elevation immediately east of Hyalite reservoir. Weather parameter sets included hourly temperature, relative humidity, wind speed, and wind direction. Weather was measured at the Bozeman airport for 48 hours from 9/5/2020 to 9/7/2020. These are the same dates as the Bridger Foothills Fire. This was done to accurately replicate realistic conditions during severe fire weather and to provide context to the wildfire simulation with a nearby wildfire that occurred under similar conditions.

Landscape data was acquired from Landfire and includes an LCP formatted file containing remotely sensed data from 2020 (LANDFIRE, 2020). This file also contains fuel model information in accordance with the 40 fuel models (Scott & Burgan, 2004). As well as elevation, slope, aspect, canopy cover, stand height, canopy base height, and canopy bulk density. These data were entered into FlamMap6.2 where they were visualized and compiled for use in a Farsite simulation (Missoula Fire Sciences Lab). Gridded winds for 1-hour timesteps were generated via WindNinja in atmosphere (.atm) file formats. WindNinja simulates diurnal and topographic wind effects from prevailing wind speed and direction inputs. Fuel moisture is the same for each time step at 6% - 1hr, 7%-10hr, and 8%-100hr. These values represent default conditions to be used in Farsite (NWCG). Farsite was used to simulate wildfire proliferation. Weather, ATM, LCP, fuel moisture, ignition site, and burn periods were inputs. The simulation encompassed 3 burn periods beginning at 0600 on the first day and ending at 0600 on the 3rd day. Ember spot probability was set to 20% which is 10% above default to simulate high intensity fire (Fire.org). Minimum spotting distance was 30 meters. Foliar moisture content was 100%. Crown fire calculation used was Scott &

Reinhardt (2001). No rate of spread (ROS) adjustments were made. Farsite outputs used included Arrival Time, Flame Length, Rate of Spread, and Heat Per Unit Area. Output data was exported to ArcGIS Pro for visualization and analysis. Additional GIS data such as structures, and boundaries were acquired from the Montana State Library GIS Clearinghouse (MSDL).

Equation 1. $log\, log\, (NO_{3-}) = 0.013x - 1.6, r^2 = 0.76$

Equation 2. $NO_{3-} = 0.07e^{(0.03x)}$

Nitrate concentrations were calculated for the high-elevation scenario in the headwaters of the watershed. Catchment area was delineated based on a pourpoint designated along Hyalite creek immediately downstream of the burn area. Burn extent and catchment area were calculated using geoprocessing tools in ArcGIS Pro. Equation 1 was then used to calculate nitrate concentrations from burn extent. Riparian exposure was calculated by applying a 20-meter buffer on all streams in the catchment area. Via geoprocessing tools, stream buffers that intersect burn extent were used to calculate the ratio of affected stream channels to non-affected stream channels. Equation 2 was then used to calculate nitrate concentrations from riparian exposure. Both concentration values were summed to represent a conservative estimate of nitrate concentrations from the high elevation simulated wildfire.

Results

Lower Hyalite Canyon – Without Treatments (Appendix A)

This scenario was characterized by rapid proliferation with high flame lengths and large burn extent. Total burn extent was 8658 acres in 48 hours. Peak growth rate was 364 acres per hour occurring at run time hour 12. Fire severity was moderate. Fire intensity was high. Initial growth rate (<4hrs) was high. Significant fire growth occurred at runtime hours 12 and 36. The fire perimeter reached most of the surrounding wildland urban interface within 32 hours. The number of structures threatened was 140. Lower hyalite canyon road was consumed within the first 4 hours. Fire spread followed the topography of steep canyon walls and continued north and west following ridge contours and wind direction. After 32 hours the fire quickly spread down smaller drainages to the north and up east facing slopes to the west.

Lower Hyalite Canyon – With Treatments (Appendix B)

This scenario was similar to Lower Hyalite Canyon without treatments. Total burn extent was 8493 acres in 48 hours. Peak growth rate was 375 acres per hour which occurred at run time hour 12. Fire severity was moderate. Fire intensity was high. Initial growth rate (<4hrs) was high. Number of threatened structures was unchanged at 140. Arrival time North of Hyalite Canyon was significantly less than simulated wildfire without treatments. Fire arrival times were retarded by up to 20 hours in the Hodgeman canyon area. The simulation with treatments showed a significant reduction in wildfire growth rate during the runtime of 32 to 36 hours when compared to the simulation without treatments. Alternatively, differences in arrival times show that arrival times were accelerated up to 24 hours in areas west of the entrance to Hyalite Canyon.

Langhor Campground (Appendix C)

This scenario was characterized by slow initial spread out of the campground area and along the stream corridor paralleling Hyalite Canyon Road. Fire established in nearby fuels at 30 hours causing fire growth rate to significantly increase. A wind event occurred at 34 hours that caused large flame lengths and rapid spread of wildfire down the canyon. As fire reached steep canyon slopes, wind and topography aligned, causing large spikes in wildfire growth rates in the last 6 hours of the simulation. Fire intensity was initially low then high. Fire severity was high. Total burn extent was 2410 acres in 48 hours. Peak growth rate was 302 acres per hour occurring at run time hour 44.

Hyalite Reservoir (Appendix D)

This simulation was characterized by slow initial spread out of the campsite area along Hyalite Reservoir. After 28 hours of runtime Fire growth dramatically increased as fire established in the denser fuels north and east of Hyalite Reservoir. Fire intensity was moderate. Fire severity was moderate. Total burn extent was 1520 acres in 48 hours. Peak growth rate was 113 acres per hour occurring at run time hour 40. Burn extent was 14.248% of the contributing catchment area. Riparian exposure was 13.278% of the contributing stream channels. Total estimated nitrate concentration at pourpoint was 0.1 mgL^{-1}. 0

1. $log\, log\, NO_3{}^- = 0.013(0.14248) - 1.6 = 0.02523\ mgL^{-1}$
2. $NO_3{}^- = 0.07e^{(0.03*0.13278)} = 0.07028\, mgL^{-1}$
3. $Total\ NO_3{}^-\ conc.at\ pourpoint = 0.1\, mgL^{-1}(conservative\ estimate)$

Discussion

Lower Hyalite Canyon (Appendices A&B)

Both simulations with and without treatments were significantly larger in burn extent than simulations at higher elevations in the watershed. These wildfires were characterized by rapid initial fire growth and impacted a large portion of the surrounding WUI. Particularly concerning was the speed at which fire consumed Hyalite canyon road, effectively barring any traffic within 4 hours. This simulation had ignition occurring at 6 am. If ignition were to occur in the afternoon, which is common in human caused ignitions, initial spread could be much quicker. The danger of disabling egress from Hyalite canyon would be high. Suppression efforts would also be difficult due to the large flame lengths and moderate severity. Suppression was most likely to succeed after the first primary burning period that started at midnight or 18 hours into the simulation. At that time growth rate and temperature were lowest and relative humidity was highest. The introduction of fuels treatments did little to change fire behavior in the first 16 hours. However, a significant reduction in arrival time beginning at 18 hours northwest of the ignition point showed the positive effects fuels treatments had on growth rate in this simulation. Growth rates at 34 and 36 hours were significantly reduced when compared to the simulation with treatments. The location and timing are significant as it subsequently reduced arrival times to much of the structures within the WUI North of the ignition point. Often, high intensity wildfire during red flag conditions is difficult to mitigate for. It appears that the proposed fuels treatments had a positive effect on arrival times north of hyalite canyon. However, in the simulation with treatments, a large area immediately east of Hyalite canyon experienced earlier arrival times. This could be due to complex processes involving consequences of ember spotting occurring because of wildfire being on a different position on the landscape during peak fire spread events.

Langhor Campground (Appendix C)

Wildfire growth in this simulation was relatively low for the first 24 hours. This was most likely due to unreceptive fuels in the area with fuel models along the campground and riparian corridor having low-spread characteristics. The peak wind event that occurred at runtime hour 18 did not affect wildfire spread for this scenario. This could be due to non-receptive fuels or topographic effects of the canyon walls of Hyalite canyon. Where and when significant wildfire growth did occur was when fire reached receptive fuel beds during high wind events that also aligned with slope. This is called wind slope alignment and is responsible for significant fire growth on many fires. This was evidenced by extreme fire behavior, growth, and spotting in the latter half of the simulation. This scenario showed the necessity of suppressing and containing fire in the canyon as quickly as possible before wind slope alignment occurs.

Hyalite Reservoir (Appendix D)

Wildfire spread was minimal for the first 24 hours of the simulation. This was most likely due to Hyalite Reservoir being a significant barrier to spread. Other factors included sparse and non-continuous fuels along the east bank of the reservoir. Early wind events had little effect on wildfire spread due to the low position of the ignition point which was shielded by the high canyon walls. Once wildfire established in dense, late-seral forests north and east of the ignition point, wildfire growth was significantly increased. Steeper slopes and higher elevations allowed for later wind events to rapidly increase wildfire spread. Growth rates were more consistent in the last 24 hours than in the other simulations due to the high fuel loading in the high alpine forests surrounding Hyalite reservoir. Fire spread stopped at Lick creek where wind had less influence in the draw and riparian vegetation slowed fire growth. Estimated nitrate concentrations were negligible at 0.1 mgL^{-1}. This is far below the EPA limit for drinking water of 10 mgL^{-1}. This was due to a lower burn extent contributing to the catchment area ratio. Large portions of Lick, Wild Horse, and Hood creeks were affected by wildfire. However, due to the large number and length of contributing stream channels in the catchment area, resulting nitrate concentrations were diluted.

Conclusion (Appendix E)

Simulations of wildfire during severe fire weather conditions have shown the susceptibility of the wildland urban interface south of Bozeman. Modeled wildfires spread differently at three different ignition zones with varying elevation throughout Hyalite canyon. It is especially concerning to see the speed at which a wildfire near the mouth of the canyon will block egress along the road. This is concerning due to the high amount of recreation traffic the canyon receives during peak wildfire season. A generalized analysis of nitrate runoff concentrations showed negligent levels of stream nitrate concentrations following a modeled wildfire occurring near Hyalite reservoir. Burn area extent and riparian exposure are highly correlated with nitrate runoff concentrations. The modeled wildfire in question did not burn enough of the contributing catchment area to pose any risk to eutrophication of Hyalite creek.

The Bozeman Municipal Watershed Project is a promising start to addressing the risk of wildfire proliferating south of Bozeman, Montana. The incorporation of planned fuels treatments yielded results that showed wildfire proliferation slowing in treated areas. This translated to increased wildfire arrival times in the WUI south of Bozeman and north of the ignition point. This is critical when planning evacuations and suppression efforts as every hour counts during a fast moving fire. However, wildfire is dynamic and hard to model. The introduction of treated fuels also yielded reduced wildfire arrival times to the WUI immediately west of Hyalite canyon. A combination of best management practices, wildfire preparedness, and stakeholder commitment to reducing wildfire risk is necessary to protect the communities and resources south of Bozeman.

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Conclusion:

Recent times have made witness to the wildfire-dominated landscape across the West—faults in historical forest management, intensifying effects of climate change, and an ever-expanding WUI have created a wildfire crisis with a myriad of effects and uncertainties. The unprecedented rise and severity of wildfires have far-reaching implications for human health and communities, ecological systems, and the economy.

The underlying causes of this wildfire crisis are complex and multifaceted. Contributing factors include the "Smokey Bear" era, where aggressive wildfire suppression policies led to an accumulation of highly-combustible forest-fuels, and the rapid development of residential structures in fire-prone areas like the WUI, which increases the risk and extent of ignitions. Furthermore, climate change is a significant factor that exacerbates the severity of these wildfires.

Wildfire has numerous effects—from the heavily publicized destruction of communities and lives, to the more subtle ecological consequences—it can be a detrimental force on the landscape. Fortunately, there are ongoing initiatives to address the negative consequences of wildfire through a holistic approach. This may include improved forest management practices, prescribed burning, more effective land-use planning, grazing, and greater investment into research, technology, and fire-resistant infrastructure.

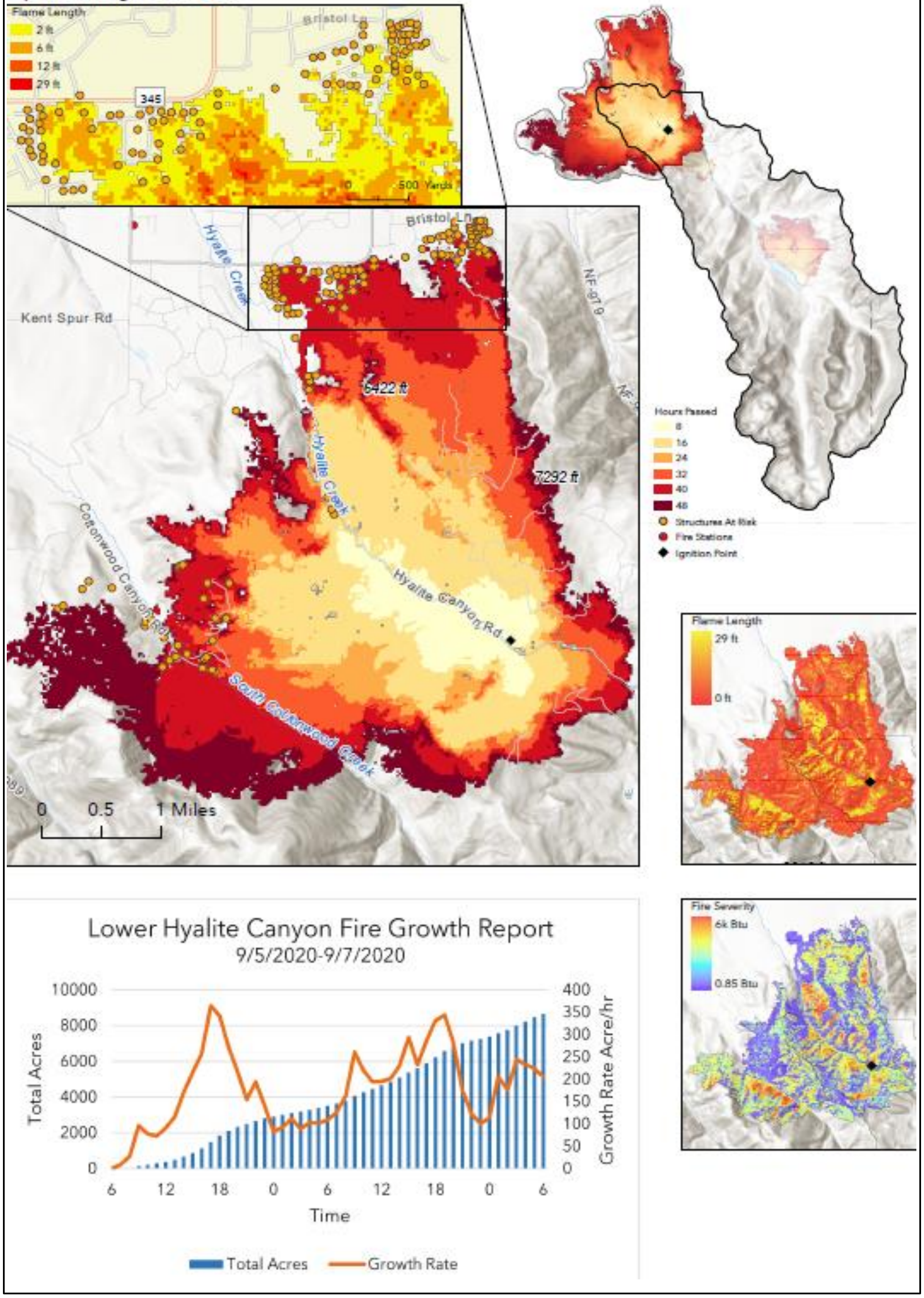
Likewise, this integrated approach has been utilized by the BMWP, albeit the efficacy of this plan is contentious. Based on the ignition scenarios and proliferation, it remains rather unclear whether fuel treatments will effectively curb the impacts to the WUI and quality of public drinking water.

Appendices:

A.

Lower Hyalite Canyon

Ignition scenario representing discarded smoking apparatus, tow chain spark, vehicle accident, or other road related ignitions along the popular hyalite canyon road. Ignition and burning period begins at 0600.



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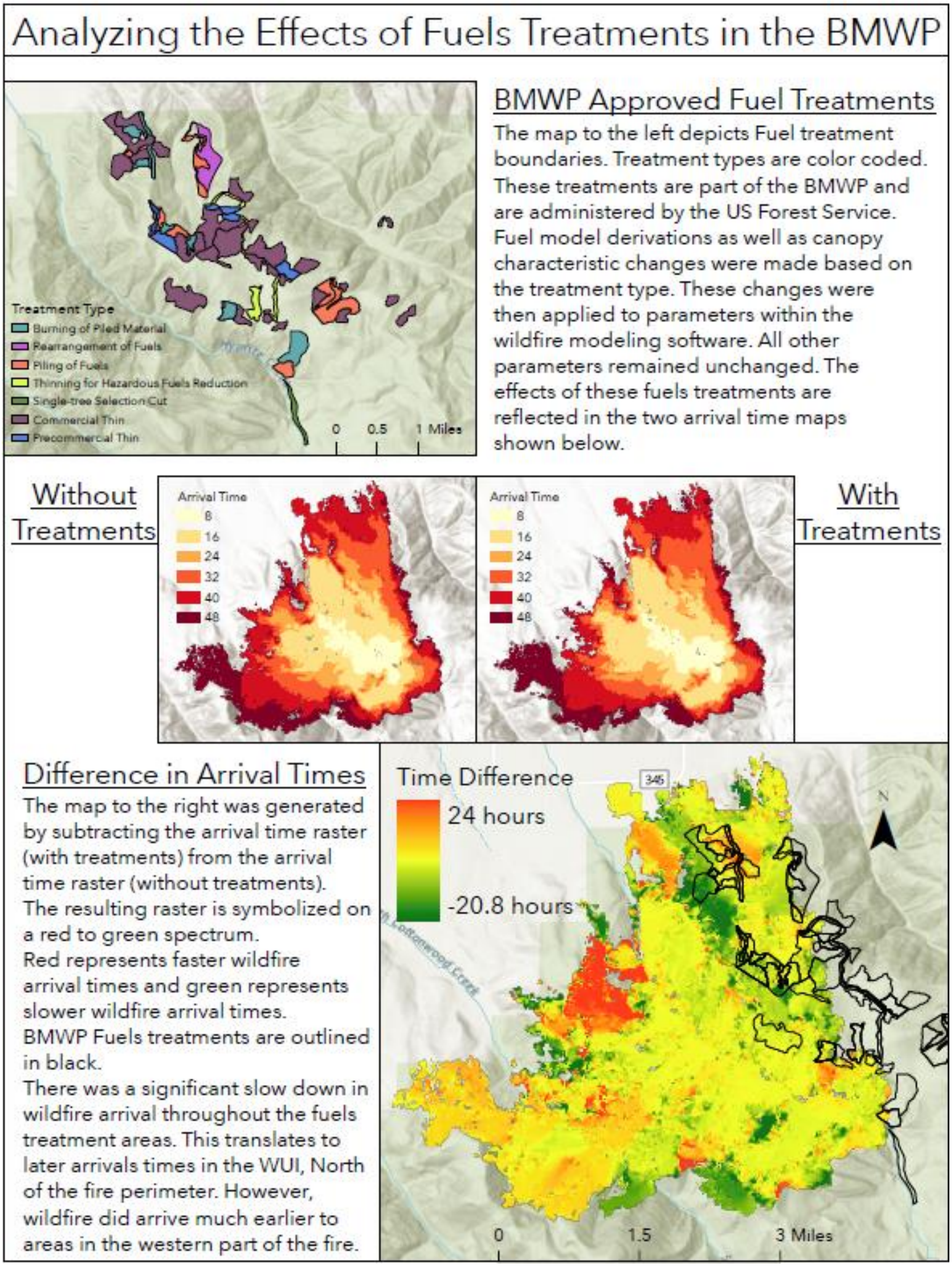


Analyzing the Effects of Fuels Treatments in the BMWP

BMWP Approved Fuel Treatments

The map to the left depicts Fuel treatment boundaries. Treatment types are color coded. These treatments are part of the BMWP and are administered by the US Forest Service. Fuel model derivations as well as canopy characteristic changes were made based on the treatment type. These changes were then applied to parameters within the wildfire modeling software. All other parameters remained unchanged. The effects of these fuels treatments are reflected in the two arrival time maps shown below.

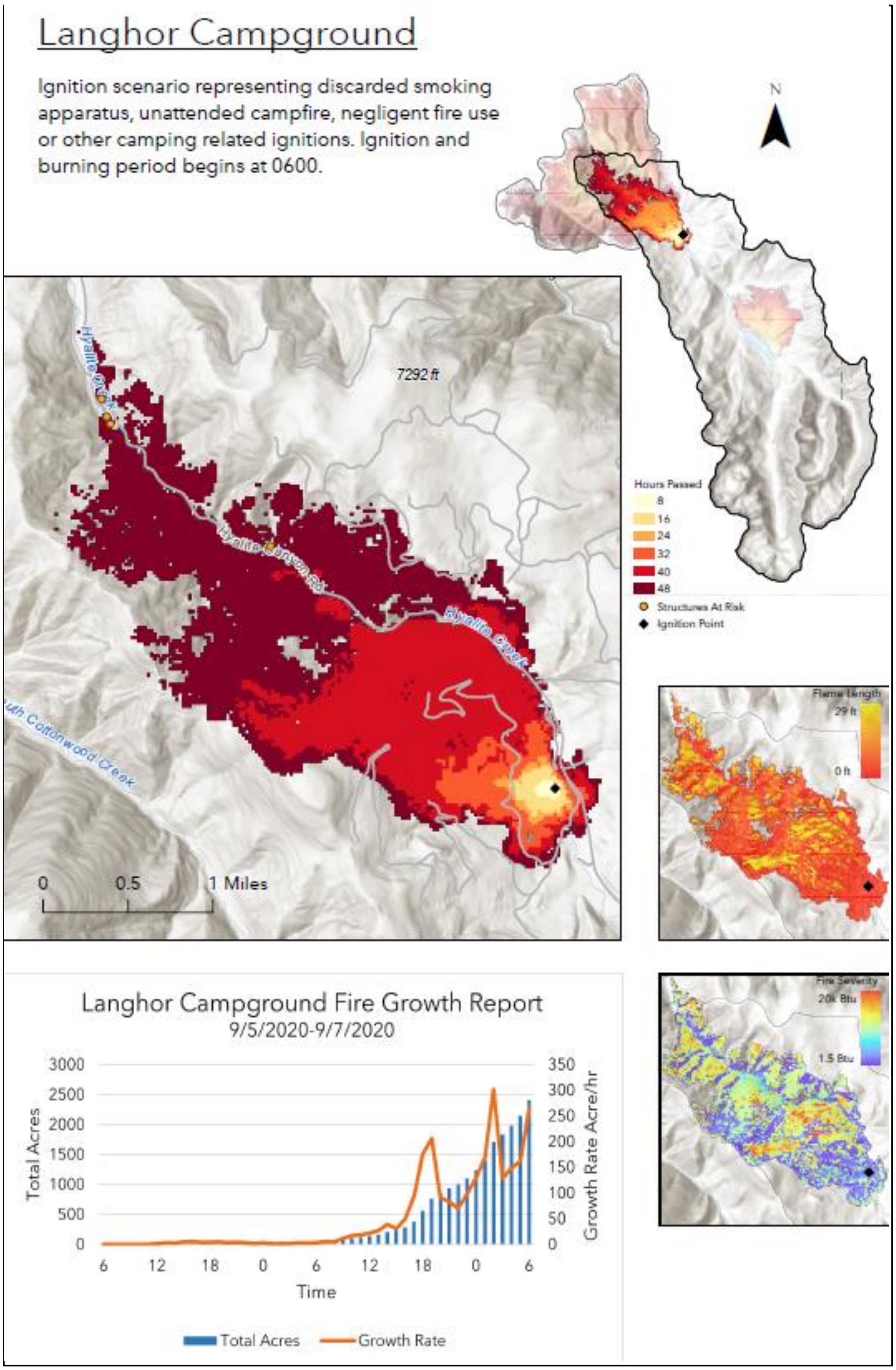
Without Treatments

With Treatments

Difference in Arrival Times

The map to the right was generated by subtracting the arrival time raster (with treatments) from the arrival time raster (without treatments).
The resulting raster is symbolized on a red to green spectrum.
Red represents faster wildfire arrival times and green represents slower wildfire arrival times.
BMWP Fuels treatments are outlined in black.
There was a significant slow down in wildfire arrival throughout the fuels treatment areas. This translates to later arrivals times in the WUI, North of the fire perimeter. However, wildfire did arrive much earlier to areas in the western part of the fire.

C.



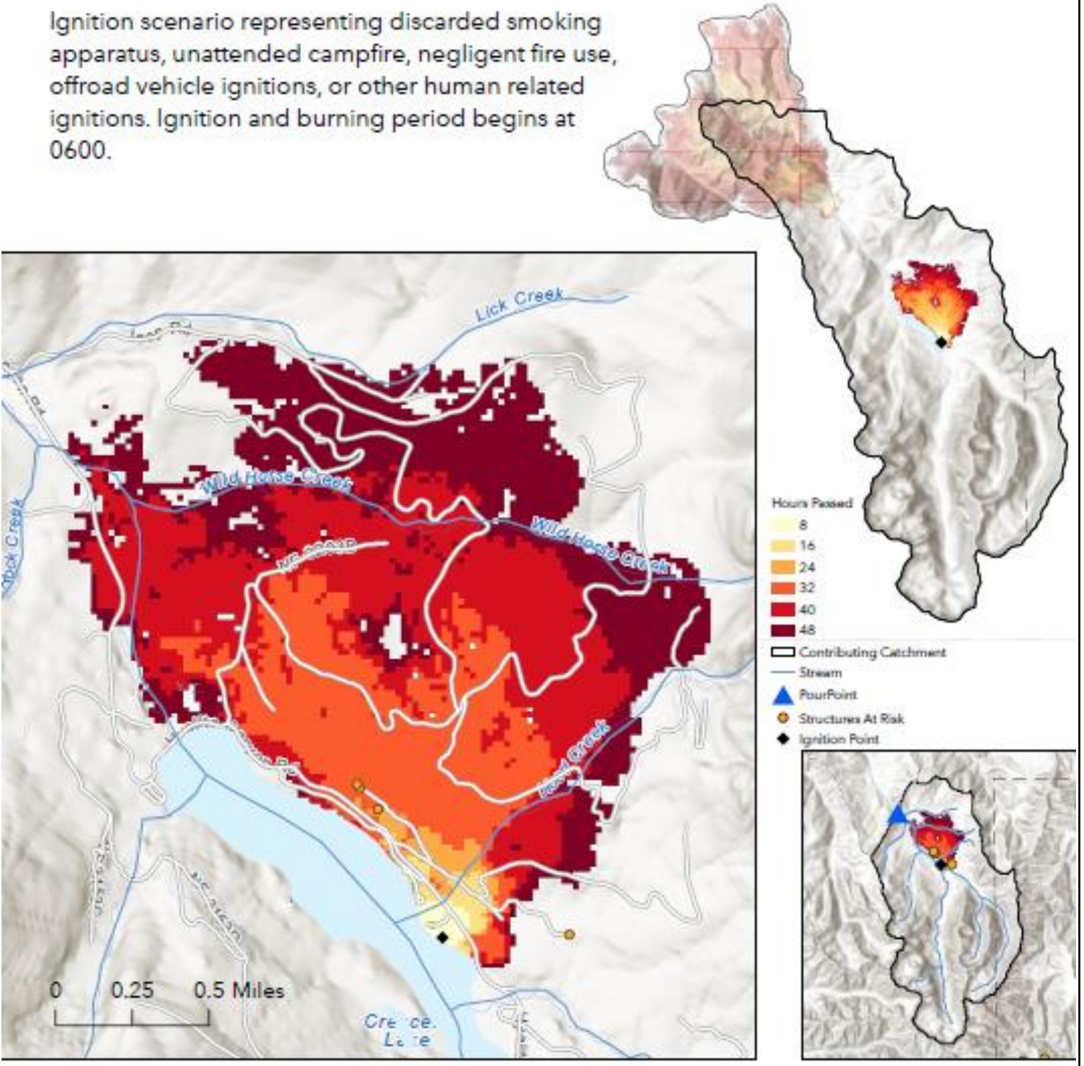
Langhor Campground

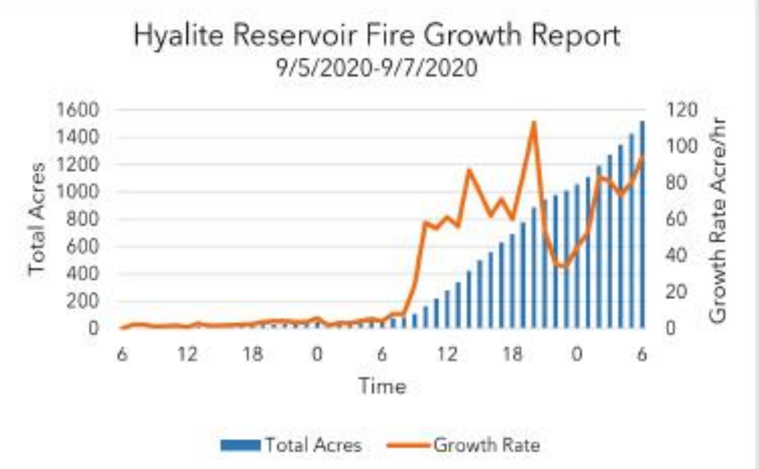
Ignition scenario representing discarded smoking apparatus, unattended campfire, negligent fire use or other camping related ignitions. Ignition and burning period begins at 0600.

D.

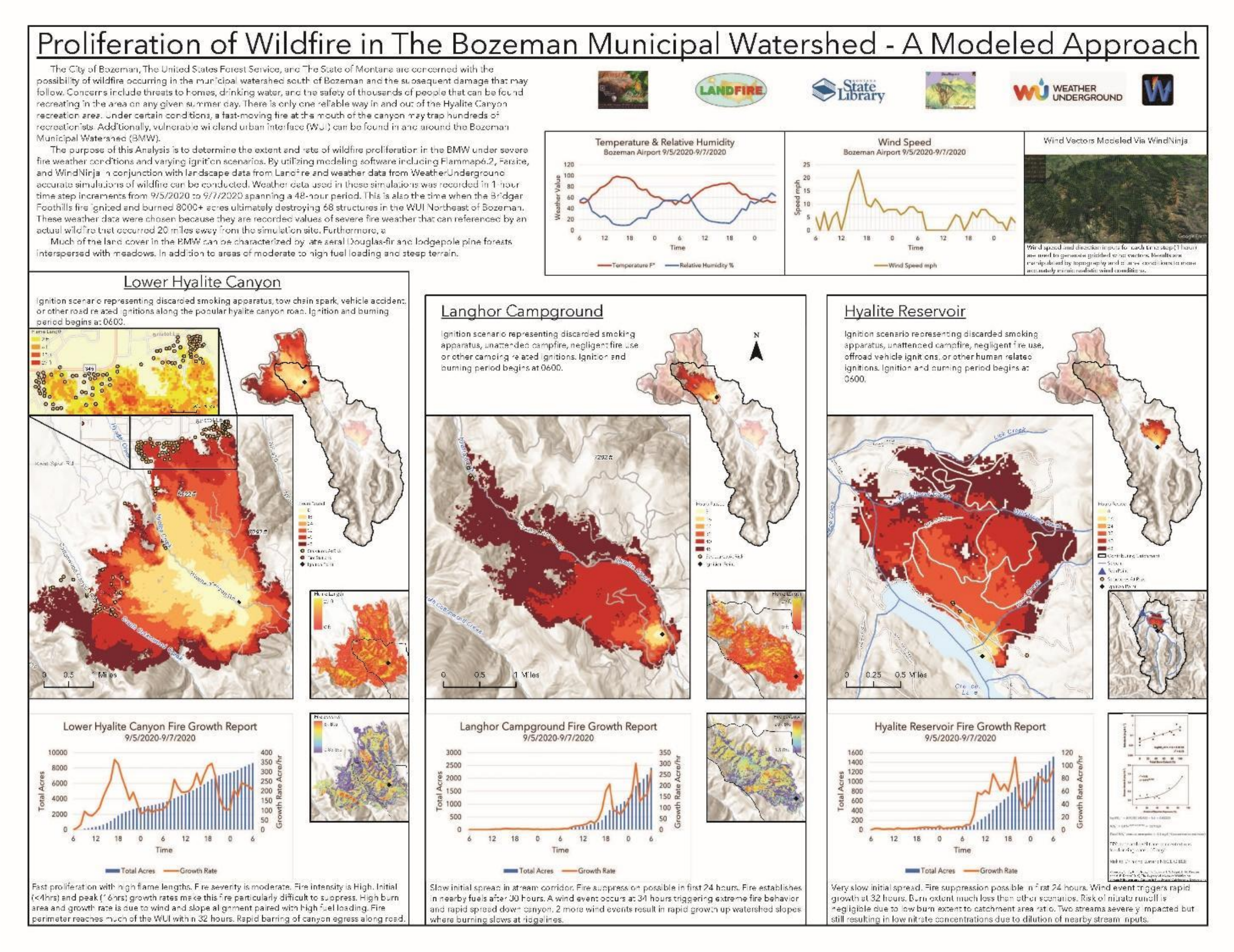
Hyalite Reservoir

Ignition scenario representing discarded smoking apparatus, unattended campfire, negligent fire use, offroad vehicle ignitions, or other human related ignitions. Ignition and burning period begins at 0600.




Hyalite Reservoir Fire Growth Report
9/5/2020-9/7/2020

E.



Proliferation of Wildfire in The Bozeman Municipal Watershed - A Modeled Approach

The City of Bozeman, The United States Forest Service, and The State of Montana are concerned with the possibility of wildfire occurring in the municipal watershed south of Bozeman and the subsequent damage that may follow. Concerns include threats to homes, drinking water, and the safety of thousands of people that can be found recreating in the area on any given summer day. There is only one reliable way in and out of the Hyalite Canyon recreation area. Under certain conditions, a fast-moving fire at the mouth of the canyon may trap hundreds of recreationists. Additionally, vulnerable wildland urban interface (WUI) can be found in and around the Bozeman Municipal Watershed (BMW).

The purpose of this Analysis is to determine the extent and rate of wildfire proliferation in the BMW under severe fire weather conditions and varying ignition scenarios. By utilizing modeling software including Flammap6.2, Farsite, and WindNinja in conjunction with landscape data from Landfire and weather data from WeatherUnderground accurate simulations of wildfire can be conducted. Weather data used in these simulations was recorded in 1-hour time step increments from 9/5/2020 to 9/7/2020 spanning a 48-hour period. This is also the time when the Bridger Foothills fire ignited and burned 8000+ acres ultimately destroying 68 structures in the WUI Northeast of Bozeman. These weather data were chosen because they are recorded values of severe fire weather that can referenced by an actual wildfire that occurred 20 miles away from the simulation site. Furthermore, a

Much of the land cover in the BMW can be characterized by late seral Douglas-fir and lodgepole pine forests interspersed with meadows. In addition to areas of moderate to high fuel loading and steep terrain.

Wind speed and direction inputs for each time step (1 hour) are used to generate gridded wind vectors. Results are manipulated by topography and climate conditions to more accurately mimic realistic wind conditions.

Lower Hyalite Canyon

Ignition scenario representing discarded smoking apparatus, tow chain spark, vehicle accident, or other road related ignitions along the popular hyalite canyon road. Ignition and burning period begins at 0600.

Fast proliferation with high flame lengths. Fire severity is moderate. Fire intensity is High. Initial (<4hrs) and peak (16hrs) growth rates make this fire particularly difficult to suppress. High burn area and growth rate is due to wind and slope alignment paired with high fuel loading. Fire perimeter reaches much of the WUI within 32 hours. Rapid barring of canyon egress along road.

Langhor Campground

Ignition scenario representing discarded smoking apparatus, unattended campfire, negligent fire use or other camping related ignitions. Ignition and burning period begins at 0600.

Slow initial spread in stream corridor. Fire suppression possible in first 24 hours. Fire establishes in nearby fuels after 30 Hours. A wind event occurs at 34 hours triggering extreme fire behavior and rapid spread down canyon. 2 more wind events result in rapid growth up watershed slopes where burning slows at ridgelines.

Hyalite Reservoir

Ignition scenario representing discarded smoking apparatus, unattended campfire, negligent fire use, offroad vehicle ignitions, or other human related ignitions. Ignition and burning period begins at 0600.

Very slow initial spread. Fire suppression possible in first 24 hours. Wind event triggers rapid growth at 32 hours. Burn extent much less than other scenarios. Risk of nitrate runoff is negligible due to low burn extent to catchment area ratio. Two streams severely impacted but still resulting in low nitrate concentrations due to dilution of nearby stream inputs.