MULTIDECADAL TRENDS IN BURN SEVERITY AND PATCH SIZE IN THE SELWAY-BITTERROOT WILDERNESS AREA 1900-2007

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ABSTRACT

Quantifying how the proportion of area burned severely has changed over time is critical to understanding trends in the ecological effects of fire. Most assessments over large areas are limited to 30 years of satellite data, while historical and contemporary fire return intervals are often longer. The change in proportion burned severely was analyzed across 346,304 ha within the Selway-Bitterroot Wilderness Area in Idaho and Montana, USA using fire perimeters and burn severity class for all burned patches as inferred from 1900-2000 digitized aerial photography and 1984-2007 Landsat Thematic Mapper imagery from the Monitoring Trends in Burn Severity project. Understanding how proportion of area burned severely has changed over time through three periods of contrasting fire management (1900-1934, 1935-1974, and 1975-2007) at large spatial and temporal scales will help ecologists and land managers better understand vegetation response post fire and will help to inform predictions of future fire effects.

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CHAPTER ONE

INTRODUCTION

Although fires are a major disturbance shaping ecosystems globally (Bowman *et al.*, 2009; Higuera *et al.*, 2011), multidecadal trends in burn severity and patch size are poorly understood despite their implications for ecological effects and fire management. We analyze a temporal depth of geospatial data spanning 1900-2007 through three different fire management periods across 346,304 ha within the topographically diverse Selway-Bitterroot Wilderness Area (SBW). This provides a unique and valuable context for investigating trends in burn severity especially given predictions that area burned may increase in the future (Littell *et al.*, 2009; Littell *et al.*, 2010). Fire extent as influenced by climate, vegetation, and land use has been extensively studied (Schoennagel *et al.*, 2004; Dillon *et al.*, 2011), but we know less about burn severity (Morgan *et al.*, 2001; Keeley, 2009a), defined as the degree of ecological change resulting from a fire (Lentile *et al.*, 2006). Temporal trends in burn severity, species diversity, and patch size distribution have been little studied, yet are important as they influence vegetation composition, erosion potential, wildlife habitat, and other values (Turner *et al.*, 1997; Lentile *et al.*, 2007; Keeley *et al.*, 2008; Romme *et al.*, 2011).

Burn severity over time and across space

Burn severity refers to the ecological magnitude of change pre-fire to post-fire (Morgan *et al.*, 2001; Lentile *et al.*, 2006), and can be measured by several factors, but should not be quantified by one single measure alone (Lentile *et al.*, 2006). Burn severity can be inferred from remote sensing or on the ground. In remote sensing, burn severity is related to consumption of vegetation, changes in soil properties, and presence of ash, all which can change surface reflectance (Lentile *et al.*, 2006), while burn severity on the ground is measured by vegetation mortality, soil color change, and litter/duff consumption (Ryan and Noste, 1985; Parsons *et al.*, 2010). On the ground classification commonly uses a measure called the Composite Burn Index (CBI) (Key and Benson, 2006). Remote sensing indices such as the Normalized Burn Ratio (NBR), differenced Normalized Burn Ratio (dNBR) and the Relative differenced Normalized Burn Ratio (RdNBR) (Miller and Thode, 2007) are available from the Monitoring Trends in Burn Severity Project (MTBS) and have been applied in analyses across regions to evaluate trends in severity (Miller *et al.*, 2009; Dillon *et al.*, 2011), although they have limitations (Roy *et al.*, 2006). However, such analyses are limited by the temporal record of satellite data (1970's to present). Burn severity can be separated into discrete classes ranging from unburned to high severity (Lentile *et al.*, 2006).

Increases in the extent of area burned severely from 1984-2003 have been documented in the Sierra Nevada Mountains (Miller *et al.*, 2009) and in forests of the US Southern Rockies ecoregion (Dillon *et al.*, 2011), but contrasting results have also been found in the Sierra Nevada Mountains (Collins *et al.*, 2009; Hanson and Odion, 2013) and in five other ecoregions (Dillon *et al.*, 2011). A longer time series is needed to evaluate such trends, especially where time elapsed between fires can be long and climate drivers vary over decades. As wildfires become more frequent and the number of large fires increases (Westerling *et al.*, 2006; Littell *et al.*, 2009), there is a greater need to understand how fire severity affects ecosystem processes (Keeley *et al.*, 2008). As more area burns, more area burns severely (Holden *et al.*, 2011), but what is less known is whether proportion of area burned severely is also increasing over multiple decades (Miller *et al.*, 2009). We would expect that if area burned has shown increases (Westerling *et al.*, 2006; Miller *et al.*, 2009; Dillon *et al.*, 2011), burn severity might also increase. Although amount of area burned and subsequent burn severity are correlated, there are other underlying factors influencing burn severity such as topography (Dillon *et al.*, 2011), weather (Schoennagel *et al.*, 2004), and vegetation type and structure (Collins and Stephens, 2010). We hope to learn more about whether burn severity is influenced by past management including fire exclusion (Haire *et al.*, 2013), time since fire (Collins *et al.*, 2009), and previous fire effects (Parks *et al.*, 2013) and how these variables affect area and patch size (Teske *et al.*, 2012) of high severity burns.

Burn severity is an important driver of forest ecosystem and recovery processes. Tree seedling recruitment, vegetation response, alien plant invasion, resprouting, and species richness are affected by burn severity (Keeley, 2009a, b; Miller *et al.*, 2009). High severity patches are the slowest to recover, likely because of their size and resulting low tree seedling recruitment (Turner *et al.*, 1997; Lentile *et al.*, 2007) which translates into a slower rate of ecosystem recovery. High severity fires can provide the catalyst for seed germination for many plant species, habitat in snags and burned logs, and a diversity of age classes and vegetation structures (Hanson and Odion, 2013). We used only high severity patches for our analysis for these reasons and because we are most confident with high severity patch recognition and delineation. The agreement between field and remotely sensed data is better relative to other burn severity classes (Cocke *et al.*, 2005; Hudak *et al.*, 2007; Lentile *et al.*, 2007).

Patches are ecologically important

Patches are essential to understanding the landscape ecology of fire regimes (McKenzie *et al.*, 2011), because patch size and shape and burn severity can affect post-fire vegetation response (Baker, 2009), but the patch size distribution over time is unknown. Fires burn heterogeneously creating a mosaic of burn severity, with unburned islands (Baker, 2009) and burned openings, referred to as patches, where post-fire regeneration occurs (Agee, 1998). Greater distances from unburned edges have shown delays in conifer seedling establishment post-fire (Turner *et al.*, 1997; Greene and Johnson, 2000) which suggests that the core area of burned patches exhibits different vegetation responses than locations nearer to the edges of large patches (Halofsky *et al.*, 2011). Patch size becomes increasingly important to post-fire vegetation response when the area burned is large and the residual trees are few and far between (Turner *et al.*, 2001) because tree seedling establishment post-fire is dependent of seed source availability (Agee, 1998; Greene and Johnson, 2000). The unburned edge likely has less effect for understory vegetation diversity and species richness because many fire-tolerant species are able to resprout post-fire or establish from existing seed banks (Lyon and Stickney, 1976; Lentile *et al.*, 2007). Although vegetation response, including seedling densities, graminoid and forb cover, and species richness have been found to be greatly impacted by burn severity and patch size, the effect of patch size has not been widely studied and longer-term studies are needed (Turner *et al.*, 1997).

Mixed severity fire regimes

Mixed severity fire regimes not only describe the differences in canopy mortality between low severity (<20%) and high severity (>70%) burns (Agee, 1993) but also the mix of patches with varying fire effects (Halofsky *et al.*, 2011). Mixed severity fire regimes are one of the most prevalent disturbance regimes in the western United States, yet the effects are poorly understood (Halofsky *et al.*, 2011). The heterogeneity, both spatially and temporally, of mixed severity fires (Halofsky *et al.*, 2011) is reflected in the wide variability in how the fires burn (Perry *et al.*, 2011). We expect to see a distribution of many small patches and a few very large patches on the landscape (Perry *et al.*, 2011).

Large area and long temporal series offer unique opportunities to study fire

The Selway-Bitterroot Wilderness area offers an ideal location to study the spatial patterns of wildfire because of the large spatial extent and long temporal data series available. A large study area that covers a diverse topography and climate range provides a broader context within which to observe trends in spatial patterns of burn severity and the subsequent vegetation response. Our data spans 108 years offering a multidecadal approach to study long-term trends of fire patterns. Much of the research regarding vegetation response trajectories occurs either in a relatively short time interval (1-5 years) (Turner *et al.*, 1997) or at long intervals (75+ years) post fire (Kipfmueller and Kupfer, 2005), and most contemporary studies of spatial patterns and extent of burn severity patches use satellite data that have only been available for the past 30 years. Aerial photography has been used to study characteristics of burned patches through time (Minnich and Chou, 1997), and can be reliable when coupled with historical data and interpreted with local expertise (Hessburg *et al.*, 2007).

The SBW has a long history of large fires influenced by three different periods of fire management (Brown *et al.*, 1994; Rollins *et al.*, 2001; Teske *et al.*, 2012; Haire *et al.*, 2013; Parks *et al.*, 2013). We divide this temporal series into three periods: Early (1900-1934), Middle (1935-1974), and Late (1975-2007) according to other research in which extent and frequency of area burned was related to land management (Rollins *et al.*, 2001). The United States Wilderness Act of 1964 set aside land including the SBW with the goal of having an area that is managed by the forces of nature instead of those dominated by people in order to preserve its natural condition (McCloskey, 1966). In the Early period, fires typically burned without suppression because the ability to detect and suppress fires was not well developed, especially in the remote, rugged montane terrain of the SBW (Brown *et al.*, 1994; Rollins *et al.*, 2001). In the mid-20th century, during the Middle years 1935-1974, fire suppression was active and often effective with improved technology especially in air operations (Pyne, 1982), including smoke jumpers from Missoula, MT, Grangeville, ID and Boise, ID (Brown *et al.*, 1994; Rollins *et al.*, 2001). In the 1970's, the U.S. Forest Service and the National Park Service recognized that suppression tactics kept fire from having a natural role in the environment as a central ecosystem process (Pyne, 1982; Brown *et al.*, 1994; Rollins *et al.*, 2001). The Late period marks a change: in 1974 managers in the SBW were among the first to adopt a wildland fire use plan to let fire play a more natural role under carefully prescribed conditions (Frost, 1982; Brown *et al.*, 1994; Rollins *et al.*, 2001). Still, wildfires are often suppressed within SBW when necessary to protect property and to confine fire to within the wilderness boundary (Brown *et al.*, 1994).

Extensive fires occurred in wilderness areas during years of widespread fire within the region, particularly Early and Late (Morgan *et al.*, 2008; Morgan *et al.*, In Press). In this large wilderness area we can study the spatial patterns of high severity fires with fewer confounding effects such as: anthropogenic fire ignition, grazing, roads, and timber harvest. We expect to find differences in burn severity and patch size as a result of fire management with Late years exhibiting similar size distribution and number of high severity patches to those of Early years though with less area burned (Brown *et al.*, 1994; Rollins *et al.*, 2001). Alternatively, the extensive fires in the early 1900s and before may have resulted in smaller patches in recent decades (Collins *et al.*, 2009; Teske *et al.*, 2012; Parks *et al.*, 2013).

Research objectives and hypotheses

Our first objective was to evaluate if area burned severely and proportion of area burned severely have varied with fire management under distinct time periods. We hypothesized that the lack of fire over multiple years during the Middle period (1935-1974) resulted in a greater extent of burned area with high severity in the Late period (1975-2007), relative to Middle but less than Early. Our second objective was to evaluate whether patch characteristics of high severity fires have changed through the three management periods. We hypothesized that the increase of area burned severely would be reflected in a larger patch size. Our third objective was to observe how distance to unburned edge affects vegetation response in high severity burned areas. We expected that within large patches burned with high severity, areas at greater distance to unburned edge would have decreased tree seedling densities, and decreased plant species diversity and richness. Burn severity is the common denominator in evaluating the ecological effects of landscape recovery and processes post-fire, and identifying the changing landscape patterns of burn severity improves our understanding of the consequences of historical fire management decisions, and informs spatial and temporal interpretations of the ecological effects of fire.

CHAPTER TWO

METHODS

Study area

We analyzed burn severity from 1900-2007 for 346,304 ha within the SBW (Figure 1), which is a subset of the entire wilderness boundary. This study extent represents the overlapping area from the two datasets used in this study, one that focused on only the SBW watershed, and the other that we limited to the wilderness boundary. With elevations ranging from 550 to 3,050 m, the climate in the SBW varies widely (Finklin, 1983). An inland-maritime climate dominates with daytime mean temperatures ranging from -10 ˚C in January to about 21˚ C in July and August (Finklin, 1983). Mean temperatures from 1931-2007 for January ranged from -9˚C to 3˚C and July temperatures ranged from 15˚C to 24˚C (http://www.ncdc.noaa.gov). Most of the precipitation falls as snow, and snowpack usually persists through late June (Finklin, 1983). January is typically the wettest month with about 75-250 mm falling as snow, whereas summer months are the driest with only 20-30 mm of precipitation falling as rain (Finklin, 1983).

Historically, fires were relatively infrequent in the SBW. Calculating fire rotation and fire return intervals are used to describe frequency of fire on the landscape. Fire rotation, which is represented by the number of years it would take to burn the specified study area (Baker, 2009) is calculated by dividing the number of years by the proportion of area burned within a defined time period. Calculated using fire perimeter data, the average fire rotation during 1880 – 1996 for all fire regimes was 194 years in the SBW (Rollins *et al.*, 2001) Mean fire interval is the length of time between fires within specified study area (Agee, 1993). From 1528 – 1935 estimated fire return intervals for high severity stand-replacing fires ranged from 54 - 197 years (Brown *et al.*, 1994) and 22 – 56 years for low and mixed severity (Brown *et al.*, 1994). Historical mean fire return intervals for stand replacing fire in subalpine forests are estimated to range from 50-300 years (Arno, 1980). Prior to 1900, mean fire return intervals ranged from 19 - 173 years using fire scar records from whitebark pine (Kipfmeuller, 2003). Using tree-ring records and charcoal in lake sediments from the Holocene, Brunelle *et al.* (2005) documented 1 to 3 fires per century (1700 - 2000) in subalpine forests in the Selway-Bitterroot Wilderness Area.

The forests of the SBW vary with topography (Habeck, 1972; Brown *et al.*, 1994; Kipfmueller and Swetnam, 2000; Rollins *et al.*, 2001; Teske *et al.*, 2012). Cold forests dominate at high elevations. The subalpine zones cover nearly 70% (Rollins *et al.*, 2001) of the SBW which primarily consists of subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), lodgepole pine (*Pinus contorta* Douglas ex Loudon), Engelmann spruce (*Picea englemannii* Parry ex Englem.), whitebark pine (*Pinus albicaulis* Douglas) and subalpine larch (*Larix lyallii* Parl.). The middle elevations are dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and grand fir (*Abies grandis* [Douglas] Lindl.) with lodgepole pine and western larch (*Larix occidentalis* Nutt.) present as well. On drier sites at lower elevations, ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) and Douglas-fir dominate. Mesic forests dominated by grand fir, western redcedar (*Thuja plicata* Donn ex D. Don.) and western hemlock (*Tsuga heterophylla* [Raff.] Sarg.) are also common at lower elevations.

Two sources of burn severity data

To extend the analysis of burn severity through time, we used fire perimeters and burn severities derived using two methods. These two spatial data sets identify high severity patches at 30 m resolution (Figure 1). For 1900 - 2000 we used data digitized from aerial photography that we call 'historical aerial photograph severity' (HAPS). For the years 1984-2007, we obtained data from the Monitoring Trends in Burn Severity (MTBS) project. Patches less than 1 ha were removed from both data sets; this eliminated 0.02% of the HAPS and 6.4% of the MTBS area. The minimum mapping unit was applied to make the two data sets more compatible and to eliminate very small patches which were numerous, not as ecologically significant, and may be potential errors.

For the HAPS data, the fire year, fire perimeter, and burn severity class (unburned, low, moderate and high) were interpreted from fire atlases and aerial photographs as part of another study (P. Green, unpublished data). Green (unpublished data), a local fire ecologist with extensive experience in field and aerial photo interpretation, digitized fire perimeters and assigned burn severity onto 1:24,000 orthophoto topographic maps using fire atlases for the Nez Perce and Bitterroot National Forests, and then used aerial photographs to refine fire boundaries and delineate burn severity classes within the fire perimeters. The earliest aerial photographs available were used, which were taken 1932 - 1939, and were supplemented with more recent aerial photographs from 1948, 1954, 1970, 1980, 1985, 1991, and 1994 – 1995; photos varied from 1:12,000 to 1:24,000. This prior study drew upon other historical documents, including Nez Perce National Forest fire perimeter map (1910-1940), Lieberg's (1899) Survey of the Bitterroot Forest Preserve 1898, Selway National Forest Land Classification (1914), Shattuck's (1910) Report on the Forestal Conditions and Possibilities of the

Clearwater National Forest, and Habeck's (1972) Report on Fire Ecology Investigations in the Selway-Bitterroot Wilderness (P. Green, unpublished data). Burn severity classes were assigned based upon percent tree mortality, with low severity classified as less than 30% mortality, moderate as 30 - 70% mortality, and high severity as greater than 70% mortality based on snags and percentages of forest openings (P. Green, personal communication). We used the term 'area burned severely' for this data set, as what Green defined as high severity.

MTBS data consist of fire perimeters and burn severity classes for individual fires interpreted from Landsat TM satellite imagery available for all western wildfires greater than 404 ha (1,000 ac) since 1984 (MTBS, *public communication*, http://www.mtbs.gov; (Eidenshink *et al.*, 2007). These data were processed by the MTBS project using the Relative differenced Normalized Burn Ratio (RdNBR) which accounts for pre fire vegetation (Miller and Thode, 2007; Dillon *et al.*, 2011). The RdNBR values are classified by MTBS into five severity categories: increased greenness, unburned to low severity, low, moderate, and high. A typical range of the RdNBR threshold between moderate and high severities is 695-704 (Miller and Thode, 2007; Holden *et al.*, 2009; Cansler, 2011; Dillon *et al.*, 2011). We used the term 'area burned severely', for this data set, by what MTBS categorized as high severity.

To assess agreement between the HAPS and MTBS data, we first compared the nine years of overlapping fire data (1984, 1985, 1986, 1987, 1988, 1991, 1994, 1996, and 2000) using 16 burned patches mapped in both data sets which totaled 12,416 ha from HAPS data and 11,018 ha from MTBS data. We assessed agreement for patch area and both area and proportion of area burned severely for HAPS and MTBS. Because these three metrics agreed well, we analyzed long-term (1900 - 2007) patterns by combining the two data sets using the HAPS data from 1900 - 1983 and MTBS data from 1984 - 2007 with the exception of years 1989 and 1992 which were only mapped using aerial photography. We also compared short-term trends calculated from each of the HAPS and MTBS datasets for the nine years of overlapping data using the Wilcoxon rank sum test and identified temporal trends using Spearman's Rank Correlation.

Temporal trends of patches

Both the area and proportion of area burned severely were analyzed through time graphically and statistically using the non-parametric Wilcoxon rank sum test which is suitable for non-normal distributions. To determine if both area and proportion burned severely were correlated with area burned, we used Spearman's rank correlation. We calculated fire rotations for all severities combined across the SBW as well as just for high severity. We evaluated patch characteristics, including mean and median patch size, largest patch, number of patches, perimeter-to-area ratio, and distance to edge, to see how spatial patterns of high severity fires varied through time. We contrasted all these metrics using three fire management periods by comparing box plots by Early, Middle, and Late periods and by using Wilcoxon rank sum tests. Additionally, we looked at distance to unburned edge as a way to quantify the ecological effects of patch size as a measure of distance to potential seed source. Distance to unburned edge was evaluated with a script written in R (2.15.2, The R Foundation for Statistical Computing, Vienna, Austria) that uses a raster image of a patch, and calculates the distance from each pixel in a burned patch to the next adjacent pixel that is unburned. All other statistical analyses were performed using MATLAB software (R2012a; MathWorks, Inc., Natick, Massachusetts, USA).

Vegetation response

We collected field data to assess the effects of distance from edge on vegetation response in large patches of high severity fires. To quantify vegetation response as a function of distance to edge, we measured tree seedling density, species diversity, species richness, and abundance of understory vegetation, for 20 patches using transects parallel to unburned edge located at 10, 40, and 80 m from unburned edges of fires from the year 2000. The elevations of our sampling sites ranged from 1,555 m to 2,275 m. Sampling sites were selected from the environmental site potential (ESP) cold/wet forest and woodland (http://www.landfire.gov), which best represents the predominant vegetation types of the SBW. Sampling sites were selected to fit our criteria: patches from the year 2000, correct ESP, accessibility, and patches of high severity that bordered unburned areas. We sampled within the SBW in three different areas: Mill Creek, Magruder Corridor, and Paradise Guard Station (Figure 1). In 1 m x 1 m quadrats located at 0 m, 15 m, and 30 m along each transect at each location, we recorded fractional cover of tree bole, bare soil, litter/duff, moss, rock, and vegetation as well as percent cover of grass, tree, forb, and shrub, and overstory cover. In these quadrats and two additional ones located at 7.5 m and 22.5 m, we estimated the percent canopy cover of each grass, forb, and shrub species. These measurements were used to calculate species richness and diversity. Shannon Wiener Diversity index and species richness were compared using a one-way ANOVA in MATLAB. We counted tree seedlings within a belt transect of varying widths (60 m^2 to 300 $m^{2)}$ since tree seedling densities are highly variable depending on site. We recorded a minimum of 30 seedlings per transect. Tree seedling densities (seedlings/m^2) were analyzed using the Wilcoxon Rank Sum test in MATLAB.

CHAPTER THREE

RESULTS

Of the 346,304 ha study area, 78% (267,121 ha) burned at least once from 1900 - 2007, and 49% (131,198 ha) of that area burned with high severity. Although there were no gaps in the 108-year record, fires were recorded in only 38 years; 12 of these occurred in the Early period (1900 - 1934), 5 in the Middle (1935 - 1974), and 21 in the Late (1975 - 2007) (Figure 2; Table 1). Using the 108-year record from the combined data set of only high severity burned areas, the 90th percentile of area burned severely in a year is 1,700 ha. Of the 11 years that exceeded the 90th percentile, six occurred in the Early period (1910, 1914, 1919, 1920, 1931, 1934), none in the Middle, and five in the Late (1979, 1988, 2000, 2005, 2007) (Table 1).

Comparing the two data sets

We compared the HAPS and MTBS data and found that patch areas were highly correlated (Spearman's rank correlation, $n = 16$, $\rho = 0.59$ and $p = 0.01$) and similar for the two data sets (Wilcoxon rank sum test $p = 0.63$) (Figure 3). Total area burned and area burned severely for the nine years of overlapping data were not significantly different (Wilcoxon rank sum $p = 0.73$ and $p = 0.60$ respectively). Number of patches and size of the largest patch did not differ (Wilcoxon rank sum $p = 0.77$ and $p = 0.86$ respectively) (Table 2), but mean, median, perimeter-to-area ratio, and distance to edge differed (Wilcoxon rank sum $p = 0.05$, $p < 0.01$, $p < 0.01$, and $p < 0.01$, respectively) (Table 2). HAPS data showed slightly higher averages for mean and median patch sizes, greater median distances to edge, and lower patch perimeter-to-area ratios than MTBS data.

Trends through time

Total area burned severely varied considerably year to year from 1900 - 2007 (Figure 2). Most (89%) of the area burned severely did so in a few years (1910, 1914, 1919, 1920, 1931, 1934, 1979, 1988, 2005, 2007). No single year in Middle or Late years exceeded 10,000 ha of area burned severely, but there were three years in Early that did (1910, 1919, and 1934). The amount of area burned severely was greatest Early, least in the Middle period (2% of Early), and intermediate in the Late period (24% of Early area burned severely) (Table 1). Area burned severely differed throughout the management time periods: Early to Middle periods were significantly different

(Wilcoxon rank sum, $p = 0.01$), Middle to Late periods were significantly different (Wilcoxon rank sum, $p = 0.005$), but Early to Late periods were not significantly different (Wilcoxon rank sum, $p = 0.88$) (Figure 4).

Proportion of area burned severely through time also varied greatly (Figure 2). Out of the ten years with the highest proportion of area burned severely (1910, 1914, 1931, 1933, 1934, 1961, 1967, 1988, 1989, 1992), five occurred in the Early period, two in the Middle, and three in the Late (Table 2). Proportion of area burned severely also differed throughout the management time periods: Early to Middle periods were significantly different (Wilcoxon rank sum, $p = 0.02$), Middle to Late periods were significantly different (Wilcoxon rank sum $p = 0.01$), but Early to Late periods were not significantly different (Wilcoxon rank sum, $p = 0.91$) (Figure 4).

Area burned severely was highly correlated with amount of area burned (Spearman's rank correlation $\rho = 0.88$ and $p = 0$) (Figure 5), meaning as more area burns, more area burns severely. On the other hand, proportion of area burned severely was not correlated with area burned severely (Spearman's rank correlation $\rho = 0.07$ and $p = 0.66$) (Figure 5), meaning that there are other factors than just extent affecting proportion of area burned severely.

Fire rotations of all fire severities combined were shorter than rotations of only high severity fires. Early years had the shortest fire rotations, Middle the longest, and Late intermediate (Table 1).

Patch characteristics and vegetation response

The size of severely burned patches has not increased through time (Figure 6). Instead, the mean patch size ($n = 38$ yr, Spearman's rank correlation $\rho = -0.63$ and $p < 0.01$), median patch size ($n = 38$ yr, $\rho = -0.73$ and $p < 0.01$), area of the largest patch ($n = 38$ yr, $\rho = -0.34$ and p 0.03), and distance to edge ($n = 38$ yr, $\rho = -0.72$ and $p < 0.01$) all decreased through time (Table 3). Number of high severity patches ($n = 38$ yr, $\rho = 0.35$ and $p = 0.02$) (Figure 6) and median perimeter-to-area ratio of high severity patches increased ($n = 38$ yr, $\rho = 0.79$ and $p < 0.01$) (Figure 6, Table 3).

Patch metrics in the Early and Middle periods were not different for any of the patch metrics: mean, median, number, largest, or perimeter-to-area ratio (Figure 7), even though there were fewer years with fire in the Middle period, the years that did burn had large amounts of area burned severely (Figure 2). In contrast, mean, median, number of patches and perimeter-to-area ratio (Figure 7) were similar (except for size of the largest patch) in the Middle and Late periods. In the Early and Late periods, mean, median, largest patch size and perimeter-to-area ratio differed, but there were more high severity patches in the Late period (Figure 7). In all years, there were very large patches on the landscape, with the average largest patch for all years 1,662 ha and the median largest patch for all years 225 ha. Median distance to edge ranged from 30-210 m with a median value of 64 m for all years. Median distances for the time periods are: Early = 116 m, Middle = 95 m, and Late = 42 m. Tree seedling density 12 yr post-fire in severely burned patches decreased with distance from unburned edge (Kruskal-Wallis ANOVA $p = 0.005$). Total tree seedling density 10 m from edge was significantly greater than at 40 m and 80 m ($p = 0.03$ and $p = 0.01$, respectively) (Figure 8). Understory species richness (ANOVA $p = 0.72$) and diversity (ANOVA $p = 0.45$) did not differ as a function of distance from edge (Figure 8).

CHAPTER FOUR

DISCUSSION

Data uniquely valuable for long-term trends in burn severity

Our continuous, spatially explicit record of area and proportion burned severely and patch characteristics of high severity fires 1900 - 2007 provides a useful context for evaluating burn severity in recent decades. Although underutilized, aerial photography has been shown to provide accurate data for spatial patterns of fire perimeters and patch dynamics (Minnich and Chou, 1997; Hessburg *et al.*, 2000; Hessburg *et al.*, 2007) to extend the temporal range beyond what is available from satellite data. Our research is valuable in a broader context as it refines our knowledge of changing fire regimes (Rollins *et al.*, 2001; Baker, 2009; Teske *et al.*, 2012), and adds to our understanding of mixed severity fire regimes (Halofsky *et al.*, 2011; Perry *et al.*, 2011; Haire *et al.*, 2013). This research is especially timely and pertinent for the US northern Rockies where fire extent has increased in recent decades relative to mid 1900s (Westerling *et al.*, 2006; Littell *et al.*, 2009; Spracklen *et al.*, 2009).

Fire through time: comparisons of Early, Middle, and Late

More and larger high severity fires burned Early (1900-1934). Brown *et al*. (1994) found that over the range of elevation and forest types, the total area burned was 1.7 times greater in early years than late, and area burned severely, defined by stand replacing fire, in early years was 1.5 times greater than those of recent years. Others document greater occurrences of fire extent in the pre-settlement time period than of recent (Arno, 1980; Brown *et al.*, 1994; Keane *et al.*, 2008). Rollins et al. (2001) studied fire extent in the SBW and found that 70% of the area burned in their record (1880 - 1996), with 6 years (1889, 1910, 1919, 1929, 1934, and 1988) accounting for 75% of all area burned in the 116 year record. This is congruent with our research that most area burned in just a few years and more area burned in the Early period than either Middle or Late periods. Although some of these studies evaluated fire extent, it is relevant to use as a comparison since area burned severely is highly correlated with area burned (Holden *et al.*, 2011) (Figure 5). Thus, although fire extent has increased in recent decades relative to mid 1900s, both area burned and area burned severely are far less than occurred early in 1900s in our study area.

Rotations for high severity fires were longer than those for other severities, meaning high severity fires burn less often (Table 1). Fire rotations were longer in middle and late relative to early which is similar to what Rollins *et al*. (2001) found. Fire rotations reflect a combined effect of both size and frequency of fires (Agee, 1993). Our results demonstrate that fire patterns in Late years, despite a more natural fire regime, are not yet a return to Early years.

Area and proportion of area burned severely were greater in Late than Middle years for a number of reasons. Morgan *et al*. (2008) documented regional fires with large areas burned in Early years, lesser in Middle years, and some increase in Late years. They attributed the relative lack of fire during the Middle period to fire suppression efforts and climate differences (Morgan *et al.*, 2008). Similarly, both climate and management have likely affected burn severity in forests of the SBW. The subalpine forest ecosystems that dominate there (Rollins *et al.*, 2001) are possibly less affected by past fire exclusion in part because climate is more limiting than fuels in cold forests than in dry forests (Schoennagel *et al.*, 2004). Historically, long fire-free periods are typical in higher elevation regions in the US northern Rockies (Schoennagel *et al*., 2004), which exhibit infrequent, stand-replacing fire (Baker, 2009). This suggests that fire suppression tactics in Middle years and climate (drought) events of large but infrequent high severity fire events may not be significant enough to alter severity patterns in the Late period. Because it is remote, rugged and designated wilderness, the SBW has not been logged and roaded, but extensive fires 1900 - 2007 have likely influenced number of patches and the severity with which those patches burned (Teske *et al.*, 2012), although the effect likely varies with time since fire, vegetation, topography and climate (Teske *et al.*, 2012; Haire *et al.*, 2013; Parks *et al.*, 2013).

Since we hypothesized Late period increases in area burned severely, we also expected increases in size of high severity patches. Instead we found the opposite. Although Early fire years experienced a larger extent of area burned severely and more frequent fires than Middle years, most of the patch characteristics were similar for these two time periods. There were only a few years of fire in the Middle period, but the extent of high severity for those years was great, with area burned severely approaching the threshold of the 90th percentile. The fires that did burn during Middle years exhibited patch characteristics to those of Early years, except that the largest patch was significantly greater in Early than both Middle and Late periods. Middle and Late patch characteristics were very different largely because patch size was decreasing and number of patches was increasing. Early and Late patch characteristics were significantly different, suggesting that the Late period is not yet a return to the patterns we saw in the Early period. The effects of climate and management are inherently entwined in spatial patterns of fire, but research shows for areas that typically experience a stand replacing fire regime or mixed severity fire at higher elevations, fire suppression has little influence on size and severity of fires, and variations of climate are the predominate drivers of high severity fires (Schoennagel *et al.*, 2004).

Like us, Hanson and Odion (2013) found no increase in mean annual or maximum annual patch size for the years 1984-2010 for the whole Sierra Nevada study region. In contrast, Miller *et al*., (2009b) found an increase in high severity patch size in the Sierra Nevada region with mean annual patch size doubling from 2.8 ha (1984-1994) to 5.3 ha (1995-2004), and was positively correlated to size of fire. These trends though were evaluated on a shorter time scale and may not be relevant over a longer time series.

Effects of historical fire on the landscape

We speculate that the extensive high severity fires in Early years have left a lasting legacy of landscape heterogeneity in the SBW, as most of the recent fires have burned outside of areas that burned Early (Figure 1, bottom). The heterogeneous landscape pattern left from previous fires can affect the patterns of future fires by limiting fuels for subsequent fires, which can be defined as self limiting (Parks *et al.*, 2013). Although there is a high level of complexity and variability of these fire-on-fire interactions, evidence suggests that large wildfires often reduce the probability of smaller subsequent fires within the fire perimeter (Teske *et al.*, 2012). Areas with a more 'natural' fire regime tend to display self-limiting characteristics, and the effect should theoretically diminish as time since fire increases, but has not been studied beyond 22 years, and is dependent on site characteristics such as site productivity, vegetation, and severity of previous fires (Parks *et al.*, 2013). The limited amount of high severity reburn in our data suggests that the SBW displays self limiting behavior.

Time since fire and successional stage influence the future severity of fires by mimicking the previous severity in the reburn (Halofsky *et al.*, 2011; Parks *et al.*, 2013), meaning that areas burned with high severity will likely burn again with high severity. We found areas that burned with high severity fire experienced reburns 6% of the time, while areas that burned with all severities experience reburns 38% of the time. Thus, we are seeing fewer reoccurrences of high severity wildfires. Teske *et al.* (2012) found that 15% of the SBW burned in recent years (1984-2007) with only 1% of the area experiencing a re-burn. The SBW has had a long history of high severity fire and a limited extent of reburn (Rollins *et al.*, 2001; Teske *et al.*, 2012) suggesting that areas of reburn are a relatively small portion of the landscape due to the legacy of previous fires. Although a growing amount of research supports this idea of fire frequency and extent limiting subsequent fires (Miller and Urban, 2000; Collins *et al.*, 2009; Teske *et al.*, 2012; Haire *et al.*, 2013; Parks *et al.*, 2013), the length of time evaluated in studies is relatively short especially for some ecoregions where fire return intervals are longer and may not be relevant on a larger geographical scale (Haire *et al.*, 2013).

More and smaller patches of high burn severity in recent decades

Severely burned patches are more numerous and smaller in recent decades. The number of patches shows a dramatic increase after the year 2000. We would expect that if this trend were an artifact of data source, then we should see the increase beginning earlier, in 1984. The largest patch size has decreased through time (Figure 6). We would expect that if this trend an artifact of interpreting aerial photography at longer time-since-fire intervals than MTBS, where patches may appear larger, then HAPS patches would be larger than MTBS for the years of overlap. Although HAPS patches are generally larger than MTBS (Figure 9), our data suggest that this is a legitimate temporal trend through time (Table 3).

The differences in mean and median patch size for MTBS and HAPS are due to the presence of small patches on the landscape. For both metrics there is a high level of variability through time, and even though HAPS and MTBS datasets do not agree particularly well for these metrics, the long-term trends are consistent for the two data sets (Figure 6). Distance to edge also had a decreasing temporal trend. As patch size decreases, than the distance to edge should also decrease. Although patch size and distance to edge area are variable through time, both decrease through time. In contrast, the high perimeter-to-area ratio does reveal an artifact; more unburned islands and more complex perimeters were inferred from satellites than from aerial photography where patch perimeters were manually drawn (Figure 9).

We know that extensive areas have burned through time supporting the notion that previous fires limit the size of subsequent fires (Collins *et al.*, 2009; Teske *et al.*, 2012; Parks *et al.*, 2013), and long term climate and fire research suggests a future of many small fires (Millspaugh *et al.*, 2000). A study of a wilderness area in central Sierra Nevada, California found support for a trend in smaller high severity patches within pine dominated stands attributing it to the heterogeneity from the continued natural fire frequency (Collins and Stephens, 2010). The heterogeneity created by previous fires leaves a lasting legacy on the landscape creating a patch mosaic of different successional stages and variation in fuel suitability which may help to explain the presence of numerous but smaller high severity patches in Late years.

Patches in a mixed severity fire regime

Fires were of mixed severity with 49% of the area burned with high severity; this is different than the dominance by stand replacing fires many describe as characteristic of cold forests (Schoennagel *et al.*, 2004; Baker, 2009). Further, the patch size distribution we found is characteristic of a mixed severity fire regime in which there are many small patches and few large patches (Perry *et al.*, 2011). The heterogeneity of mixed severity fires are characterized by the variation in patch age and structure as a result of previous fire patterns that display an assortment of fire frequency and severity on the landscape (Halofsky *et al.*, 2011; Perry *et al.*, 2011). This heterogeneous mix of fuels and stand structure plays a large role in subsequent fire pattern and severity and may aid in self limiting (Halofsky *et al.*, 2011), but extreme climate and weather conditions often trump the influence of these factors (Schoennagel *et al.*, 2004). Separation of mixed severity fires from other severities has been noted by higher edge to interior ratio of burned patches, and by a spatial mosaic that is augmented with subsequent fires (Halofsky *et al.*, 2011). Mixed severity fires regimes are highly variable making it difficult to quantify characteristics such as: patch characteristics (Collins and Stephens, 2010), the role climate plays, (Halofsky *et al.*, 2011), and how to pinpoint whether the trends are due to the previous fires, historical management, or other factors.

Ecological implications for high severity patches

Although we found that high severity patch sizes are decreasing through time, there are still many large patches on the landscape. The values for largest patch recorded each year in the Early period range from 5 - 26,000 ha whereas in the Late period high severity patches range from 2 - 2,800 ha. The patch mosaic created by wildfires is widely discussed as a key factor in understanding post-fire succession and the spatial patterns characterized by size, shape, and severity are important to understanding post fire vegetation response (Turner *et al.*, 1997; Baker, 2009), and has long been associated with the community recovery. Patch size is important indicator of regeneration post-fire because of the environmental occurrences affecting nutrient availability, light, space, and competition that occur near the unburned edge (Angelini and Silliman, 2012). Additionally, mapping the unburned islands, which is currently not common practice, may aid in understanding post-fire regeneration (Kolden *et al.*, 2012).

Delayed establishment and lower densities of conifer seedlings have been identified in the interiors of large patches and as a function of distance to edge (Greene and Johnson, 2000; Donato *et al.*, 2009), and vegetation response is directly related to both burn severity and patch size. Results from one large fire in the Greater Yellowstone area show larger patch sizes had lower species richness and lower herbaceous cover (Turner *et al.*, 1997). We found similar trends that seedling densities decreased as the distance from unburned edge increased, showing that the interior of large high severity patches have delayed seedling establishment. Turner et al. (1997) found that after 50 m tree seedling density declined. Baker (2009) suggested that at 50 m ~15% of lodgepole pine seeds are dispersed, or at 20 m 50% of seeds are dispersed. Our results suggest that distances greater than 40 m had significant decreases in tree seedling establishment 12 years post-fire (Figure 8). Tree seedling regeneration relies heavily on seed dispersal from an unburned edge and is directly related to seed dispersal distances. On the other hand, many understory vegetation species can regenerate via sprouting or are well evolved to wind dispersed seeds (Lentile *et al.*, 2007). Our research shows that there are many large patches on the landscape, which are large enough to reflect delayed seedling regeneration post-fire, but the decreasing trend in patch size and distances to edge may have a positive effect for ecosystem recovery of conifers post-fire.

CHAPTER FIVE

OTHER CONSIDERATIONS

Our remotely sensed data provide detailed information about perimeter and severity of burned patches but have limitations. Widely used, dNBR has proven effective in mapping burn severity in some vegetation types (Allen and Sorbel, 2008), but interpretation across multiple vegetation and topographic conditions can be problematic. Severity inferences from remotely sensed indexes such as NBR, dNBR and RdNBR receive criticisms that fire severity is a qualitative measurement and therefore cannot be quantified accurately and consistently, suggesting that the indices were designed not to evaluate severity but to detect burned areas (Roy *et al.*, 2006). To bypass the disadvantage of the relatively short time series of satellite data, we merged it with carefully interpreted aerial photography. We focused on high burn severity because those areas are ecologically important and are more reliably detected remotely and in the field (Hudak *et al.*, 2007), and most likely to appear in fire atlas data. Neither our fire atlas data nor aerial photography have extensive field data for accuracy assessment, but the agreement between the HAPS and MTBS data is encouraging. Our data share strengths and limitations of fire atlases (Morgan *et al.*, In Press). Fire atlases provide spatially explicit fire perimeters, something that other fire-history reconstruction methods can't achieve as well. Fire atlases are limiting in that not all fires are represented in the atlas, particularly the smaller fires that contribute most to the patch number metric. Although not all small fires (< 40 ha) get recorded (Rollins *et al.*, 2001; Shapiro-Miller *et al.*, 2007), most of the largest fires are included and these are responsible for the majority of area burned.

The limitations of inferring burn severity from aerial photographs arise in assessing burn severity as a function of time-since-fire. Our earliest mapped fires occurred in 1900, but the earliest available aerial photography date is from the 1930s. If photography interpretation is too long post-fire, the signature of a given fire begins to disappear with ecological recovery and re-vegetation. Interpretation immediately post-fire is the most accurate since patches may appear larger and more severe with time-since-fire, as standing snags fall (Flanagan *et al.*, 2004) and red needles from scorch disappear from the perimeter trees. On the other hand, satellite detection methods of burned perimeters may be better at picking up finer detail and heterogeneity within patches (Figure 9), and often pick up the unburned islands better than fire atlases or aerial photography depending on spatial resolution (Shapiro-Miller *et al.*, 2007; Kolden *et al.*, 2012). There are inherent limitations with combining the datasets. High severity fires are the easiest to detect leaving large openings with a high percentage of tree canopy mortality that are more clearly delineated than other severities in both satellite and aerial photography detection (Hudak *et al.*, 2007; Miller and Thode, 2007). Additionally, there are a limited number of aerial photographs available for this study given the resolution and the dates of our study. Some of the error is unavoidable, but historical aerial photos provide the best available information for this time period. Despite these limitations, the richness of the data is immensely valuable as a relatively long-term record of patches created by fires. Although our data extent is much longer than contemporary studies utilizing only satellite data, 108 years may still be too short relative for the historical fire return intervals in the SBW. Similarly, although the SBW is one of the largest wilderness areas in the conterminous U.S., it may still be too small to extrapolate severe fire patterns to other locations outside of the study area. Indeed, the pattern of severe fire presence in the Early period appears to persist as patterns of fire absence in the Middle and an increase in Late period (Figure 1, bottom row of panels).

CHAPTER SIX

CONCLUSION

Our case study is valuable as it provides a detailed look into fire patterns over 108 years bridging the entire 20th century with changing fire management. Our research helps put the spatial patterns of high severity fires into a broader temporal and spatial context for landscape ecology of fire regimes (McKenzie *et al*., 2011), which helps to better understand the historical range of variability (Landres *et al.*, 1999; Keane *et al.*, 2009). High severity fires were extensive in the 20th century and are likely to be extensive in the future (Haire *et al.*, 2013), though fires may be self-limiting. Our records show a legacy of historical fire with large, high severity patches that have been replaced by more and smaller high severity patches. There is a need to understand the causes and consequences of burn severity, particularly in complex terrain and in mixed conifer forests where fires often burn with mixed severity and to better understand the role of burn severity in a changing climate. Additionally, there is a need to explore how the role of burn severity and shifting patterns of high severity patches affect the recovery and ecology of the post-fire setting in different locations. Burn severity is a poorly understood aspect of fire regimes despite the importance for ecological processes (Turner *et al.*, 1997; Lentile *et al.*, 2007; Keeley, 2009b). This study helps to understand the spatial and temporal patterns of high severity patches on the landscape, but there is still much to learn about the interactions and drivers of patch patterns on the landscape.

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FIGURES

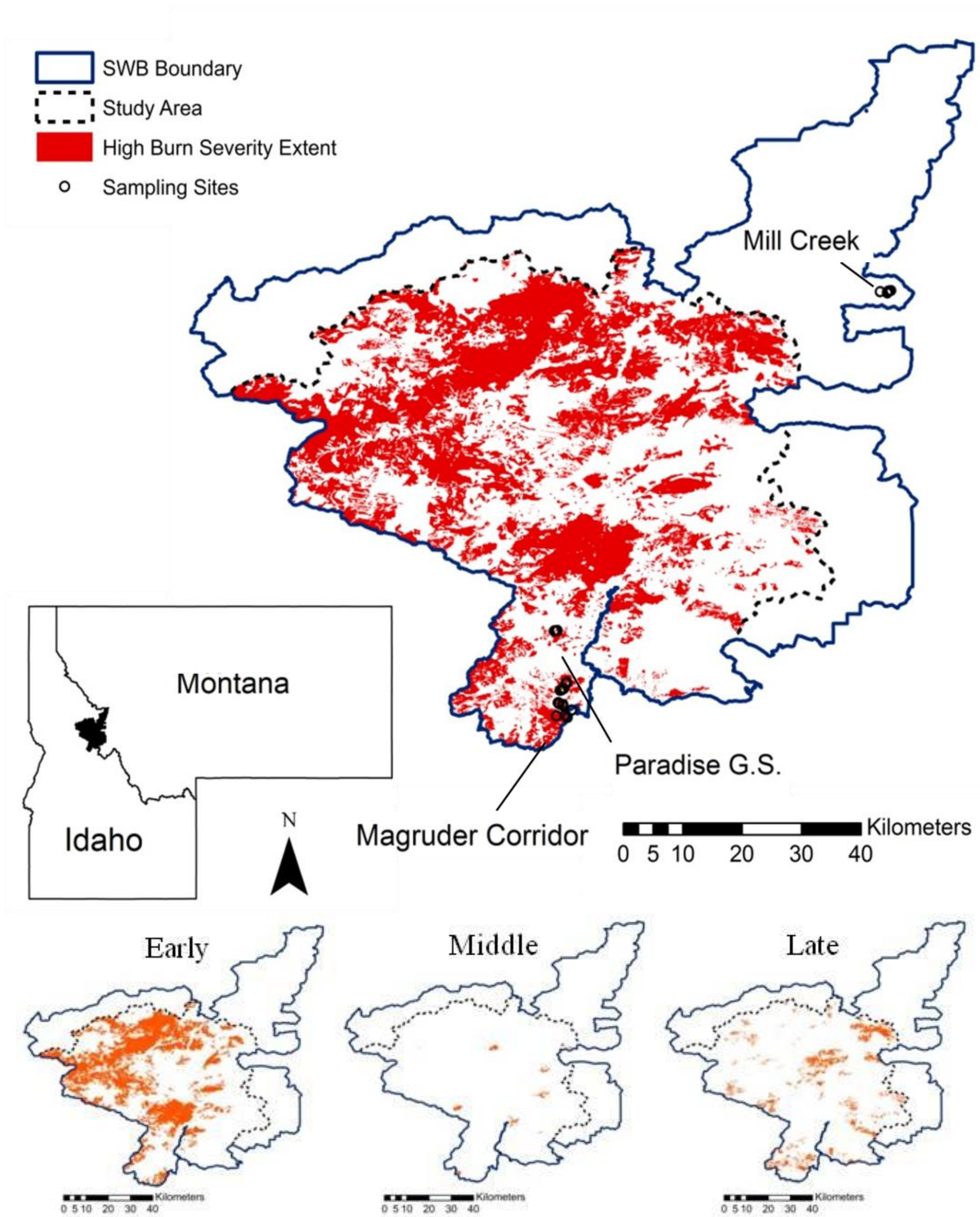

Figure 1. The Selway-Bitterroot Wilderness Area on the border of Idaho and Montana. Study area encompasses 346,304 ha within the Selway-Bitterroot Wilderness Area. Colored area represents only high severity burn extent from 1900-2007 (Top). Sampling sites were accessed from Mill Creek, Paradise Guard Station, and Magruder Corridor (Top). High severity burn extent divided by the fire management time periods: Early (1900-1934), Middle (1935-1974), and Late (1975-2007) (Bottom).

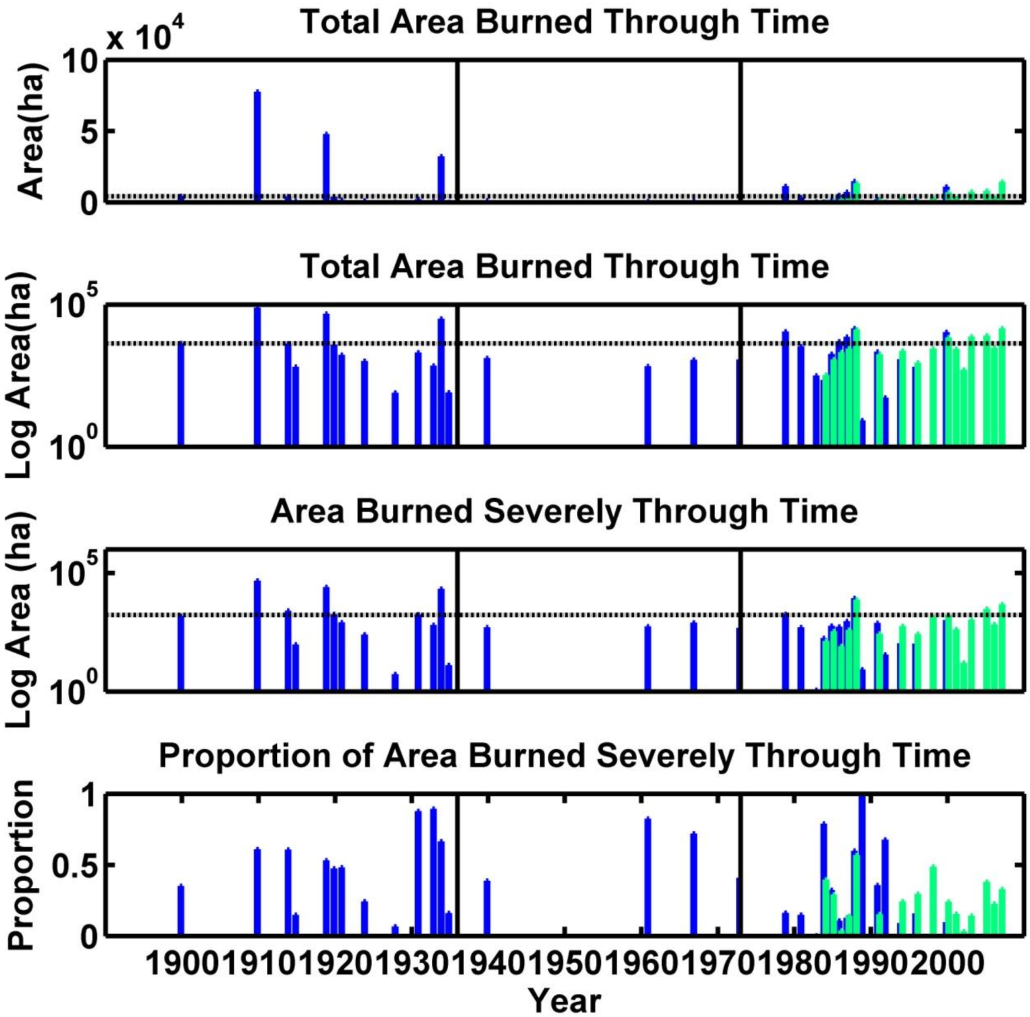

Figure 2. Total area burned through time on a natural scale (ha) (Top), total area burned through time on a log scale (Second Down) area burned severely on a log scale (ha) (Third Down), and proportion of area burned severely (Bottom) through time for the years 1900 – 2007 for 346,304 ha in the Selway-Bitterroot Wilderness Area. HAPS data categorized high severity as >70% tree canopy mortality, while high severity for MTBS is based on RdNBR. The dashed line in total area burned and area burned severely represents the 90th percentile of area burned. HAPS data represented in dark blue and MTBS data represented in light green. Black bars divide the time sequence into: Early (1900 - 1934), Middle (1935 – 1974), and Late (1975 – 2007).

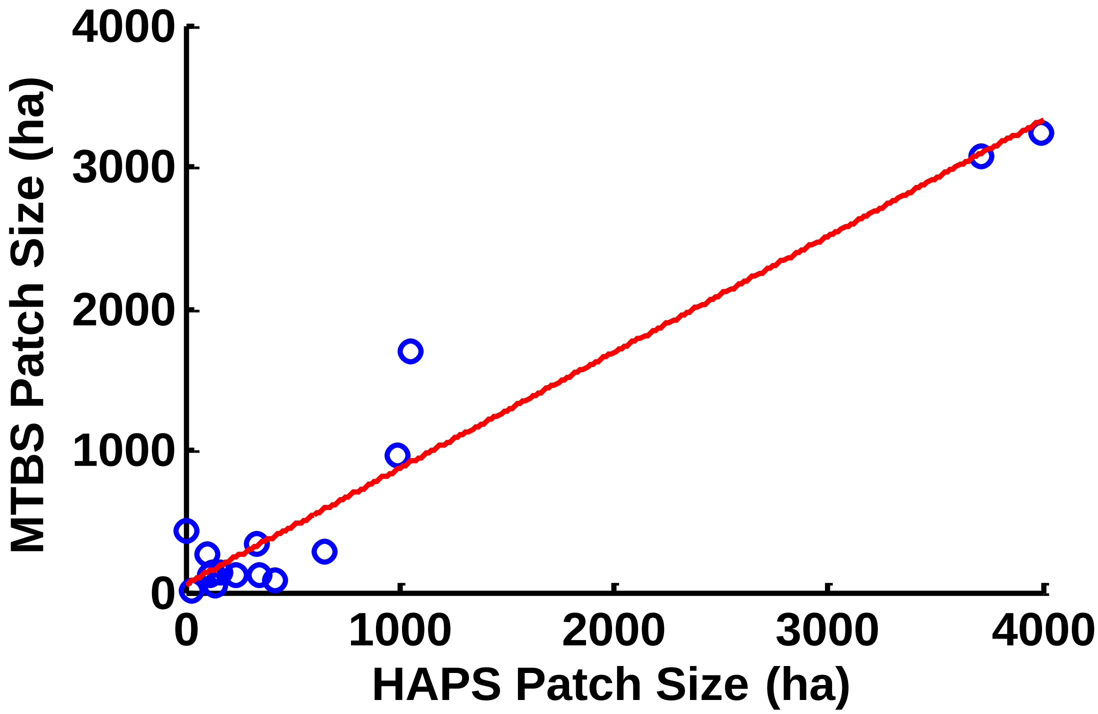

Figure 3. Comparison of size of 16 patches burned with high severity as mapped from HAPS and MTBS (Spearman's Rank Correlation Test was used $\rho = 0.5941$ and $p = 0.01$). There were 9 years (1984, 1985, 1986, 1987, 1988, 1991, 1994, 1996, and 2000) of overlap between both data sets.

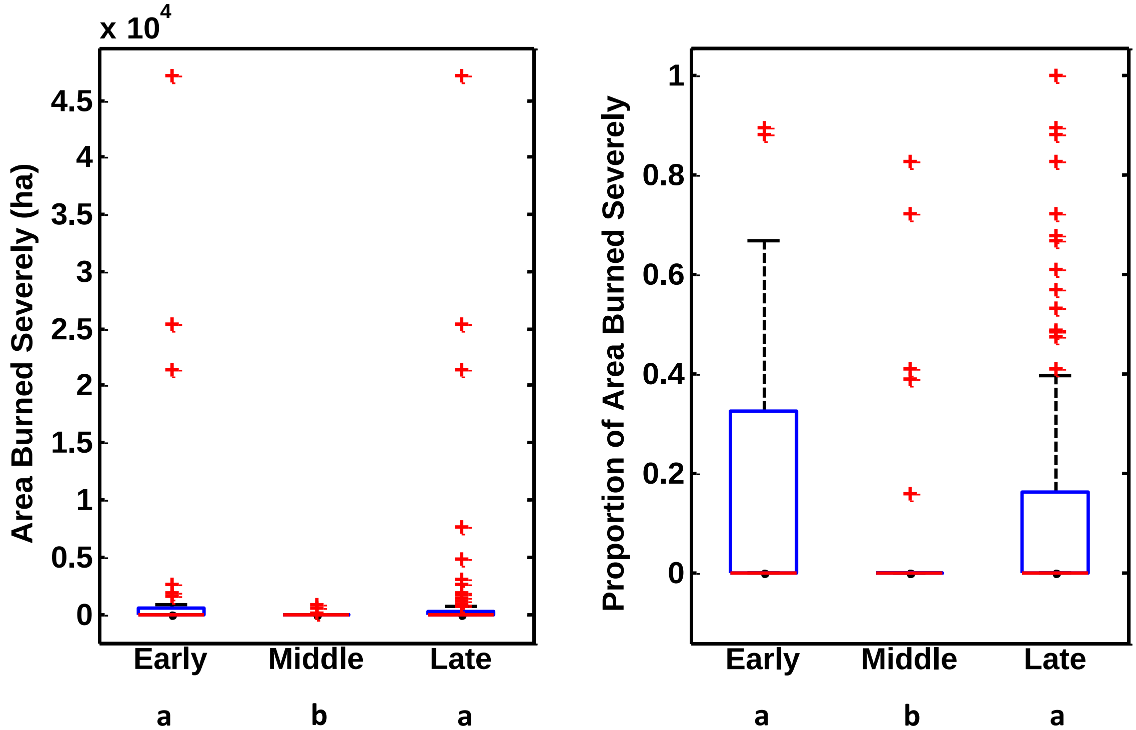

Figure 4. Area (ha) (Left) and proportion of area burned severely (Right) for the management time periods: Early (1900 – 1934), Middle (1935 – 1974), and Late (1975 – 2007). Wilcoxon rank sum was used to compare the time periods. Significant differences between time periods are denoted with a change in letter combinations. The same letter represents no difference between samples

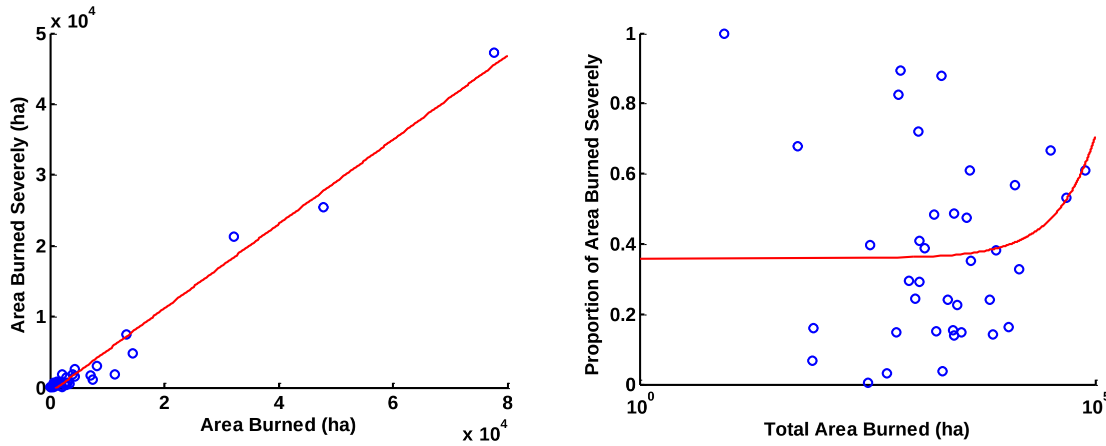

Figure 5. Area burned (ha) and area burned severely (ha) are highly correlated (Left). A linear model was fit and statistics were performed using Spearman's rank correlation $\rho = 0.88$ and $p = 0$. Total area burned (ha) and proportion of area burned severely are not correlated (Right). A non-linear model was fit and statistics were performed using Spearman's rank correlation $\rho = 0.07$ and $p = 0.66$.

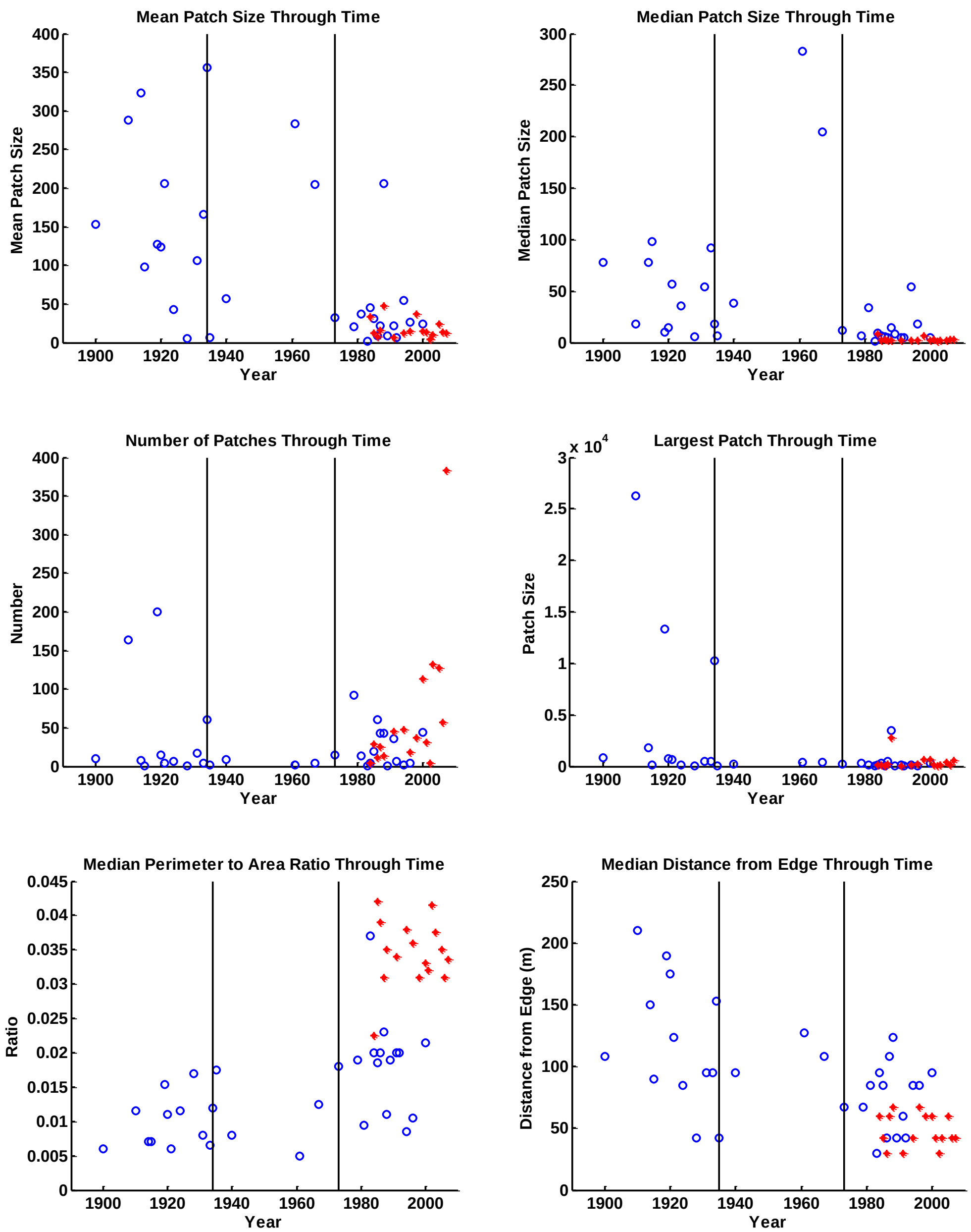

Figure 6. Mean patch size (ha), median patch size (ha),number of patches, largest patch size (ha), perimeter-to-area ratio, and distance to edge (m) using both HAPS data (blue circles) and MTBS data (red stars) for the years 1900-2007. Black bars represent the three time periods: Early (1900 – 1934), Middle (1935 – 1974), and Late (1975 – 2007).

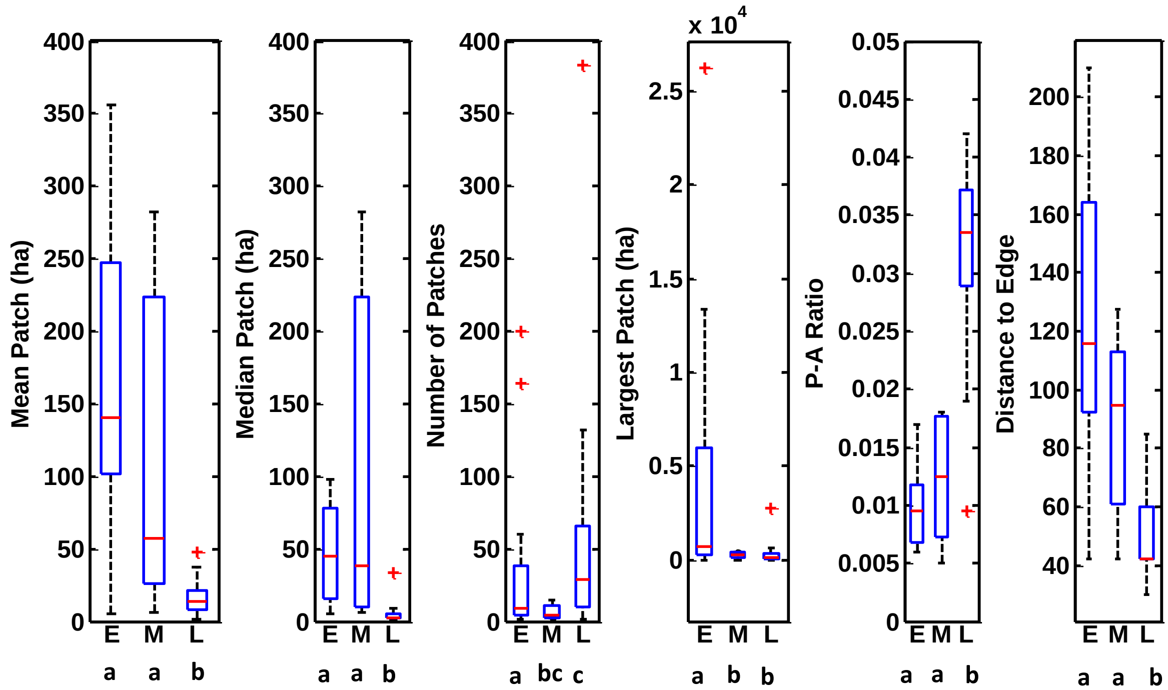

Figure 7. Box plots of mean, median, number, largest patch, perimeter to area ratio, and distance to edge, for the three fire management periods: Early (1900-1934), Middle (1935-1974), and Late (1975-2007) using combined data. Wilcoxon rank sum test was used to compare sample medians between each of the time periods. Significant differences are represented by a combination of different letters. The same letter represents no difference between samples.

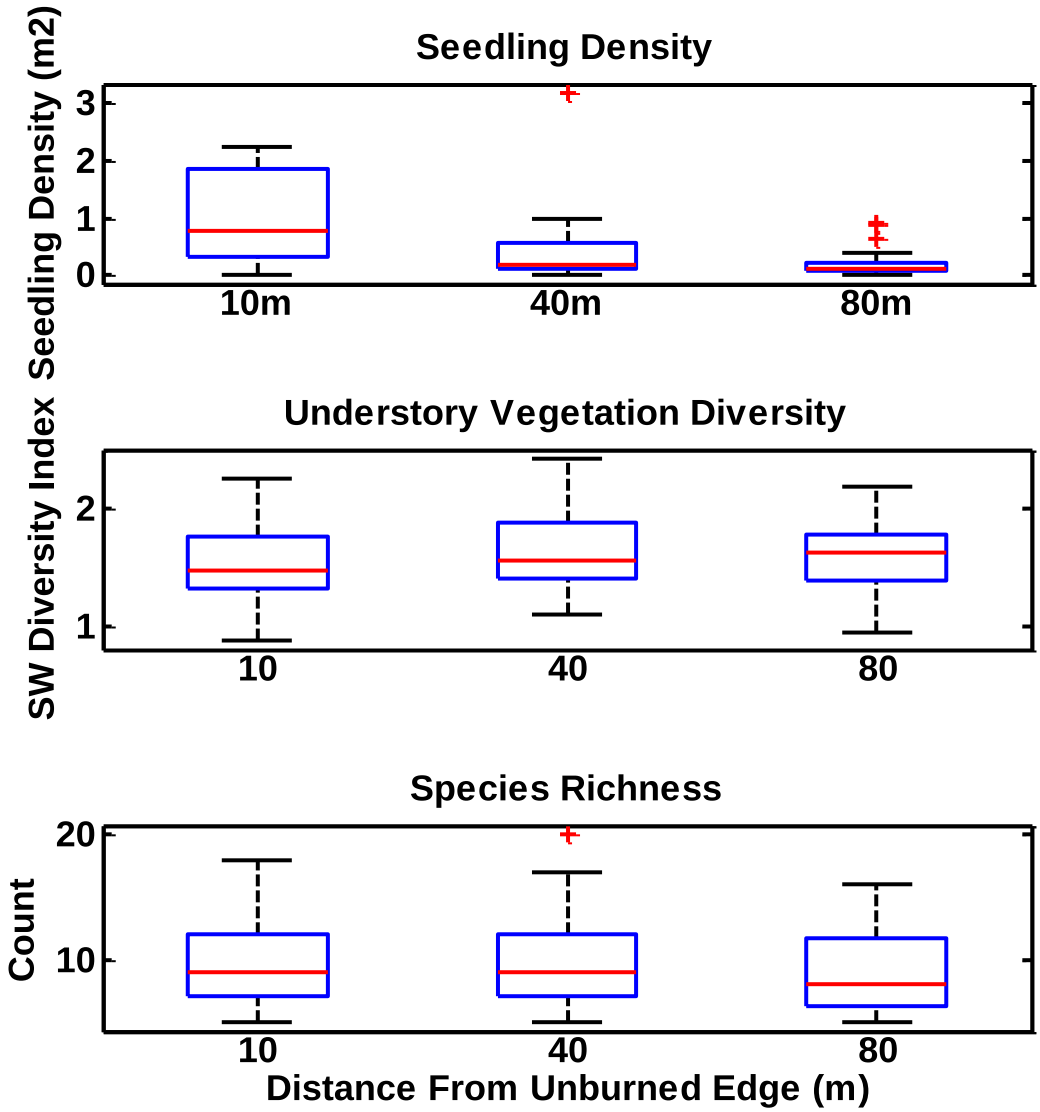

Figure 8. Tree seedling density (#/m^2) (Top) species diversity using Shannon Wiener Diversity Index (Middle) and species richness (Bottom) for each plot (n = 20) as a function of distance from unburned edge at 10 m, 40 m, and 80 m.

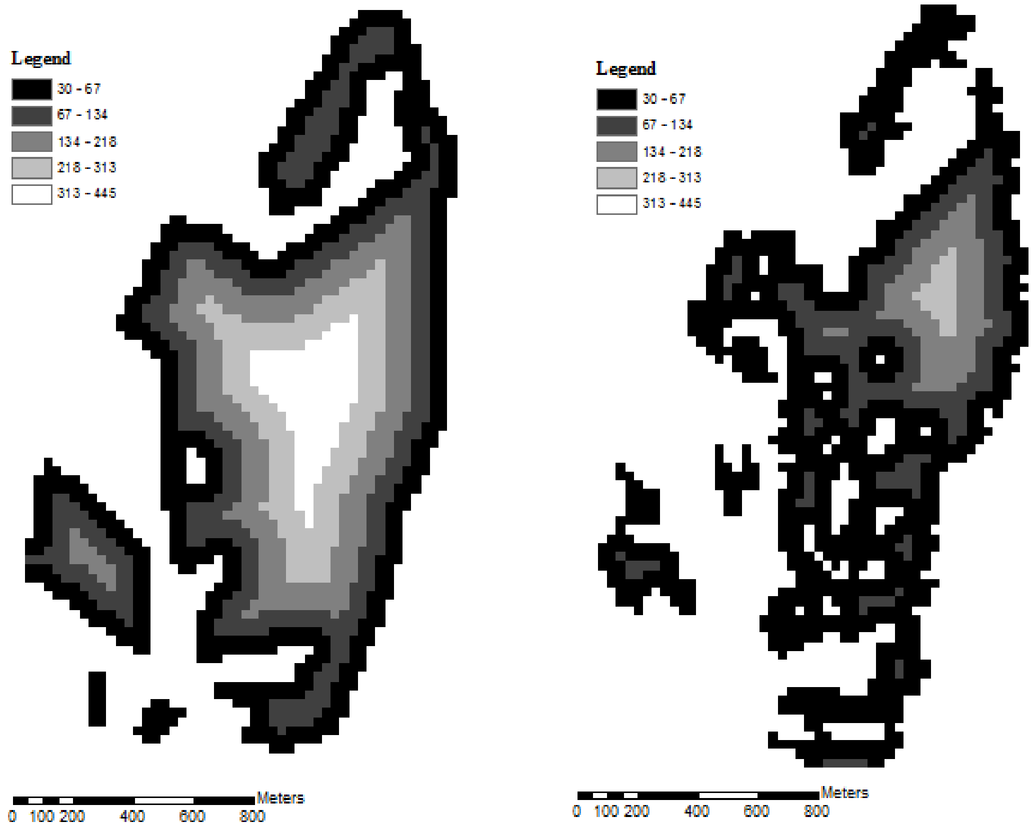

Figure 9. Distance to edge (m) for the same patch burned with high severity in 1984 from HAPS (Left) and MTBS (right) data. Mean and median distance to edge were 133 m and 95 m for HAPS (Left). Mean and median distance to edge were 70 m and 60 m for MTBS (Right). The perimeter-to-area ratio for the largest patch for HAPS was 0.005 and the sum of all the patches was 0.095 (left). For MTBS the perimeter-to-area ratio for the largest patch was 0.01 and the total burned area was 0.096 (right). This patch, the only patch burned in our study area in 1984, was mapped by both HAPS and MTBS, and is a good representation of the differences in mapping techniques.

TABLES

Table 1. Number of years with high severity burned area, number of years exceeding the 90th percentile of area burned severely (1,700 ha); 10 years of highest proportion of area burned severely, mean and median patch size (ha) of high severity patches, and fire rotations for high severity and all severities for the combined data.

Time Period	Number of Fires	Number of Fires Exceeding the 90th Percentile	Amount of Area Burned Severely (ha)	10 Years of Highest Proportion of Area Burned Severely	Mean Patch Size (ha)	Median Patch Size (ha)	Fire Rotation	High Severity Fire Rotation
Early 1900-1934	12	6	103,633	5	140	45	113	110
Middle 1935-1974	5	0	2,390	2	57	38	5650	3888
Late 1975-2007	21	5	25,174	3	13	3	440	218
All Years	38	11	131,198	10	28	7	282	194

Table 2. Patch characteristics compared for the nine years of overlap between the HAPS and MTBS datasets using the Wilcoxon Rank Sum tests.

Patch Characteristic	**p value**
Mean	0.05
Median	< 0.01
Number	0.77
Largest	0.86
Perimeter-to-Area Ratio	< 0.01
Distance to Edge	< 0.01

Table 3. Characteristics of high severity burned patches in three time periods for HAPS (9 years of overlap), MTBS (9 years of overlap) and combined data (38 years, 1900-2007) sets. Rho and p values for Spearman's Rank Correlation were calculated using MATLAB software.

	Aerial Photography		MTBS		Combined Data Set	
	rho	p	rho	p	rho	p
Mean	0	1	-0.15	0.7	-0.63	< 0.01
Median	0.13	0.74	-0.2	0.55	-0.73	< 0.01
Number	0.01	0.98	0.35	0.35	0.35	0.02
Largest Patch Size	-0.18	0.63	-0.01	0.98	-0.34	0.03
Perimeter-to-Area Ratio	0	1	0.66	0.05	0.79	< 0.01
Distance to Edge	0	1	0.24	0.51	-0.72	< 0.01