
Photo by Matthew Harris

A Quantitative Approach to Living Sustainably with Wildfire

by Alex Harros and Matt Valido, 2017-18 State of the Rockies Project Fellows

Introduction

This past summer marked the five-year anniversary of the Waldo Canyon Wildfire in Colorado Springs, Colorado, which consumed over 18,000 acres, 346 homes and took the lives of two individuals. The fire's destruction persisted long after the last of the embers smoldered out; downstream of Waldo's burnscar, the city of Manitou Springs and sections of the Highway 24 corridor, a major Colorado highway, experienced numerous flood events and debris flows during the year following the burn. Though homes are being rebuilt and the forest is recovering, how can Colorado Springs and the greater Pikes Peak region reconcile its extensive wildfire history to better prepare for the next catastrophic fire?

Adding to wildfire's complexity, wildfires have been, and continue to be, significantly modified by anthropogenic influences which make them burn hotter, longer and extending the length of the fire season itself (Gorte 2013). Perhaps the most immediate effect of anthropogenic influence is on vegetation density and type in North American forests. In the twentieth century, economic pressure from the logging industry as well as the biblically destructive "Big Burn of 1910", spurred the newly formed United States Forest Service to develop a strict wildfire exclusion policy. This lofty campaign mandated that all wildfire on national forest were to be suppressed as quickly possible, regardless if the ignition source was naturally occurring or not. As a consequence, the naturally occurring fire regimes of forests were halted, leading to overgrowth of vegetation that would have normally been consumed by fire. This change in vegetation density has drastically increased the fuel load for wildfires increasing "the likelihood of unusually severe and extensive wildfires" (Arno et al., 227).

Fuel loads of forests are also increased by insect and disease epidemics which are more likely due to decreased vegetation resiliency from the added competition of overgrowth (Ibid). Though the extent of influence is not clear, the unusually high severity of the Front Range's Hayman Wildfire of 2002 was undoubtedly influenced by decades of fire suppression, leading Front Range forests' to "have developed a very different stand structure during the 20th century" (Romme et al., 198). Currently, mitigation efforts such as prescribed burning or vegetation chipping reduce fuel loads in forests, however performing these efforts on large scales is unfeasible.

The next significant source of anthropogenic influence on wildfire is from global climate change. Climate change increases the severity and frequency of wildfires via three mechanisms: hotter temperatures, earlier mountain snowpack melt, and drought (Gorte, 2013). Hotter temperatures and drought make wildfires burn hotter and increase the chances of ignition through the decrease of water content of vegetation. Earlier spring snowmelts lengthen the fire season itself by extending the period of time Western forests rely on summer precipitation for moisture (Ibid). Both the Hayman and Waldo Canyon wildfires occurred during summers of extreme drought and hot temperatures on the Front Range. Another climatic influence, though understudied, is the increase of insect outbreaks (mentioned above) with rising temperatures. Increasing epidemics in Western

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forests could influence wildfire severity due to greater fuel loads from mortality and less fire-resilient tree stands (Ibid). Though the extent is not fully understood, climatic influence on wildfire needs to be considered when preparing for the annual fire season.

As a natural occurrence in our ecosystem, wildfires are an inherent burden to those living in the West. Yet, fires play a key role in healthy forest dynamics by clearing out layers of vegetation, and at times entire tree stands, thereby decreasing competition and promoting succession within the fire-adapted ecosystem. Front Range's forests are characterized by a mixture of Ponderosa pine and Douglas-fir trees, which are dependent on wildfire regimes. Wildfire assists Ponderosa Pine seedlings by clearing out competing shrubs and grasses as well as creates fertile, nutrient rich soil for Douglas-fir and Ponderosa pine seeds to grow (CSU 2012). The Rocky Mountain's iconic aspen stands are also dependent on fire as being the primary successional species to rapidly grow following a burn (United States Forest Service). The duality of wildfires, as a source of both destruction and regeneration within forests, creates difficult and complex policy issues for communities living in landscapes where wildfires are a natural phenomenon. Colorado Springs is no exception. Wildfires are not influenced by jurisdictional boundaries yet people and policy decisions are. The difficulty of living with wildfire necessitates research to better assist ecosystem managers, policy makers, and private citizens alike.

Over the past twenty years, the Pikes Peak region has experienced the costly and lethal consequences of catastrophic wildfires, namely the Hayman, Waldo Canyon, and Black Forest wildfires. As evidenced by the Waldo Canyon Wildfire of 2012, burn scars alter the hydrology of a landscape and significantly increase the likelihood of flooding and debris flows (Young et al., 2012). Again, the destructive perimeter of a wildfire expands spatially and temporally beyond the burn scar itself, endangering homes, roads and lives that are downstream. Increased erosion and chemical transport following a burn damages the health of aquatic ecosystems as well as vital water resource infrastructure such as reservoirs and water treatment plants.

The Waldo Canyon Wildfire was particularly potent due to its proximity to Colorado Springs' wildland-urban interface (WUI), which in this study is defined as the margins between Pike National Forest and Colorado Springs. The term is also more generally used as a working definition for areas of Colorado Springs primarily at risk from wildfire.

To prepare for the next catastrophic wildfire effecting Colorado Springs, this report uses qualitative 'lessons learned' and quantitative data from the Pikes Peak region's extensive wildfire history. By using the Hayman and Waldo Canyon fires as model wildfires, this research extracted remotely-sensed, physical data from the burns' respective pre-fire landscapes and correlated those data to the resultant burn severity. From this correlation, a predictive model was made that is used to simulate both the magnitude and spatial extent of a potential wildfire within the research's area of interest (AOI) encompassing the Colorado Springs WUI. To understand the impacts of post-fire flooding, elevation data from the AOI was then used to measure potential hydrologic flow power, which is used to identify areas with highest potential for debris flows. Using geographic information systems (GIS), a composite model of both burn-severity and erosive potential was rendered over the AOI. The results display areas most susceptible to the severe burn and erosion intensity.

The AOI is, overall, bounded by Colorado Springs' WUI. Further, to interpret the results of the predictive model more clearly, Colorado Springs' WUI was subdivided by watersheds. The predictive model overlaid on a watershed scale allows for comparison between different areas of the WUI.

By mapping areas within Colorado Springs of highest concern, our research can be used to prioritize mitigation efforts and resources. Further, by highlighting the high number of people, property, and infrastructure at risk, our research can be used to stimulate policy and management decisions.

Lessons Learned

Though over a decade has passed since the Hayman Wildfire of 2002, it remains the geographically largest

Figure 1: “Moonscaping” in the Hayman Burn Scar

The Hayman Wildfire in 2002 severely burned 35% of its total area, resulting in “moonscaping” which is still visible 15 years later. Source: Jonah Seifer

wildfire in Colorado’s history and become a pivotal event in shaping the relationships between Front Range communities, the USFS, and wildfires. The fire consumed approximately 138,000 acres of Pike National Forest and the South Platte River corridor and ‘moonscaped’ vast swaths of land, leaving areas so intensely burned that the landscape, devoid of any vegetation, resembled the surface of the moon (Graham 2003). The fire ignited on June 8th, 2002 from a campfire near Lake George, Colorado and burned until June 28th (Ibid). In total, the wildfire completely destroyed 132 homes, damaged another 662, and scorched Cheeseman Reservoir, a vital link in a chain of water resource infrastructure utilized by the City of Denver (Ibid). The fire was also responsible for the deaths of six individuals. Many lessons can be extrapolated from the Hayman wildfire, including being an example of a mega fire whose behavior was undoubtedly exacerbated by anthropogenic influence.

The most striking feature of Hayman’s burnscar is the continuous amount of severely burned landscape where the fire’s intensity was able to burn entire tree stands. Though the Hayman burnscar is considered a mosaic of burn severity ranging from unburned to severe, a post-burn analyses by the USFS concluded that the majority of the landscape, 35% or 48,000 acres, ranked as severely burned (Robichaud et al., 2003). Wildfire intensity classification is measured through the condition of the landscape’s physical characteristics, such as vegetation and soil. In general, a burned area is classified as ‘high severity’ when all biomass at ground level and entire tree-stands are killed, whereas ‘low severity’ burns are characterized by the fire’s consumption of vegetation only at the ground level and not tree-stands (Ibid). The USFS has a standardized method of measuring this using pre- and post-fire satellite imaging. The scale and intensity of the Hayman wildfire brings into question of the role that 20th century fire exclusion and grazing practices played in the fire’s behavior. Dendrochronology records show that Hayman’s high intensity and total fire perimeter were consistent with the historic fire regime of the region (Romme et al., 2003). However, the isolated feature of Hayman to consider is the size of severely burned areas: “[no] fires documented from the early 1300s through 1880 created such a large contiguous patch of severe stand-replacing fire” (Romme et al., 193). That the fire reached stand-replacing intensity is not unprecedented, however it is unprecedented that 35% of the total area was severely burnt in contiguous pieces.

20th century fire exclusion has occurred in the Hayman landscape: before the summer of 2002, the last large fire in the Hayman area occurred in 1880 yet the one before that burned in 1851 (Ibid). The time period between Hayman and the last large wildfire in the area is over four times longer than the previous fire interval of only 29 years. While the extent to which fire suppression and human activity contributed to the fire’s behavior and magnitude is uncertain, the high vegetation density within Hayman's landscape directly contributed to the fire's growth and intensity. Historical photographs of the Cheeseman Reservoir show "in 1900… a canopy cover of 30 percent or less, and only 7 percent was dense enough to support a crown fire "and thus "it is clear that the contemporary forest and landscape structure contributed to the size and severity of the fire" (Romme et al., 200).

the severity and size of Hayman. Anthropogenic climate change increases a landscape's predisposition to wildfire through magnified drought and decreased vegetation resilience (Gorte 2013). Further, once a wildfire has started, hotter temperatures can contribute to the severity of the fire directly, providing more ambient heat energy (Quadrennial Fire Review, 2014).

Figure 2: Comparison to Historic Forest Density in Manitou Springs

Historically, forests have been far patchier and spatially variable, as seen in the left photo from Manitou Springs in 1906. Recent trends in fire suppression have led to denser forests which store more fuel and have the potential for more catastrophic canopy fires. This increased density can be seen in the right photo which was taken from a similar location in 2017. Source: Colorado Springs Pioneer Museum (left) and Tom Kuehl (right)

Another unprecedented aspect of the Hayman fire was its speed. Fires of similar size took up to months to burn whereas Hayman burned on the order of mere weeks (Ibid). Colloquially referred to as 'the blowout day', on June 9th extreme wind caused the fire to grow from "1,200 acres to approximately 61,000" (Finney et al., 59), close to half of the total burned area. Like other wildfires, Hayman's behavior was most strongly influenced by local weather and climate. Anthropogenic influences like climate change need to be considered when analyzing Hayman's behavior. These influences may be indirect but are still contributing factors, especially when considering Hayman's unprecedented burn-severity and the blowout day of June 9th.

The summer of 2002 marked the fourth year of acute drought in the Front Range where "fuel moisture conditions were among the driest seen in at least the past 30 years" (Graham, 4) which greatly contributed to

The Hayman wildfire is, in part, a product of two anthropogenic influences: 20th century fire exclusion practices and climate change. For the Pikes Peak community, the unprecedented size of the Hayman wildfire acted as a major wake-up call. Since 2002, wildfire awareness by private homeowners and management by the USFS and municipalities has improved. USFS wildland fire crews have improved their effectiveness by using a standardized procedure for organizing resources and people most efficiently between themselves and other responding agencies (Botts, personal communication 2017). In 2011, the City of Colorado Springs issued its Community Wildfire Protection Plan (CWPP) that includes fuels mitigation projects, at-risk neighborhood mapping, and promotes sound homeowner practices and awareness. Unfortunately, the Pikes Peak region was reminded of their vulnerability to wildfire when the Waldo Canyon wildfire burned in June of 2012, a decade after

Hayman. The Waldo Canyon wildfire stands as the current model fire occurring closest to Colorado Springs.

The Waldo Canyon wildfire was markedly different than Hayman in both size and effect. Though Hayman remains catastrophic in its own right, the Waldo Canyon wildfire is comparatively more destructive despite being significantly smaller in size and intensity. The fire started on June 26th, 2012 on Pike National Forest land between Colorado Springs and Woodland Park and was fully contained by July 10th. In total, the fire burned 18,247 acres, completely destroyed 347 homes, and took the lives of two people (City of Colorado Springs, 2013). The fire also scorched the perimeter of Rampart Reservoir, one of the major drinking water sources of Colorado Springs. A post-fire analysis by the USFS concluded that the majority of the burnscar, 41.6%, is either unburned or low in severity, with only 18.6% classified as high severity (Young et al., 2012).

Unlike Hayman, the Waldo Canyon wildfire's destructive potency is based on its proximity to communities and human infrastructure. The most poignant lesson learned from Waldo Canyon is that Colorado Springs has a WUI problem: one of the largest in the nation, the Colorado Springs' WUI comprises of 28,800 acres, 24% of the population, and 36,485 homes (Colorado Springs Fire Department, 2014). During the fire, all of the homes destroyed were located in the Mountain Shadows neighborhood, which was previously identified as being in the WUI (Fire Adapted Communities, 2012). Not only are many lives and homes at risk within the WUI, fire protection against homes is largely ineffective and highly challenging. In an analysis of home destruction within the Mountain Shadows community, 54% of homes ignited were from fire embers blown downwind from the burn while only 8% of home ignitions were sourced from the fire front itself (Colorado Springs Fire Department, 2014). Further, "90% of homes ignited were completed destroyed" (Fire Adapted Communities, 10). These two alarming findings further expose Colorado Springs' WUI problem.

The Waldo Canyon wildfire also reflects the lasting, destructive implications after the fire itself has burnt out. In an initial assessment of watershed burn severity, the USFS found that "large runoff producing storms will likely create increased surface flow volumes and velocities that can transport available sediment from the slopes" (Moore et al., 7). This prediction came true as major flooding and sedimentation events occurred just weeks after the fire and in the following summer of 2013 within the City of Manitou Springs and the Highway 24 corridor.

Ultimately, the Hayman wildfire represents an apocalyptically severe force lurking in the Front Range's forests while the Waldo Canyon wildfire represents a less severe yet more destructive fire due to its proximity to a WUI. If a "Hayman" level of wildfire were to occur in the same geographic location as Waldo Canyon, its destructive potential would dwarf that of Waldo Canyon and be unprecedented to any Western city living with wildfire.

Figure 3: Flash Flooding after Waldo Canyon Fire

Flash flooding events continued to damage infrastructure weeks after the Waldo Canyon Fire was extinguished. Source: Colorado Springs Water Resources Engineering

Methods

The purpose of this work was to create a map of wildfire severity in the wildland-urban interface based on the ecosystem characteristics of the Hayman and Waldo wildfires. The quantitative focus of the research primarily utilized ArcGIS, a popular GIS software. Per our objective of using GIS techniques to compare the Hayman and Waldo Canyon pre-fire landscapes to the resultant burn severity, the first step in our research was compiling historical data from both fires. The United States Geological Survey's (USGS) *Earth Explorer* website provided open access to federal research satellite imaging from which raster filetypes were downloaded. Images from the National Aeronautical and Space Administration's (NASA) Landsat 5 and Landsat 7 satellites were used, which provided 30-meter resolution images in both the visible color and infrared spectra. Image searches were filtered by geographic area and date using *Earth Explorer's* user interface. Only images encompassing the entire Hayman or Waldo pre-fire landscape were used. Further, image dates were refined to June through August and up to three years prior to each wildfire. Images with excessive cloud and snow cover had to be omitted due to processing challenges encountered later on.

The Normalized Difference Vegetation Index (NDVI) was selected as a key landscape characteristic to measure and correlate to burn severity. NDVI is a calculation derived from the relative amounts of red and near-infrared spectral reflectance from vegetation which, in turn, is a measure of the 'greenness' of the photosynthetically active vegetation (NASA, 2017). NDVI was selected as a variable to measure for a variety of reasons. In accounting for wildfire fuel conditions, NDVI can be used as an approximation of live fuel moisture content (Dennison et al., 2005). As acute drought was shown to be a major factor in the Hayman wildfire, an interpolation of vegetation health was desired to be used in our model. Further, NDVI could be calculated from our available dataset in ArcGIS.

The next pre-fire landscape features calculated were topographical slope and aspect, using Lidar-based digital elevation models (DEM). For both the Hayman and Waldo Canyon wildfires, the steepness of the terrain and the orientation of hillsides relative to the Sun were variables effecting wildfire behavior (Finney 2003, Botts personal communication 2017). Topographic data would also be used later on in flood and sedimentation modeling.

The USFS's *Monitoring Trends in Burn Severity* (MTBS) program provided geospatial burn severity data for the Hayman and Waldo Canyon wildfires. The MTBS program uses the differenced Normalized Burn Ratio (dNBR) to classify burn severity. dNBR is a calculation of the difference in pre- and post-fire thermal reflectance in the infrared spectrum (United States Forest Service, 2017).

Having compiled pre-fire data on NDVI, slope, and aspect as well as burn severity data post-fire, we then geospatially aligned the four data points. Within each burnscar, every 30x30 meter pixel had attached numerical values of the pre-fire landscape variables and of resultant burn severity, resulting in a dataset with ~500,000 pixels for each day for 10 days. Aligning the data this way allowed compiled data to be represented and manipulated in a tabular format, a necessary step towards burn severity modeling.

Two tabular data sets, one for Hayman and the other for Waldo, were input into *R*, a statistical computing software. The software was used for statistical comparison between burn severity and individual variables. The software was also used to create two linear regression models, correlating each fire's burn severity to NDVI, slope, and aspect. Because slope aspect is not mathematically linear, the dataset was split into different aspect classes and then the model was run for each aspect grouping.

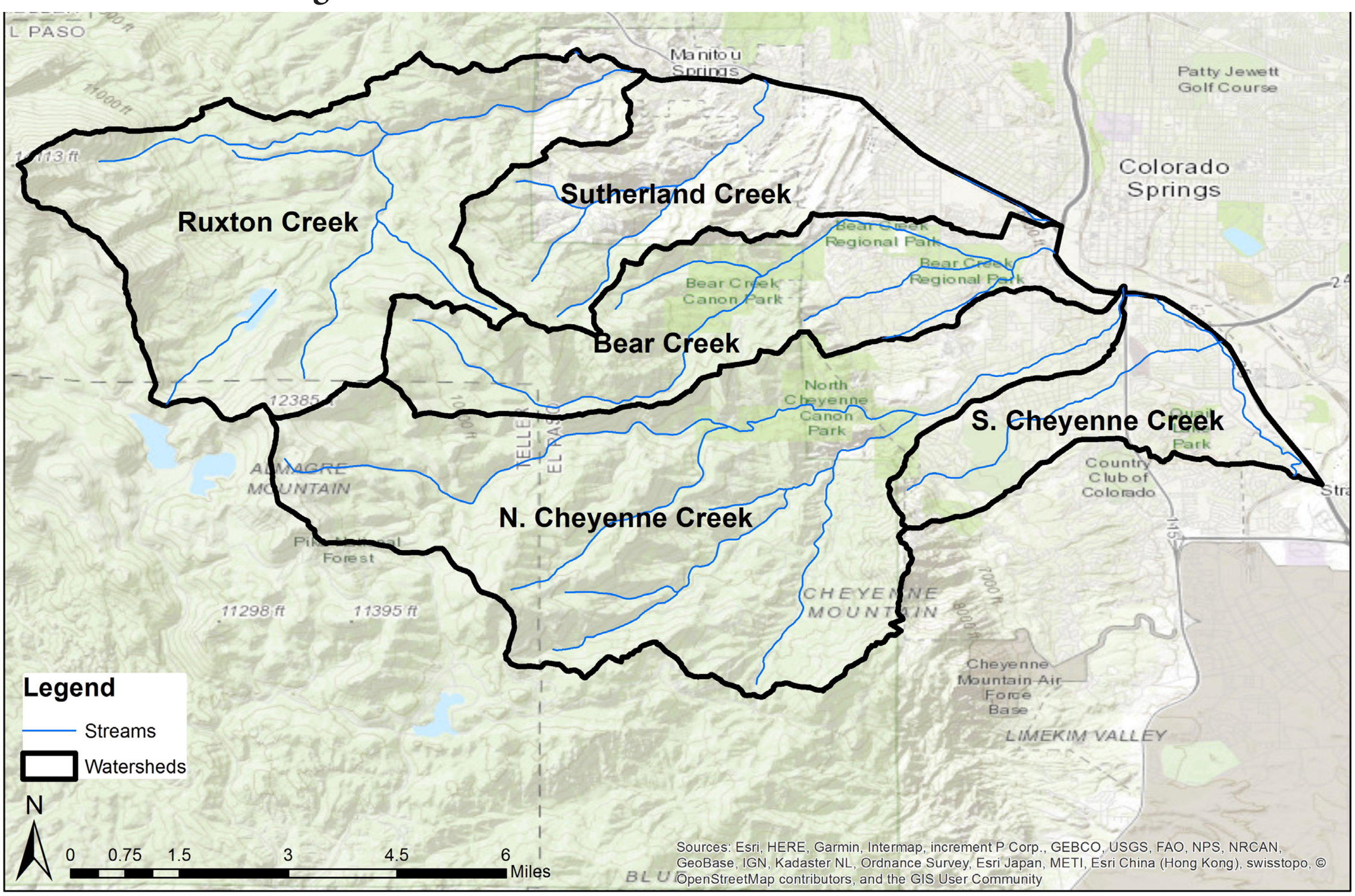
The two respective burn severity equations could then input back into the GIS software. Using current data on the AOI's NDVI, slope, and aspect as the input variables, the models computed a predictive burn severity spectrum overlaid on the AOI. A range of potential burn severity was visually depicted over a map of Colorado Spring's WUI. To better interpret the results, the models were depicted over the watersheds comprising the WUI, specifically the North & South Cheyenne, Bear, Sutherland, and Ruxton Creek watersheds. Further, the burn severity models were filtered to depict only the areas with the highest potential for a severe burn.

To address the soil instability and erosion that follows a severe burn, we coupled the existing burn severity map with a map of erosional power. ArcGIS's Hydro Tools used the DEM layer to compute a Stream Power Index (SPI) layer. SPI is a measure of the erosive power of flowing water and is calculated based upon slope and upstream contributing area. SPI approximates locations where gullies might be more likely to form on the landscape. The SPI layer was multiplied with the burn severity map and rendered a map depicting where heavy erosion is likely to occur if an area were to burn severely.

While no technical definition of 'wildland-urban interface' (WUI) was created by our research project, a parcel-scale WUI map created by University of Wisconsin's SILVIS Lab was used in conjunction with the burn severity model to calculate the proportions of Colorado Springs' WUI subject to varying degrees of potential burn severity. Proportions of the Springs' WUI (bounded by the AOI) overlapping with the burn severity potential, broken into a four-point scale, were calculated in ArcGIS. Tabular data was then extracted from the spatial overlap of the two maps.

Because this analysis required geospatial calculations in ArcGIS, Colorado Springs' WUI was implicitly defined through the WUI map used from UW's SILVIS Lab. The WUI map is also distinguished into two WUI types, intermix WUI and interface WUI. The technical definitions for each designation are as follows: a parcel is first considered WUI if it contains a minimum density of one structure per 40 acres (Stewart et al 2007). Next, if a parcel is also covered by greater than 50% wildland vegetation, it is considered intermix WUI. If a parcel is not covered by at least 50% wildland vegetation, but is within 1.5 miles of significant wildland vegetation, then it is considered interface WUI. This distance is established to account for the distance a fire ember can travel during a wildfire (Ibid).

Figure 4: Wildland-Urban Interface Area of Interest



This research's area of interest is comprised of the Bear Creek, Ruxton Creek, Sutherland Creek, North Cheyenne and South Cheyenne Creek Watersheds. Source: National Hydrography Dataset and inset sources.

Colorado Springs WUI Study Area

Our study's area of interest (AOI) is the Colorado Springs WUI, which is located in the eastern foothills of Pikes Peak and is largely contained within the Pike National Forest in the southern portion of the Colorado Front Range. The AOI is comprised of a mixed-conifer forest predominated by Ponderosa pine and Douglas fir. The lower montane and grassland portions of the AOI are historically predominated by Pinyon pine, Ponderosa pine and Gambel oak woodlands. This area was chosen as the area of interest in response to the spatial nature of the Waldo Canyon Fire. It burned up to the edge of the AOI and would have likely burned this area at a similar severity if not for specific environmental factors and effective wildland fire-fighting. The AOI has the same fire regime and anthropogenic consequences that were covered in the introduction, and as a result, is predicted to burn severely.

To further our understanding of the preventative and reactive actions taken in the face of fire risk and to better understand the resources needed for this region's management, the State of the Rockies Project Wildfire team studied the impacts of the Hayman and Waldo Canyon Fires on the local Colorado Springs community. The team received first-hand information from Forest Service personnel, Colorado Springs Utilities professionals and local management groups regarding their views on the response to the two fires. Time and time again experts in forest fire management claimed that resources are scarce in forest management, and with the fire season becoming longer and more severe, means to efficiently identify fire prone areas of forest for preventative management are extremely useful. Our predictive burn severity model was developed to address this need, and the following section outlines key experts who provided first-hand accounts that helped inform the predictive burn severity model.

Actors

Brent Botts – United States Forest Service (USFS), Pikes Peak District Ranger from 1981 to 2011:

Botts' thirty years of experience working in the Forest Service was invaluable throughout the development of the model. Fire mitigation in the WUI and the greater Pikes Peak Region, Botts said, is a difficult task. Noting the lack of jurisdiction that the USFS holds over the private property of the WUI, Botts spoke on homeowners' views on fire mitigation and forest thinning. Given that the majority of the WUI is privately owned, the USFS has to communicate with homeowners and educate them on the necessity of creating defensible space around properties. Many understand the danger of fire within the Colorado Springs WUI and are willing to work with managers to decrease fire risk. Unfortunately, some residents are more difficult to work with, which, as Botts noted, stems from a lack of education.

When a problematic area of the forest is identified and under USFS jurisdiction, they can carry out mitigation practices such as thinning. Due to the immense amount of private property, Botts' staff often had to speak with owners and homeowners associations regarding the necessity of risk mitigation. He spoke solemnly about this process because many homeowners cherish the dense forest aesthetic and the privacy it affords. As a result of these values, many homeowners are reluctant to change this aesthetic. Another problem arises in the Colorado Springs WUI given the steep topography of many fire-prone areas. Botts explained how expensive it is to thin a sufficient stand of forest to effectively mitigate fire risks, and how this is even harder in the steep slopes of Cheyenne Canyon. The issue of fire mitigation boils down to funding; with limited resources managers need to be highly calculated about where they direct their efforts.

Botts also gave detailed accounts of combatting the Waldo Canyon Fire. He was on site throughout the fire and shared how the topography of the area made it unusually difficult to contain. He confirmed slope aspects' role in fuel production, and how denser parts of the forest were "hot spots" for thinning. He commented further on how steeper slopes burn extremely fast and should therefore be a focus for thinning.

John Markalunas – United States Forest Service, Salida Ranger Station Incident Commander

The Incident Commander "keeps the trains running" at a wildfire operations center. They are responsible for all aspects of emergency response in a team of wildland firefighters, ranging from quickly improvising incident objectives to allocating resources to different parts of a burning area and maintaining the safety of his teams. Markalunas has been at the forefront of operations at many fires within Colorado and knew exactly how the Fire Team could help. He emphasized how quickly protocols need to be triggered when a severe wildfire is burning, especially near a WUI. Usually, homes are prioritized if they are near the front of the fire. However, in other scenarios, fire spread modeling allows for the quick allocation of fire-fighting personnel. Dozens of topographic, vegetative, and weather based variables are considered, as accurately as possible, to predict fire spread and show Markalunas where he should send his fire crews. Predictive fire spread modeling was immediately highlighted as one of the most important resources and his emphasis on the necessity of predictive burn severity models provided additional confidence in the value of this study.

Kim Gortz - Colorado Springs Utilities, Source Water Protection Project Manager

Gortz provided a tour of the Rampart Reservoir, one of Colorado Springs' main water sources where the Waldo Canyon Fire burned up to its perimeter. She took this time to explain the consequences that a catastrophic fire has on water resources, and the immense amount of work necessary to maintain the integrity of our water system. Given the severity of the Waldo fire, Gortz explained, her team knew that there was no fix to the post-fire erosion that would come, they could only lessen the impact of soil instability. She recounted stories of her work after the Waldo Fire in Manitou Springs. She explained how the reservoir itself wasn't badly damaged, but the drainage culverts overflowing and flooding downstream in Manitou brought about problems. Specifically, a "2-year" storm (that is, a storm whose severity has a 50% chance of occurring each year) on July 30th, 2012, produced a "10-year" flood in the burn area. The debris flows brought massive mudslides into the Manitou Springs area, inundating homes and businesses with sediment, destroying cars, and even killing one man. She described this as a "wake-up call" for Colorado Springs Utilities, and they quickly responded with increased preventative measures after this event.

Gortz also demonstrated different parts of the burn scar that required significant flood mitigation. Gortz explained to us the different hydraulic features, like the log-drop, which in absence of roots, stabilizes slopes, disperses runoff and prevents massive gullies from forming. These gullies, she explained, create fast moving runoff that cuts down hillsides, rushes downstream, and can lead to devastating floods like the one which ravaged Manitou Springs. Today, thanks to Gortz and her team, vegetation is beginning to grow back in the burn scar and stabilize the soils, and massive concrete reinforced storm water diversion drainages protect the city from future floods. Kim's emphasis on the danger of post fire erosion and debris flows inspired us to include an erosion prediction variable into our model.

With limited resources, management agencies like the USFS have increasingly supported the use of software based models to quickly find and analyze at-risk areas that are appropriate for wildfire mitigation. With massive swaths of land under their jurisdiction, the United States Forest Service utilizes predictive models that take into account fuel levels, topography, and local weather data to streamline the management process (Botts, 2017). Robust

Figure 5: Kim Gortz near Log Crib Dam

Kim Gortz gestures toward a log crib dam upstream of a partially filled sediment-catch basin near Rampart Reservoir. The dam is constructed of local timber and helps slow the flow of water, encouraging sediment deposition. Source: Jonah Seifer predictive burn severity models exist to this end (Holden and Jolly 2011, Holden et al. 2009) but few "learn" from previous fires in the region of study.

As a response, this study's predictive burn severity model is based off of some key pre-fire topographic and biological factors that directly influenced the resulting burn severity of the Hayman and Waldo Canyon wildfires. This study's model was built as a preventative fire tool, intended to find fire prone areas and enable management personnel to treat them before a wildfire event. The model was then applied to the Colorado Springs WUI to create a map of predicted burn severity and erosion potential for land managers to consider when planning and carrying out projects.

Results

The results of the burn-severity model were rendered over the research's AOI, comprised of the Ruxton, Sutherland, Bear, and North and South Cheyenne Creek watersheds. The burn-severity spectrum ranges from the lowest, in blue, through the highest potential, in red. In general, the highest burn-severity potential is concentrated in the foothills of Pikes Peak, at the transition of plains to mountains and also penetrates into some of the Springs' parks and open spaces. Burn-severity potential then extends westward into Pikes Peak, concentrated on slopes surrounding roads and creeks. Burn-severity potential is proportionally higher on steeper areas versus flatter areas. In the event of a wildfire in the Pikes Peak area, the fire would prominently burn into the hills of Colorado Springs' WUI due to its heavily saturated burn-severity potential. The fire would also heavily burn into the drainages surrounding the creeks and rural roads that extent into Pikes Peak, leaving substantial repercussions for the precipitation events that follow.

A stream power index (SPI) was also rendered over the AOI, where the highest erosive potential are highlighted in dark blue while the areas with the least erosive potential are highlighted in light green. Exacerbated by the brittle composition of Pike's Peak Granite and steep gullies, the potential for debris flows is very high for communities situated on the eastern alluvial plains.

Areas of erosional concern are expectedly concentrated around the streams of the AOI. Specifically, in the northern portion of the AOI in Manitou Springs, Ruxton Creek will be heavily impacted by rain events. Ruxton flows along the iconic Pikes Peak Cog Railway and into Manitou Springs on Ruxton Ave. In Manitou Springs the urban creek is lined with residences and driveways are bridged across the culvert. Heavy debris flows, like the one following the Waldo Canyon Fire could block the culvert and potentially overflow and inundate homes and roadways. Further south, Bear Creek has high SPI values. Gold Camp Road and Bear Creek road run adjacent to this creek and could similarly be impacted by heavy debris flows and runoff. Continuing south, both North and South Cheyenne creek have high SPI values. The residences at the lower elevation eastern portions of the canyons are in the trajectory of runoff. It is important to note the high SPI values in the steeper areas above all of the mentioned WUI neighborhoods in the AOI. It can be inferred that the higher SPI values upstream to the west of the densely populated WUI will likely erode significant portions of the landscape and bring debris into the more populated areas.

The changing fire regime raises concerns for nearly all residences within the Intermountain West's WUI areas. Our predictive burn severity-erosion potential model only confirms these concerns with specific areas within Colorado Springs' WUI that are in dire need of preventative fire management. The compounding impacts of wildfire and debris flows have not been studied at great length and we believe that the ability to pinpoint fire-prone areas that can trigger soil instability is invaluable for resource managers given the limited funding that they are afforded.

In order to account for erosive potential and to view the burn-severity model on a finer scale, the watersheds comprising the AOI were split into two groups. The following maps depict areas of intermediate to highest composite burn severity-erosive potential over the Ruxton and Sutherland Creeks watersheds, and Bear and Cheyenne Creek Watersheds. The results of the composite model show that the two groups of watersheds act as case studies in different, yet nonetheless destructive, outcomes of a wildfire in the Colorado Springs WUI.

Figure 6: Predicted Burn Severity over the AOI

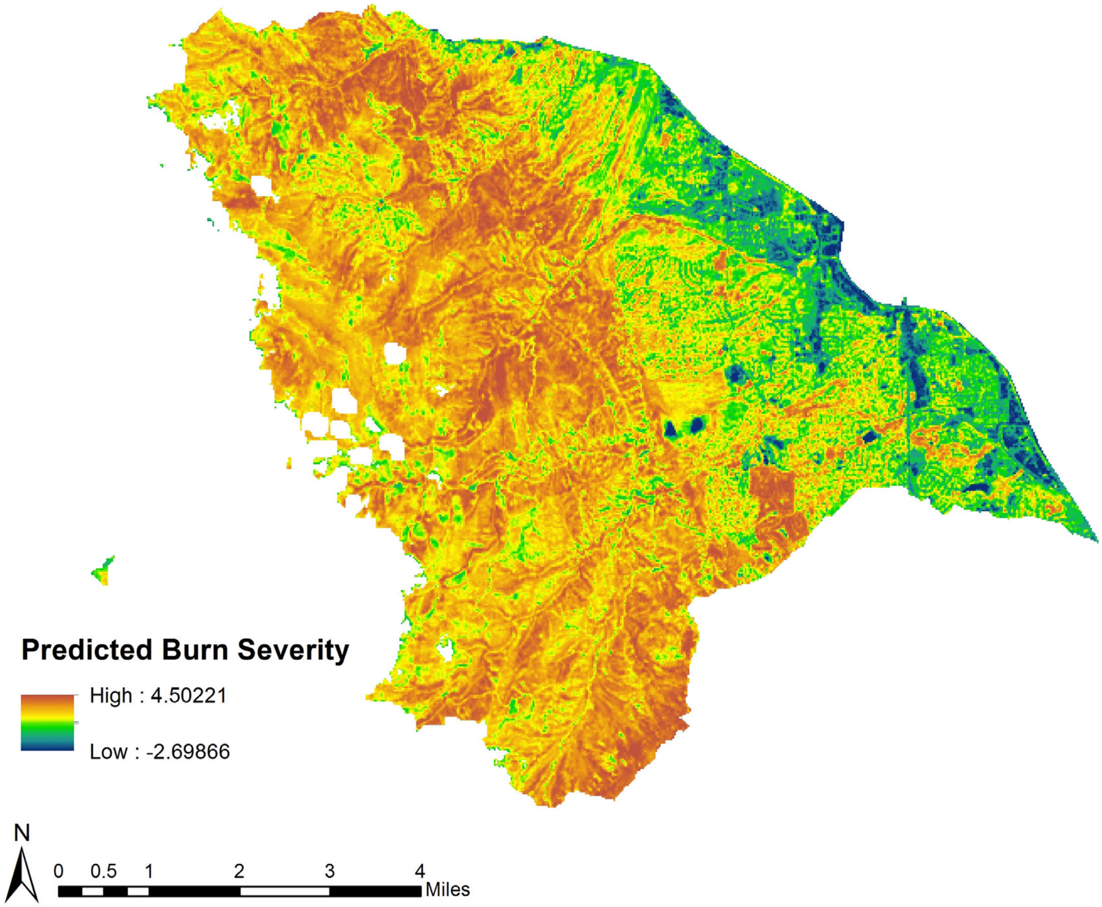


Figure 7: Erosive Potential within the AOI

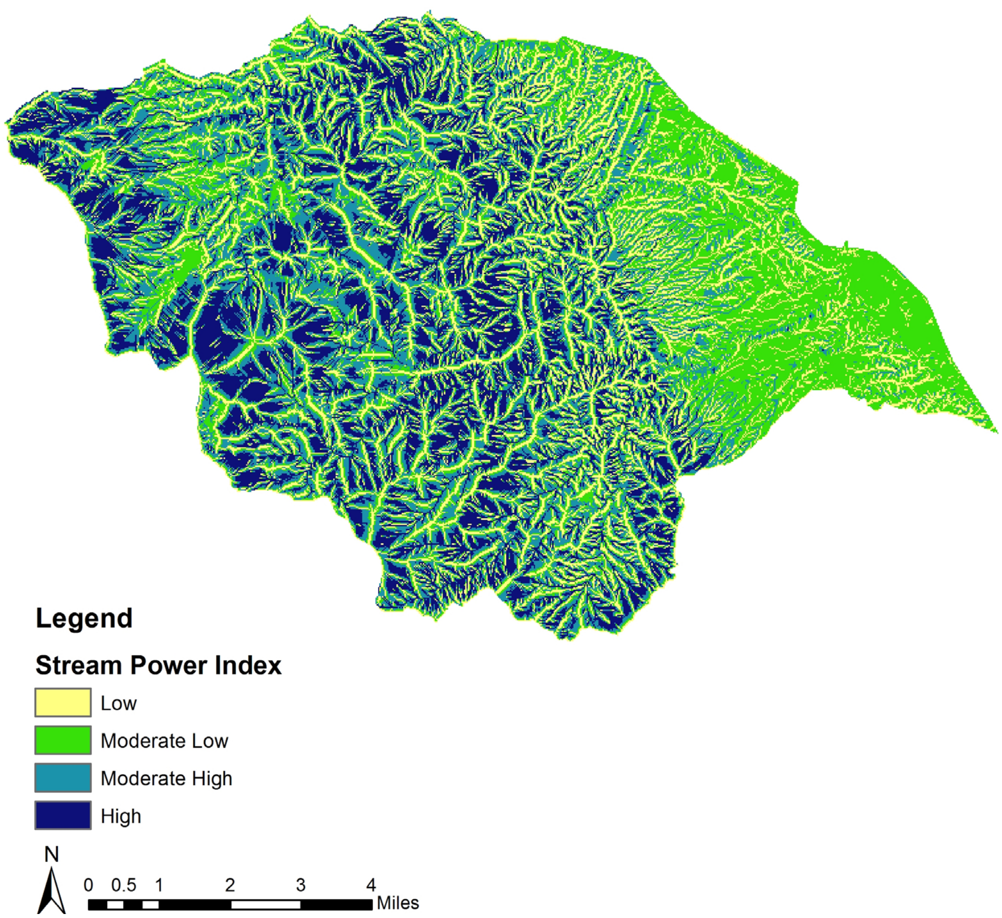


Figure 8: Composite Burn Severity-Erosive Potential in Ruxton Creek and Sutherland Creek Watersheds

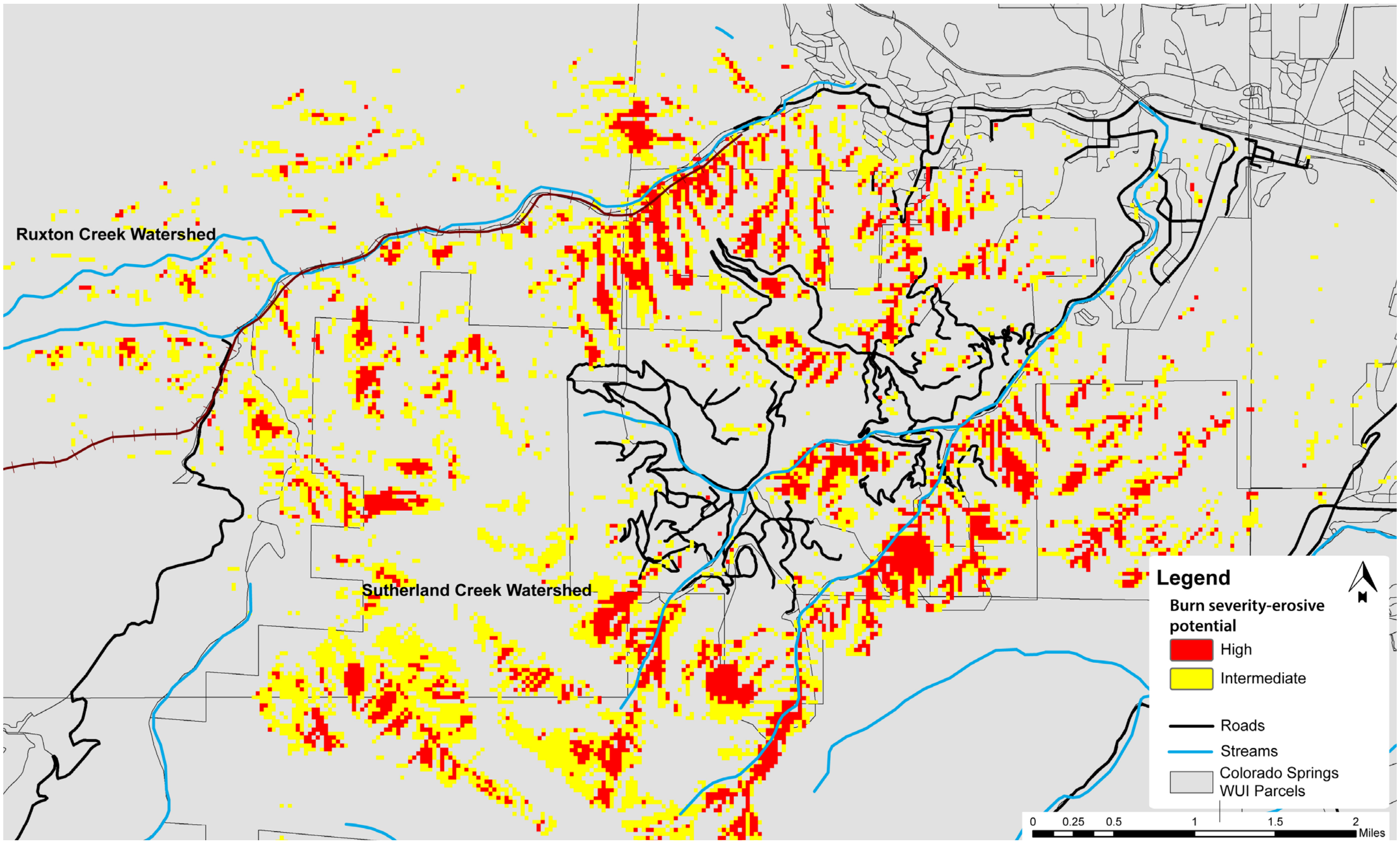
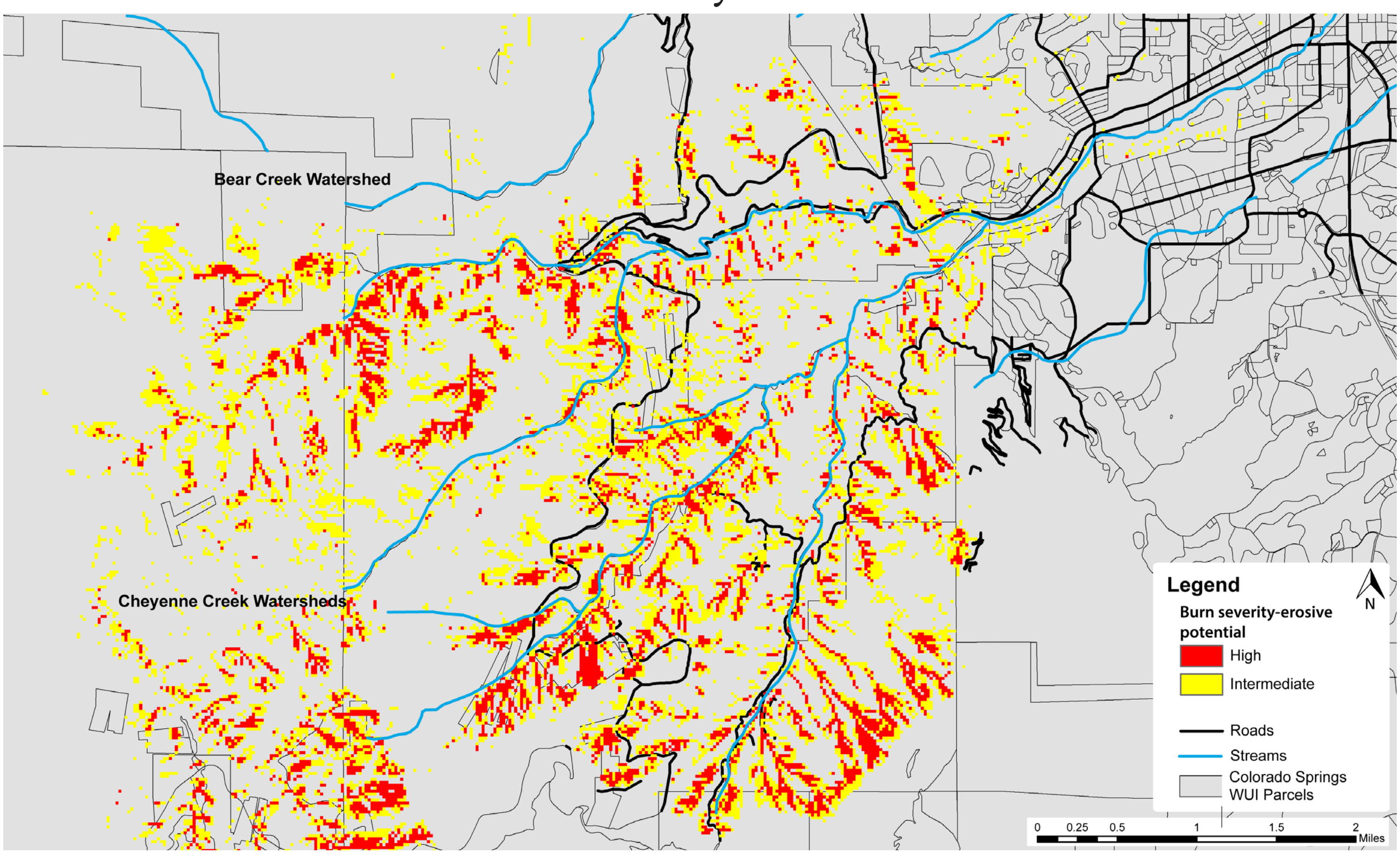


Figure 9: Composite Burn Severity-Erosive Potential in Bear Creek and Cheyenne Watersheds



Overall, the upper portion of Sutherland Creek and the lower portions of both Ruxton and Sutherland watersheds display the potential for acute burn and erosive severity. The upper portion of the Ruxton watershed reflects lesser burn-erosion potential, which, in the aftermath of a wildfire in the area, may have a lesser flood risk. However, the lower portion of the Ruxton watershed shows a different story. When considering the combined effects of the upper and lower portions on the waterway, there is potential for severe debris flows and erosion: Manitou's iconic Cog Railway, hydroelectric plant and the surrounding homes and other infrastructure at the top of Ruxton Avenue are all located in areas of severe burn-erosion potential.

Further, Ruxton watershed's lower side drainages contain acute burn-erosive potential. These drainages increase the magnitude of debris flows into Manitou Springs following a fire. As demonstrated by the aftermath of the Waldo Canyon Fire, a culvert backed up by debris impedes the downward flow of water and pushes any and all sediment that has flowed down the mountain up and over the culverts and into the surrounding areas. The high erodibility of the AOI's gravelly soils compounds this process and further exacerbates this risk. Residents of Manitou Springs must be educated on the risk that they are taking in living downstream of Ruxton Creek and city officials should prioritize the danger posed by this watershed and take preventative action.

For an area still at risk of flooding and debris flow from the Waldo Canyon burnscar, Manitou Spring's infrastructure, including some of its critical economic sources, are at extreme risk from another wildfire and precipitation events. In the case of the predicted fire event, Manitou springs would be surrounded by unstable soil from the predicted fire and from the Waldo Canyon burn scar. If preventative, reinforced culverts aren't strategically placed around Ruxton Creek, flooding could severely damage Manitou Springs' infrastructure.

The model depicts large, contiguous swaths of severe burn-erosion potential in the upper portion of the Sutherland Creek watershed. This elevates the magnitude of post-burn flooding and debris flow, posing severe risk downstream of the Sutherland Creek watershed. Crystal Park neighborhood is located within the Sutherland Creek Watershed, where nearly all of its course occurs within potentially moderate or severe burn-erosive areas. These high burn-erosive values are consistent across the AOI but the limited accessibility of this neighborhood raises extreme concern.

The gated community's only ingress and egress road is Crystal Park Road, a two lane paved road that runs adjacent to Sutherland Creek. Its proximity to Sutherland Creek should invoke thoughts of the devastation that the flooded culverts of Manitou Springs created in the surrounding WUI communities. The high erosion potential along this road is severe and the event of a reactive evacuation in response to either fire or a debris flow should be concerning to residents. Helicopter evacuation sites are in place amongst the community, however, given the limited air resources experienced during the Waldo Canyon Fire, they should not instill total confidence in residents. We suggest heavy thinning of the area and further flood mitigation along the Crystal Park Road. Further, the Crystal Park Homeowners Association must alert community members of this risk. The danger posed in this area should call for mandatory development of defensible space in and around the neighborhood. The relatively gradual grade of the area makes Crystal Park an ideal location for mechanized thinning and preventative fire management.

The model depicts severe burn and erosive potential for the Bear and Cheyenne Creek areas that extend into the steep canyons on the southeastern flanks of Pikes Peak. Infrastructure directly at risk includes neighborhoods of West Stratton, Gold Camp, Old Stage, and Cheyenne Canyon Roads, as well as Helen Hunt Falls and the Seven Falls recreation areas, two popular tourist sites for Colorado Springs. Relative to the Ruxton and Sutherland watershed analysis, the model depicts less at-risk human infrastructure within the Bear and Cheyenne Creek watersheds. However, due to the high and widespread burn-erosion potential in the upper portions of each watershed, a flood event would have catastrophic consequences downstream from the Broadmoor/Cheyenne area to as far as the Nevada Bridge, at the junction of Highway 25 and Nevada Avenue. The steep, rugged terrain of Cheyenne Canyon prevents feasibly performing wildfire mitigation efforts, such as tree-thinning, this characteristic also contributes to the canyons' especially high-velocity flows over loose gravel (Botts, personal communication 2017).

This section of our AOI's WUI presents a good opportunity for education of residents. The WUI is a common source of ignition and if residents were required to thin around their homes and create defensible space, the spread of a fire throughout the WUI could be mitigated. Unfortunately, given the private property that dominates the WUI and Cheyenne Canyon neighborhoods, mandatory fire mitigation is not a feasible option. Rather, if information on the risk of wildfire and debris flows is provided to homeowners, similar to our modeled burn-erosive potential map, research like ours could directly catalyze the creation of defensible space.

Using the burn-severity potential model in conjunction with a Colorado Springs WUI map, proportions of burn potential, on a four-point scale, were spatially analyzed into two categories of WUI: intermix and interface. Areas within the Colorado Springs WUI are considered intermix WUI if the area of human development also contains 50% or more wildland vegetation (Stewart et al. 2007) Areas within the Colorado Springs WUI are considered interface WUI if areas of human development contain less than 50% wildland vegetation but are within 1.5 miles of wildland (Ibid). For the intermix WUI, burn severity potential is relative uniform where extreme burn potential encompasses ~28% of the area while low burn potential encompasses ~22% of the intermix area. The interface WUI displays more variability where extreme burn potential encompasses ~9% of area and low burn potential encompasses ~59% of the interface area.

While Colorado Springs' WUI as a whole necessitates wildfire management, the differences in burn-severity potential between the two WUI types could influence specific management practices. Because areas of intermix WUI show higher proportions of extreme burn severity than do areas of interface WUI, 28% and 9% respectively, fuels mitigation efforts could be prioritized in intermix areas to most efficiently use limited resources. Further, fire-resistant construction requirements and zoning laws could be refined to distinguish between human development in intermix versus interface.

An important feature to note of this analysis is that only areas of WUI that contain a minimum of human development at one structure per 40 acres were used (Stewart et al 2007). The analysis does not factor undeveloped WUI areas nor areas with relatively high infrastructure density. To further mitigate Colorado Springs' WUI problem, potential growth in non-developed WUI areas as well as further growth in WUI areas overall must be managed to sustain annual wildfire risk.

This cautionary information needs effective dissemination to residents and stakeholders alike. The disconnect between the scientific community and those who could benefit from research and act upon it is discussed but not effectively addressed. Further research is necessary to find an effective means to bridge this gap and avoid the lack of education that contributes to stakeholder complacency.

The movement of a fire is heavily based on the specific weather conditions that are present at the time of ignitions. Because this study's predictive model is strictly based on topographic and biological factors, it's results should be viewed as strictly hypothetical. This study intended to provide a rough prediction of which areas within the Colorado Springs WUI are the most fire prone and have the greatest chance of influencing dangerous debris flows after a burn. The information provided should be used in conjunction with other models and field study to confidently ascertain adequate areas for thinning.

Reconciling the Past and Future for a Community Living with Wildfire

Five years from the Waldo Canyon wildfire, Colorado Springs is still reeling from its lasting effects. More recently, the West as a whole has also experienced the perennial devastation of wildfires that raged during the 2017 fire season, as seen in Southern California, Montana, Oregon, and British Columbia. Currently, the 2017 wildfire season is the most expensive on record, with suppression costs from the Forest Service alone exceeding $2 billion dollars (USDA 2017). As evidenced by the composite burn-erosion severity model, the Colorado

Springs WUI and the surrounding community is saturated in extreme risk from the inevitability of the next wildfire. In preparing for the 2018 wildfire season and beyond, Colorado Springs and the Pikes Peak region must adapt to this risk to sustainably live with wildfire.

Figure 10: Wildfires as seen from the International Space Station

The 2017 Wildfire Season cost the USFS over $2 billion in firefighting costs, making it the most expensive on record. Pictured above is a photograph taken from the International Space Station of fires in Southern California in December of 2017. Source: NASA.

In October of 2017, the Pikes Peak Forest Health Symposium served to highlight the people, policies, and recent advances in addressing wildfire. The conference brought together the local leaders of wildfire management including historians, scientists, non-profit organizations, and wildland firefighters as well as three key stakeholders: the US Forest Service, Colorado Springs Utilities, and the City of Colorado Springs, represented Mayor John Suthers. Though many individuals across different fields contribute to understanding the issue, these three main stakeholders are primarily shaping Colorado Springs' future with wildfire. The efforts and policies put forth by each stakeholder need to be critically examined in their function across the checkerboard of jurisdiction that characterizes Colorado Spring's geography.

The most current and extensive wildfire mitigation project in the Pikes Peak area is the *Catamount Fuels Reduction Project* (CFRP) which is a dual-partnership between Colorado Springs Utilities and the USFS. The CFRP is a technical approach to address wildfire through the use of prescribed burning, tree-thinning, and other physical mitigation efforts with the primary goal of protecting CSU's various water resource infrastructures scattered across Pikes Peak. CFRP is also working to protect priority WUIs of the region (Catamount Environmental Assessment 2011). Of the project's ~100,000 acre scope, 70% is on federal land with the remaining consisting of private ownership (Ibid). The CFRP's project scope encompasses this research's AOI and also identified the research's AOI as being of high priority. As of 2017, the CFRP has treated ~4500 acres with another proposed treatment of ~6500 acres in the immediate future (Howell 2017).

While the CFRP is a major component of Colorado Springs resilience to wildfire, physical solutions to mitigating wildfire risk are severely limited. In referring to the vast extent of at risk area of Pikes Peak, Eric Howell, spokesperson for the CFRP, concludes that "there is neither enough time, money or capacity to mitigate ourselves out of this situation". Colorado Springs' wildfire resilience cannot solely rely on physical mitigation and attempting to return Pike National Forest to its historical tree-stand density. Furthermore, even in the absence of anthropogenic influence on forest structure and climate, wildfires will naturally occur within the Pikes Peak ecosystem.

The City of Colorado Springs, including the Colorado Springs Fire Department and Office of Emergency Management, is the other key stakeholder in shaping Colorado Springs' wildfire resiliency through a variety of ways. In the event of a wildfire in the WUI, CSFD and the City's other emergency agencies will respond to structural fires, evacuation orders, and other necessary procedures in coordination with other responding agencies (see Appendix for detailed description of local and federal agency response during a wildfire). The City's proactive response to wildfire resiliency involves educational outreach, physical wildfire mitigation and, of particular note, policy. Colorado Springs' Community Wildfire Protection Plan engages the homeowner through stewardship education and extensive wildfire risk mapping down to a parcel-by-parcel scale.

The City also uses resources for wildfire fuel mitigation in parks and open spaces, such as the extensive fuels reduction in Stratton Open Space in the Spring of 2017 (Will, personal communication 2017). The City's most prominent policy-based response to the wildfire issue is the Hillside Overlay design manual, adopted in 2011 and updated following the Waldo Canyon fire (City of Colorado Springs 2013). This legislation requires all homeowners residing in the WUI, as defined by the City, to adhere to the technical requirements as described by the fire code such as minimum vegetation clearance around structures and use of approved roofing materials.

When polled about the single most important step in wildfire mitigation, a 42% majority of wildfire speakers and attendees at the Pikes Peak Forest Health answered with '**increase fuels reduction and forest restoration efforts**' while only 14% answered '**manage the wildland-urban interface.**' With a WUI that is 28,000 acres large and containing approximately a quarter of the total population, the City of Colorado Springs' extensive efforts to promote homeowner stewardship, along with the use of the Hillside Overlay ordinance, is a significant step. Ultimately, these efforts fall short of achieving a sustainable relationship with wildfire. Overall, the City's lack of a policy response is a significant gap in wildfire resilience and mirrors, anecdotally, the sentiment of local wildfire leaders and stakeholders.

To reiterate, the Waldo Canyon wildfire was devastating due to its proximity to the Colorado Springs' extensive WUI, not necessarily due to its abnormal intensity. Further, the results of the burn-erosion severity model of this research reflect a heavy reality for the future: the wildfire issue in Colorado Springs will get worse before it gets better.

Policy-based land-use planning decisions that manage Colorado Springs' WUI could significantly improve our long-term resiliency to wildfire. The growth of the WUI into at-risk lands in the West is primarily responsible for the rising costs of wildfire, though the extent to which this is true in Colorado Springs and the Pikes Peak region is unclear (Headwaters Economics 2014). Further, analyses show that 84% of WUI land in the West has yet to be developed (Ibid). These trends show that the West, including Colorado Springs, is at a tipping point regarding the future consequences of wildfire: the massive potential for growth and development in the WUI also carries the massive burden of increased wildfire risk. Though responsibility of wildfire is shared across many different stakeholder utilizing an array of effective strategies however, effective land-use planning in the WUI needs to be implemented to sustainably live with wildfire.

Conclusion

Annually increasing fire frequency and severity due to two centuries of land use change highlights the need for wildfire management reform. However, the top-down influence that climate has on the fire regime, considering climate change, is especially concerning because land management reform alone will not return forests to historical conditions. To minimize risk of wildfire, we must first and foremost maintain the historical lengths of the fire season by curtailing climate change and further restore montane ecosystems to their natural processes.

Further, the role that humans play in forest management must change from an anthropocentric management that focuses on human utility and, to an ecocentric system, that places pre-settlement characteristics (length/severity) of the fire regime at the forefront of concern. These levels must be used as a baseline to which managers strive to return the forest structure. At that point, we will have manageable low severity fires among western forests with much smaller extents every 20 or so years (Brown et al. 1999) that maintain a healthy and resilient forest. These resilient forests would acting as carbon sinks, rather than a forest that is frequently burning and contributing to heightened atmospheric carbon dioxide and a warming climate.

The Colorado Springs WUI is located in a similar ecosystem to that which burned severely in the Waldo Canyon and Hayman Fires. Given the densely populated neighborhoods that fall within this fire prone area, management reform is essential in order to decrease risk to those living in the WUI. This study and its findings should be viewed as a guiding precautionary outline of areas to further study before performing much needed wildfire mitigation.

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