REBURNS AND FIRE-ON-FIRE INTERACTIONS IN THE U.S. NORTHERN ROCKIES FORESTS 1900-2014

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Fire-on-fire interactions, where a fire encounters the perimeter and burned area of a previous fire, will increase if large fires become more frequent across the western US. Where fires are limited in size by previous fires, this could improve land and fire management and lower fire suppression costs. We analyzed fire perimeters recorded for 9.7 million forested ha of the U.S. Northern Rockies from 1900 to 2014 to examine fire-on-fire interactions by landscape characteristics and different fire and land management strategies. Less than 10% of the total area burned more than once. We found that fire overlapped more during regional fire years, in wilderness, in dry forests, in the late fire management era (1974-2014), with increasing years since previous fire events, and at higher elevation. Distance between fires increased as aspect moved from north-northeast to south-southwest. Fire-on-fire interactions did not vary significantly with slope. Our findings based on analyses of a large area, including both wilderness and non-wilderness, and over a long time frame support conclusions from previous studies largely limited to wilderness areas and ~30 years of satellite imagery. Fire extent is limited by previous fires on the landscape.

Keywords: fire perimeter, fire atlas, regional fire year, fire management era

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DEDICATION

I would like to dedicate this first to my wife, Lois Leigh Lauer, for always believing in me and encouraging me throughout the hard moments. Secondly I would like to dedicate this work to my father, Jerry Lynn Lauer. His knowledge and passion for natural resource management led me to follow in his footsteps and complete my graduate degree at his alma mater.

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REBURNS AND FIRE-ON-FIRE INTERACTIONS IN THE U.S. NORTHERN ROCKIES FORESTS 1900-2014

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Abstract

Fire-on-fire interactions, where a fire encounters the perimeter and burned area of a previous fire, will increase if large fires become more frequent across the western US. Where fires are limited in size by previous fires, this could improve land and fire management and lower fire suppression costs. We analyzed fire perimeters recorded for 9.7 million forested ha of the U.S. Northern Rockies from 1900 to 2014 to examine fire-on-fire interactions by landscape characteristics and different fire and land management strategies. Less than 10% of the total area burned more than once. We found that fire overlapped more during regional fire years, in wilderness, in dry forests, in the late fire management era (1974-2014), with increasing years since previous fire events, and at higher elevation. Distance between fires increased as aspect moved from north-northeast to south-southwest. Fire-on-fire interactions did not vary significantly with slope. Our findings based on analyses of a large area, including both wilderness and non-wilderness, and over a long time frame support for conclusions from previous studies largely limited to wilderness areas and ~30 years of satellite imagery. Fire extent is limited by previous fires on the landscape.

Keywords: fire perimeter, fire atlas, regional fire year, fire management era

INTRODUCTION

The number of large and costly wildfires has increased since the mid-1980’s, especially in the US Northern Rockies (Stephens 2005; Westerling et al. 2006; Dennison et al. 2014). The fire season is 70+ days longer in some regions of the western U.S. (Westerling et al. 2006; Jolly et al. 2015). Wildland fire area burned is expected to continue to grow as global temperatures increase, but this could be limited if previous fires consume fuels and so limit the extent of subsequent fires (Morgan et al. 2008; Littell et al. 2009; Westerling et al. 2011). Where fires are limited in size or severity by previous fires, this could help consume high fuel loads from a century of active fire suppression, improve fire suppression tactics and lower fire suppression costs (Houtman et al. 2013; Stevens-Rumann et al. 2014). Previous analyses have used data based on satellite imagery for fires that burned in the past 30 to 42 years, mostly in large wilderness areas (Collins et al. 2009; Teske et al. 2012; Parks et al. 2014, 2015, 2016).

Before the widespread suppression of wildland fires intensified beginning in the 1930’s, wildland fires commonly resulted in highly diverse forest landscapes of even-aged stands with early seral fire-dependent trees, multi-aged stands with large fire resistant trees and other nonforest (Arno et al. 2000; Thompson et al. 2009; Haire et al. 2013; Larson et al. 2013; Hessburg et al. 2015; Parks et al. 2015). Periodic wildland fires altered fuels, created heterogeneous landscapes and promoted fire-resilient species (Arno et al. 2000; Haire et al. 2013; Larson et al. 2013; Parks et al. 2015, 2016). The exclusion of fire from these systems limits the negative feedback mechanism that contributes to self-regulation (Arno et al. 2000; Larson et al. 2013; Haire et al. 2013; Parks et al. 2015, 2016). The resulting landscapes are susceptible to severe fire events that have the potential, depending on past land use, vegetation type and fire history, to shift to states that differ from those of the past (Larson et al. 2013, Stevens-Rumann and Morgan 2016). Thus, we interpret recent trends of fire-on-fire interactions in light of an entire century of changing fire management in the U.S. Northern Rockies.

Previous fire perimeters often limit the extent of subsequent fires on the landscape, acting as “fuel breaks” that prevents extensive “reburn” (Collins et al. 2009; Teske et al 2012; Parks et al. 2014, 2015, 2016). In the Sierra Nevada of California, Collins et al. (2009) found that the limiting effect lasted approximately nine years since the previous fire. They also found severe fire weather conditions at the time of fire-on-fire degraded the limiting effect regardless of time since previous fire. In the U.S. Northern Rockies, Teske et al. (2012) and Parks et al. (2014, 2015, 2016) similarly found the limiting effect decreased with time since previous fire. In four wilderness areas, the limiting effect lasted for 9-18 years since the previous fire (Parks et al. 2015, 2016). Average reburn sizes within previous fire perimeters increased as time since the previous fire increased (Teske et al. 2012). Fires burning during the hot, dry and windy conditions that contribute to intense and widespread fires have the potential to override any type of limiting effect a previous fire may have on subsequent fires (Collins et al. 2009; Parks et al. 2014, 2015, 2016).

Whether or not previous fires are limiting extent of subsequent fires may be influenced by forest type, elevation, aspect, regional fire years, and time since previous fire or a combination of these variables. Fire-on-fire interactions may also differ as a result of varying management strategies throughout the 20th century. Previous studies of fire-on-fire interactions focused on wilderness areas because such areas provide a large sample of fire-on-fire events with less influence of fire suppression and land management practices (Stevens-Rumann et al. 2014). However, large fires occur outside of wilderness in lower elevation vegetation types. The use of the temporal scale, 1972 or 1984 to present, in previous studies is common across these studies because it coincides with available satellite imagery. Analyzing fire-on-fire interactions over a large area as well as over a long time period provides context for how these interactions differ over time and space.

Topographic variability is known to affect fire size and the spatial distribution of reburn and fire-on-fire interaction. In large wilderness areas, Rollins et al. (2002) found that elevation and aspect influence fire frequency. If areas are more susceptible to frequent fires, the potential for reburn or fire-on-fire interaction could be greater. In the U.S. Northern Rockies, Dillon et al. (2011) found that elevation slope and aspect were the most important topographic variables in determining the probability of high severity fire. Elevation can influence wildland fire in multiple ways. Snowmelt typically occurs later with increasing elevation. Snowmelt timing influences fuel moisture, fire behavior, and fire intensity (Dillon et al. 2011). Insolation varies by aspect. The amount of solar radiation reaching southwest facing slopes tends to be greater than other aspects. The higher irradiance leads to lower fuel moistures on these slopes but site productivity may be too low for fire ignition and spread (Rollins et al. 2002). Northeastern aspects do not receive the same amount of solar radiation but tend to be more productive sites providing sufficient fuel for fire spread when fuel is dry enough (Rollins et al. 2002). On steep slopes and on high slope positions such as the crests of hills, fires spread readily (Rothermel 1972; Holden et al. 2009; Dillion et al. 2011; Morgan et al. 2014).

More area burned during regional fire years (Morgan et al. 2008, 2014) because warm dry summers follow warm springs. Morgan et al. (2008) demonstrated that in regional fire years, i.e., those years of widespread fire where annual fire extent exceeded the 90th percentile, are characterized by different climate. Throughout the 20th century, regional fire years have occurred in the Northern Rockies when the Pacific Decadal Oscillation was positive (Morgan et al. 2008; Dillon et al. 2011).

The patterns of how fire burns on the landscape have also been changed over the last century. Since the mid 1930's, there has been a shift in fire regimes within areas that have experienced aggressive fire suppression (Hessburg and Agee 2003). This is most evident in low dry forest types, where active suppression activities have increased the time between fire events and changed forest structure making areas more susceptible to high severity fire (Hessburg and Agee 2003). Fire management and land use have impacted lower elevation more accessible forest types to a greater extent than higher elevation and more remote forest types (Hessburg and Agee 2003; Morgan et al. 2014). Lower elevation, accessible forest types have historically seen more aggressive fire suppression than high elevation, remote forests during the 20th century (Hessburg and Agee 2003).

Fire management in the U.S. Northern Rockies can be split into three time periods (Rollins et al. 2001; Hessburg and Agee 2003; Morgan et al. 2014). During the early period, 1900 to 1934, fire suppression activity was limited, especially in remote areas now designated as wilderness and roadless. The middle period, 1935 to 1973, saw the rise of aggressive and effective fire suppression (Hessburg and Agee 2003). During this middle period, trained fire suppression crews became common, and advances in detection of fires coupled with use of smokejumpers and airplanes to detect fires and drop fire retardant greatly increased the capability of fire managers to suppress fires while very small. (Pyne et al. 1996). The middle period had climate more conducive to fire suppression than earlier or later (Morgan et al. 2012; Higuera et al. 2015). The late period, 1974 to present, has been characterized by less aggressive initial attack and wildland fire use in many large wilderness and roadless areas (Pyne et al. 1996; Hessburg and Agee 2003). The early and late eras had a greater fire extent and a higher number of fires than the middle of the 20th century (Morgan et al. 2014). Currently, fire management in the U.S. Northern Rockies varies across the landscape. As fire and land management have changed, some naturally ignited fires have been allowed to burn for resource benefit in remote areas if pre-established conditions outlined in fire management plans are met (Pyne et al. 1996; Morgan et al. 2014). This limited fire suppression in wilderness and remote areas has likely increased fire-on-fire interactions compared to areas outside of wilderness. Additionally, these remote areas receive lower priority during years of widespread fire activity as values at risk could be considered lower compared to more accessible areas (Morgan et al. 2014).

Using fire atlas data, we evaluate fire-on-fire interactions across multiple decades through multiple management eras, in years of widespread fires, and across topography. Fire atlases are historical records of annual fire perimeters (Shapiro-Miller et al. 2007; Morgan et al. 2008, 2014). Fire atlases do not include all fires as typically only the larger fires are mapped though this accounts for most of the burned area (Shapiro-Miller et al. 2007; Morgan et al 2008). The atlas data are also georeferenced, allowing the user to incorporate other georeferenced data such as topography, forest type and wilderness or not, to better understand how these other factors are influencing fire extent (Morgan et al. 2008, 2014).

Using the U.S. Northern Rockies fire atlas, Morgan et al (2014) binned the study area by wilderness designation, Environmental Site Potential (ESP) group, elevation, aspect, and slope and examined forest fire extent across three different fire management periods: 1900 to 1934, 1935 to 1973 and 1974 to 2008. Using these variables they explored the pyrogeography of modern fire regimes and examined how the spatial distribution of fire varied through the fire management periods with respect to topography, climate and fire management. Morgan et al. (2014) found that fires burned disproportionately more inside wilderness than outside wilderness, and by elevation and slope in the southern part of the study area. We address the need for a quantitative understanding of fire-on-fire interactions over larger spatial and temporal distributions by analyzing fire perimeters between 1900-2014 in forests of the US Northern Rockies.

Our research objectives

To understand how previous fire perimeters affected subsequent fire extent in the U.S. Northern Rockies, we

1) Compared distribution of reburn occurrence to landscape condition to determine if reburns occur disproportionately compared to the fire atlas recording area and total area burned between 1900 and 2014, and we
2) Examined where fire-on-fire interactions occur by analyzing how distance between fires varied with the individual and interacting effect of landscape condition as well as years since

previous fire.

We expected reburn occurrence and fire-on-fire interactions to differ between forest types, topography, wilderness vs. non-wilderness status, regional fire years, fire management era, and years since previous fire. We expected that cold forests should exhibit the fewest fire-on-fire interactions because fires in cold forests are limited more by climate than by fuel (Schoennagel et al. 2004; Littell et al. 2009). Thus, when fire-on-fire interactions do occur in cold forest, we expected the occurrence of reburn to be greater when compared to dry and mesic forests which are typically fuel limited (Schoennagel et al. 2004; Littell et al. 2009). We expected more fire-on-fire interactions in dry forests. We believed that wilderness areas would experience more fire-on-fire interactions in the late fire management era due to implementation of the wildland fire use policy (Pyne et al. 1996; Hessburg and Agee 2003; Morgan et al. 2014). We expected that when more area burns, as during regional fire years, there will be more fire-on-fire interactions and potentially more occurrence of reburn. Because area burned differed among three time periods with contrasts in fire management and climate, we expected reburn and fire-on-fire interactions to differ. We believed that time since previous fire would influence reburn occurrence in the U.S. Northern Rockies as fuel accumulations at longer time periods would result in higher likelihood of reburn (Collins et al. 2009; Parks et al. 2015, 2016). We expect more frequent fire-on-fire interactions will lead to fewer reburns due to the effect of time since previous fire on vegetation (Collins et al. 2009; Parks et al. 2015, 2016), but the degree to which this is true outside of wilderness areas is unknown and likely varies with forest type and elevation, all of which differ within and outside wilderness.

METHODS

Study area

The U.S. Northern Rockies of Idaho and Montana are characterized by high, glaciated mountains separated by broad flat valleys (Morgan et al. 2008, 2014). Climatic regimes are influenced by Pacific air masses but continental influences are also apparent, especially in the southwestern portion (Morgan et al. 2008, 2014). Winters are cold with January being the coldest month with a mean temperature of -3 to -8°C (Morgan et al. 2008, 2014). Summers are warm with July being the warmest month on average with a mean temperature of 18 to 19°C (Morgan et al. 2008, 2014). Annual total precipitation ranges from 24 to 72 cm, much of which falls as snow (Morgan et al. 2008, 2014).

Forests in the U.S. Northern Rockies can be classified into three major ESP groups: dry forest, mesic forest, and cold forest (Schoennagel et al. 2004). ESP group is the classification of sites based on the potential vegetation that could be supported (Dillon et al. 2011). Cold forests occur above 1500 m and are dominated by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). Dry forests occur above and below 1500 m and are comprised of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). Mesic forests occur below 1500 m and are dominated by grand fir (*Abies grandis*), Douglas-fir and western larch (*Larix occidentalis*). Due to a buildup of fuels in the late twentieth century, dry forests have burned at high severity as much as cold forests in the twentieth century as a consequence of fire exclusion (Hessburg and Agee 2003; Morgan et al. 2014).

Fire perimeters from the U.S. Northern Rockies fire atlas

We used fire perimeters mapped in the U.S. Northern Rockies Fire Atlas for 12,070,086 ha of which 9,731,691 ha are forested (Gibson et al. 2014). Digital fire perimeter and year of occurrence records from 12 national forests and Glacier National Park are included from 1900 through 2014 (Gibson et al. 2014; Morgan et al. 2014). Although some histories record a fire in nearly every year while some contain long gaps, these data encompass the largest fires and have been used successfully to examine area burned across time and space (Morgan et al. 2014). Federally-designated wilderness areas, including the Frank Church River of No Return Wilderness, Gospel Hump Wilderness, Selway Bitterroot Wilderness, Sawtooth Wilderness, and the Bob Marshall Wilderness Complex, and Glacier National Park, comprise 17% of the lands covered by the fire atlas (Morgan et al. 2014)

Though imperfect, the fire atlas is a valuable long-term record of fire. Fire perimeters are not 100% accurate. The perimeters in the fire atlas were developed using multiple methods from hand drawn perimeters to satellite derived perimeters (Morgan et al. 2014). These different methods of developing perimeters can lead to over-simplified boundaries where fire perimeters closely follow natural breaks such as ridgelines not the actual burned area and unburned patches within the fire boundary are not excluded (Morgan et al. 2014). However, while fire atlas data may be locally inaccurate, at large scales local inaccuracies should not hide broad effects due to certain environmental variables and patterns should reveal meaningful information.

Reburn Area

To determine reburn area, we identified all 30-m pixels within the 9,731,691 ha forested fire atlas recording area that had burned more than once using the count overlapping polygons tool in ArcMap 10.3 (Figure 1). Then, we used overlay analysis to determine how the burned and reburned areas were distributed over time and space. We binned each of the influencing variables as done by Morgan et al. (2014). For ESP group, we binned each 30-m pixel of the fire atlas into one of three forest types: dry forests, mesic forests or cold forests as defined by Morgan et al. (2014). We also binned the atlas data into one of three fire management eras: early (1900-1934), middle (1935-1973), and late (1974-2013). We designated each pixel of the fire atlas as federally designated wilderness (yes) or other-lands (no). We binned elevation into three groups: less than 1500 m, 1501-2500 m and greater than 2501 m. We binned aspect into four azimuth groups: northeastern (0-89°), southeastern (90-179°), southwestern (180-269°) or northwestern (270-360°). We binned slope into three groups: less than 30%, 30-60%, and greater than 60%. We binned slope position index into three groups: lower slope (<30%), middle slope (30-70%) and upper slope (>70%).

To determine if reburn is occurring disproportionately over space and time, we compared the proportion of reburned 30-m pixels within each bin to the proportion of 30-m pixels in each bin for the entire forested fire atlas recording area using a Pearson's chi-squared test. We expected that if reburn areas were random on the landscape the proportions would be equal. Due to the large sample sizes, we considered comparisons to be significantly different at $\alpha \leq 0.0001$. We then repeated the process looking this time at the proportion of reburn 30-m pixels within each bin to the proportion of 30-m pixels within each bin for areas that had been burned at least once. We expected that if fire had a habitat, places where fire is more likely on the landscape, then the proportion of reburned pixels would be proportionate to the number of pixels in each bin for the burned areas.

Fire-on-Fire Interaction

To evaluate the degree to which fire-on-fire interactions varied by our selected variables, we analyzed the distance between fires (Figure 2). This was a multi-step approach. We first added a 120-m buffer to all of the perimeters within the fire atlas dataset to encompass the likely perimeter mapping errors within the fire atlas. We then placed 17,000 random points within the buffered area of the fire perimeters. This was the most points we could place within the study area without autocorrelation between points. Values for our explanatory variables were then attributed to each point. No two random points were closer than 127.5 m to limit spatial autocorrelation between points as done by Birch et al. (2015). To determine if the previous fire is limiting subsequent fire spread, we measured the distance from each point within the buffered area of a previous fire to the nearest perimeter of a subsequent fire. For fire perimeters that overlap (i.e., reburned areas), the associated distance is negative. For fire perimeters that do not overlap, the distance is positive. Where previous and subsequent fires share a common perimeter the distance is zero. This was accomplished using a multiple step approach in ArcMap 10.3. First, the fire atlas with buffered fire perimeters was dissolved into years. The fire year areas were then intersected with themselves. This produced a file that had every possible reburn area. This process caused many repetitions. For example, a 2004 fire reburned over a 1984 fire but the intersected fire also showed 1984 reburning 2004. We only needed one of these two intersections. A python script was used to clean the file of repetition. The resulting file gave us our reburn areas. The 17,000 random points were then joined to the new reburn polygons. Each point was assigned a corresponding reburn polygon number and year if it was within a reburn area. If it was not in a reburn area it received zeros for these attributes. A python script was then used to divide this point file into separate fire years and also files for points that occurred before each fire year. For example we had a file containing just points for 1905 and a file containing all points that occurred prior to 1905. A python script was then used to loop through each fire year comparing each point to points from the file containing points from previous years. The ArcMap 10.3 tool for this is called near. The tool placed a near ID, near distance, and near angle for the nearest point into the shapefile (http://pro.arcgis.com/en/pro-app/tool-reference/analysis/near.htm). The explanatory variable information corresponding to the near point was added to the attribute table for the shapefile. The individual year shapefiles containing the new data for the nearest point were then merged into a single shapefile. To determine if the distance calculated using the near tool should be negative (i.e. a reburn distance) we examined polygon numbers for a point and the nearest neighbor. If these two distances matched, then it was determined it was an instance of reburn and the associated distance should be negative. Distance between fires was limited to 500 m, the distance at which we are confident that there is no effect of previous fire on subsequent fires. The distance between fires was limited to 500 m to also help account for uncertainty in the perimeter data. For each of these distances, we attached the attributes or values for ESP group, wilderness designation, and elevation, slope, and aspect and slope position index for the point within the perimeter of the previous fire as we were interested in whether previous fires are limiting subsequent fire spread. Values for regional fire year and fire management era were taken from the subsequent fire. These two variable values were taken from the subsequent fire as burning conditions and how the fire was managed could influence the effectiveness of a previous fire limiting the subsequent fire.

Prior to statistical analysis, we log-transformed our response variable, distance, to ensure a normal distribution. We also conducted a pair-wise comparison and found that no two predictor variables were highly correlated (Pearson's correlation, $r < 0.7$). Then, we used generalized linear models with ESP group, fire management era, regional fire year, and wilderness designation as binned variables, and elevation, slope, slope position index, aspect, and time since previous fire as continuous variables. We used an exhaustive approach to build the models using the glmulti function (Calcagno 2013; R Core Team 2015) to identify the best subset of models from all possible models. Within the best subset, we then used a mix of forward and backward regression techniques to identify the best fit dropping variables that increased the Akaike Information Criterion (AIC). The final model was selected after removing insignificant terms from the model identified by the glmulti program. AIC values between the model selected by glmulti and our final model differed slightly though the final model had nine fewer variables.

RESULTS

Reburn Area

Almost half (44%; 4,281,944 ha) of the 9,731,691 ha forested fire atlas recording area experienced fire at least once between 1900 and 2014. About one third (36%; 3,503,409 ha) experienced fire once between 1900 and 2014. Less than one tenth (8%; 778,535 ha) reburned, i.e., burned two or more times, between 1900 and 2014. Some of these areas had experienced up to 6 fire events during this time period (< 0.5%; 157 ha).

Reburn occurred disproportionately in the study area (Figure 3) (Table 1). All chi-squares tests were significant at $P \leq 0.0001$. Relative to the study area as a whole, reburn occurred disproportionately within wilderness, in early and late fire management eras, during regional fire years, in mesic forest types, on southeastern and southwestern aspects, on elevations 0 -1500 m, on slopes of 30-60% and middle slope positions. Reburn occurred disproportionately even within areas that had burned at least once 1900 to 2014 (Figure 4). Reburn occurred disproportionately within wilderness, Early and Late eras, during regional fire years, in dry and mesic forest types, on southwestern aspects, at elevations 0 - 1500 m, on slopes of 30-60% and on middle slope positions.

Fire-on-Fire Interaction

Our final model of distance between fires included the predictor variables aspect, elevation, ESP group, wilderness designation, regional fire year, fire management era, and years since previous fire (Table 2). As aspect moves from north–northeast to south-southwest facing, distance between fires increased. As elevation increased, distance between fires decreased. As years since previous fire increased the distance between fires decreased, in dry forests distances between fires were less than in cold and mesic forests. Distance between fires was less in wilderness than in non-wilderness areas, and during regional fire years. Distances in the late fire management era were less than in either Early or Middle eras (Table 3). This model also included interactions between wilderness designation and years since previous fire, between fire management era and years since previous fire, between elevation and years since previous fire, between wilderness designation and fire management era, between wilderness designation and regional fire year, and between regional fire year and fire management era.

The interaction between wilderness designation and years since previous fire has a positive estimate indicating that years since previous fire has more of an influence on distance between fires inside compared to outside of wilderness areas. The interaction between fire management era and years since previous fire has a negative estimate indicating that as we move from Early to Middle and Late eras, years since previous fires have less of an influence on distance between fires. The interaction between elevation and years since previous fire has a negative estimate indicating that at higher elevation, years since previous fires have less of an influence on distance between fires. Fire management era had significant interactions with wilderness designation and regional fire year. In both cases the estimate was negative. Designated wilderness and regional fire years both tended to cause the influence of fire management era to be less influential. The last interaction included in the final model was that of wilderness designation and regional fire year. This interaction had a positive estimate showing that the influence of regional fire years within wilderness areas tends to be stronger (Table 4).

DISCUSSION

Reburns were limited and more likely in wilderness, during the Early management era, during regional fire years and in dry forests

Reburns were more likely in wilderness, reflecting the greater area burned. Fires often receive limited suppression within designated wilderness areas, leading to more fire-on-fire interactions. The relatively recent change in fire management strategies, such as allowing wilderness fires to burn for resource benefit, led us to expect that previous fires would result in a negative feedback interaction leading to reduced reburn. While this was be true for the Late era of 1974 to present, previous fire management strategies, including full suppression, may have influenced reburn potential over the past 114 years. While others have shown previous fires to limit subsequent fires within wilderness areas (Collins et al. 2009; Parks et al. 2014, 2015, 2016), our analysis used a much longer dataset encompassing various fire management eras and included areas outside as well as inside wilderness. As we expected, reburn is occurring more inside designated wilderness areas than outside them, and varies by management era.

Reburn occurred more during the Early era compared to Middle and Late. Up until the fires of 1910, fire suppression activity was limited (Hessburg and Agee 2003). During this Early era the study area also experienced extensive area burned (Morgan et al. 2014). This Early era also experienced six of the eleven regional fire years, in which fire extent was up to ten percent of the study area (Morgan et al. 2008). With limited suppression, a high number of fires, and greater fire extent the potential for reburn was greater during this time period.

Reburns were more likely in regional fire years when dry summers follow warm springs (Morgan et al. 2008; Heyerdahl et al. 2008) and more area burns. Although we did not analyze climate, our findings that reburn is occurring more often than expected during regional fire years supports the idea that climate drives reburn as well as wildland fire frequency, size and extent as others have found (Westerling et al. 2006, 2011; Flannigan et al. 2013; Dennison et al. 2014; Parks et al. 2015).

Although we expected high elevation forests to experience more reburn due to high severity fires (Schoennagel et al. 2004), we found that dry forests experienced more reburn. Dry forests experienced more reburn, perhaps as a result of the high frequency of fire occurrence and a twentieth-century shift toward more mixed and high severity fire (Hessburg and Agee 2003).

Repeated fire has a habitat. Reburn occurred disproportionately with respect to elevation, aspect, and slope as we expected. These topographic variables influence fire spread rates, frequency and burn severity (Rollins et al. 2002; Dillon et al. 2011). Southern aspects receive more solar radiation than northern aspects leading to lower fuel moistures and fuels more susceptible to fire activity increasing potential for reburn (Rollins et al. 2002). Lower elevations experience earlier snowmelt than higher elevations. This can lead to lower fuel moistures, increased fire behavior and fire intensity (Holden et al. 2009; Dillon et al. 2011). Although steeper slopes and higher slope positions can experience fires with faster rates of spread and more frequent severe fire, we found reburn to be occurring more often on moderately steep slopes.

Fire-On-Fire interactions were more likely where and when large fires burned

Previous fires often limited subsequent fire extent. However, topography, vegetation and management often influenced a previous fire's effect.

While southern aspects tend to receive more solar radiation making them more prone to frequent fire events, site productivity may be too low for fire ignition and spread (Rollins et al. 2002). We believe this may be the case with our findings. While northern aspects may not be as prone to frequent fire as southern aspects, fuel load and continuity may be such that when extended dry periods make northern aspects susceptible to burning they are more likely to reburn than southern aspects. Although high elevations may not experience frequent fire, our findings suggest that when conditions allow for fire, fuel loads may promote large fires that are more likely to reburn areas previously burned.

Forest types in the U.S. Northern Rockies historically experienced differing fire regimes (Schoennagel et al. 2004). Although we expected reburn to be greater in extent in cold forests with limited fire-on-fire interactions, our model shows that the distance between fires in the cold forest ESP group is greater than in dry and mesic forest ESP groups. While fire conditions, such as those that occur during regional fire years, in cold forests may be conducive to reburn events, fires in this ESP group occur at much longer intervals than in dry and mesic forests (Schoennagel et al. 2004). The fewer number of fires in the cold ESP group likely leads to longer distances between fires and less fire-on-fire interactions.

Reburns and fire-on-fire interactions are occurred more inside wilderness than outside of wilderness. The decision to use less aggressive suppression on naturally-ignited fires in wilderness areas provides more potential for fires to interact and for negative feedback mechanisms to work to limit extent of subsequent fires. This supports findings of various other research projects conducted on fire-on-fire interactions (Collins et al. 2009; Parks et al. 2014, 2015, 2016). With increasing years since previous fire, fires within wilderness are burning closer together. This supports the findings from other research in wilderness that with increasing time fuel loads increase and the fuel break effect of previous fires is lessened (Collins et al. 2009; Teske et al. 2012; Parks et al. 2014, 2015, 2016).

Long term data from large areas provide useful context for recent trends in area burned

Our examination of fires over a large study area using data that spanned 114 years confirmed what Collins et al. (2009) and Parks et al. (2014, 2015, 2016) found for large wilderness areas in recent decades. Negative feedback mechanisms influence how subsequent fires interact with previously burned areas with decreasing effectiveness over time. However, we found that the influence of climate, topography, vegetation and management and interactions between these factors also play a role in a previous fires ability to limit a subsequent fire.

The U.S. Northern Rockies have experienced the largest increase in fire season length and fire frequency in the western U.S., accounting for over half of the increase in large fire occurrence in recent decades (Westerling et al. 2006; Dennison et al. 2014). In the U.S. Northern Rockies fires are burning closer together in the Late era. There were no significant differences in fire-on fire interactions between the early and middle fire management eras. However, the Late era was significantly different from the previous two eras. The Early and Middle eras are characterized by the development of organized fire suppression efforts and the rise of aggressive and effective fire management (Pyne et al. 1996; Hessburg and Agee 2003). In the Late era we have enhanced our ability to detect fires, experienced less aggressive initial attack and the development of wildland fire use (Pyne et al. 1996; Hessburg and Agee 2003). This change in management along with an increase in fire activity in recent decades has led to fires burning closer together and more fire-on fire interactions.

During regional fire years, fires are burning closer together and interacting with each other more than outside of regional fire years. Climate influences wildland fire frequency, size and extent (Westerling et al. 2006, 2011; Flannigan et al. 2013; Parks et al. 2015). Using regional fire years, years of widespread fires, where annual fire extent exceeded the 90th percentile, as a proxy for climate, we see more fire-on-fire interactions during these years (Morgan et al. 2008). However, we weren’t able to directly assess the effects of climate because we lacked sufficiently detailed climate and weather data for this long time frame.

Fires are more likely to reburn with increasing time since previous fire. As we expected, time since previous fire influenced a previous fire’s ability to act as a fuel break for a subsequent fire. Time since previous fire, included in our final model, shows that as time since previous fire increases distance between fires becomes shorter. This phenomenon however interacts with wilderness, management era, elevation and regional fire year. In wilderness and during regional fire years, the window of time between fires in which previous fire limits subsequent fire is smaller while at higher elevations and in the later management eras this window of time is larger. Our findings that fires are more likely to reburn with increasing time since previous fire supports the findings of previous studies (Collins et al. 2009, Parks et al. 2014, 2015, 2016).

This study was conducted over a large study area with differing vegetation, topography and fire history. Sample sizes were large for the chi-square analysis of variables and likely influenced p-values. While we chose a very small significance level for our analysis, it did not prevent all variables from being significant in analysis. Focusing on smaller areas may influence the significance of variables on fire-on-fire interactions.

While burn severity of previous fires have been shown to influence the severity of subsequent fires, we were not able to include burn severity in our analyses. While burn severity data can be inferred from satellite data, those data are only available for the last 30-42 years. Thus, we could not evaluate whether severity of previous fires altered severity of subsequent fires over the 114 years’ time frame.

MANAGEMENT IMPLICATIONS

Our findings support multiple previous studies regarding fire-on-fire interactions. Negative feedback can limit the extent of fires, but this is influenced by aspect, elevation, ESP group, wilderness designation, regional fire year, fire management era and time since previous fire. Previous fires are less likely to limit subsequent fire extent during regional fire year conditions, with increased time since previous fire, on northern aspects and with increasing elevation. Fire managers looking for opportunities to limit fire fighter risk of injury, reduce firefighting costs, and return fire to the landscape now can consider this information when making fire management decisions.

If fire managers are to look for areas where a previous fire may limit a subsequent fire they could look at more southerly aspects, lower elevations, cold forests, outside of designated wilderness areas, during seasons outside of regional fire year conditions, under management conditions similar to those of the late fire management era, and in areas that have burned more recently. One must also consider how these variables interact with each other to influence fire-on-fire interactions. Within wilderness there is a smaller window of time since the previous fire within which subsequent fires may be limited. As elevation is increased this window becomes larger. Areas at higher elevation tend to have shorter growing seasons potentially prolonging the amount of time it requires for fuels to regrow. This makes subsequent fire less likely as these areas are often climate limited (Heon et al. 2014; Parisien et al. 2014; Parks et al. 2015). Within wilderness areas, the effect of fire management era is less than outside wilderness. This is also true in the case of regional fire year conditions, during which conditions may override management efforts. Wilderness areas during times of regional fire year conditions may not be ideal for use of previously burned areas as fire breaks.

CONCLUSIONS

We sought to expand on previous work regarding fire-on-fire interactions to account for variables that could possibly affect fire extent when a subsequent fire interacts with previously burned areas on the landscape. Reburns occurred disproportionately in forested lands of the U.S. Northern Rockies. Reburns occurred more often in the early and late fire management eras, within designated wilderness, during regional fires years, in mesic forest types, on southeastern and southwestern aspects, at elevations of 0 - 1500 m, on slopes of 30 - 60%, and at middle slope positions. These findings suggest that negative feedback mechanisms are at work in the study area, even outside wilderness. Previous fires on the landscape help to limit, under certain circumstances, subsequent fires in the U.S. Northern Rockies.

Fire atlases provide long records (Schoennagel et al. 2004; Littell et al. 2009) that are useful despite imprecision. Outside wilderness areas, logging, grazing, roads, and fire suppression likely affected fire perimeters, yet we did not assess those.

Our findings suggest that fire managers may be able to examine fire areas and determine, based on our significant variables, whether to manage naturally ignited fires to burn into previously burned areas. This action has the potential to limit undue firefighter exposure and reduce firefighting costs, all while allowing fire to play important ecological roles, reduce fuel loads, and take advantage of negative feedback mechanisms to continue to play a proactive role with previous fires limiting subsequent fire in the U.S. Northern Rockies.

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Table 1. Signficant variables (P≤0.0001) for disproportionate occurrence of reburn on the study area as a whole and within areas that had burned at least once 1900-2014.

Both Burned and Unburned Areas		Only Burned Areas	
Variable	X^2	Variable	X^2
Wilderness	3760800	Wilderness	604960
Early and Late Fire Management Eras	3561100	Early and Late Fire Management Eras	402690
Regional Fire Years	764800	Regional Fire Years	25812
Mesic Forest Types	287410	Dry and Mesic Forest Types	180700
Southeastern and Southwestern Aspects	51154	Southwestern Aspects	20925
Elevation 0 – 1500 m	1359600	Elevation 0 – 1500 m	449550
Slopes 30 - 60%	409200	Slopes 30 - 60%	163580
Middle Slope Positions	38835	Middle Slope Positions	9845

Table 2: Final model used in the analysis of fire-on-fire interactions. Insignificant interaction terms were dropped through regression analysis to determine best model from the best subset of models selected using glmulti statistical analysis in R. Only two-way interaction terms were considered.

Variables and Interactions	Coefficient	P-Value
Intercept	4.832	<0.0001
Aspect	-0.1504	0.0914
Elevation	0.0005	<0.0001
ESP2	0.0341	0.6855
ESP3	0.4259	0.0005
Wilderness	0.3471	0.3891
Regional Fire Year	0.513	0.0137
Middle Management Era	0.0839	0.5783
Late Management Era	1.31	<0.0001
Years Since Previous Fire	0.0449	<0.0001
Wilderness and Years Since Previous Fire	0.006	0.0029
Management Era and Years Since Previous Fire	-0.013	<0.0001
Elevation and Years Since Previous Fire	<-0.0001	0.0071
Wilderness and Management Era	-0.3319	0.0155
Wilderness and Regional Fire Year	0.4399	0.006
Regional Fire Year and Management Era	-0.2353	0.0108

Table 3: Effects of individual varibales on distance between fires.. An up arrow indicates distance between fires increased as aspect moves fron north-northeast to south-southwest. A down arrow indicates distance between fires decreased as elevation increases, in wilderness, in ESP2 and ESP3 relative to ESP1, during regional fire years, in the middle and late management erasrelative to the early management era and as year since a previous fire increases.

Individual Variables	Effect on Distance Between Fires
Aspect	↑
Elevation	↓
ESP2	↓
ESP3	↓
Wilderness	↓
Regional Fire Year	↓
Mid Management Era	↓
Late Management Era	↓
Years Since Previous Fire	↓

Table 4: Effects of interaction terms in final fire-on-fire model. Up arrow indicates interactions of terms strengthens effect of terms, while down arrow indicates a weakening effect of terms.

Interaction Terms	Interaction Effect
Wilderness and Years Since Previous Fire	↑
Management Era and Years Since Previous Fire	↓
Elevation and Years Since Previous Fire	↓
Wilderness and Management Era	↓
Wilderness and Regional Fire Year	↑
Regional Fire Year and Management Era	↓

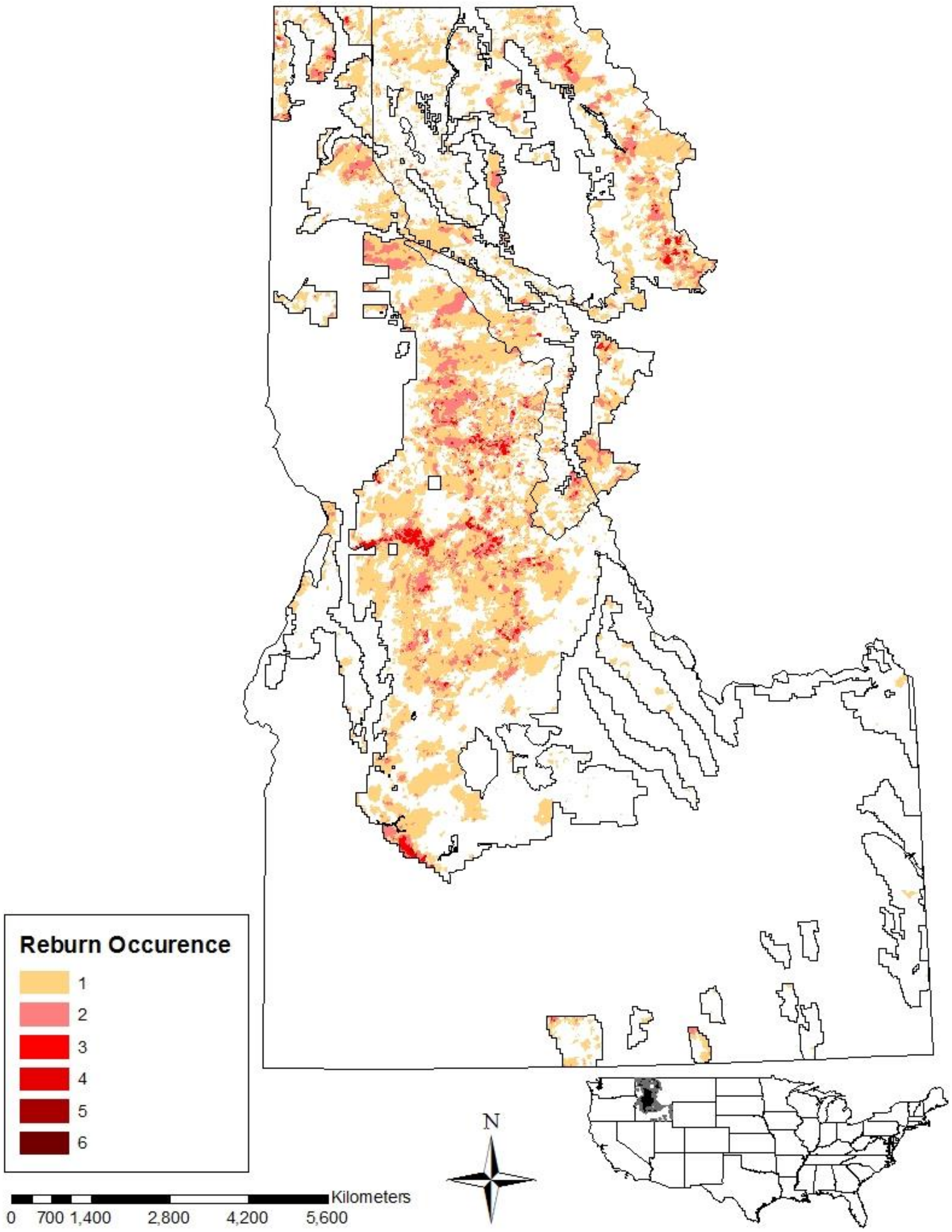

Figure 1: Reburn occurrence 1900-2014 in the U.S. Northern Rockies study area in forests of Idaho and the part of Montana west of the Continental Divide. Areas have experienced one (orange) to six fires in the same area (dark red). Data used are based on digital fire atlas records from 12 national forests and one national park. Data covers 9,731,692 ha of forested land.

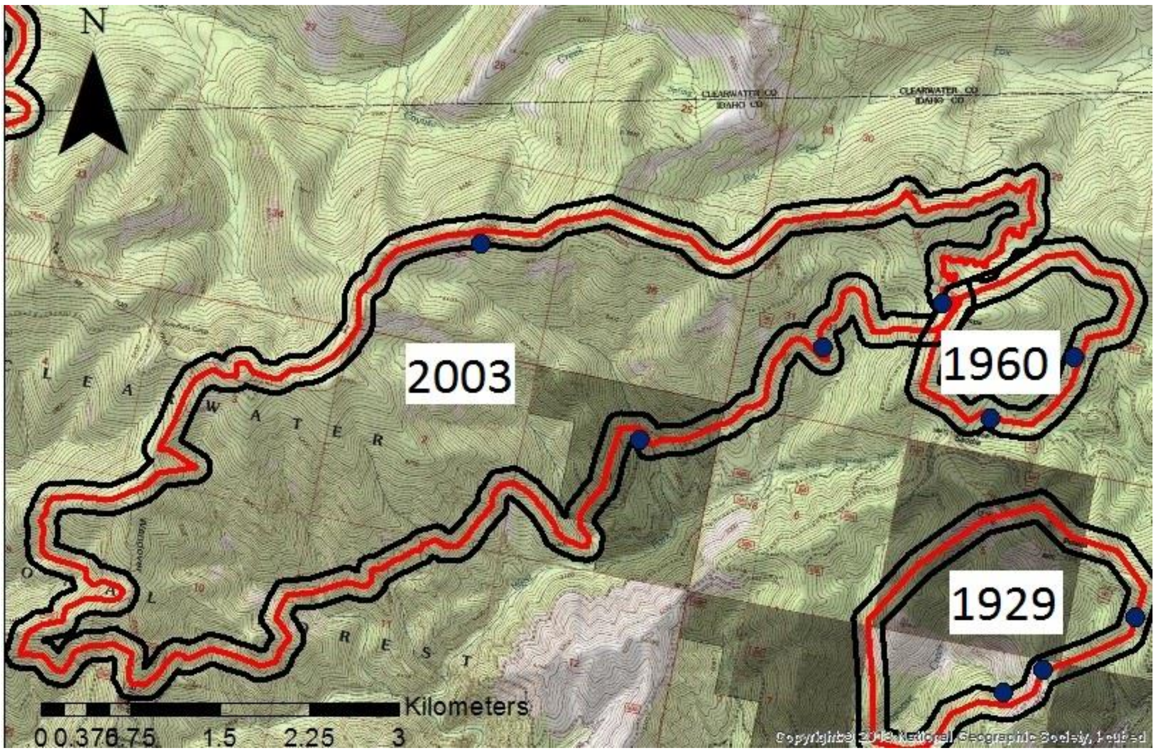

Figure 2: Fire-on-fire interactions characterized as distance between random points (blue) within buffers (black) along fire perimeters (red); buffers (black) help account for potential errors in fire mapping. Distance between the 2003 and 1960 fire would be 0, while distance between the 1960 and 1929 fires would be positive.

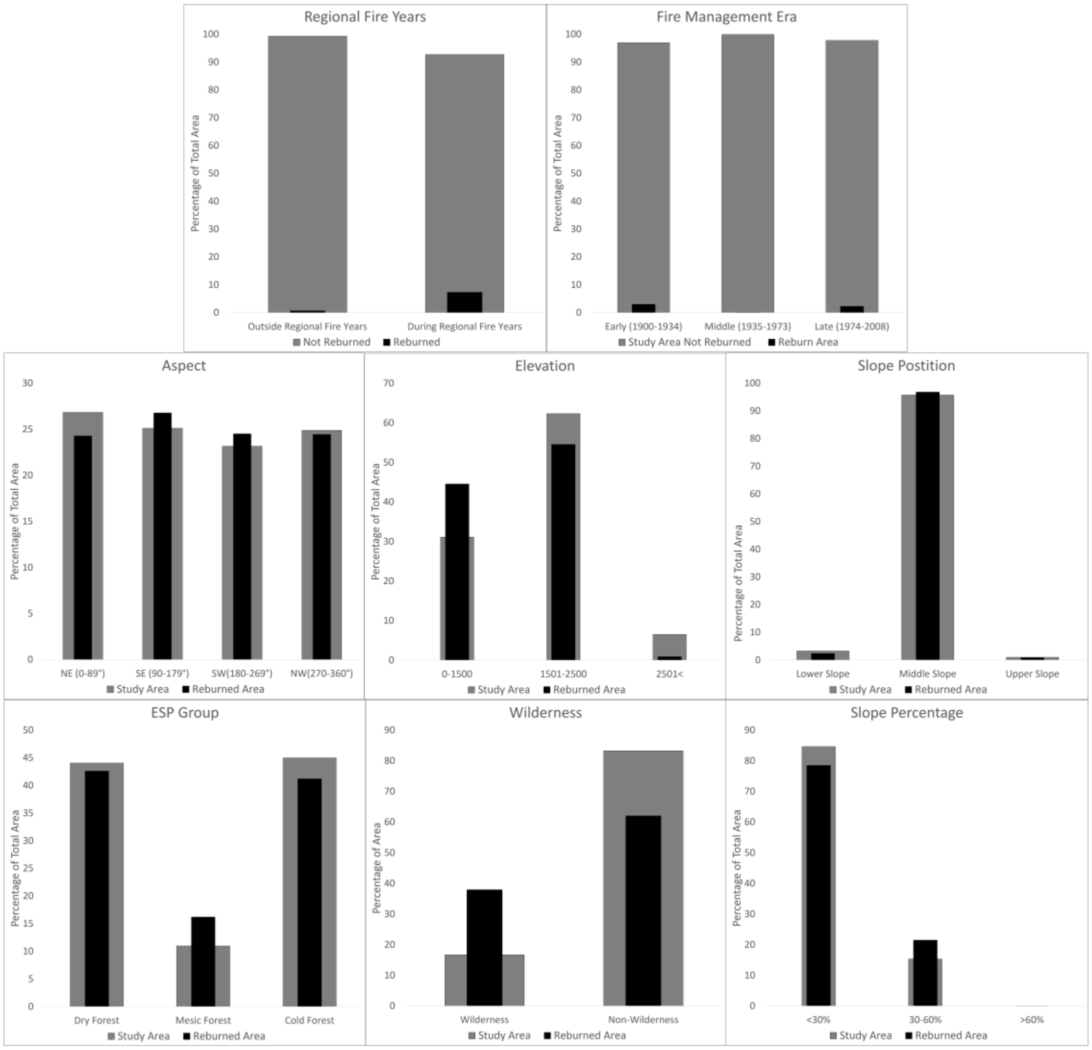

Figure 3: Proportion of area reburned within the fire atlas recording area (black) compared to proportion of land within fire atlas recoding area (grey), 1900-2014.

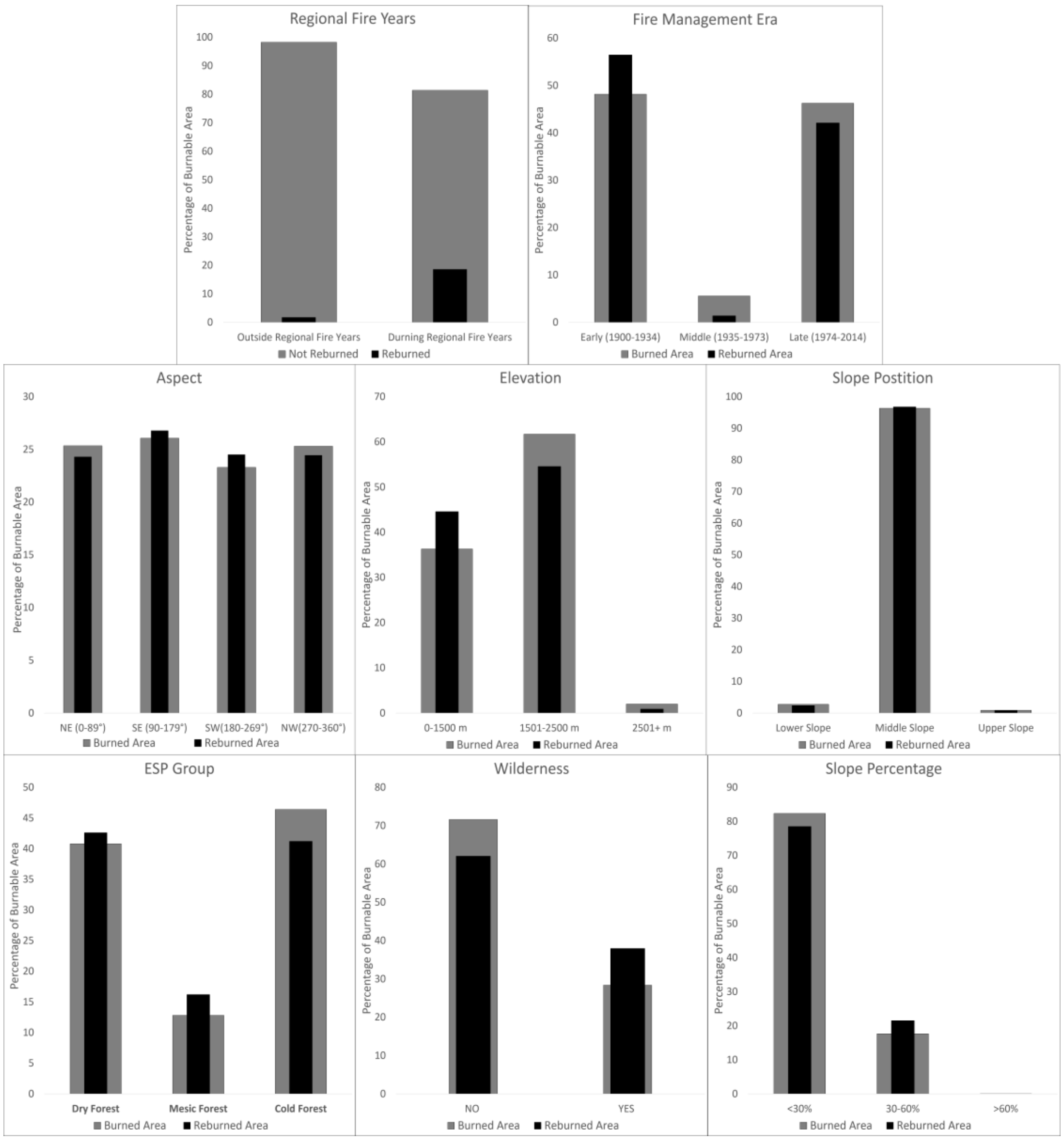

Figure 4: Proportion of area reburned within the fire atlas recording area (black) compared to proportion of burned area within fire atlas recording area (grey), 1900-2014.